SOURCE-PATHWAY-RECEPTOR-CONSEQUENCE CONCEPTUAL MODEL FOR FLOODING AND TSUNAMI AT THE AYAMAMA RIVER AND COASTAL AREA

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

İLKER ÇOBAN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

FEBRUARY 2021

Approval of the thesis:

SOURCE-PATHWAY-RECEPTOR-CONSEQUENCE CONCEPTUAL MODEL FOR FLOODING AND TSUNAMI AT THE AYAMAMA RIVER AND COASTAL AREA

submitted by **İLKER ÇOBAN** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering, Middle East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Ahmet Türer
Head of the Department, **Civil Engineering**

Assist. Prof. Dr. Gülizar Özyurt Tarakcıoğlu
Supervisor, **Civil Engineering, METU**

Examining Committee Members:

Prof. Dr. Ahmet Cevdet Yalçıner
Civil Eng, METU

Assist. Prof. Dr. Gülizar Özyurt Tarakcıoğlu
Civil Eng., METU

Prof. Dr. İsmail Yücel
Civil Eng., METU

Assoc. Prof. Dr. Orhan Gündüz
Environmental Eng., Dokuz Eylül Uni.

Assist. Prof. Dr. Cüneyt Baykal
Civil Eng., METU

Date: 15.02.2021

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : İlker Çoban

Signature :

ABSTRACT

SOURCE-PATHWAY-RECEPTOR-CONSEQUENCE CONCEPTUAL MODEL FOR FLOODING AND TSUNAMI AT THE AYAMAMA RIVER AND COASTAL AREA

Çoban, İlker
Master of Science, Civil Engineering
Supervisor : Assist. Prof. Dr. Gülizar Özyurt Tarakcıoğlu

February 2021, 112 pages

There are many sources of flooding of river basins and coastal areas such as precipitation, tsunami, and storm surge. When assessing the risk of these hazards, it is important to understand the source but also to define the flood plain characteristics considering links between elements of flood plain. Although numerical hydraulic models are widely used to evaluate the risk quantitatively, description of the multiple links between exposure and susceptibility of a specific location or population is not achieved easily. Also, they can be limited by data, quality of resources and computational tools. Source-Pathway-Receptor-Consequence (SPRC) conceptual model is an alternative method to define flood plain that describes relationships of each element inside as a snapshot. SPRC conceptual model aims to provide better understanding of the study area, existing flood protection structures, the relationship of the flood source, land use and all stakeholders. The aim of this study is to analyze the tsunami inundation and river flooding at the Ayamama River and Bakırköy coastline of Istanbul by using SPRC conceptual model. This study area has experienced multiple river flood events in the last 20 years and the coastal area is highly prone to tsunami. While SPRC model represents an alternative view for coastal flood plain, HEC-RAS and NAMI DANCE numerical models are also constructed for this area in order to compare different approaches of modelling. HEC-RAS model was run with 500 year return period flood and NAMI DANCE model was run with expected land slide source in the Büyükçekmece coast. For numerical models, CORINE database, gauge observations, meteorological data, numerical elevation model are used. For the study area, the results highlighted those locations which act as pathway for multiple receptors. These locations can be assumed as suitable locations for protection measures. Output of the studies showed that although SPRC models cannot provide a quantitative analysis of the critical areas, it can be an efficient way to describe the propagation of flood over a complex flood plain for different type of flood sources.

Keywords: SPRC, Tsunami, Flood Risk, Ayamama River, NAMI DANCE, HEC-RAS

ÖZ

AYAMAMA NEHRİ VE KIYI ALANINDA TSUNAMİ VE NEHİR TAŞKINI İÇİN KAYNAK-YOL-ALICI-SONUÇ KAVRAMSAL MODELİ UYGULAMASI

Çoban, İlker
Yüksek Lisans, İnşaat Mühendisliği
Tez Yöneticisi: Dr. Öğr. Üyesi Gülizar Özyurt Tarakcıoğlu

Şubat 2021, 112 sayfa

Nehir havzalarında ve kıyı alanlarında yağış, tsunami ve fırtına gibi birçok sel kaynağı vardır. Bu tehlikelerin riskini değerlendirirken, fırtına kaynağını anlamak ve aynı zamanda taşkın alanının karakteristiklerini ögeler arasındaki bağlantıları dikkate alarak tanımlamak da önemlidir. Sayısal hidrolik modeler riski değerlendirmek için yaygın olarak kullanılsa da, belirli bir yerin veya popülasyonun taşkına maruziyeti ve duyarlılığı arasındaki çoklu bağlantıların açıklaması kolayca elde edilemez. Ayrıca, bunlar veri, kaynağın kalitesi ve hesaplama araçlarıyla sınırlandırılabilirler. Kaynak-Yol-Alıcı-Sonuç (KYAS) kavramsal modeli, içindeki her bir öğenin ilişkilerini anlık görüntü olarak tanımlayan taşkın alanını tanımlamak için alternatif bir yöntemdir. KYAS kavramsal modeli, çalışma alanını, mevcut taşkın koruma yapılarını, taşkın kaynağının arazi ve tüm paydaşlarla ilişkisinin daha iyi anlaşılmasını amaçlamaktadır. Bu çalışmanın amacı, İstanbul'un Ayamama Nehri ve Bakırköy kıyı şeridi kısmınlarındaki nehir ve tsunami taşkınlarını KYAS kavramsal modelini kullanarak analiz etmektir. Bu çalışma alanında son 20 yılda birden fazla nehir taşkını yaşanmıştır ve kıyı bölgesi de tsunamiye oldukça

kırılgandır. KYAS modeli kıyı taşkın alanının görünümünü iyi bir alternatif olarak temsil ederken, farklı modelleme yaklaşımlarını karşılaştırmak için bu alanda HEC-RAS ve NAMI DANCE sayısal modelleri de oluşturulmuştur. HEC-RAS modeli 500 yıl dönüş periyodu taşkın debisiyle çalıştırılmış ve NAMI DANCE modeli Büyükçekmece sahilinde beklenen toprak kayması kaynağına bağlı çalıştırılmıştır. Sayısal modeler için CORINE veri tabanı, ölçüm gözlemleri, meteorolojik veriler, sayısal yükseklik modeli kullanılmaktadır. Çalışma alanı için sonuçlar, birden fazla alıcı için yol görevi gören konumları vurgulamaktadır. Bu konumlar, koruma önlemleri almak için uygun yerler olarak kabul edilebilir. Çalışmaların çıktısı, KYAS modellerinin kritik alanların nicel bir analizini sağlayamasa da, farklı taşkın kaynakları için karmaşık bir taşkın alanı üzerinde yayılımı tanımlamak için etkili bir yol olabileceğini göstermiştir.

Anahtar Kelimeler: SPRC, Ayamama Nehri, Sel Taşkını, Tsunami

To my beloved mother,

ACKNOWLEDGMENTS

I would like to express my sincerest gratitude to my supervisor Dr. Gülizar Özyurt Tarakcıoğlu. I have learned many things from her. She has always been understanding and helpful to me. I am thankful to be her student. Without her knowledge and support, this study couldn't be completed.

I would like to thank Dr. Ahmet Cevdet Yalçıner, who has always supported me before and during my study. His encouraging attitude against his students and me always helped to go one step further. His knowledge and support opened a new window for me.

I would like to thank Dr. Ayşen Ergin, Dr. Işıkhan Güler and Dr. Cüneyt Baykal for sharing their knowledge and experiences with me. All of my teachers showed the light of Coastal Engineering through my graduate study. It was an honor to be a student of the people above.

I would like to thank Dr. Gökhan Güler and G. Güney Doğan for their support. They always helped me whenever I feel stucked. Their guidance played an important role in making this study happen.

I would like to thank my friends from Coastal Engineering family, Cem Bingöl, Kadir Karakaş, Mert Yaman, Can Özsoy, Aslıhan Devran, Barış Ufuk Şentürk, Sedat Gözlet, Deniz Koray Göral, Emre Yıldırım, Arda Çiçek, Semih Batuhan Çandır, Ghazal Khodkar and Bora Yalçıner for being in my life and all of our memories.

I would like to thank my friends Emre Hesap, Mert Oytun, Halil Mutlu, Kasımcan Sarıkaya and Eylem Özkeleş for their supports.

Thanks to my dear cat, Minnak, for being in my life. Without his bites, I wouldn't be awake while this study came out.

One final thanks to my beloved mother, for everything she did for me.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS

CMN	Center Marmara Fault
CN	Curve Number
DEM	Digital Elevation Model
GEBCO	General Bathymetric Chart of the Oceans
GIS	Geographic Information Systems
HEC-RAS	Hydrologic Engineering Center's River Analysis System
LSBC	Land Slide Büyükçekmece
LST	Land Slide Tuzla
LSY	Land Slide Yenikapı
NAF	North Anatolian Fault
PIN	Prince Islands Normal Fault
SPRC	Source-Pathway-Receptor-Consequence

LIST OF SYMBOLS

SYMBOLS	
A	Area of Watershed,
D	Rain Duration That Causes Flood
h	Elevation difference for each 2 point
K	Seasonal Coefficient
L	Length of the River
l	One tenth of the lenth of the River
Q_p	Peak Discharge
S	Harmonic Slope
T_c	Gathering time of water
T_p	Peak Time
T_r	Ending time of hydrograph

CHAPTER 1

INTRODUCTION

From the beginning of the humanity, people construct their lives near coastal areas, and deal with the natural hazards against their civilizations. Thus, people tried to fight against nature. Tsunamis, river floods, hurricanes, sea level rise and pollution can be considered as the major dangers in coastal areas. These hazards cause damage to human lives, coastal structures, neighborhoods and natural areas. With the development of hydraulic and coastal engineering, Geographical Information Systems (GIS), modeling, improvement of meteorological data and various inventions, people began to menage the risks associated with these hazards. Identifying the risks of hazards is the basis of disaster management.

When the flow rate exceeds the capacity of river channel, excess amount of water spills over its banks and spread over area. It might cause damage around the river basin. This process is called river flood. Heavy rainfall, overflowing rivers, broken dams, steep channels, insufficient cross sections, bridges and other structures may lead to flooding of rivers (Nelson, 2018). Flooding is not only a problem for rivers, but also a problem for coastal areas. Sea can flood the land in many ways. High tides, overtopping, breaching barriers can be count as coastal flooding ways. The reason of coastal flooding are storms, sea level rise and tsunamis. Tsunami and river flood are the hazards considered in this study.

Models can be used to produce flood and flood-risk maps for specified events. The management of these risks requires understanding the flood system as it responds to a range of planned and unplanned interventions (e.g., better defenses, floodplain development) as well as external changes. Flood risk studies conceptualize the floodplain usually in to components; flood defenses that prevent or reduce the floodwater and the floodplain behind the defenses which is at risk from flooding.

Numerical hydraulic models are widely used to evaluate the risk quantitatively by defining hydraulic boundary conditions and integrate the flood defenses to determine the flood probabilities and damages in the floodplain. However, numerical models can be limited by data, quality of resources and computational tools. In addition, the description of the flood plain in numerical models usually does not represent the complexity and connectedness of components of the system such as multiple links between exposure and susceptibility of a specific location or population. For better understanding of the study area, existing flood protection structures, the relationship of the flood source, flood protection structures, land area and all stakeholders a conceptual approach is needed. In order to frame the study area, area's main problem, fill the gaps between the source and the flood area, Source-Pathway-Receptor-Consequence (SPRC) conceptual model can applied as an alternative method in flood risk studies (Narayan et al., 2014).

The SPRC model provides a methodology to present a snapshot of the floodplain state that is composed of elements; source, pathway or receptor (Narayan et al., 2014). Since the definition of source, pathway and receptor is relative, each element can be described dynamically according to its importance in studies, classification of an element (pathway or receptor) can be discussed based on the focus of the study. The main advantage of SPRC model comes from this approach. The relationships of the adjacent places in terms of flood propagation are not considered in detail in numerical models for assessing the risks so a valuable information regarding flood plain is usually lost. However, SPRC aims to achieve a more comprehensive description of floodplain consisting of multiple possible source-pathway-receptor linkages while still describing the risk assessment process following the event-exposure-susceptibility definitions. Thus, SPRC model can provide valuable baseline for impact assessment as well as strong and weak pathways and possible solution points. Additionally, as a preliminary approach to floodplain, SPRC conceptual model offers quick and credible results prior to advanced numerical models with high data requirements. This conceptual model is used in coastal flooding (storms) and river flooding studies previously in Europe, but the model has not been used to describe a tsunami event based on literature study done for this study. Similarly, the SPRC model study as a floodplain analysis has not been done in Turkey before.

The aim of this study is to analyze the tsunami inundation and river flooding at the Ayamama River and Bakırköy coastline by using Source-Pathway-Receptor-Consequence (SPRC) conceptual model that presents an alternative description of floodplain by describing the flood risk propagation across the area. Then, SPRC model is compared to the results of numerical models applied to this region (Hydrologic Engineering Center's River Analysis System (HEC-RAS) and NAMI DANCE models). HEC-RAS model was run with 500 year return period flood and NAMI DANCE model was run with expected land slide source in the Büyükçekmece coast. In the end of this study, applicability of SPRC model for riverine and coastal floods at an urban area in Turkey, its advantages and disadvantages, and comparison of models are presented.

In this study, literature review on SPRC and applications, past tsunamis and tsunami models in Marmara Sea, and studies on floods in Ayamama River are summarized in Chapter 2. Further details in study area and data, the applications of HEC-RAS, NAMI DANCE and SPRC models, and detailed methodology is presented in Chapter 3. Chapter 4 contains the results of the study and further discussions about results and finally, Chapter 5 summarizes the findings of this study and further studies that can be done in future.

1.1 Study Area

İstanbul is the most populated city in Turkey with more than 15 million people (TUİK, 2020) and home to 40% of the industrial facilities in Turkey (Durukal et al., 2008). Thus, İstanbul can be considered as one of the most strategic cities in Turkey. Being one of 39 municipalities in İstanbul, Bakırköy is a crowded and highly visited one. On the western side, Basınköy İstanbul Street; on the northern side, D-100 road;

on the eastern side Prof. Dr. Turan Güneş Street and on the southern side Marmara Sea limits Bakırköy. In Bakırköy, structures and facilities like Atatürk Airport, shopping centers, marinas, beaches, social facilities, fair centers, green and forest areas exist. Being passed by three different rivers (Ayamama, Çavuşbaşı and Çırpıcı Rivers) and neighbor to the sea, Bakırköy is a potential flood area. In 2009, more than 500 year return period of precipitation event happened in the Ayamama River (Demir, 2010), people died and properties take damage in this fatal disaster. Since İstanbul is close to the North Anatolian Fault, Prince Islands Fault (PIN), Center Marmara Fault (CMN) and possible landslide locations like Yenikapı (LSY), Büyükçekmece (LSBC) and Tuzla (LST), shores of İstanbul is in danger of Tsunami hazard (Hebert et al., 2005; Yalçıner et al., 2020). By combining all these factors; Bakırköy coasts can be considered as vulnerable area. A possible tsunami or river flood may cause property loses, even deaths as the previous events. Area modeled in this study extends to 41.204926 degrees at the North, 40.932081 degrees at the South, 28.775811 degrees at the West and 28.929874 degrees at the East. Project area is approximately 312 kilometer square. Main focus in the study area is the Ayamama River and the Coastline (Figure 1-1).

(a)

(b)

Figure 1-1. a. Turkey Map (www.maps.com), b. Positions of Coastlline and the Ayamama River in the study area (Satellite view)

CHAPTER 2

LITERATURE REVIEW

In Chapter 2, previous studies about tsunami events in Marmara Sea, flood events in Ayamama River, and literature on SPRC model are presented

2.1 Tsunami Events And Research in Marmara Sea

Historically, Marmara Sea is exposed to many tsunamis. More than 30 tsunamis are reported between AD 120 and 1999 (Yalçıner et al., 2002). Some of these tsunamis affected the zone of Ayamama River. Between 477 and 480, a tsunami damaged coastal areas in İstanbul (Guidoboni et al., 1994; Ambraseys and Finkel, 1991). In 545, tsunami lead to many drownings in Bosphorus (Yalçıner et al., 2002). In 553, a tsunami occurred and four years later, in 557 another tsunami was observed (Soysal et al., 1981; Altınok, 2005). In 740, an earthquake triggered a tsunami, and İstanbul, İzmit, İznik and Thrace was affected (Guidoboni et al., 1994; Ambraseys and Finkel, 1991). In 989 a tsunami was observed in the eastern part of the Marmara Sea (Altınok, 2005; Ambraseys and Finkel, 1991). In 1344, an earthquake sourced tsunami affected the coasts of İstanbul, the Thrace coasts and Gelibolu, and inundated 2 kilometers of land (Yalçıner et al., 2002). In 1509, another tsunami affected İstanbul; this tsunami was triggered by a 8.0 magnitude earthquake and tsunami wave height was over 6 meters. In 1641, a tsunami damaged 136 ships in İstanbul. In 1766, a tsunami that damaged Bosphorus and Gulf of Mudanya was triggered by an earthquake. In 1894, a tsunami with a wave height of 6 meters inundated 200m of land in Azapkapı Bridges and Golden Horn area. 10 minutes before the earthquake, sea had receded 50 meters (Yalçıner et al., 2002). In the 20th century, first known tsunami in Marmara Sea was in 1935 because of an earthquake at Hayırsız Island (Altinok et al., 2011). Tabular form of the past tsunamis in

Marmara Sea is summarized in Table 2-1. The first column represents the year of tsunami and the second column represents the Area.

Table 2-1 Historical Tsunamis in Marmara Sea

Year	Location	Effect on the Ayamama River Zone
120	Kapıdağ Peninsula	No
358	İzmit	No
477	İstanbul	Yes
545	İstanbul	Yes
553	İzmit	No
557	İzmit	Yes
740	İstanbul, İzmit, İznik	Yes
989	Eastern Marmara	Yes
1344	İstanbul, Gelibolu	Yes
1509	İstanbul	Yes
1641	İstanbul	Yes
1754	İzmit	No
1766	Bosphorus, Mudanya	Yes
1894	Azapkapı, Golden Horn	Yes
1935	Hayırsız Island	Yes
1963	Bandırma, Mudanya	No
1999	İzmit	No

As Marmara Sea is one of the critical regions in Turkey, several risk assessment studies are prepared for Marmara Sea. In this section, methodologies and results of key studies are summarized.

In 2002, Yalçıner et al. studied the possible 3 cases of tsunami in Marmara. The first case is a landslide event offshore Yenikapı, the second one is again a landslide event offshore Tuzla and the third one is earthquake source at Armutlu Fault. The models are constructed using a numerical model, TWO_LAYER, that is developed by Tohoku University. Grid size of 300 meters are used in cases. In the first case, water depth reached up to 3 meters where inundation in to the land was 8 kilometers. In the second case, water depth reached up top 3 meters for 5 kilometers inundation distance. Water depth reached up to to 5 meters in the third model.

Hebert et al. (2005) presented both earthquake and landslide sourced tsunami models. For seismic source, shallow water equations are used. Solving mass and momentum conservation equations by finite difference method, run-up values onshore are obtained. In order to identify shoaling effects, 300 meters, 60 meters and 20 meters of bathymetry grid cells are used. For landslide model, mass and momentum conservation equations are written in a (x,y) coordinate system linked to the topography. For landslide model, 60 meters of grid cells are used. Fault width with 15 km and a M_W magnitude of 7.2 with mean displacement of 4.3 m are used as seismic source for different scenarios of rake angles from -180 degrees to -120 degrees and rupture length of 40 km. Resulting run-up values are between 0.2-2.5 meters. To identify landslide source, friction angle from 6 degrees to 15 degrees is studied, and volume of mass is taken as 0.15, 0.6 and 1.5 km^3. Tsunami reached to the shore within 5 to 10 minutes. Maximum water level values are determined as 0.5 to 5.5 meters (Hebert et al., 2005). These results provides an initial estimate of maximum water level for the study area.

Hayir et al. (2008) identified a potential landslide source as depth of the top and the bottom of sediment as 800 meters; slope of failure as 10.31 degrees, failure inclination as 52.44 degrees in the offshore zone of Tuzla. Using TELEMAC-2D, numerical results are obtained as up to 2.5 meters of wave height (Hayir et al., 2008). Özeren et al., (2010) determined 15 meter of wave height when deep water equations are used for submarine landslide model for Tuzla. These studies do not contain Bakırköy Coasts, however, studies show a possible scenario of submarine landslide sourced tsunami in Marmara Sea and its results.

Latcharote et al. (2016) discusses two different models, one is focused on landslide and other one is focused on earthquake source. For both cases, the worst scenarios are used according to the writers. The worst possible scenario is predicted by past tsunami events. Compared to Hebert (2005), M_W magnitude of 7.5, 7.6 and 7.3 are used with different displacements. For fully rupture, M_W magnitude of 7.7 with 5 meters of slip, 160 kilometers of fault length and 15 kilometers width, 117.85 degrees of strike slip, 70 degrees of dip slip and -150 degrees of rake angle used. For landslide, 1.5 km^3 volume, 15 kilometers of length, and 5 kilometers of width with 20 m thickness used. Grid size for the models is 90 meters. Maximum 4 meters of tsunami height is observed for earthquake sourced tsunami. For landslide source, maximum of 14 meter tsunami height is calculated. Tsunami waves reach to İstanbul shores within 5 minutes (Latcharote et al., 2016). This study includes the Bakırköy Coasts. Results give an opinion about the duration of the first tsunami waves that reach to shores and the order of the inundation height in inundation area.

A risk assessment was prepared for Ayamama River (Tüfekçi, 2016). Earthquake sourced tsunamis are modelled and maximum of 5.7 meters of wave height, 350 meters of horizontal inundation and 1.7 kilometers of river inundation is determined in Ayamama River area. The study area matches with the one in this thesis. Since as tsunami source Yalova Normal Fault (YAN) is used by Tüfekçi (2016) , which is less critical than LSBC source used in this thesis, the lower results are obtained as it can be seen from Figure 2-1.

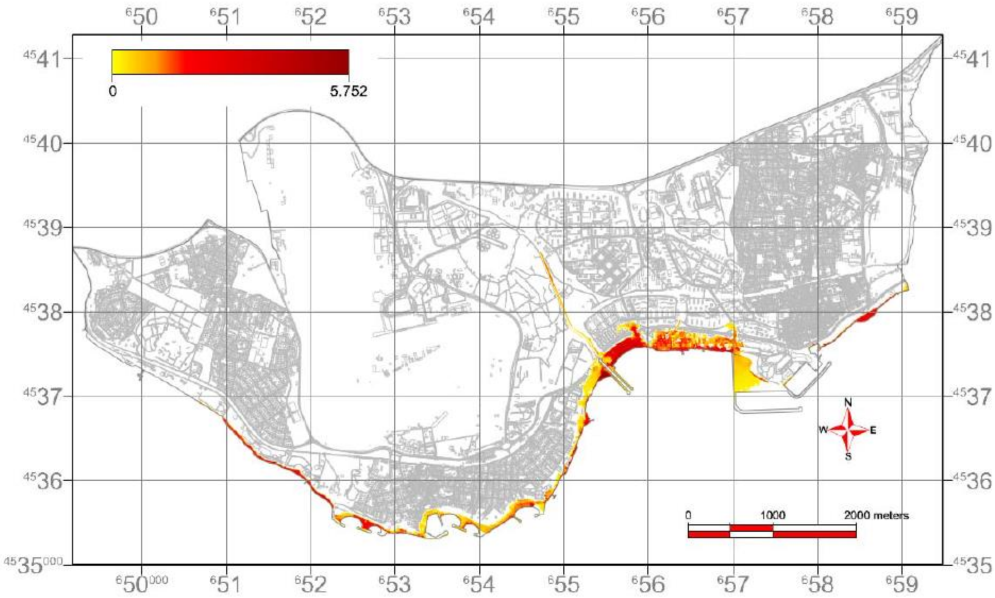

Figure 2-1 Inundation map for Bakırköy Coasts for YAN sourced Tsunami (Tüfekçi, 2016)

In project of "İstanbul Tsunami Action Plan" that is jointly prepared by METU and IBB (2020), inundation maps for several municipalities in İstanbul are presented. In this study, inundation maps with and without structural protections are compared. This study contains LSBC, LSY, PIN sources, possible hard protection suggestions and numerical model results with that hard protections. In this study, Ayamama River is shown as one of the most critical locations for tsunami hazard. It is indicated that the neighborhoods near Ayamama River have closer elevations and in the shape of plateau. Therefore the tsunami waves come from the river can easily affect closer areas. This study provides the source information used in this thesis. Inundation analysis, risk maps and regional disaster management approaches of this study are also used as the guidelines for the thesis.

Figure 2-2 Inundation Map of Bakırköy Coast (Yalçıner et al., 2020)

2.2 Flooding Events of The Ayamama River

In recent years, the Ayamama River is flooded several times, triggered by high precipitation and intense flow. In 1995, a flood occured in the Ayamama River. There was no life loss in this flood. However, a lot of business and vehicles were damaged due to flood (Şen, 2015). In 2009, another flood occured in the Ayamama River. This flood caused 31 life loses and properties were damaged (Şen, 2015). This flood inundated an area of 100-150 meters on both sides of river channel and water depth rised up to 6-7 meters (Özcan, 2017). İkitelli Organized Industrial Zone and Atatürk, Evren, İnönü and Çobançeşme districts were damaged seriously, in addition to deaths, 50 people were injured (Gülbaz, 2019).

Einfalt and Keskin (2010) used SCS-Curve number method and a hydrological model was constructed by using Mike 11. In the simulation results, two peaks are shown as 250 m^3/s flow and 220 m^3/s flow. Estimated discharge in the basin for this study is in the range of 300 to 310 m^3/s.

Yucel (2015) presented a study for the flood event of 2009 in Ayamama River watershed. In this study, station precipitation values on 8 September 2009 is shown as 27-50 mm in the watershed, whereas satellite values are between 5-15 mm. Average slope is specified as 6.94 percent, time of concentration is 7.11 hours, longest length of the river is 41.314 kilometers and Area is 71.02 km^2. After applying HEC-HMS hydrological model, flow on the 9 September 2009 is specified as 260 m^3/s.

Bahçeci (2014), used Environmental Protection Agency Storm Water Management Model and Watershed Modeling System in order to establish the model of Ayamama River Basin. For 100 year of return period, 101.58 m^3/s flow is found.

Özcan (2017) presented a study using SCS-CN method, and maximum flow rates between 1975-2009, in which hydraulic and hydrologic models are prepared. In this study, it is stated that whenever the flow rate passes 180 m^3/s in the Ayamama River, the possibility of flooding is 97.2 %.

Şen (2015) studied the flow in the Ayamama River using Rational Method as 366.53 m^3/s and 519.91 m^3/s, for 100 and 500 year return period, respectively. For LP III method, flows are calculated as 189.8 and 253.8 m^3/s, respectively and for Gumbel EV I, 185.81 and 232.51 m^3/s, respectively.

These studies showed that Ayamama River is prone to flooding. Flow for Ayamama River with return period of 500 years is presented between 250 and 520 m^3/s. Therefore, river flow to be used in thesis is also expected to be around these values. However, these studies do not include relationships of river-land connection. In other words, path of the water in land isn’t included in previous studies. In this thesis, both numerical model and conceptual models are constructed. Therefore, river-land relationship is presented by SPRC model and it will be compared to numerical models.

2.3 Source-Pathway-Receptor-Consequence Method

The term of “Source-Pathway-Receptor” concept as basic model of risk assessment is firstly used in 1970’s to describe flow of environmental pollutants from a source to potential receptors (Narayan, 2011). In order to identify the risk, there must be a relationship between the source, receptor and pathway. Source can be a hazardous substance or material, receptor can be an entity like human or building or water body that is vulnerable to the effects of source, and pathway is the bridge between source and receptor while they contact (Darmendrail et al., 2002). This methodology is firstly used for waste management in late 1970's, used for environmental risk assessments in 2000's and the first use in coastal flooding was in the early 2000's (Narayan et al.,2011).

The idea of using SPR conceptual model in hydraulic engineering is offered by Thorne Evans and Penning in 2007. In the study, sources are identified as weather events or sequences of events that causes flooding, pathways are identified as mechanism that convey floodwaters and receptors are identified as people, industries, buildings or nature itself that can be damaged by flooding (Thorne et al., 2007). In FLOODsite 2009 final report, SPR concept is developed further; possible source pathway and receptor varieties are increased and risk acceptance section is integrated to the model. This study presented expected damages, loses and tolerable flood risk in the conceptual model (Narayan et al., 2011).

In 2011, SPR Model is developed once again by Narayan et al.. In the study, the idea of using System diagrams is applied. The system diagram is a conceptual model that combined elements in source receptor pathway relationship and describes the floodplain in terms of constituent elements. This system model could be one directional or multi-directional. 1D models describes a flooding as a cross section, only one direction of flooding can be observed in this type of model (Figure 2-3). For 2D models, flood direction can be observed in planar view.

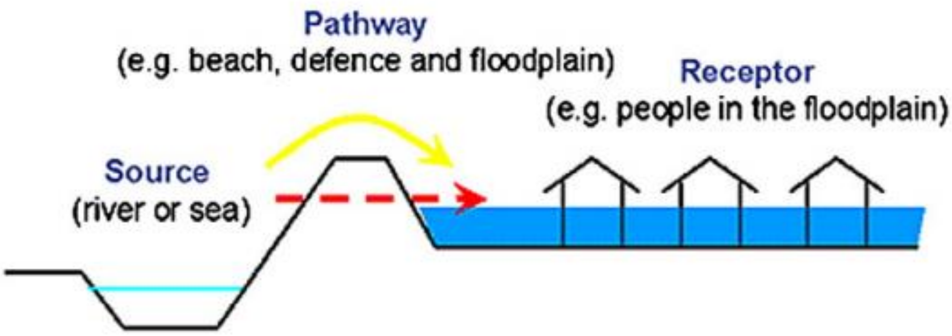

Figure 2-3 1D SPRC model for Coastal Flooding (Narayan et al., 2011)

In Narayan's (2011) study, the model is applied to Estuary of Western Scheld. One uni-directional and one multi-directional diagrams are made and connections are presented on the diagrams. While one uni-directional diagram is the simple version of SPRC and provides less details, multi-directional diagram provides more details and spatial analysis. After constructing diagrams, one major separation for SPR models is revealed; scale of the diagrams. While multi-directional diagrams can have finer scales, uni-directional diagrams are limited to large scale. Multi directional diagrams can be focused on finer resolution areas, however, uni-directional model is more effective in showing large scale areas. Narayan's study also reveals that in multi-directional diagrams can have large scale, but since it is not feasible, it is not applied in the study.

In 2014, Narayan et al. developed quasi-2D SPR for floodplain system. And integrated consequences section to the SPR model. With this approach, SPRC model is formed to current application state. In Nicholls et al. (2015), model built is investigated in four steps; the first step is to decide landward boundaries of the coastal area for the worst case scenario based on the source(s). The second step is to map all the elements of the floodplain. The third step is identifying the links between the elements. The final step to identify the sources on all boundaries of the floodplain. Within the scope of THESEUS project, SPRC models are applied to

Scheldt Estuary, border of Netherlands and Belgium, Vama Bulgaria, Yangtze estuary China, Girondle Estuary France, Elbe Estuary Germany, Cesenatico Italy, Cancun Mexico, Hel Peninsula Poland, Santander Bay Spain and Teign Estuary United Kingdom (Narayan et al., 2014). In Figure 2-4, SPRC diagram that is applied for Girondle Estuary is shown. On the bottom of the figure, S1 and S2, on the top of the figure S3 are the sources of the model, the elements mapped in the middle are pathways and receptors.

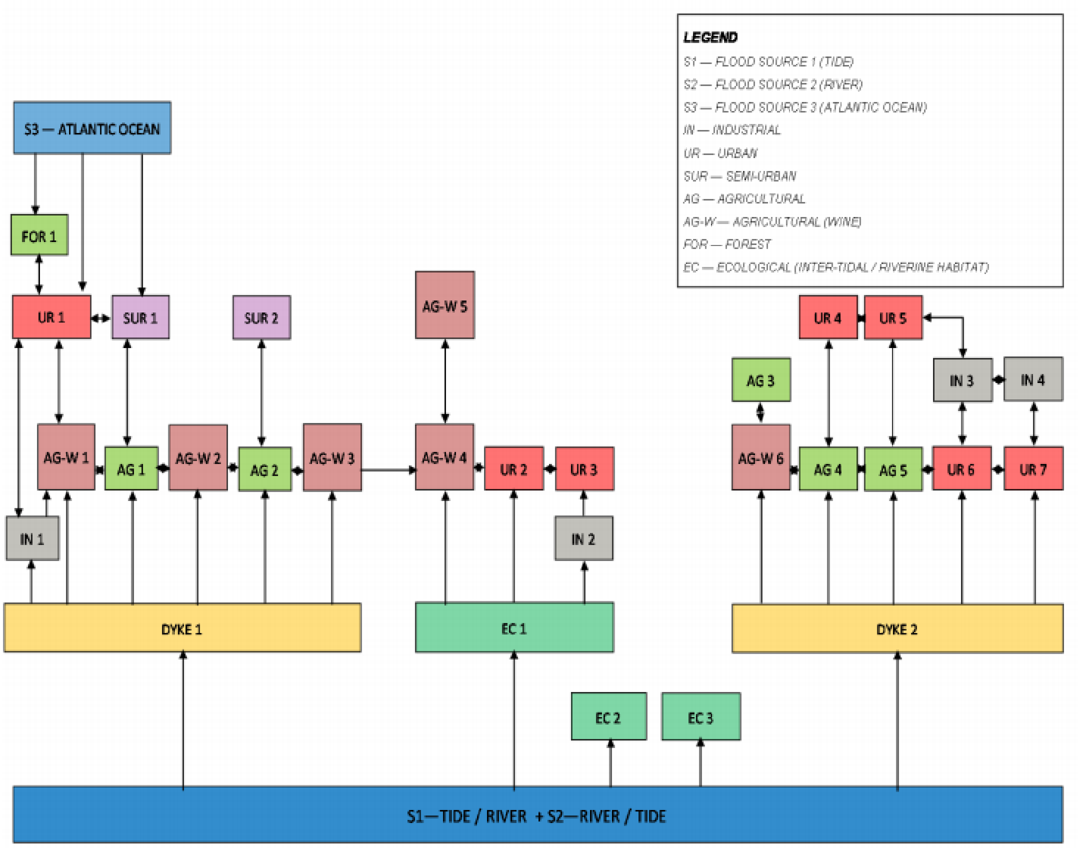

Figure 2-4 SPRC Diagram for Girondle Estuary, France (Narayan et al., 2011)

While in 1970's the model was used to only describe flow of pollutants, today a SPRC model can describe all areas, neighborhoods and stakeholders with all links between them (Narayan et al., 2014). Coastal risk assessments can be done by using up-to-date 2D SPRC method. Potential receptors and consequences can show the risks, damages and threats over coastal areas. As a result of previous studies, characterisation of system, elements that is prone to flood sources, possible flooding of downstream elements, details on flood entry points and information on possible flood routes and designated pathways within and between the elements (Narayan et al. 2012) are obtained.

In Turkey, Koç et al. (2020) used SPRC method to describe the sources and the pathways of the most severe river flood events across the country. In this study, climatic factors, circulation patterns, rainfall data are considered as sources, soil characteristics, topography, land use, surface runoff are considered as pathways and people and properties are considered as receptors (Koç et al., 2020). The use of SPRC in Koç et al. (2020) is different than the use in this thesis. The main difference is SPRC is used to describe the rainfall to flood process in the Koç et al. (2020) study, while in this thesis, the floodplain is investigated using the SPRC model.

CHAPTER 3

METHODOLOGY

In this chapter, the models used in the study are introduced and methodologies are explained. NAMI DANCE version 10.06 is used for tsunami modeling. ArcMap 10.5 is used as GIS platform. HEC-RAS version 5.06 is used as numerical hydraulic model. At the end of the chapter, SPRC model is explained in detail.

3.1 Hydraulic Model

The Ayamama River hydraulic model is constructed using ArcMap 10.5 and HEC-RAS 5.06. In order to construct the model, input data such as flow hydrograph, Digital Elevation Model (DEM) are needed.

In the section 3.1.1, Digital Elevation Model (DEM) is explained. All procedures to calculate flow are explained in the section 3.1.2. GIS procedures and HEC-RAS model setup is presented in the sections 3.1.3 and 3.1.4 respectively. In Figure 3-1, flow chart of hydraulic model process is tabulated from beginning to end. Since there is no flow gauges exist in Ayamama River, a calculation of flow is needed.

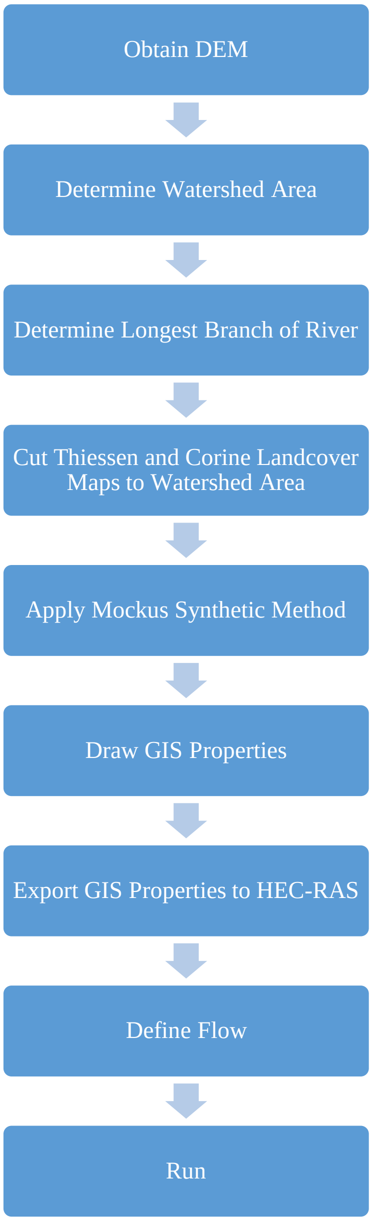

Figure 3-1 Flow chart of Hydraulic model

3.1.1 DEM

A DEM is a 3D representation of a specific area. In x and y directions, a DEM has cells and each cell has an elevation value. Grid spacing of a DEM is important in most of the studies because with finer grid spacing, more detail can be obtained from a DEM. In hydraulic modelling part of this study, DEM is obtained from the project of "İstanbul Tsunami Action Plan" (Yalçıner et al., 2020). In order to obtain detailed results from HEC-RAS model, raw DEM with 5 meter grid spacing for Marmara Sea is cut to the study area and resolution is increased to 1 meter by interpolation using ARCGIS tools. In Figure 3-2, the prepared DEM is shown. Watershed area is investigated in section 3.1.2 in details.

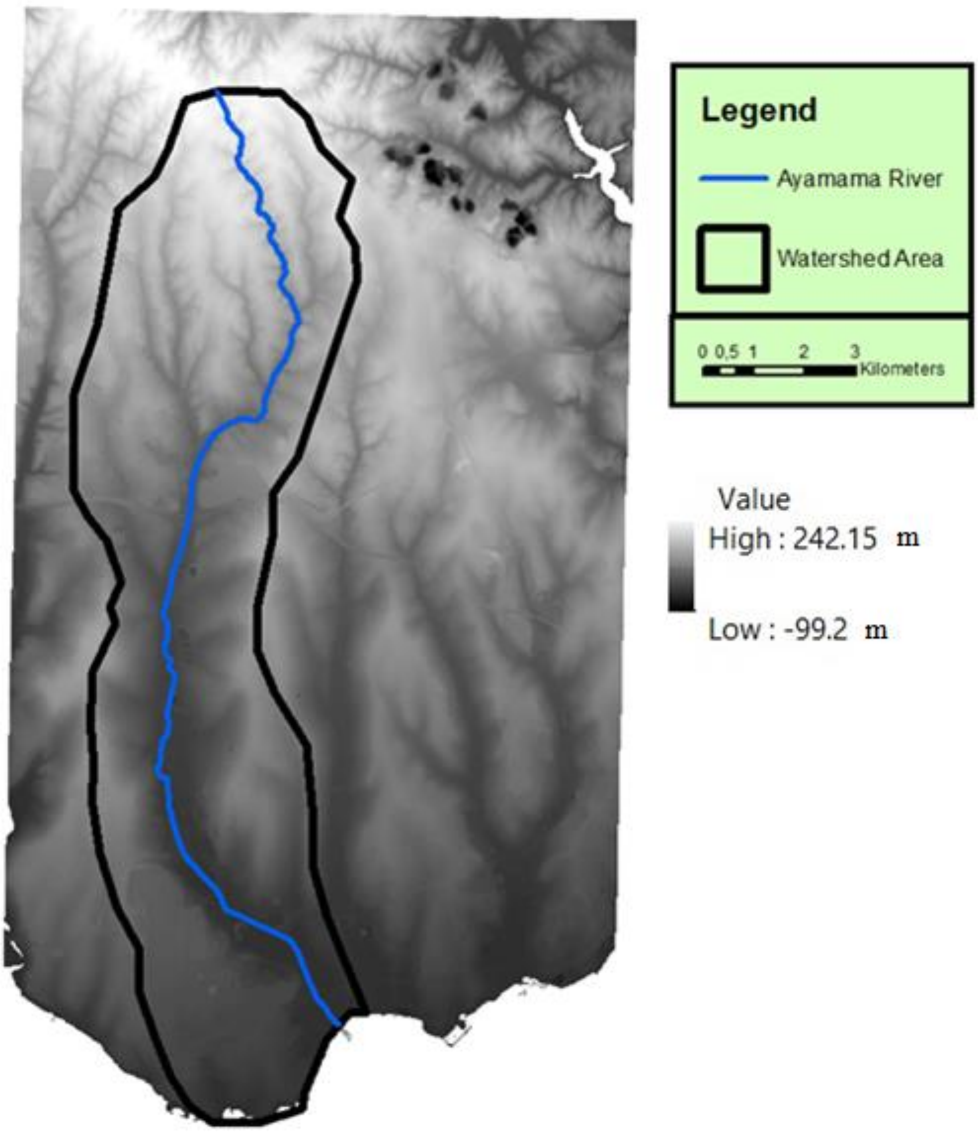

Figure 3-2 DEM for study area

In order to calculate the flow in Ayamama River, firstly river channel must be drawn for the longest branch. In Figure 3-2 longest branch of the Ayamama River is drawn in blue color. After estimating the longest branch of the river, watershed must be delineated. Boundary of a watershed consists of the line drawn across the contours joining the highest elevations surrounding the basin. The river has many other minor branches (dark colored areas in Figure 3-2), but none of them leave the watershed area, in other words, all of the minor branches start within the watershed area and join the main branch. It can be seen that upstream of Ayamama River starts is in Başakşehir, passes through highly populated areas and downstream is in Bakırköy. The main branch length is measured as 21,856.21 meters.

In the DEM, -99.22 m values represents the corrupted data. Because of technical problems while producing DEM, these kind of problems can occur. Since These corrupted area is not in the watershed area, it is not a problem for this study. In watershed area, there is no corrupted elevation value exists. If any corrupted data were inside the watershed area, depending of the size of corruption, an interpolation process could be applied or not corrupted data should be obtained. In this case, there is no need for interpolation for this study. The only minus values in DEM except these corrupted data is in the river channel.

In Figure 3-3, Watershed area is shown on sattelite view. Watershed area is estimated as 76.85 km^2.

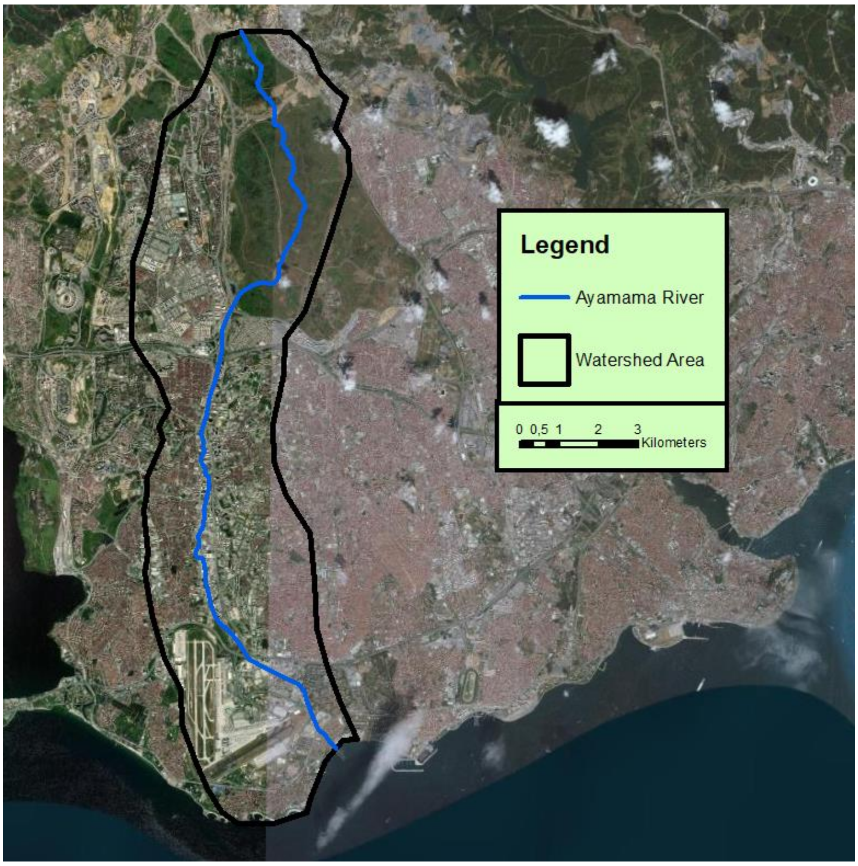

Figure 3-3 Watershed Area In Satellite View

3.1.2 Flow

Near watershed area, closest precipitation observation stations of The General Directorate of State Hydraulic Works are determined. These stations are; Istanbul Airport (17060 station number), Florya (17636 station number), Eyüp (18101 station number), Fatih (17454 station number) and Gungoren (17814 station number). All of closest precipitation observation stations are shown in the Figure 3-4.

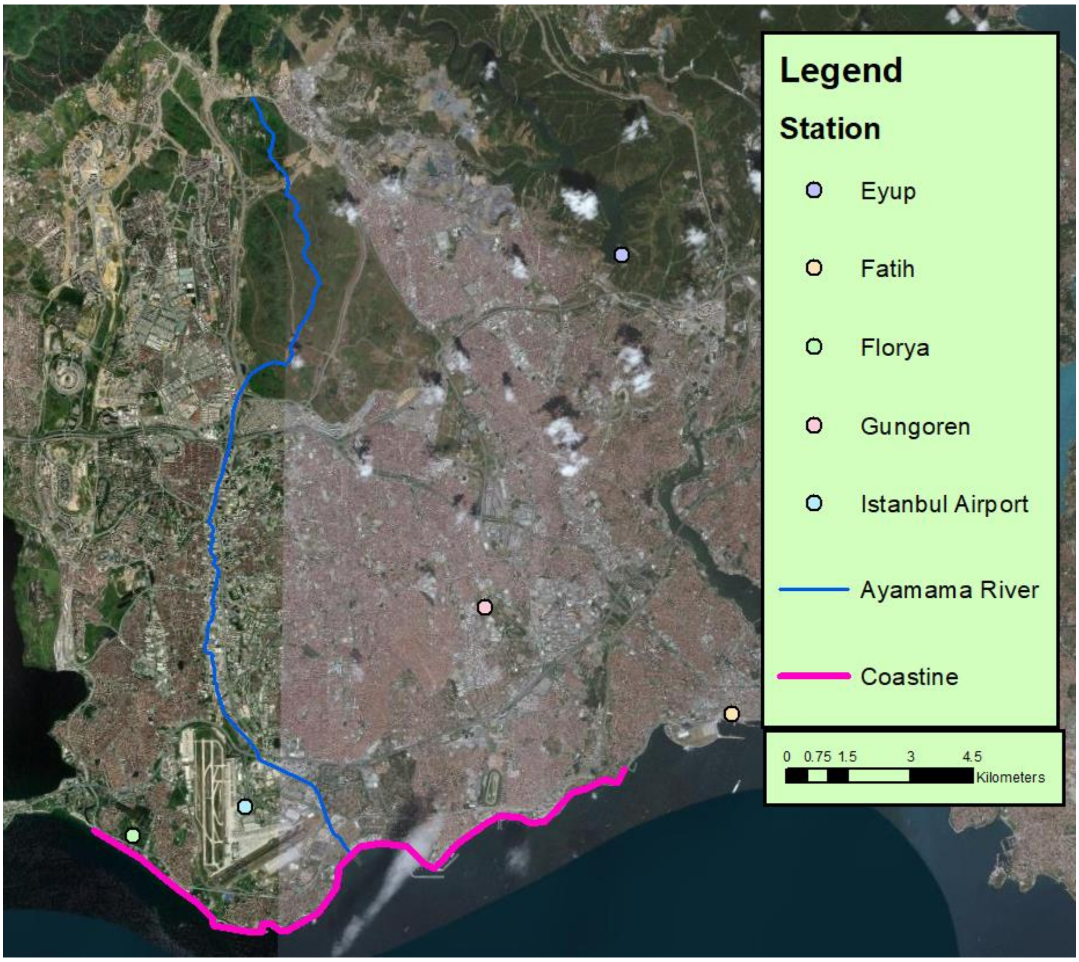

Figure 3-4 Precipitation observation Station Locations

In order to identify the stations that have area in the watershed, thiessen polygons are drawn according to the method stated in Usul (2015). In the Figure 3-5, thiessen polygons of these stations are shown with different colors. As can be seen from the figure, only Eyüp, Florya and İstanbul Airport stations have area in the watershed. Thus, only 3 of them are used in calculations.

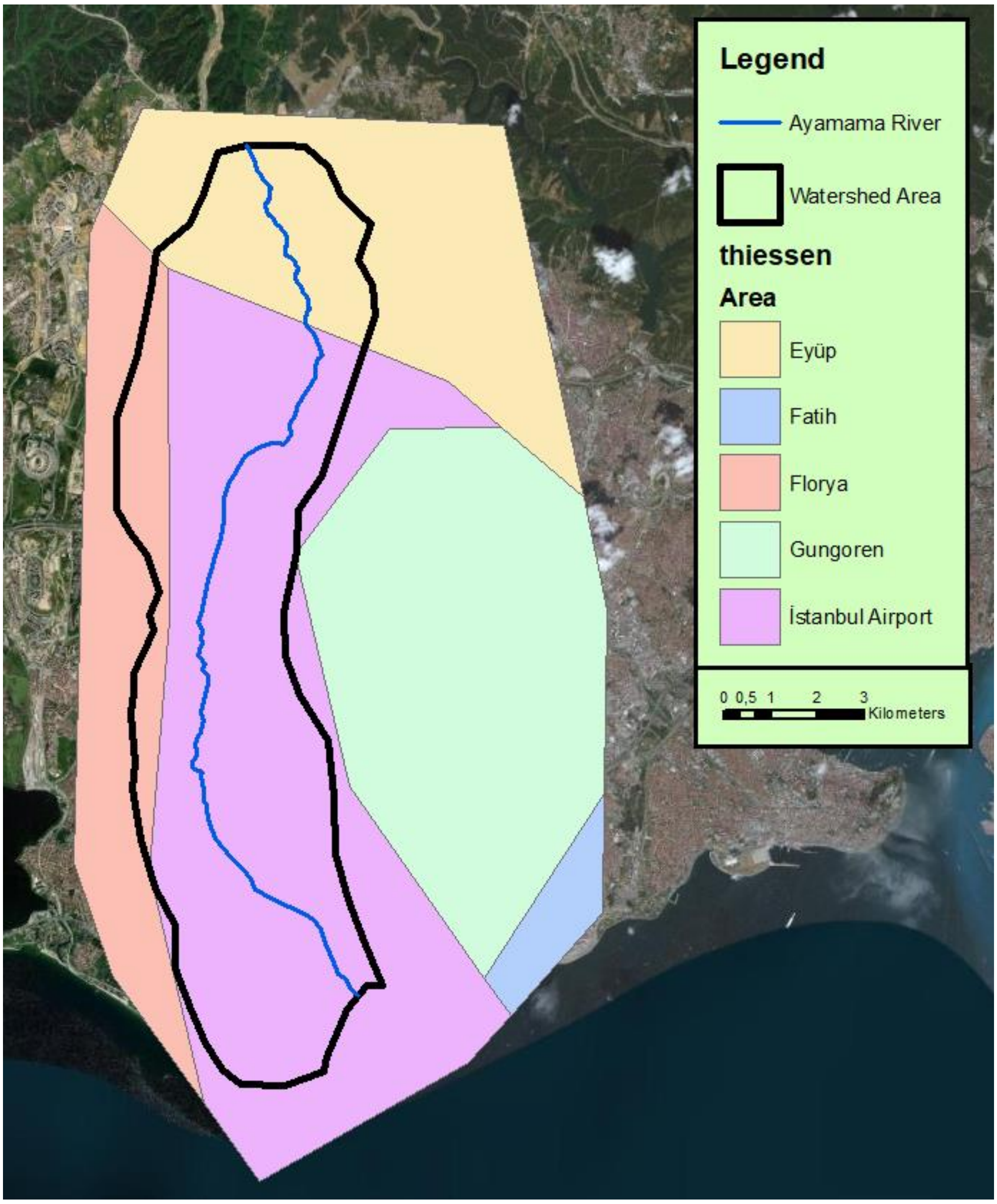

Figure 3-5 Thiessen Area of 5 stations

Istanbul Airport Station has 13 year of data, from 2006 to 2018. Florya Station has 19 year of data from 2000 to 2018; and Eyüp station has 6 years of data from 2013 to 2018. The maximums of monthly rainfall data (mm) during years are tabulated below. The data is taken from Turkish State Meteorological Service.

Table 3-1 Maximum Monthly Rainfall Values (mm) of Stations in the Ayamama River Watershed

Year	İstanbul Airport	Florya	Eyüp
2000	-	44.8	-
2001	-	44.5	-
2002	-	27.2	-
2003	-	31.8	-
2004	-	49.9	-
2005	-	56	-
2006	36	24	-
2007	150.2	40.5	-
2008	59.2	63	-
2009	56.6	62.7	-
2010	40	47.8	-
2011	23.4	30	-
2012	37.2	41.1	-
2013	33	29.2	22.7
2014	34	56.2	57.9
2015	31.2	44.7	48.3
2016	67.4	70	72.7
2017	25	34.4	44.6
2018	33.8	27.2	39.6

As Turkish State Meteorological Service suggests Smirnov-Kolmogorov test in order to determine the best distribution, the test is applied in order to establish 2, 5, 10, 25, 50, 100, 500 year return periods of these rainfall data. In the test, Normal Distribution, Log-Normal (2 Parameter), Log-Normal (3 Parameter), Pearson Type 3, Log-Pearson Type 3 and Gumbel distributions are used. Using the values in the Table 3-1 the following results are taken using Smirnov-Kolmogorov test. Units in

Table 3-2 are mm. In appendices section, p values for Smirnov-Kolmogorov test results are tabulated.

Table 3-2 Results of Smirnov-Kolmogorov Test for 3 stations (mm)

Station	İstanbul Airport	Eyüp	Florya
Accepted Distribution	Log-Pearson Tip-3	Pearson Tip-3 (Gama Tip-3)	Gumbel
2 Year	37.30	47.49	41.41
5 Year	59.13	61.82	56.09
10 Year	81.27	69.39	65.81
25 Year	121.45	77.52	78.09
50 Year	163.26	82.80	87.20
100 Year	217.96	87.57	96.24
200 Year	290.22	91.97	105.25
500 Year	386.43	96.36	117.13

For 76.85 km^2 of total watershed area, distribution of these stations are prepared. Istanbul Airport has 56.41 km^2, Florya has 7.99 km^2 and Eyüp has 12.44 km^2 area in the watershed. When it is mirrored to percentage, stations have 73.41 %, 10.40 % and 16.19 % of area, respectively. By multiplying the areas with the Smirnov-Kolmogorov test results, and summing them up, the following rainfall data of the watershed area(Table 3-3) is obtained.

Table 3-3 Rainfall Data of the Ayamama Watershed

	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	500 Year
Total (mm)	39.98	59.25	77.74	109.83	142.32	184.19	311.46

Since the basin area is under 1000 km^2, T_c, gathering time of water is less than 30 hours, Mockus Synthetic Method can be applied to find discharge that will be used in hydraulic model. In order to apply Mockus Method, following formula is applied (Keskiner and Çetin, 2016).

$$T_c = 0.00032(\frac{L^{0.77}}{S^{0.385}}) \quad \text{Eq. 3.1}$$

In order to calculate slope (S), the river is divided into 10 equal pieces (L in the Table 3-4). At the edge of the each piece, a point is attached. In total, 11 point is obtained. From DEM, elevation values are identified to 11 points. Where Elevation represents the digital elevation of the specific point, h represents the difference between elevations of two points, l represents the length between two points.

$$S = [10/\sum(\sqrt{\frac{l}{h}})]^2 \quad \text{Eq. 3.2}$$

Table 3-4 Calculation of Harmonic Slope

Number	Elevation (m)	h (m)	l (m)	$\sqrt{l/h}$
0	0.1	0	2185.62	-
1	0.87	0.77	2185.62	53.28
2	4.16	3.29	2185.62	25.78
3	17.11	12.95	2185.62	12.99
4	17.62	0.21	2185.62	65.46
5	33.1	15.48	2185.62	11.88
6	50.21	17.11	2185.62	11.30
7	69.02	18.81	2185.62	10.78
8	97.18	28.16	2185.62	8.81
9	139.45	42.27	2185.62	7.19
10	199.61	60.16	2185.62	6.03
			Total	213.50

$\sqrt{S}$= 10 / 213.50 = 0.046839

S= 0.002194

Then,

T_c= 7.522 hours.

$$D = 2\sqrt{T_c} \qquad \text{Eq. 3.3}$$

D= 5.485 hours.

$$T_p = 0.5D + 0.6\,T_c \qquad \text{Eq. 3.4}$$

$$T_r = 1.676\,T_p \qquad \text{Eq. 3.5}$$

T_p = 7.26 hours and T_r= 12.12 hours.

$$Q_p = \frac{(K.A)}{T_p} \qquad \text{Eq. 3.6}$$

K is taken as 0.163 as typical value in Turkey.

Q_p= 1.73 m^3/s.

Where,

T_c is the time elapsed until the runoff formed by precipitation falling at the farthest point of the basin reaches the project section; L is the measurement of the longest branch of the river; l is the one tenth of L; S is harmonic slope; D is rain duration; T_p is the time to peak unit hydrograph; Q_p is the peak of unit hydrograph.

To calculate surface runoff, firstly CN (Curve Number) number should be obtained from Corine landcover dataset. Following assocation tables (Table 3-5, Table 3-6) are used to calculate CN number, in these tables levels and type of surfaces are universal, but corresponding CN numbers are the values that can be used in Turkey (Ministiry of Agriculture and Forest, 2018).

Table 3-5 Level 1 Corine Landcover Types

Level 1	Type
1	Artificial surfaces
2	Agricultural areas
3	Forest and seminatural areas
4	Wetlands
5	Water bodies

Table 3-6 Level 2 Corine Landcover Types and Corresponding Curve Numbers

Level 2	Type	CN
11	Urban fabric	92
12	Industrial, commercial and transport units	88
13	Mine, dump and construction sites	85
14	Artificial, non-agricultural vegetated areas	85
21	Arable land	69
22	Permanent crops	74
23	Pastures	61
24	Heterogeneous agricultural area	75
31	Forests	55
32	Scrub and/or herbaceous vegetation associations	75
33	Open spaces with little or no vegetation	69
41	Inland wetlands	98
42	Maritime wetlands	98
51	Inland waters	98
52	Marine waters	98

In Table 3-5, only the first level landcovers are shown. After one more level classification, Table 3-6 is constructed (Ministry of Agriculture and Forest, 2018). Typical Corine Numbers for Turkey are paired with related landcover in this table. Although there is level 3 dataset which is more detailed, in this study Level 2 detail was assumed as accurate enough to determine flow characteristics.

After defining curve numbers, in GIS platform, landcovers of the watershed area are defined in level 2 (Figure 3-6).

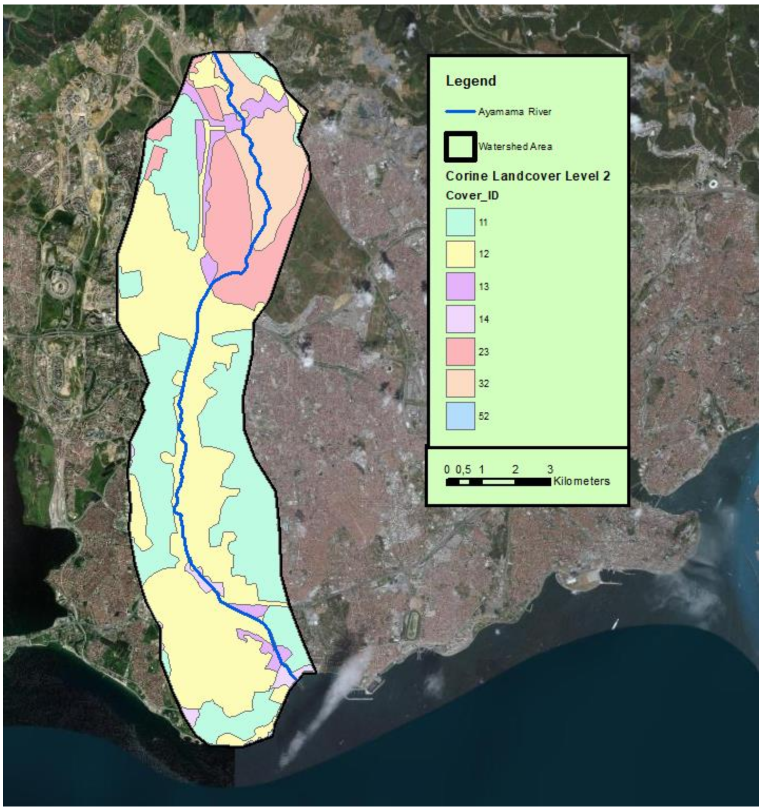

Figure 3-6 Level 2 Corine Landcovers in Ayamama Watershed

In order to calculate total CN of the watershed, weighted average method is used (Table 3-7).

Table 3-7 Level 2 CN Calculation in the watershed

Area	Corine Code	Type	CN	Partial CN
24.73	11	Urban fabric	92	29.61
32.44	12	Industrial, commercial and transport units	88	37.16
3.21	13	Mine, dump and construction sites	85	3.55
1.05	14	Artificial, non-agricultural vegetated areas	85	1.16
8.22	23	Pastures	61	6.53
7.14	32	Scrub and/or herbaceous vegetation associations	75	6.97
0.04	52	Marine waters	98	0.05
			Total	**85.03**

Yücel (2015) presented that basin-averaged curve number is estimated as 65, and stated that because of only one event exists in this study area, calibration study was not possible. In this study, curve number is estimated as 85 using Ministiry of Agriculture and Forest 2018 values. Urbanisation and changing the land use can lead this difference.

The multiplication of Pluviograph and Precipitation Area Distribution coefficients is used as 0.68. Correction factor is taken as 1.13 (Keskiner, 2018). By multiplying these values with the results in the Table 3-3 and Table 3-2, total Precipitation values (P) of the watershed for each return period are obtained (Table 3-8) .

Table 3-8 Precipitation Values of the Ayamama Watershed

	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	500 Year
Total (mm)	30.26	45.52	59.73	84.39	109.36	141.53	239.33

Surface Runoff (Q) is calculated and shown in the Table 3-9 using the following formulas (Örnek et al.,2016);

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \quad \text{Eq. 3.7}$$

$$S = \frac{2540}{CN} - 25.4 \quad \text{Eq. 3.8}$$

Where Q is runoff, P is Precipitation, S is potential maximum retention after runoff begins, CN is curve number.

Table 3-9 Runoff (Q) Values of the Ayamama River

	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	500 Year
Total (m^3/s)	6.86	16.42	26.96	47.31	69.41	99.07	192.84

This runoff values for different return periods can be also estimated using monthly maximum series of rainfall series in hydrological model and applying frequency analysis to output. In this study, runoff values for different periods are calculated using rainfall values for corresponding return periods.

The final step for calculation of flow data is to determine baseflow. In order to determine baseflow, nearest possible river that has a “Flow Observation Station” of The General Directorate of State Hydraulic Works is determined, which is Nakkaş River. Watershed area of Nakkaş River is estimated as 4.64 m^2 in the General Directorate of State Hydrolic Works archives (https://www.dsi.gov.tr/Sayfa/Detay/744). Usually, closest river with similar watershed area is used in determining the baseflow of a river that is without an observation station on it. However, since there is no available data with a river of similar meteorological data or closer area, Nakkaş River is the only available river that has baseflow data closer to the Ayamama River. The baseflow data during 12 months is available for 22 years from 1967 to 1992 with some missing years (https://www.dsi.gov.tr/Sayfa/Detay/744). Average baseflow values of each month is taken for 22 years. Then, the greatest values of three months in a row is determined as December, January and February. In the each baseflow values of the recorded years, and the averages of the months December, January and February in the Nakkaş River is shown. Taking average of the last row, the baseflow in the Nakkaş River is estimated as 0.623 m^3/s. Taking the two third of watershed area ratio as in equation 3.9, baseflow of the Ayamama River is calculated as 4.05 m^3/s.

Table 3-10, each baseflow values of the recorded years, and the averages of the months December, January and February in the Nakkaş River is shown. Taking average of the last row, the baseflow in the Nakkaş River is estimated as 0.623 m^3/s. Taking the two third of watershed area ratio as in equation 3.9, baseflow of the Ayamama River is calculated as 4.05 m^3/s.

Table 3-10 Greatest Three Month Baseflow (m^3/s) Average in Nakkaş River(https://www.dsi.gov.tr/Sayfa/Detay/744)

YEAR	DECEMBER	JANUARY	FEBRUARY
1967	0.548	1.355	0.641
1968	0.257	2.692	0.306
1969	1.080	1.665	0.919
1971	0.389	0.728	0.303
1972	0.440	0.240	0.366
1975	0.077	0.526	0.291
1976	0.508	0.164	0.275
1977	0.754	0.486	0.114

Table 3-10 Greatest Three Month Baseflow (m^3/s) Average in Nakkaş River(https://www.dsi.gov.tr/Sayfa/Detay/744) (continued)

1978	0.511	1.652	0.990
1979	0.491	0.519	0.136
1980	0.482	1.128	1.007
1981	0.392	2.479	1.301
1982	2.878	2.319	0.910
1983	0.020	0.626	0.746
1984	0.032	0.234	0.200
1985	0.094	0.443	0.210
1986	0.216	0.570	0.341
1987	0.130	0.635	0.667
1989	0.231	0.088	0.109
1990	0.039	0.050	0.118
1991	0.145	0.360	0.601
1992	1.550	0.313	0.042
Average	0.512	0.876	0.482

Baseflow is determined as,

$$Q_1 = (\frac{A_1}{A_2})^{\frac{2}{3}} Q_2 \quad \text{Eq. 3.9}$$

Where

$A_1 = 76.85\ m^2$,

$A_2 = 4.64\ m^2$,

$Q_2 = 0.623\ m^3/s$.

Baseflow value of $4.05\ m^3/s$ can be acceptable for 70 km^2 basin. However, Ayamama river doesn't have that amount of baseflow. The baseflow in the river mainly comes from industrial waste water. Therefore the flow is accepted same with Nakkaşdere, 0.623 m^3/s.

In the final calculation of flow values, following equation is used;

$$Q_{flow} = Q * Q_p + Q_{base} \quad \text{Eq. 3.10}$$

Table 3-11 shows the flow values with return periods from 2 years to 500 years that will be used in hydraulic model.

Table 3-11 Flowrate Values of the Ayamama River

	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	500 Year
Total (m^3/s)	12.46	28.98	47.17	82.30	120.45	171.65	333.54

For the unsteady model, flow hydrograph is created by "SCS Dimensionless Unit Hydrograph" method which is developed by Victor Mockus in 1972. Ratios for dimensionless unit hydropgraph and mass curve are tabulated in the following table (Table 3-12 and

Table 3-13) (Fang et al.,2005).

Table 3-12 Ratios for dimensionless unit hydrograph

Time Ratios (t/T_p)	Discharge ratios (q/Q_p)	Time Ratios (t/T_p)	Discharge ratios (q/Q_p)
0	0.000	1.7	0.460
0.1	0.030	1.8	0.390
0.2	0.100	1.9	0.330
0.3	0.190	2.0	0.280
0.4	0.310	2.2	0.207
0.5	0.470	2.4	0.147
0.6	0.660	2.6	0.107
0.7	0.820	2.8	0.077

Table 3-12 Ratios for dimensionless unit hydrograph (continued)

0.8	0.930	3.0	0.055
0.9	0.990	3.2	0.040
1.0	1.000	3.4	0.029
1.1	0.990	3.6	0.021
1.2	0.930	3.8	0.015
1.3	0.860	4.0	0.011
1.4	0.780	4.5	0.005
1.5	0.680	5.0	0.000
1.6	0.560		

Since 0.623 m^3/s base flow exists in the river, the hydrograph shown in

Table 3-13 starts and ends with this value. This hydrograph used as an input ofr HEC-RAS model.

Table 3-13 Hydrograph for Q_{500} Flow

Time (hour)	Discharge Without Base Flowrate (m^3/s)	Discharge With Base Flowrate (m^3/s)
0	0	0.62
0.5	6.97	7.59
1	19.03	19.65
1.5	35.74	36.36
2	56.64	57.26
2.5	82.04	82.66
3	111.72	112.34
3.5	148.88	149.50
4	191.21	191.84
4.5	233.29	233.91

Table 3-13 Hydrograph for Q_{500} Flow (continued)

5	270.44	271.07
5.5	297.82	298.44
6	318.83	319.45
6.5	332.76	333.38
7	335.78	336.40
7.5	335.83	336.46
8	333.07	333.70
10	268.70	269.33
15	86.07	86.69
20	28.15	28.77
25	9.16	9.78
30	3.16	3.78
36	0	0.62

3.1.3 GIS Model

In the preparation of HEC-RAS model, ArcGIS is also used. GIS models are used in a wide variety of fields. Hydraulic modelling, Geometric networks, Cartographic modelling, Geostatics, Agricultural Applications, Telecom and Network Services, Transportation Planning and many more can be shown as usage of field. In this study , GIS model is used for hydraulic moddelling as a step tool. As GIS model, ArcMAP ArcGIS version 10.5 is used.

First thing to do in the ArcMAP is to define projected coordinate system. “ITRF96 UTM Zone 35” is defined to the model. Then, Basemap with world imagery is added. After adding DEM, ArcMAP workspace is ready for calculating flow steps (Figure 3-2). The details of flow calculation is written in the section 3.1.2.

Firstly, RAS Geometry Layer is constructed as mdb file. Then, from beginning to end, river is drawn as center line. Then, river banks are drawn for left and right boundary sides. For the non-urban areas cross sections are drawn with maximum of 1 km intervals, and for urban areas cross sections are drawn with maximum of 250 meters to optimize the detail of the study. In addition to these cross sections, additional cross section lines are drawn for upstream and downstream sides of bridges (Figure 3-7).

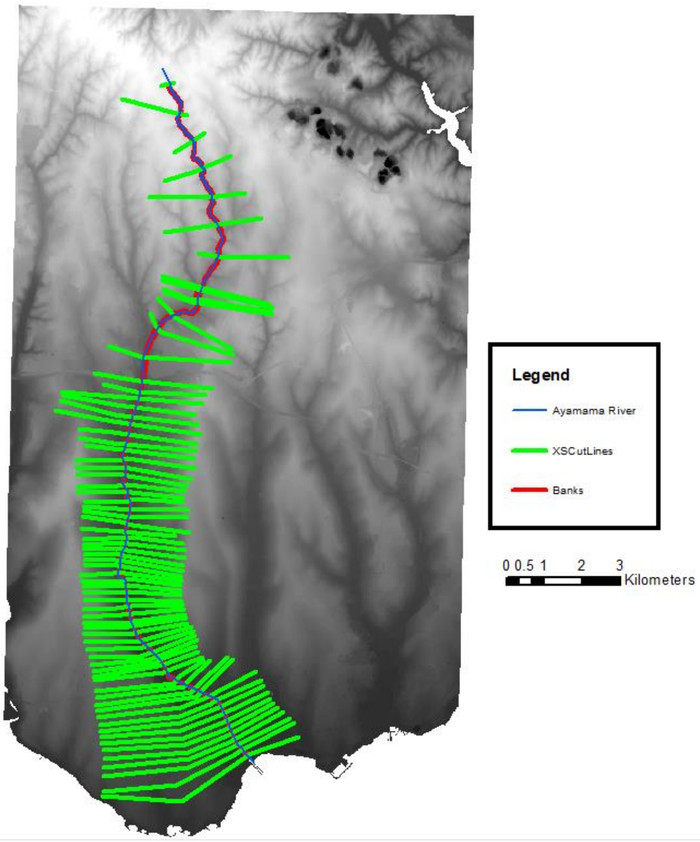

Figure 3-7 Cross Sections, Banks and River Centerline

Left Bank is drawn as 21281 meters and right bank is 21441 meters. Cross sections ends generally 10 meters higher than bank elevations since more than 6-7 meters river flood height is not expected in the Ayamama from historical events (Özcan, 2017). Flowpath is defined with banks and centerline. With this step, flow direction is identified. In layer setup section, DEM is defined to the RAS layer as elevation reference. Then, 3D versions of river and cross sections are obtained. Stations with elevations and banks are constructed. By exporting this RAS layer as GEORAS file, HEC-RAS model base is constructed.

3.1.4 HEC-RAS Model

HEC-RAS is a computer program that is developed by US Army Corps of Engineers. The program is mainly used for one dimensional steady flow and two dimensional steady and unsteady flow simulations for rivers (HEC, 2016). In this study, one dimentional unsteady flow analysis is prepared. Model version 5.0.6 is used with SI unit system. The interface of the version is shown in the Figure 3-8.

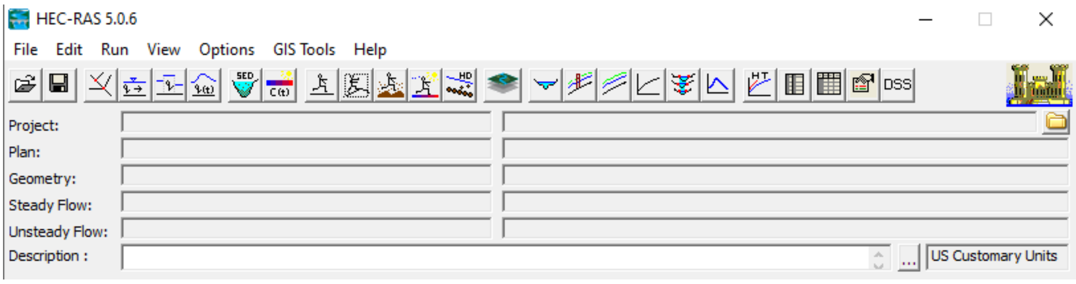

Figure 3-8 HEC-RAS version 5.0.6 Interface

A new project is created in the HEC-RAS. Then, the GEORAS file that is taken from ArcMAP is imported to the model (Figure 3-9).

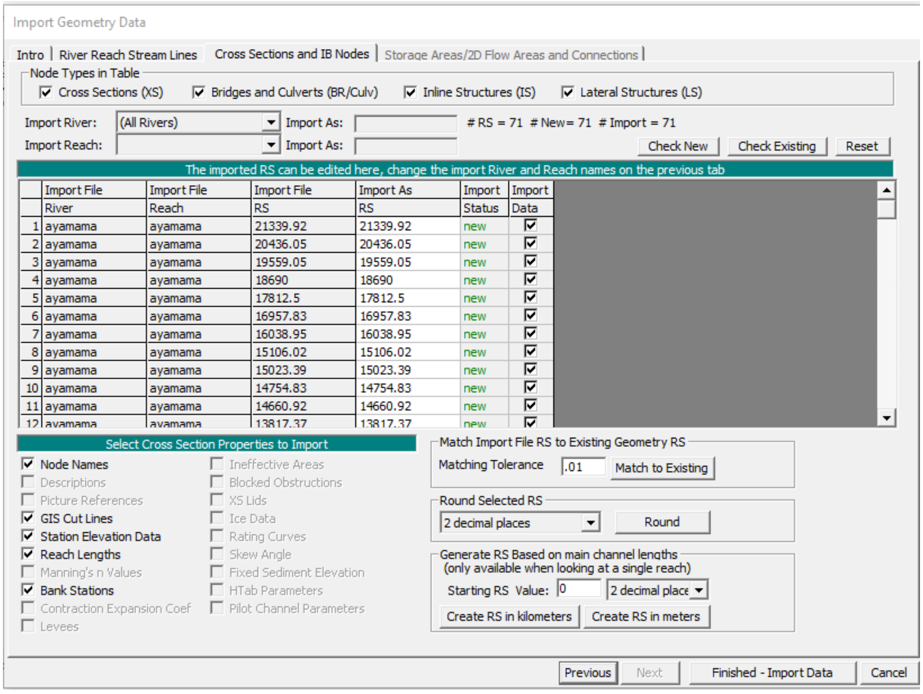

Figure 3-9 Imported GEORAS File

As it can be seen in the Figure 3-9, 71 cross sections are imported to the model. The next step is to fix shifted points. Sometimes bank points on the cross sections does not exactly overlap the DEM grid. Therefore, when the 3D layer is created, bank points may be selected as the nearest grid point. This problem causes the wrong bank point identification in the cross sections. As it can be seen in the Figure 3-10, while left bank is on the correct place, right bank is located in river bed. All cross sections are investigated and problematic ones determined. Validation of this process is made by measuring the river width from both Google Satellite view and DEM.

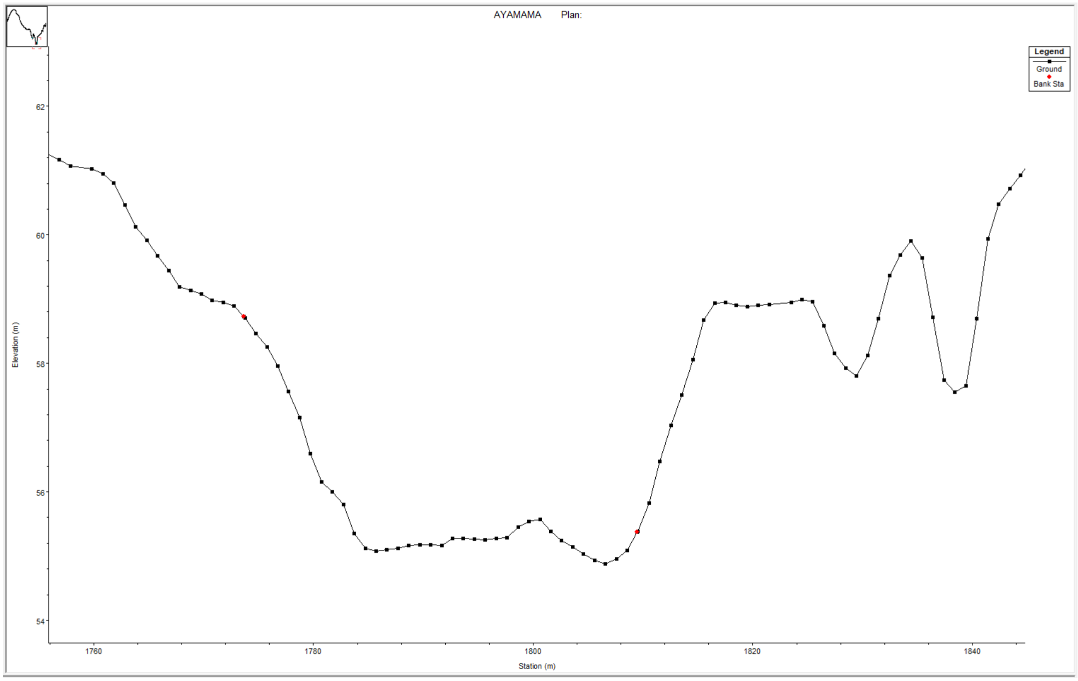

Figure 3-10 Shifted Right Bank Point

If the bank points are at the wrong place and it is validated from Google Satellite measurement, the bank point is moved to the right place (Figure 3-11). Then, the RAS Mapper feature is opened from the interface. Projection is defined as “ITRF96 UTM Zone 35”. After defining projection. DEM is defined as a float file and a basemap is defined in project area. New cross sections are added to the critical places like sharp curves or manning changes (Figure 3-12).

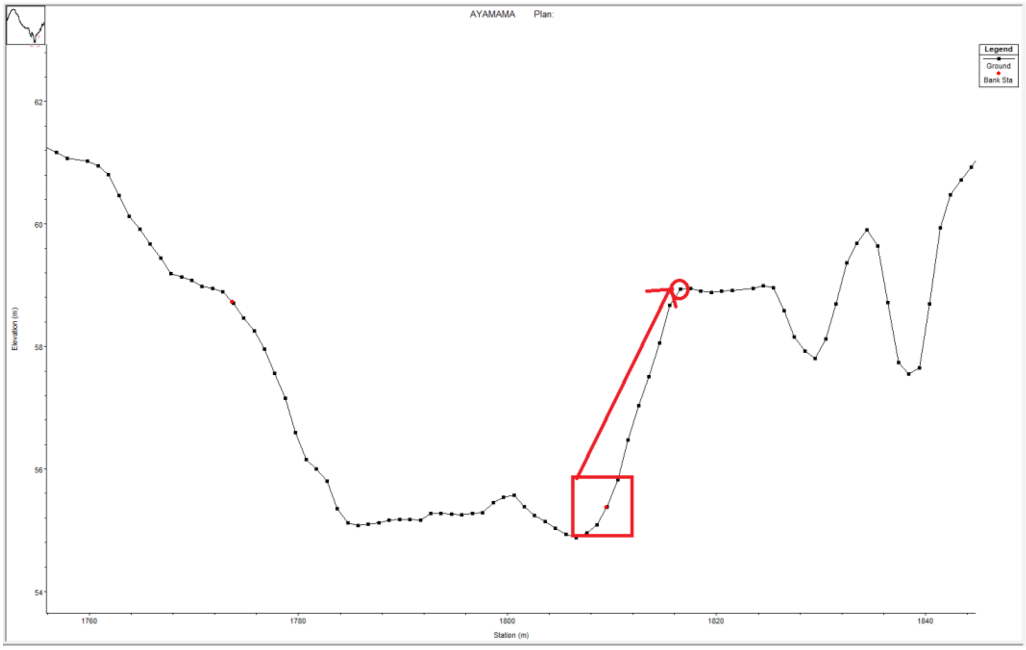

Figure 3-11 Correction of bank point

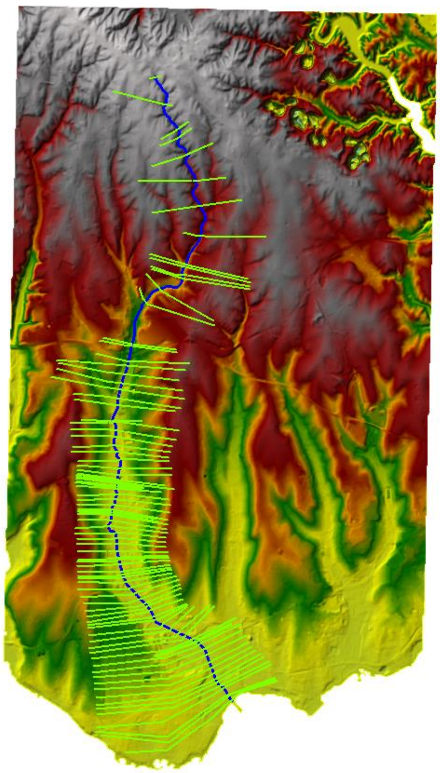

Figure 3-12 RAS Mapper View after adding extra Cross Sections

Structures that are determined by field research and Google Earth Web Imagery views are added to the model. In total 16 structures are added. Some examples are shown in figures below (Figure 3-12-Figure 3-21). The first image from every cross section represents HEC-RAS model cross section data, the second image represents the real life photos of cross sections that taken by me, and the third image are the Google sattelite images of the represented cross section. The location of the structures are defined as distances in meters from the upstream point of main river branch in the watershed of the study.

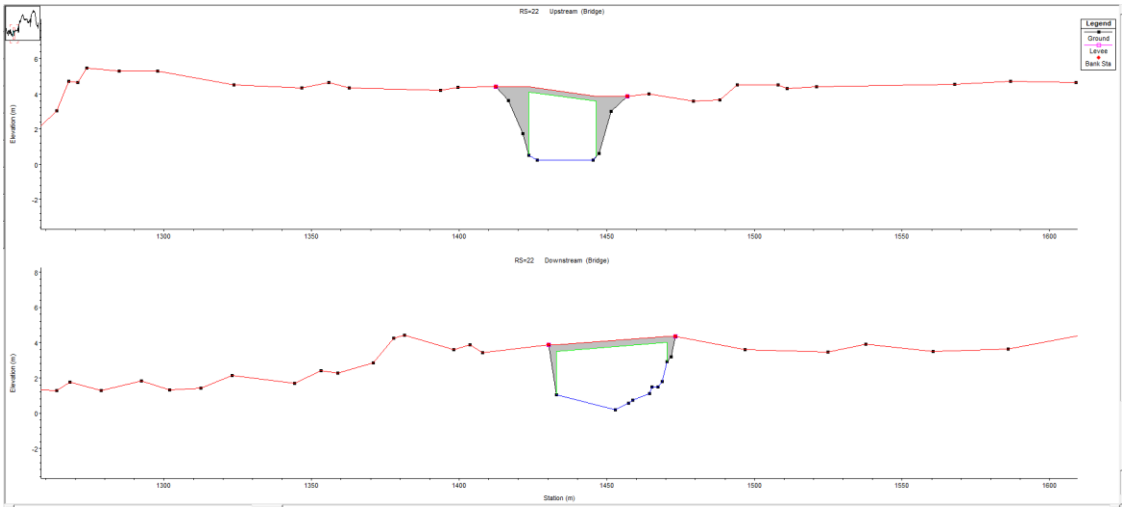

Figure 3-13 Bridge at the station 22 meters

Figure 3-14 View over Bridge at the station 22 meters

Figure 3-15 Google Satellite View at the bridge station 22 meters

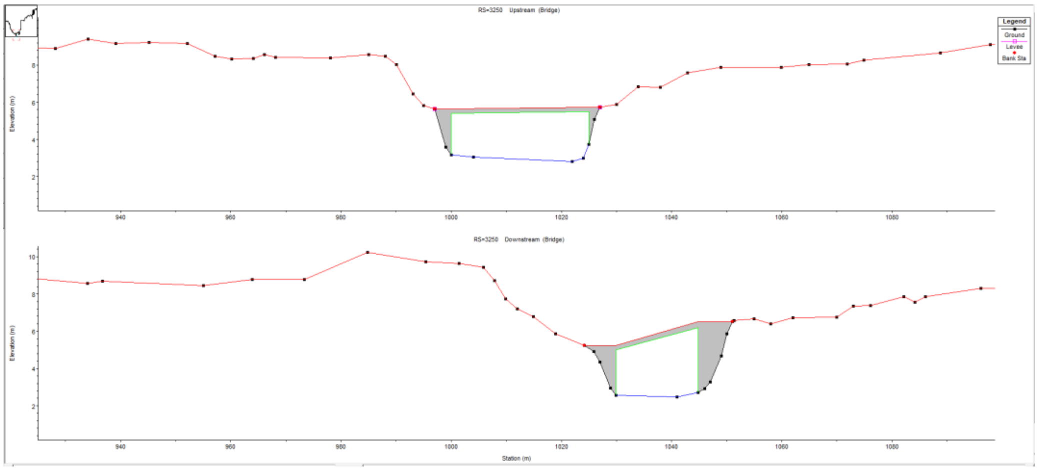

Figure 3-16 Bridge at the station 3250 meters

Figure 3-17 View near the bridge at the station 3250 meters

Figure 3-18 Google Satellite View at the bridge station 3250 meters

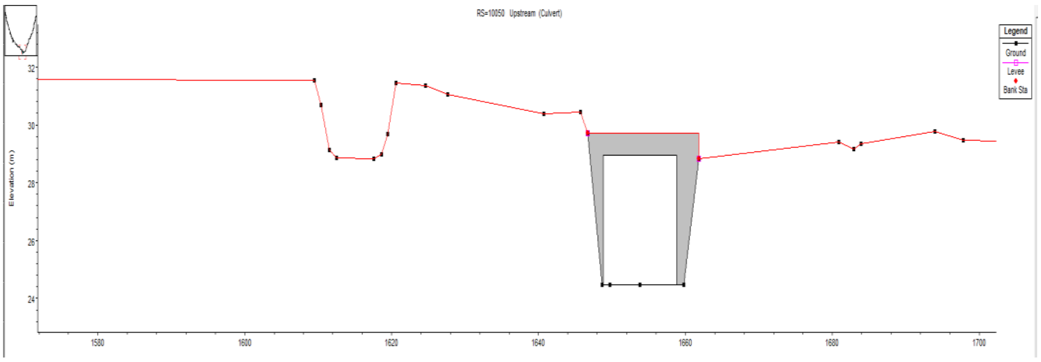

Figure 3-19 Bridge at the station 10050 meters (Upstream only)

Figure 3-20 View near the bridge at the station 10050 meters

Figure 3-21 Google Satellite View at the bridge station 10050 meters

Model cross sections and bridges are validated by real life observations and Google satellite images. After configuring all the 16 bridges, manning values for the all cross sections of the river are defined. For outside of the channel, 0.05 constant value is used which corresponds to pavement and other urban areas. For inside of the channel,Table 3-14 is used (Arcement et al., 1989) .

Table 3-14 Manning values for the Ayamama River

Type	Manning Value	Cross Sections
Natural River Bed	0.035	Upstream-13256 9614-8658 6363-5531
Concrete Rectengular Bed	0.016	11939-9662 8374-6560 5329-2670
Trapezoidal Stone Bed	0.02	2417-Downstream

In all cross sections, levee points are described in the model. Levee points are set to the structures or obstacles like barrier. By doing this, potential flood area is controlled such that small obstacles like a tree does not prevent flooding in the model. Model setup is now ready for importing the steady and unsteady flow data. Firstly, steady flow data is imported. Then, as a boundary condition, normal depth as 0.1 meters is defined (Figure 3-22).

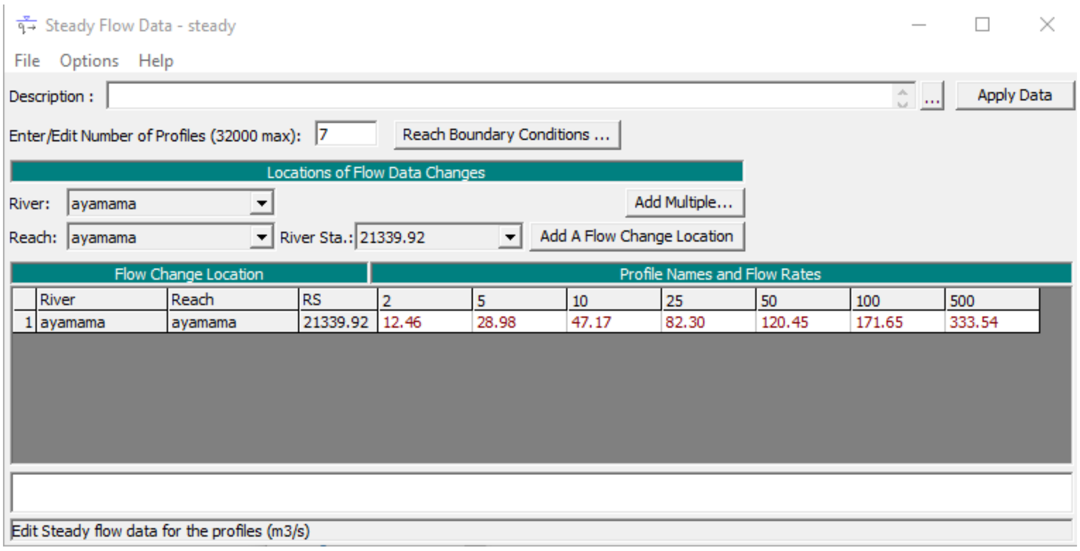

Figure 3-22 Steady Flow Data

For steady flow run, mixed flow is selected (Figure 3-23).

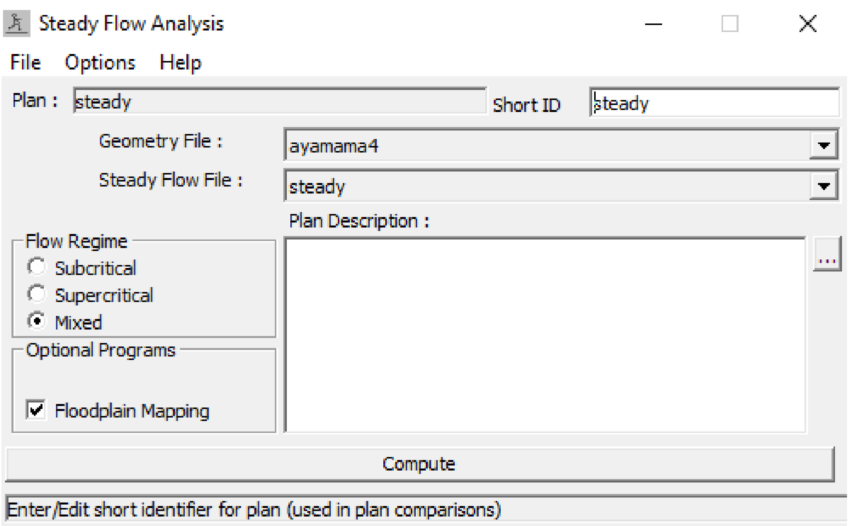

Figure 3-23 Steady Flow Analysis

Steady model run results are used to provide rating curves for unsteady run model. This step is made for stable unsteady run. While steady run provides only one flow to channel without time dependency, unsteady run provides hydrograph as a flow with time dependency.

For unsteady model, unsteady flow hydrograph with 500 year return period is given as input. Minimum and initial flow is given as 0.62 m^3/s in any time. As downstream boundary, 0.1 meters of normal depth is given. 30 minutes of flow intervals used in hydrograph (Figure 3-24).

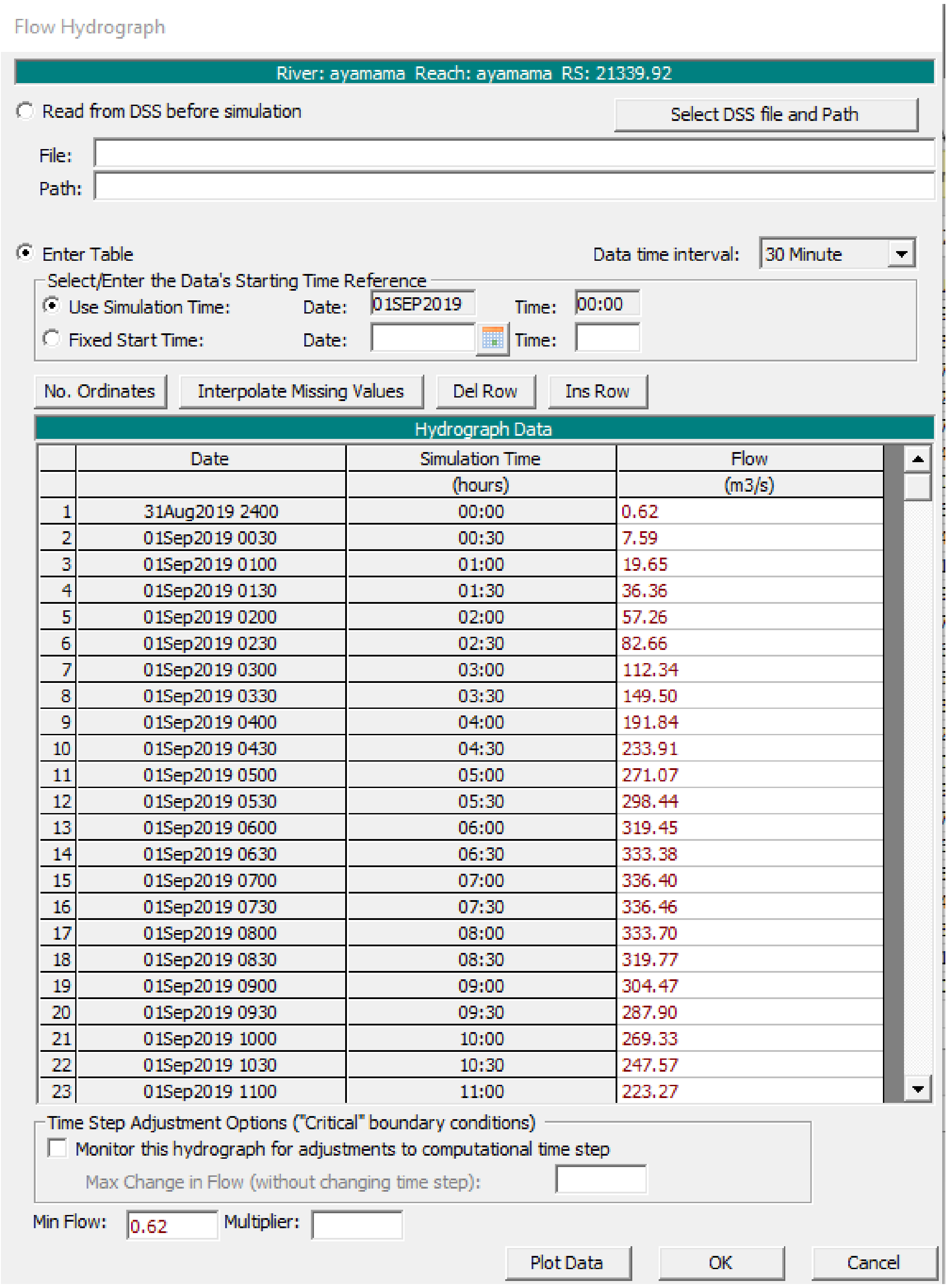

Figure 3-24 Unsteady Flow Hydrograph Data

For unsteady run , 30 seconds of computation interval, 30 minutes of hydrograph output interval, mapping output interval and detailed output interval selections are made. Simulation duration is set to 12 hours.

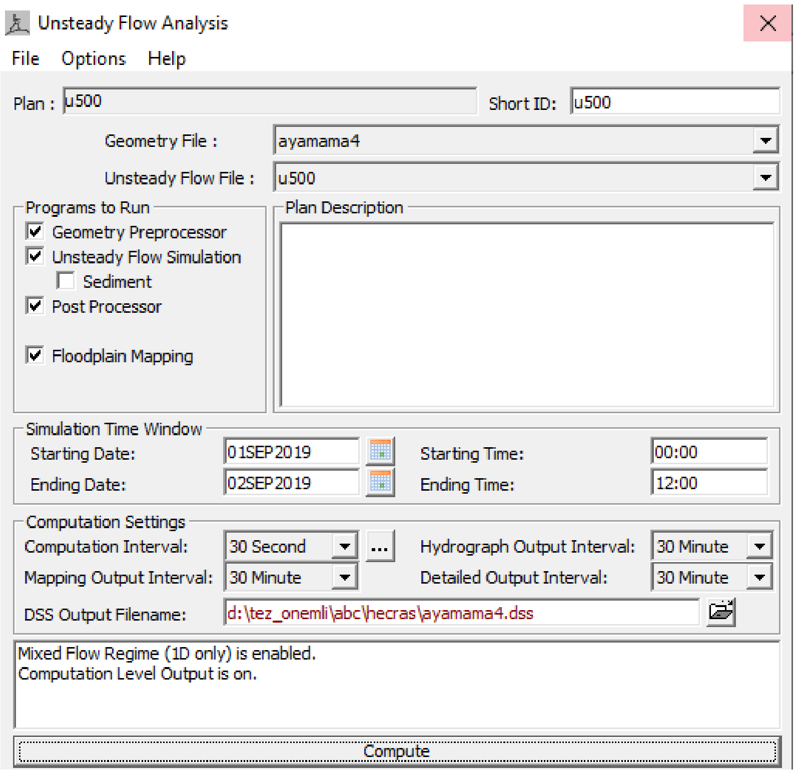

Figure 3-25 Unsteady Flow Analysis

As output of HECRAS numerical model, water depth, water velocity, water surface elevation and inundation maps are obtained with 30 minutes of intervals for Ayamama watershed.

3.2 Tsunami Model

Tsunami model is constructed via NAMI DANCE 10.06 combined with Surfer version 8. In order to construct the model, bathymetry and tsunami sources are needed to be defined. In section 3.2.1 bathymetry of the study area is investigated. Tsunami source that will be used in the model is explained in section 3.2.2. NAMI

DANCE Model setup is explained in section 3.2.3. General flowchart is also given in Figure 3-26.

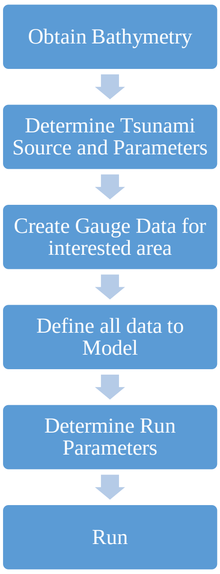

Figure 3-26 Run Flowchart for Tsunami Model

3.2.1 Bathymetry

For a tsunami inundation numerical model, one of the most important detail is the bathymetry quality. Working with high resolution bathymetry will generate more accurate results. The bathymetry data used in this study are taken from the Department of Coastal Engineering, METU. These bathymetries are also used in 2020 joint IBB and METU "İstanbul Tsunami Eylem Planı" project. The raw bathymetry data is taken from GEBCO (General Bathymetric Chart of the Oceans). Coarser grid spacing is 42 meters. Finer bathymetry that is used for nested run has a grid spacing of 5 meters. In Figure 3-28 and Figure 3-27, legend color scale is in meters. Note that minus values means the land in tsunami bathymetry , positive values means sea level.

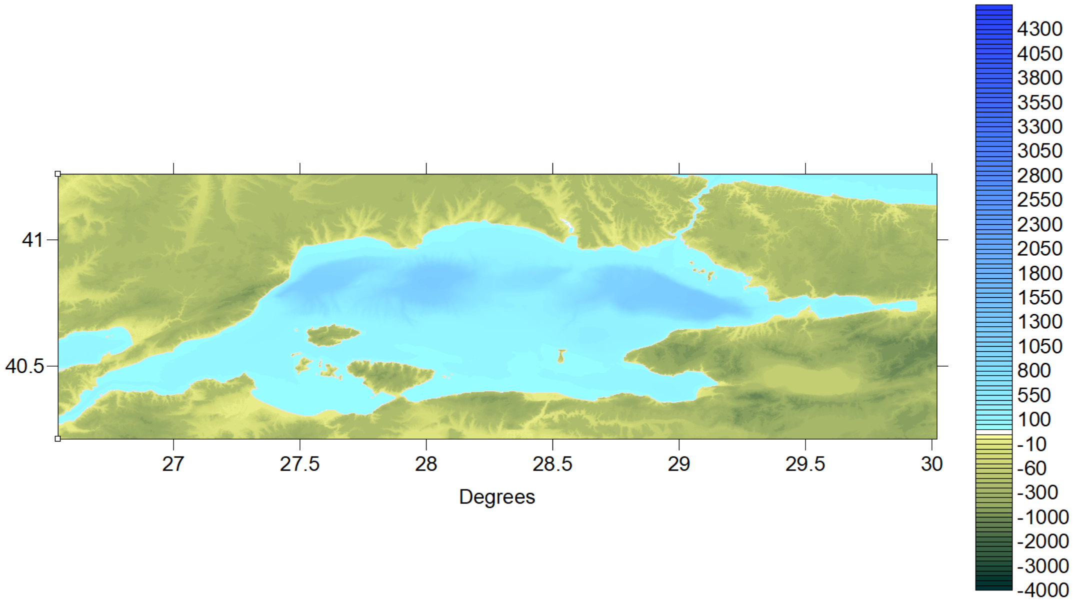

Figure 3-27 Coarse Batymetry in Surfer 8

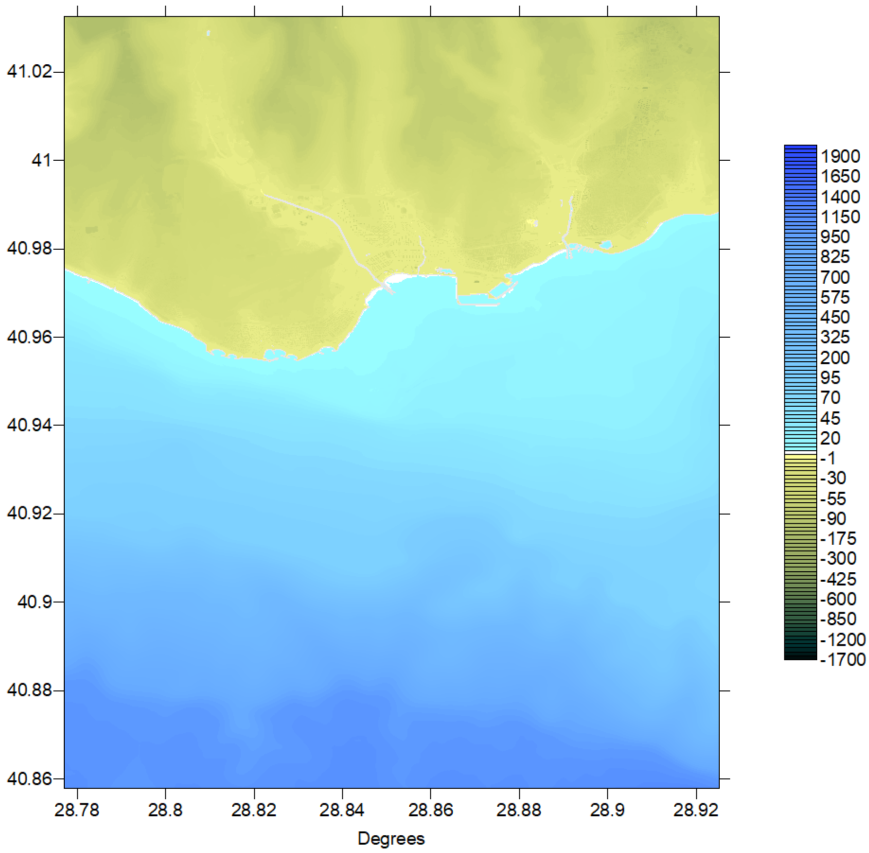

Figure 3-28 Nested Bathymetry in ArcMAP

3.2.2 Tsunami Source

From the literature review, Prince Island Normal Fault (PIN) and Landslide over Büyükçekmece water territory (LSBC) is determined as the most critical two tsunami sources for the Ayamama River and closer areas (Alpar et al., 2001; Aytöre, 2015; Tüfekçi, 2016).

3.2.2.1 PIN

Tsunami source PIN is the normal form of the first four oblique segments of Prince Islands Fault (PI). In this scenario, it is assumed that all of four segments are broken (Yalçıner et al., 2019). The segment and break parameters are given in the Table 3-15.

Table 3-15 Tsunami Source PIN parameters (OYO-IBB, 2007)

Latitude	Longitude	Depth	Strike Angle	Dip Angle	Rake Angle	Length	Width	Displacement	Initial Max Wave Amplitude	Initial Min Wave Amplitude
Degree	Degree	m	Degree	Degree	Degree	m	m	m	m	m
40.75691	29.12942	744	108.15	70	270	8753	17027	5	1.05	-2.57
40.78610	29.06928	740	123.15	70	270	6024	17027	5	0.94	-2.41
40.81653	28.99465	779	118.85	70	270	7148	17027	5	0.98	-2.47
40.87251	28.90432	1210	129.90	70	270	9834	17027	5	0.92	-2.36

In the Figure 3-29, PIN source is shown on Marmara Sea. On the color scale on the left, red part shows positive instant displacement, blue part shows negative instant displacement. On the right hand side of the figure, Blue colors show the sea depth and the green colors show the land area. Both left and right hand side scale units are in meters.

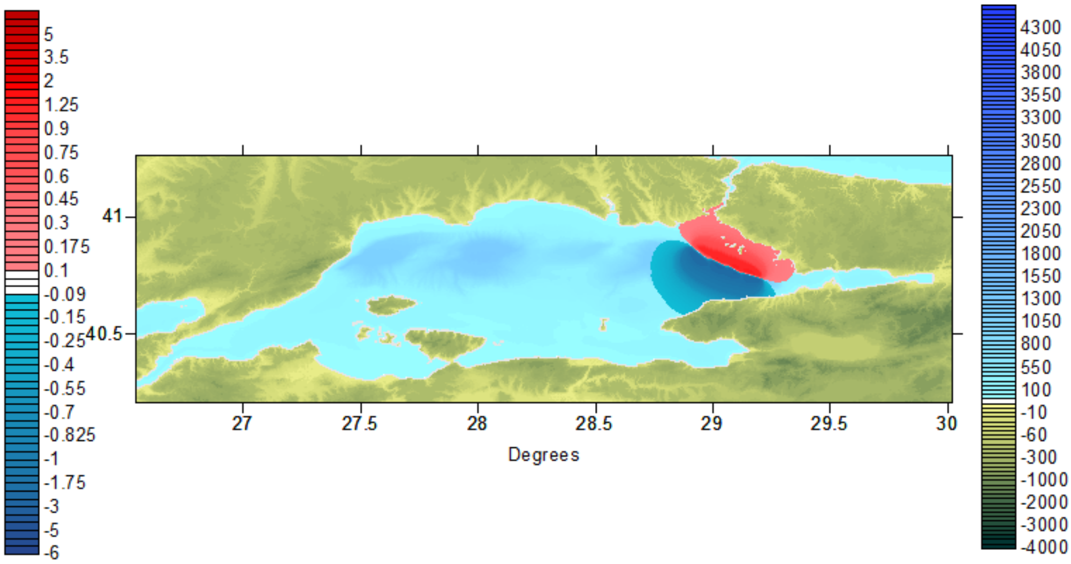

Figure 3-29 Tsunami Source PIN

3.2.2.2 LSBC

LSBC is the possible tsunami source at the offshore part of Büyükçekmece territory. The source is created by 25 kilometers of parallel and 5 km of perpendicular with 15 meters of thickness land slide. In the Figure 3-30, scale on the left represents the instant displacements of water in terms of meters. While red scale represents the positive displacement, blue scale represents negative displacement. On the right side, the scale represents bathymetry in terms of meters. Blue colors show the sea depth and the green colors show the land area. Initial maximum displacements are 16.5 and minus 11.5 meters for this tsunami source.

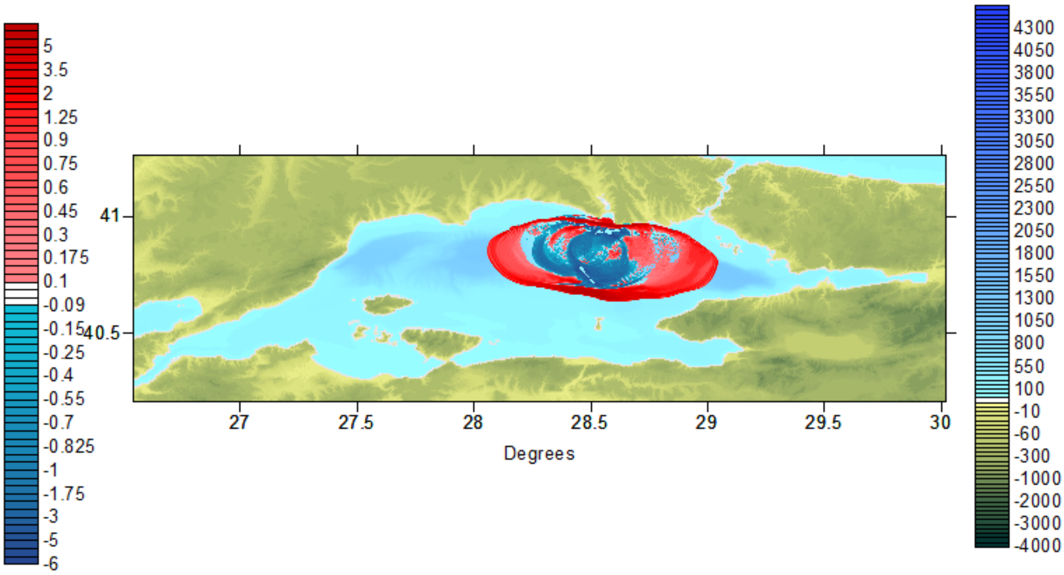

Figure 3-30 Tsunami Source LSBC

3.2.3 NAMI DANCE Model

NAMI DANCE is a numerical computational tsunami model that is developed by Zaytsev, Yalciner, Chenov, Pelinovsky and Kurkin. Program is developed in C++ programming language. In order to understand tsunami behavior and analyze it, to making risk analysis, NAMI DANCE is a proper tool with computation of nonlineer long wave equations in shallow water. NAMI DANCE can be used for computation of current velocities, fluxes and relative damage levels (http://namidance.ce.metu.edu.tr/).

NAMI DANCE computes the tsunami source for specific parameters and rupture characteristics, propagation of tsunami waves and its arrival times to a specific point, coastal amplification, inundation over land, animation of tsunami progress and many more features. In this study, most important feature of NAMI DANCE is inundation part.

The program needs a bathymetry, a source, gauge points and model run parameters in order to start computation. For bathymetry preparation, Surfer Computer program is used in this study. Raw bathymetry file is used as input. From Grid Data dialog, x axis is represented in Column A, y axis is represented in Column B and z axis is represented in Column C. For z axis, land elevations are taken negative, sea level is taken as positive values. After saving this grid data as ASCII grid file format, bathymetry is prepared. From Source Generation section, both elliptic and seismic sources are prepared with given data in sections 3.2.2.1 and 3.2.2.2. Outputs of tsunami source data is in grd files. For gauge data, 84 points are attached to the area of interest as shown in the Figure 3-31.

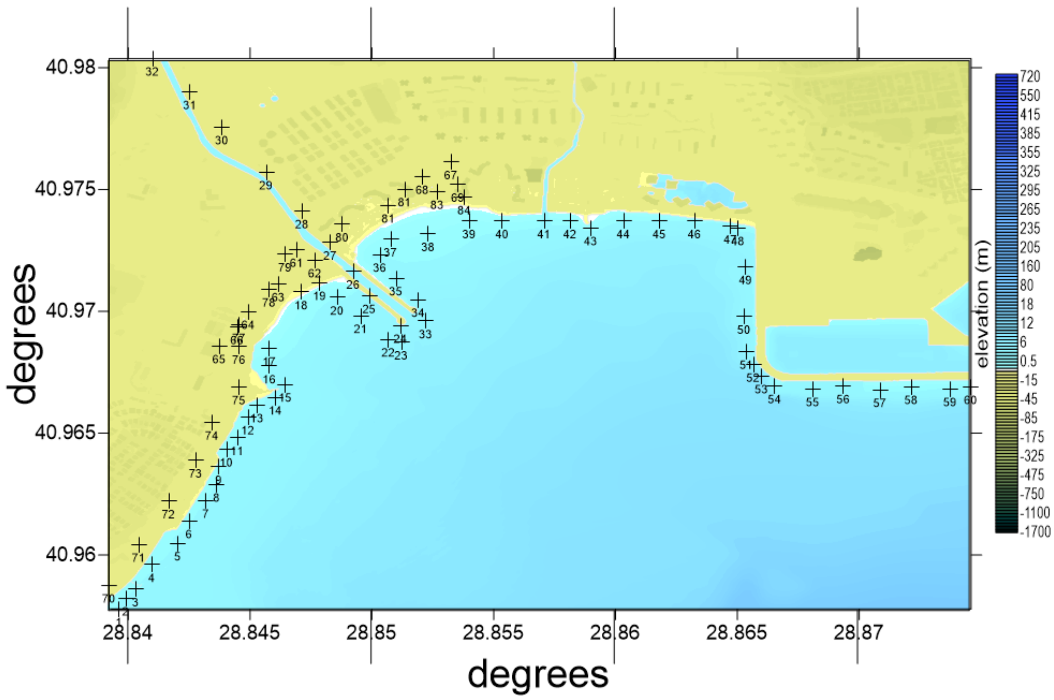

Figure 3-31 Gauges on the Study Area

The gauge data is saved as dat file. The first column represents the name of the gauge, the second column represents the lateral coordinate and the last column represents the longitude coordinate of the gauge. This data is presented in Appendix A.

Next step is to provide NAMI DANCE model run parameters. In Tsumilator section, the first input parameter is bathymetry. Coarser bathymetry is added to the model with gauge points that are identified above. Then, nested bathymetry is uploaded with same gauge points. For LSBC model, input sources for this source are uploaded.

Initial displacements are given as eta data logic, and horizontal flux inputs are given as flux x and flux y data logic. From previous research, it is shown that run duration for the initial waves are observed within 1 hour, but to observe the complete process, 4 hour run duration is determined. As the model suggests maximum Δt time step duration as 0.0307216 seconds, it is taken as 0.03 seconds. Gauge storage step is taken as 1 output per 10 time step. Eta output (water level) is taken as 60 seconds. Model run is processed with GPU since rendering and computation process is faster than CPU. For PIN model, source part is changed with PIN source. After run processes, the most critical model is run again with finer time periods in order to observe wave motion clearly for inundation process for the first wave. Eta output (water level) are taken for each 5 seconds. Figure 3-32 is an example of NAMI DANCE interface.

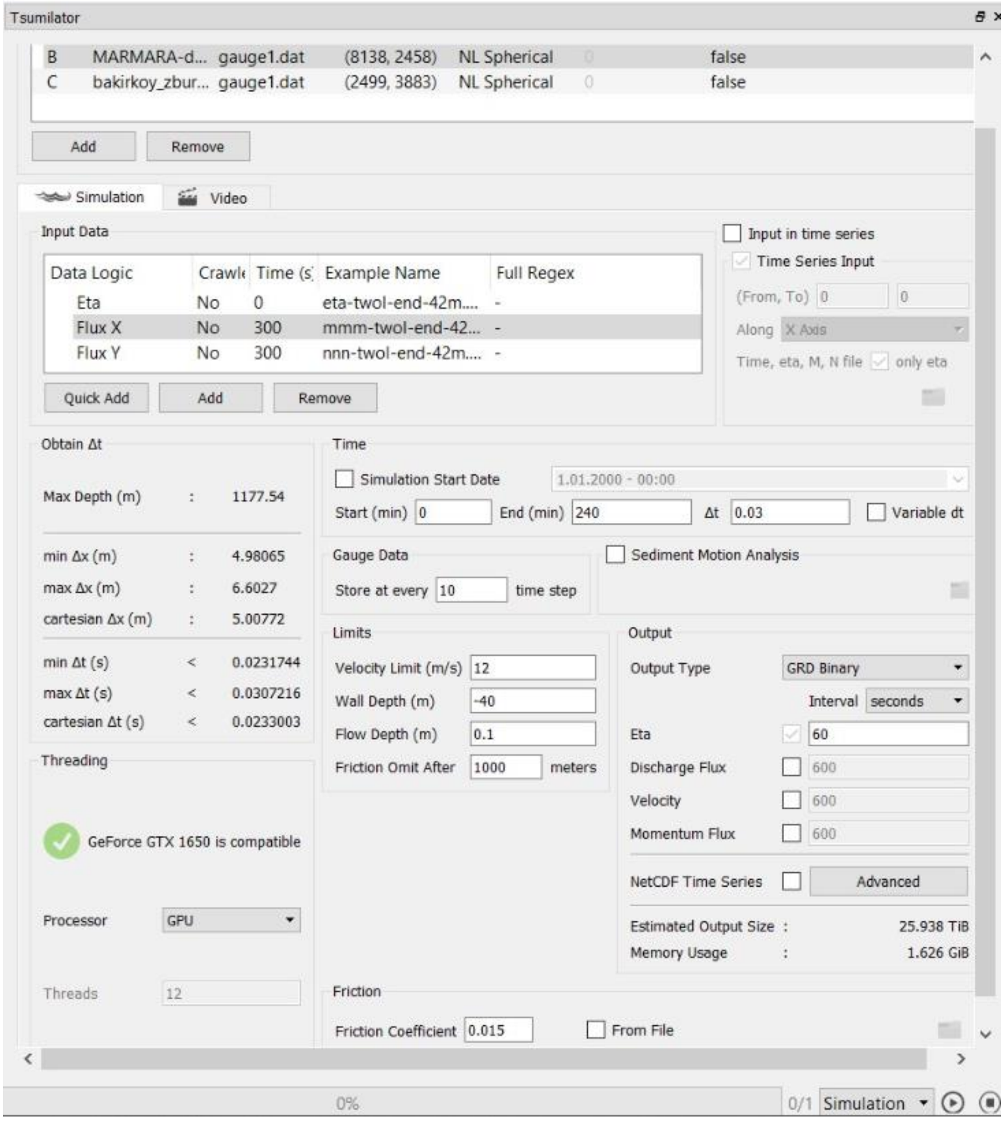

Figure 3-32 Nami Dance Run Parameters For LSBC Model

3.3 SPRC Model

An SPRC Conceptual Model is a representation of a dynamic process that starts with an source, passes through pathway to receptor and investigation of impacts on receptors. In this study, in order to understand the study area as flood basin and pathways of flood, this conceptual model is used. Two different models are constructed; one for the river flood on the Ayamama River, and one for the tsunami inundation on Bakırköy coasts. Then intersection of these two models at the

Ayamama River Mouth is also investigated to present similarities and differences of inundation process of two different flood sources.

Methodology of 2D-SPR model consists of 4 steps (Narayan et al., 2014) as shown in Figure 3-33. The first step is to determine the land boundaries of the model using the most extreme water level that can occur. This assumption is done by considering failure of all coastal defence systems. Past events, numerical model results can be used to determine the most extreme water level. The second step is determining of elements of flood plain in the model. All defence systems and land use elements are mapped and categorized. For specific places, number of the elements can be increased so resolution of model in that part can be improved. Categorization of the elements (such as protection structures, roads, etc.) can make the model easier to follow and understand. The third step is defining all relationships between neighbor elements. Pathways and receptors are identified in this step. While considering the relationship between two neighbor elements, elevation difference, slope, natural flow direction, habitation, friction and other parameters should be considered. The final step is to define source as a boundary in the model.

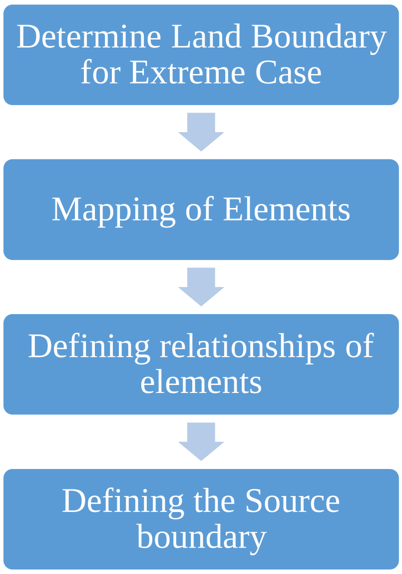

Figure 3-33 Methodology Flowchart for SPRC model

Before constructing river diagram, study area is determined. As it is stated in literature review section, a flood is not expected to be over 8-10 meters above the bank points. Since 100-150 meter horizontal inundation area is another criterion, limits of the flood plain for the river system diagram is determined.

Next, places and key points are categorized in the study area defined for river system diagram. Categories are determined as follows to reflect land use and human activities; Airport, Construction, Industrial, Military, Recreational, Residental, River, Road and Social. On a blank page, each unit is mapped. This map is not scaled, but gives general opinion about the locations and their topology within the system. Each unit is numbered and described properly in another file, so that one can follow the general classifications, or specific place in diagrams. All categories are colored for ease to follow where any of them located in the model. Since river is the major source in this model, specifications around Ayamama River are detailed to reflect the structures along the river channel such as vertical walls and culverts. These important points are added to the model map. Then, for each neighbor unit in the model, relationships are investigated. Flow direction, elevation and slope between units, characteristics are taken into consideration. The worst possible case is thought and estimated flow chart is added to the map. If two units are not neighbor, they can’t have any relationship. In other words, there must be a pathway between two non neighbor units. Results of hydraulic model (HEC-RAS) is also added on to this system diagram, so that a comparison can be made.

For tsunami SPRC model, literature review and NAMI DANCE model results obtained in this study are taken into consideration to determine the flood plain of system diagram along the coast. Since maximum water elevation of 15 meters and maximum of 2-2.5 km inundation area is observed in both previous studies and NAMI DANCE model results, study area is accepted as similar. If any previous study is not available, study area would be decided by wave height at the shores, pathways and elevation of neighborhoods, with emprical run-up formulas. For tsunami system diagram, categories are determined. In addition to categories in the river SPRC model, “Beach” category is added in this model since 3 different beaches exist in the study area. Similar procedure of developig river system diagram is applied to the tsunami study, with a few changes. Instead of river, specifications around the shore are detailed in this model such as revetments or vertical walls. This information allows us to observe the inundation motion from shore, as pathway. As in the river system diagram, all relationships between units are investigated, the worst scenario of inundation is applied and estimated flowchart is added to the tsunami SPRC model. Results of NAMI DANCE is also added on to this system diagram, so that a comparison can be made.

Finally, another SPRC system diagram is constructed for Ayamama River Mouth to analyze the area where river flood and tsunami inundation overlaps. In this intersection system diagram, units in both Tsunami and River Flood SPRC models are investigated. This system diagram includes both river and tsunami flow charts, and corresponding numerical model results.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, results of hydraulic model, tsunami model, and SPRC models are presented. Based on these results, affected areas, highlights of the study, relationships between sources, pathways and receptors, and comparison of models are investigated and discussed.

4.1 Hydraulic Model

In this study, hydraulic model is constructed via HEC-RAS with help of ArcGIS. The flood maps are discussed in three sections as it can be seen from Figure 4-1. The upstream of the river is identified as section 1, middle of the river is identified as section 2 and downstream of the river is identified as section 3. Figure is between 40.950 - 41.134 degrees latitudes, 28.737 - 28.977 degrees longitudes. Ayamama River, numerical model inundation result for 500 year return period of flood values, and coastline are shown in the figure.

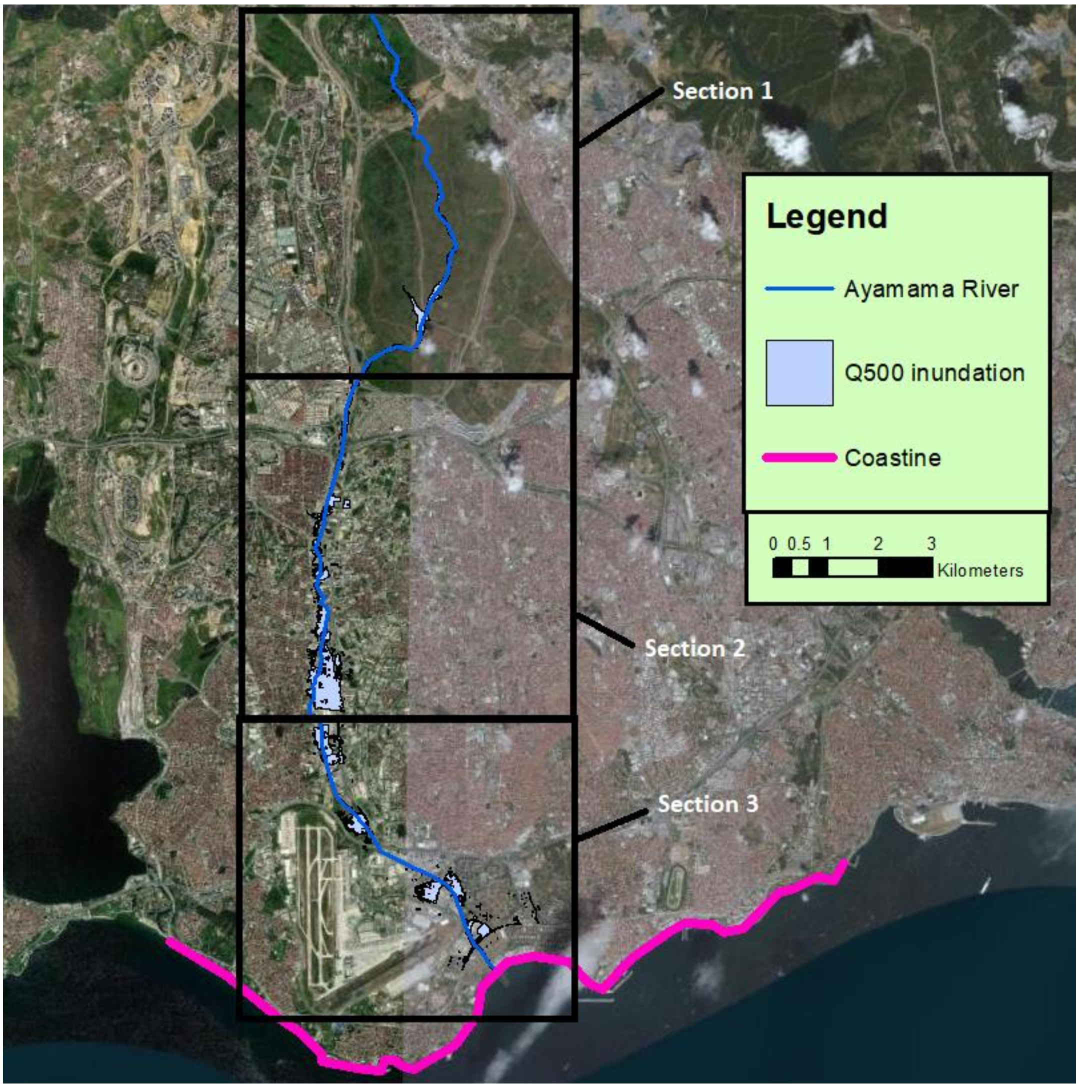

Figure 4-1 Three sections of inundation maps for 500 year return period

In Figure 4-2, inundation of 500 year return period flow flood at the upstream part of the Ayamama River is shown. This part of the river is in the Oruçreis Military Recreational area. Average of 80-100 meters of inundation from the river channel is observed in this section. At the bottom of the figure, it can be seen that the right hand side of the river is flooded into the shorter branch of the Ayamama River around 600 meters. In this section of the basin, 450756 m^2 area is determined to be flooded and all of it is in the recreational area. Therefore, damage is expected to be limited in this area. Maximum flood water depth is obtained as 6 meters and average of maximum water depth in inundation area is between 3-4 meters. This section is the least flooded section along the watershed of the three sections of the whole river basin modeled in this study.

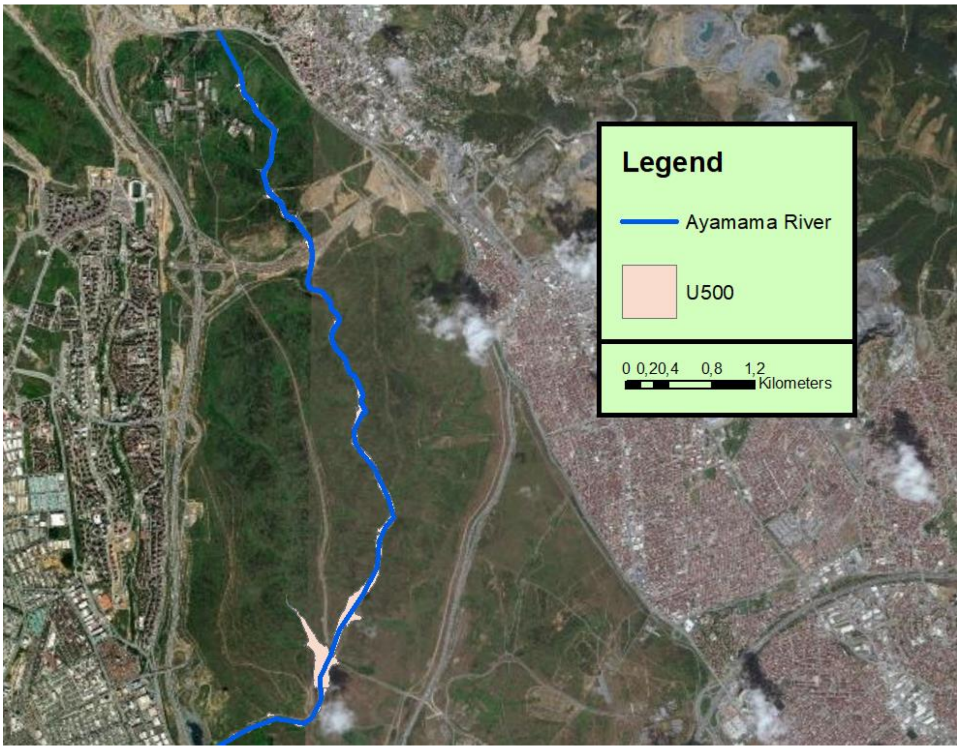

Figure 4-2 Flood inundation with 500 year return period flow in the Ayamama River (Upstream)

In Figure 4-3 second section of the flooded area is shown. The area starts from İstoç OSB Highway Connection and ends at Değirmenbahçe Street. Average of 100-150 meters and maximum of 550 meters of inundation from the river channel is observed. In this section, mostly neighborhoods (settlements) and industrial areas are flooded. With a total of 973185 m^2 inundation area, this section is the highest flooded area of the three sections. Mahmutbey, Atatürk, Halkalı Center, Evren, Tevfikbey, Yenibosna, İnönü Neighborhoods are the flooded areas. Maximum water depth is obtained as 6 meters and average of maximum water depth in the inundation area is between 1-2 meters.

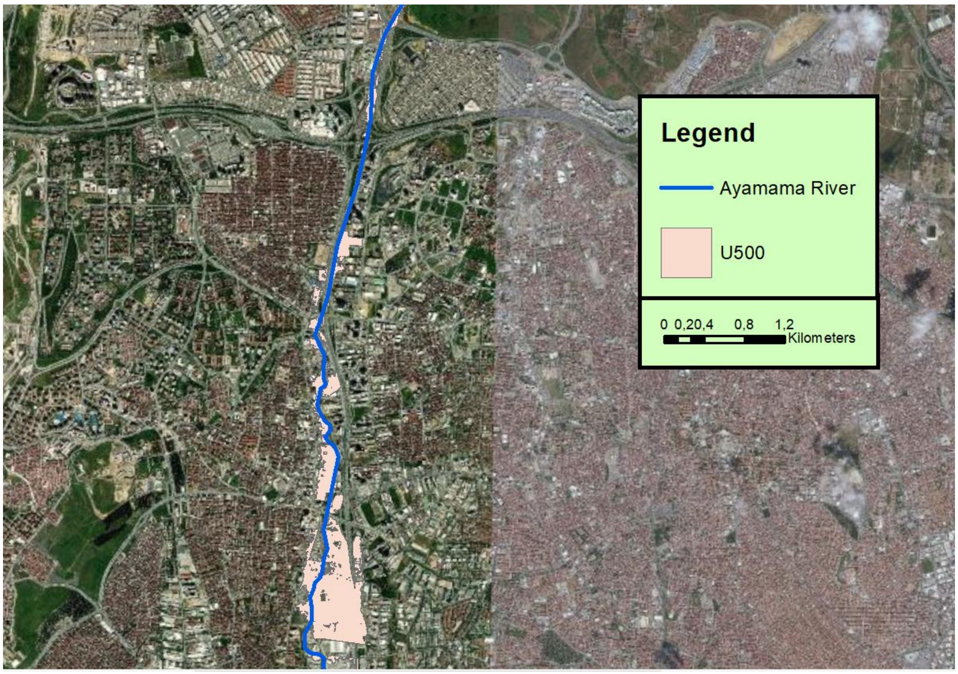

Figure 4-3 Flood inundation with 500 year return period flow in the Ayamama River (Center)

In Figure 4-4, flooded area of downstream section of the Ayamama River is shown. This section starts at Değirmenbahçe Street and ends at Marmara Sea. Maximum 450 meters of inundation is observed from the river channel. In this section, the river does not overflow along the river bed, but at specific locations contorary to the other two sections. At the locations where river overflows, generally 150 meters of inundation is observed. Yenibosna Center and Ataköy 7-8-9-10 neighborhoods, biological waste plant and World Trade Center Fair Area are inundated in the model. 841306 m^2 area is flooded in this section. Maximum of 2 meters water depth is observed in flooded area. Average maximum depth is between 0.5-1 meters.

Figure 4-4 Flood inundation with 500 year return period flow in the Ayamama River (Downstream)

In 2009 flood event, 100-150 meter inundation with maximum 6-7 meters of depth was observed in this area. Similar to 2009 flood event, Atatürk, Evren, İnönü and Çobançeşme districts are flooded in the model, however İkitelli Area which was also flooded in 2009 is not shown as flooded in the numerical model. Previous investigations showed that an uncontrolled filling for truck parking area and inadequate vent opening lead to the flooding in 2009 event and this blocked the highway connection. As a result, İkitelli Area was flooded in 2009 flood event (İBB DEZİM, 2009). However, effects that can be done by blockage of trucks are not added in the numerical model as this was a specific occurrence valid only for 2009 event. Except İkitelli Area, numerical model and 2009 flood event are consistent in the flooded areas. This numerical model showed that flood occurred in 2009 had a high flow which corresponds to a return period around 500 years.

From Figure 4-5 to Figure 4-8 flood propagation of the 500 year return period event modeled in this study can be seen. The first flooding is observed at Yenibosna and Halkalı Center Neighborhoods 3:30 hours after the hydrograph starts. The inundations at 4:00, 6:00 and 10:00 hours after the beginning of the run are also shown in the figures. Inundation area is at its maximum at 10:00 hours after the model start. These figures are compared with SPRC model pathway and receptors in SPRC section.

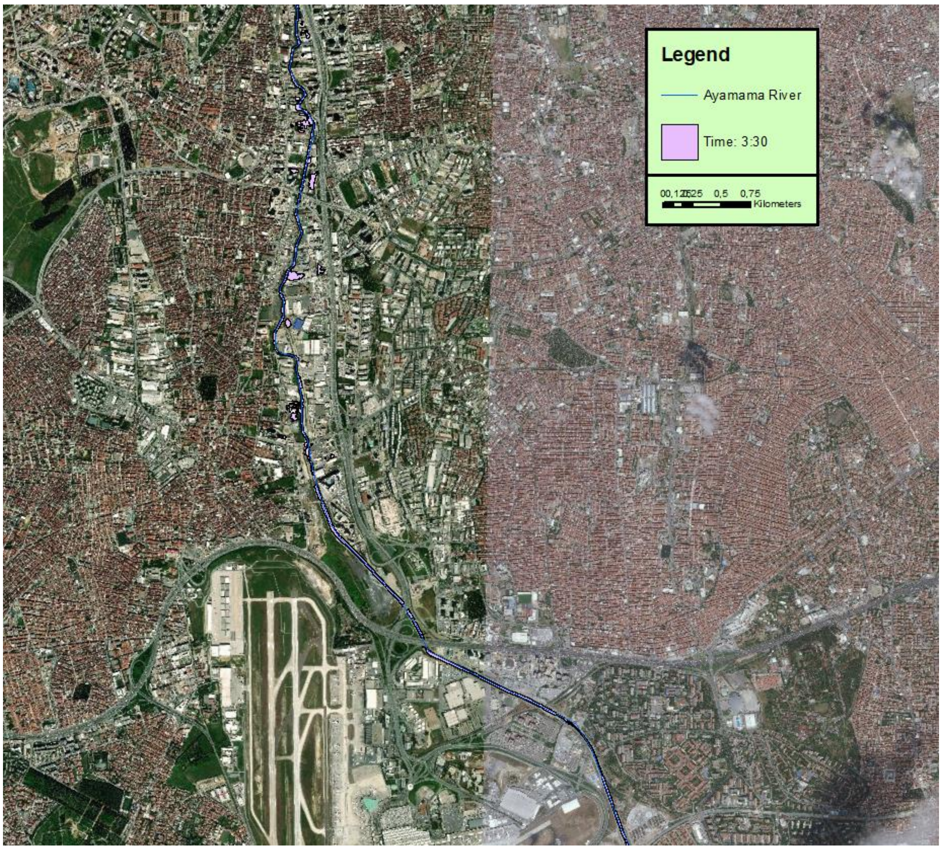

Figure 4-5 Flood inundation at 3:30

Figure 4-6 Flood inundation at 4:00

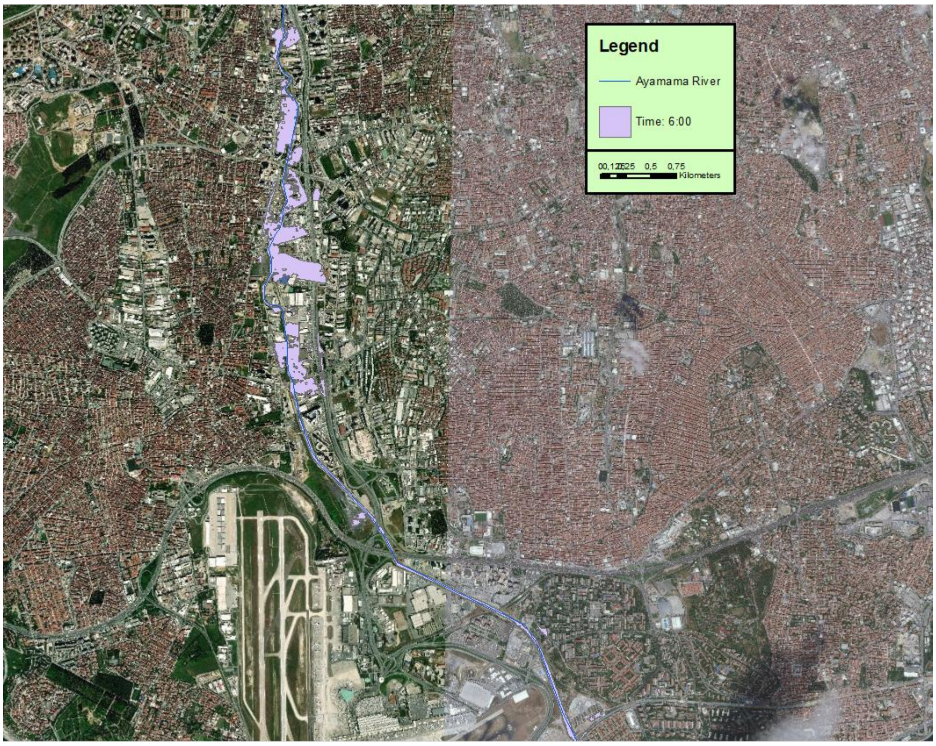

Figure 4-7 Flood inundation at 6:00

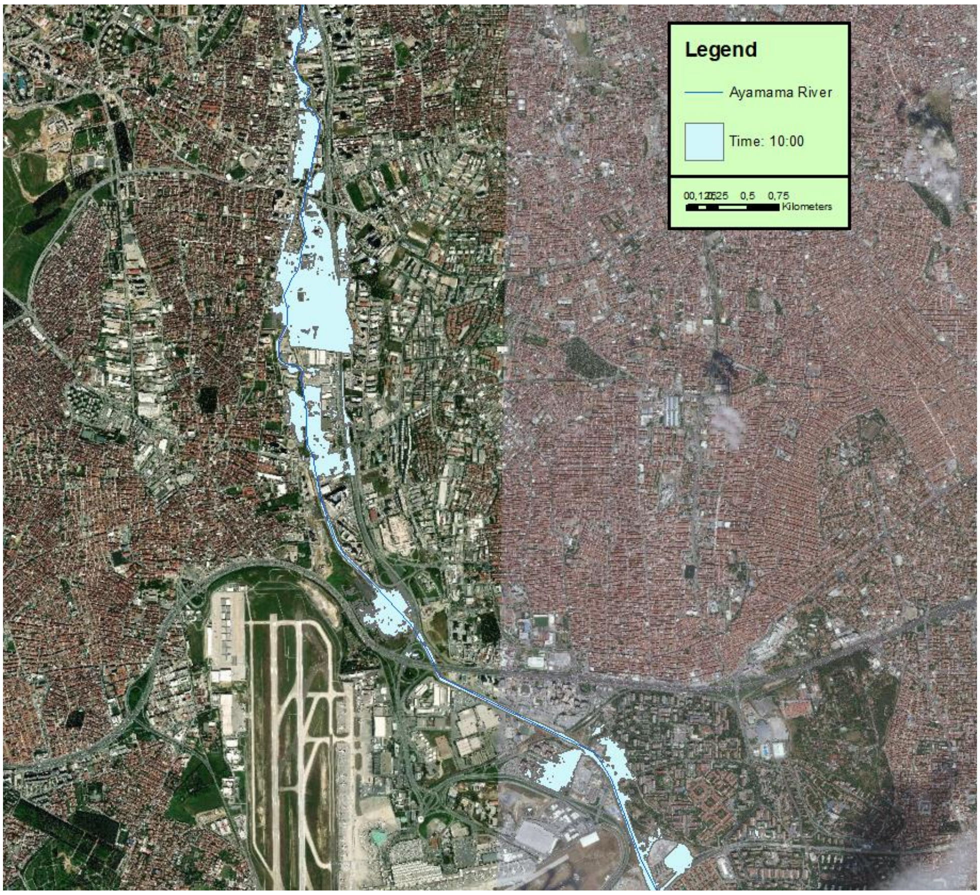

Figure 4-8 Flood inundation at 10:00

4.2 Tsunami Model

In this study, tsunami model is constructed using NAMI DANCE. Both LSBC and PIN sources are used as model inputs, and maximum eta values are compared. As it can be seen from Figure 4-9 and Figure 4-10; LSBC sourced tsunami model is more critical than PIN sourced tsunami model in Bakırköy Coast since inundation area for LSBC sourced tsunami is wider. Moreover, run-up heights are higher in the LSBC sourced model. Thefore, LSBC model is decided as the most critical scenario for Bakırköy Coasts, results and details are given and discussed for this model run. Following figures (Figure 4-9 and Figure 4-10) belong to nested view of results.

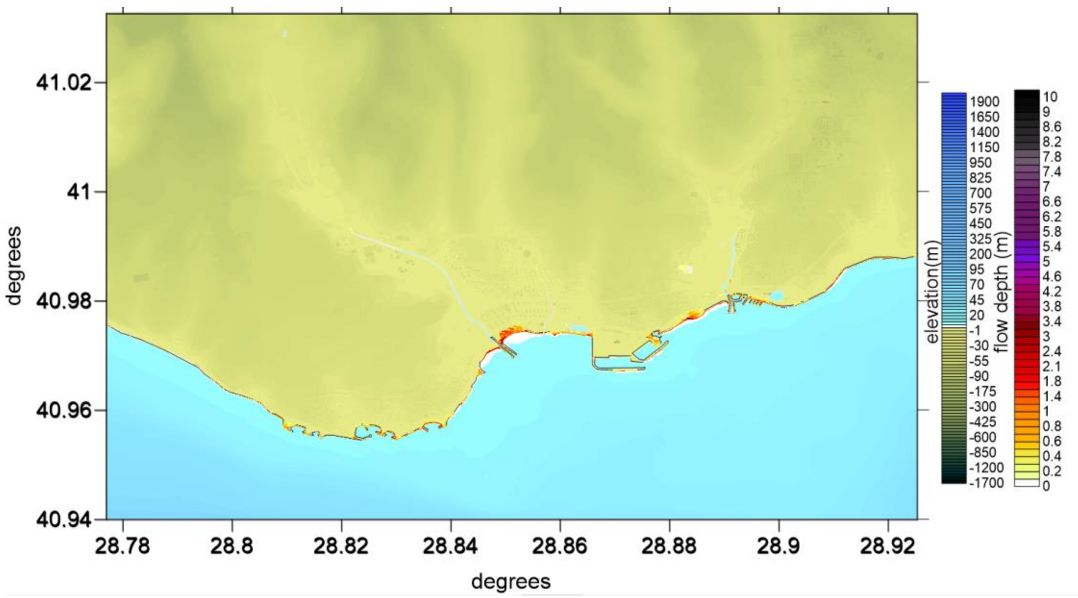

Figure 4-9 Maximum Flow Depth Map of PIN Sourced Model

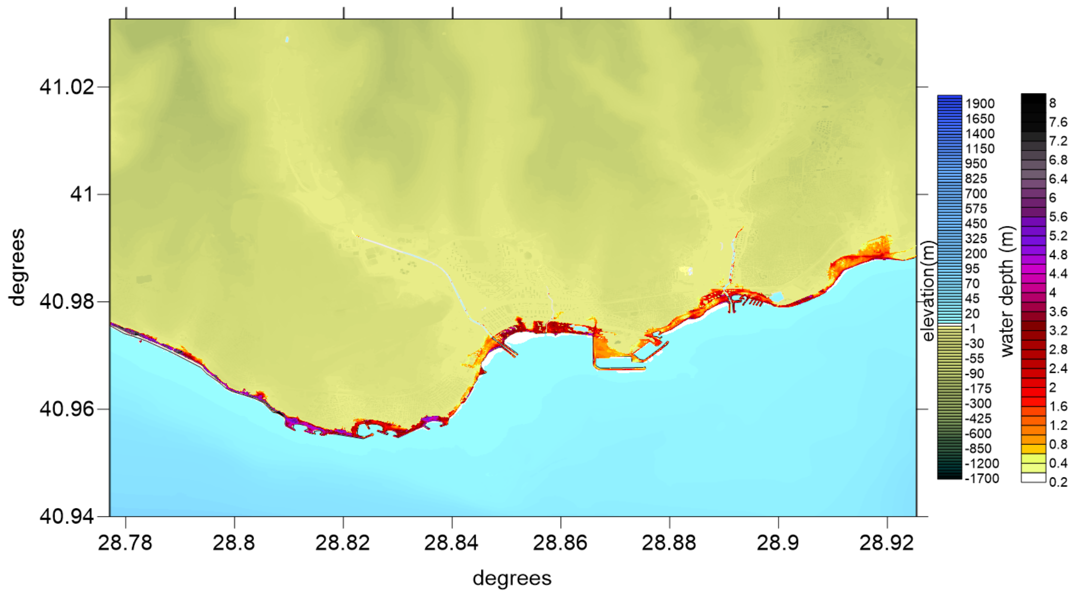

Figure 4-10 Maximum Flow Depth Map of LSBC Sourced Model

The results of LSBC scenario shows that maximum value of 12.03 m and average of 3-5 meters of water depth is observed in the land part of the study area. When the minimum eta map is analyzed (Figure 4-11), minus 8.73 meters of eta value is obtained as lowest value. Minus values only occurs on the sea.

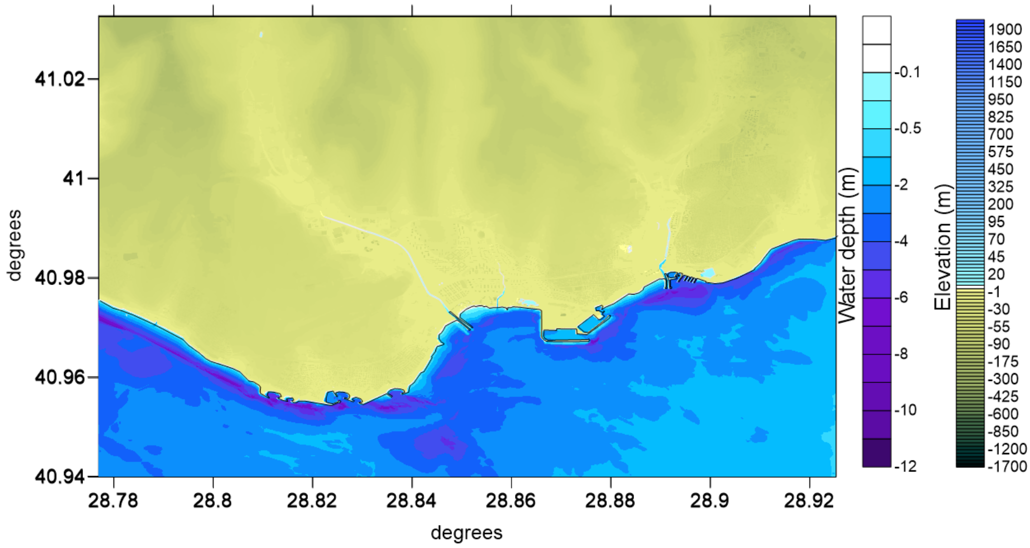

Figure 4-11 Minimum Eta Map of LSBC Sourced Model

Instant eta profile outputs are taken at 1 minute intervals for tsunami propagation. These outputs are used to compare the results with SPRC method. Inundation of tsunami waves can be seen in the first 10 minutes of propagation (Figure 4-12 to Figure 4-17). Tsunami waves reach to the Ayamama River at 5th minute. Then, it inundates onward to the land. In Ayamama River, approximately 5 km of inundation is observed, and in the land, maximum of 500 meter inundation is observed.

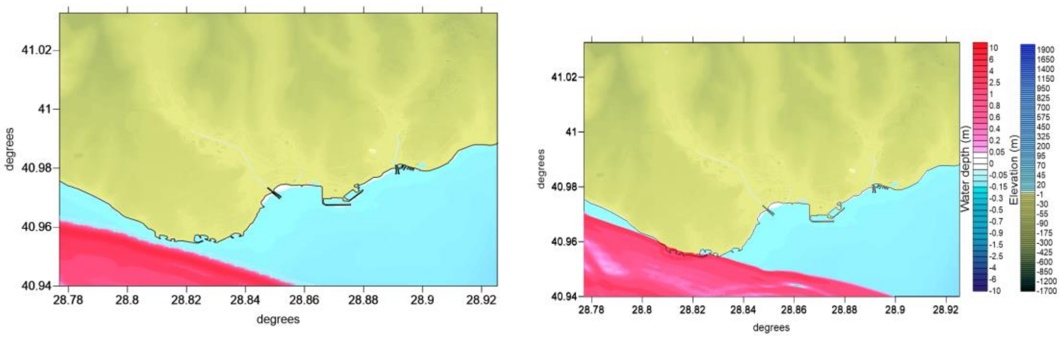

Figure 4-12 Tsunami propagation at 0-1 minutes

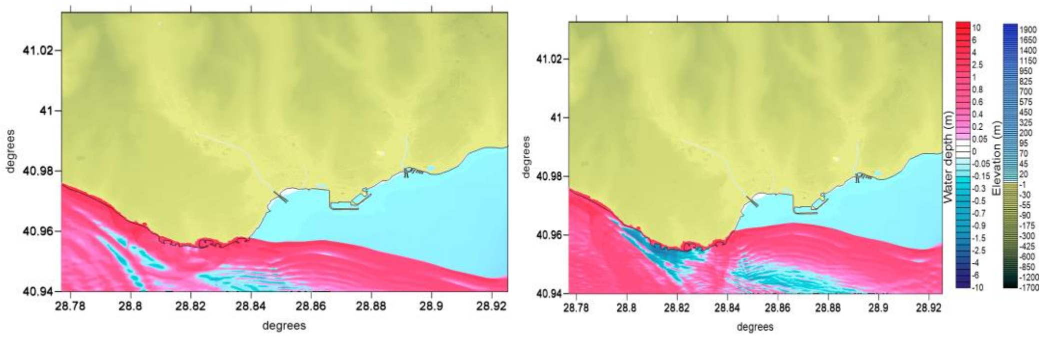

Figure 4-13 Tsunami propagation at 2-3 minutes

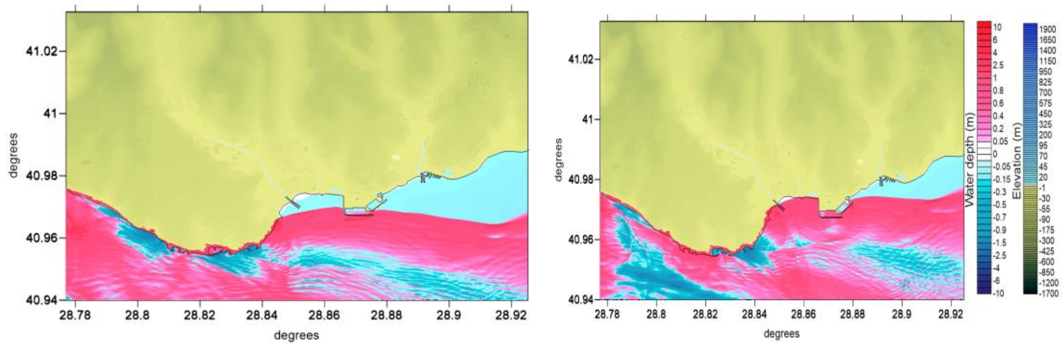

Figure 4-14 Tsunami propagation at 4-5 minutes

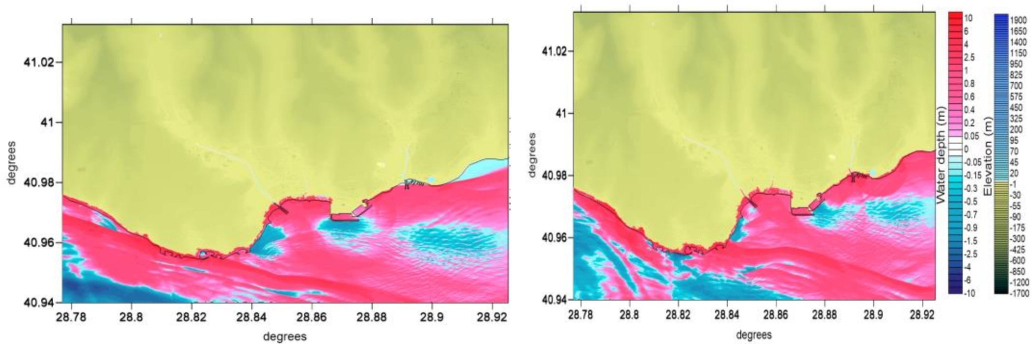

Figure 4-15 Tsunami propagation at 6-7 minutes

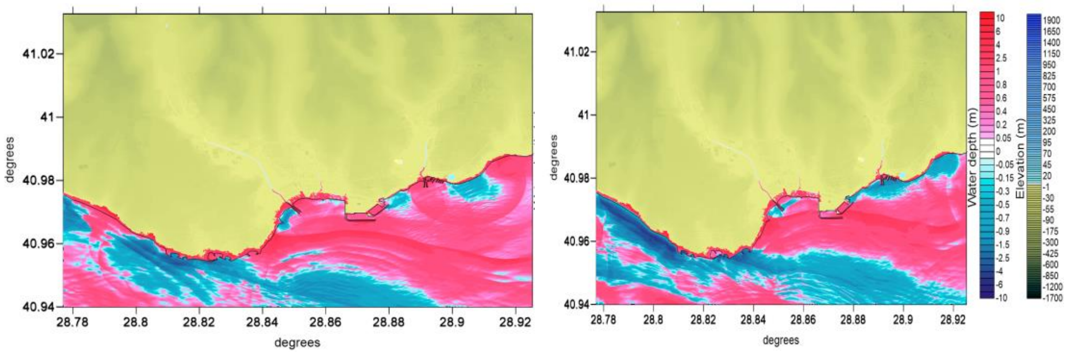

Figure 4-16 Tsunami propagation at 8-9 minutes

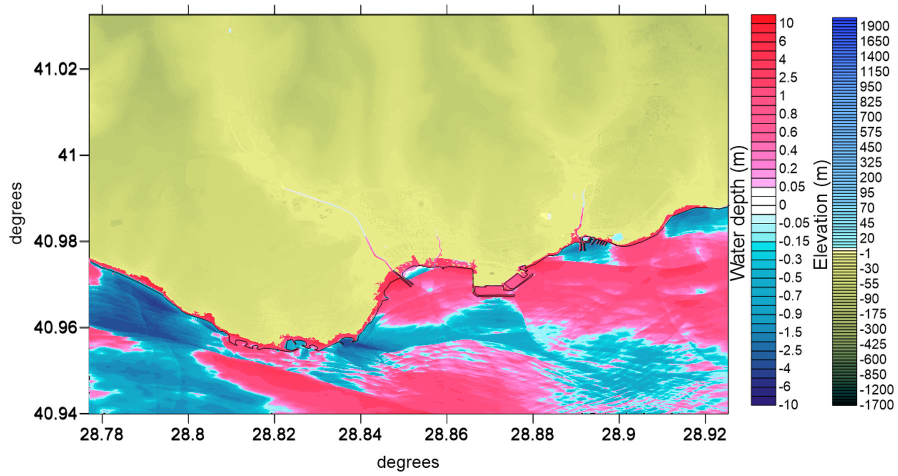

Figure 4-17 Tsunami propagation at 10 minutes

LSBC model is run with 84 gauge points, 31 of them located on the land, 53 of them located on the sea. For 4 hours, water profile data is collected for each 0.3 seconds. Each tsunami wave passes through the gauges and its profile is obtained by this procedure. Maximum eta value out of 84 gauge points is observed on Gauge Point 19 with 7.22 meters. Figure 4-18 shows the time history of Gauge Point 19 and Figure 4-19 shows the location of it, which is on the land. Y axis represents the initial eta value in terms of meters and X axis represents the time in terms of minutes. Arrival time of maximum wave is 14.82 minutes for this gauge.

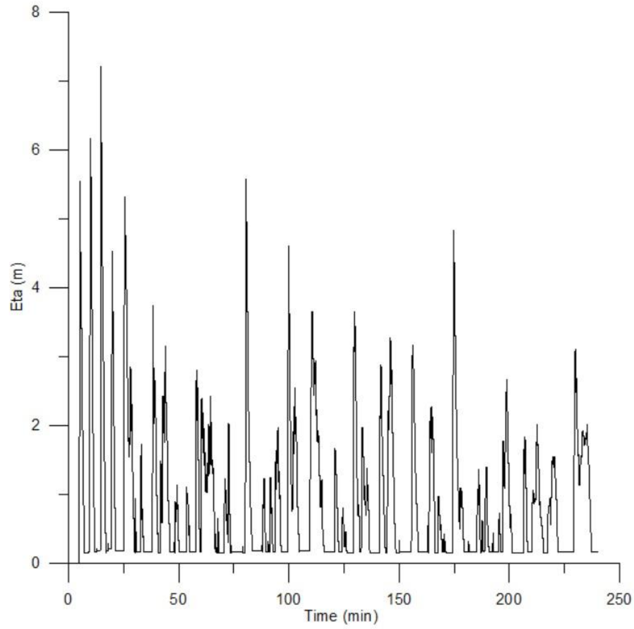

Figure 4-18 Time History of Gauge Point 19

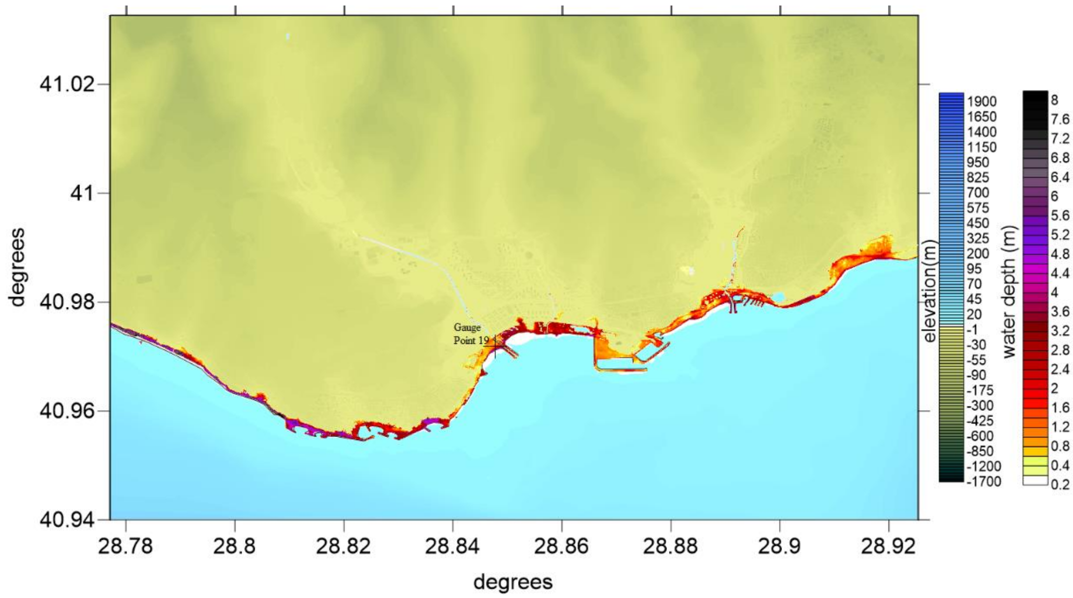

Figure 4-19 Location of Gauge 19 on Maximum Flow Depth Map

In Figure 4-20, flow depth distribution on the Ayamama River mouth is shown. As it can be seen on the figure, maximum of 4 meter flow depth is observed in this section.

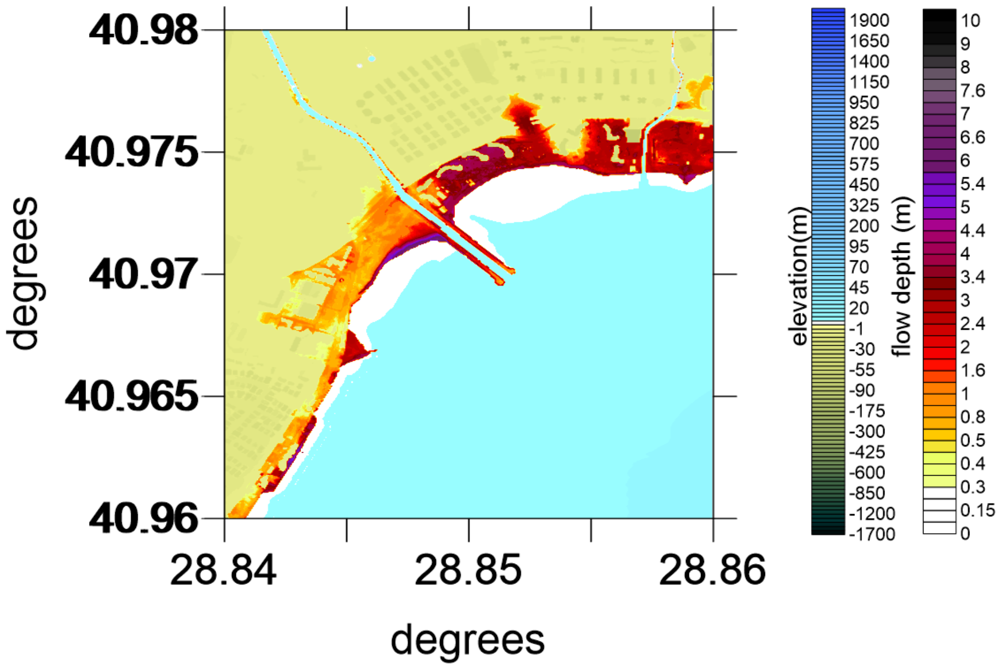

Figure 4-20 Flow depth distribution for LSBC sourced Tsunami focused on the Ayamama River Mouth

In this study, the gauge data is mainly used to see when the waves inundate the land. As gauge output, arrival time of maximum wave, maximum and minimum eta value, maximum current and angle of the maximum current is taken as output. For Gauge point 19, output is obtained as follows:

Table 4-1 Output Summary For Gauge Point 19

Name	Depth(m)	Arrival Time of Maximum Wave (min)	Max Eta (m)	Min Eta (m)	Max Current (m/s)	Angle of The Max Current (degrees)
GP19g	-0.15	14.82	7.22	0	9.09	16.32

Minus sign in the depth means that the gauge is on the land. Minimum Eta shows as 0 since the gauge is on the land.

As result of tsunami model, Basınköy Neighborhood and Basınköy İstanbul Street, Florya Beach Park, Yeşilköy Beach, Yeşilköy Marina, Yeşilköy Neighborhood, Yeşilköy Beach Park, Yeşilyurt Neighborhood, Military Area, Ayamama River, Ataköy 2-5-6, Rauf Orbay Street, Yalı Ataköy, Ataköy Marina, Kennedy Street, Aytekin Kotil Park, Sakızağacı Neighborhood, Veli Efendi Racetrack, Zeytinburnu Pier, Kazlıçeşme Neighborhood, Kazlıçeşme Park and Yedikule Neighborhood are under risk of tsunami flooding. In study area, total of 2992623.55 m^2 land inundated.

4.3 SPRC Models

In this section, SPRC system diagrams developed for river flood case and tsunami case are presented. The flood direction and pathways derived from numerical model results are also shown in these diagrams to compare the information provided by different models and to discuss SPRC approach in flood management.

4.3.1 River Case

River SPRC system diagram (Figure 4-21) is drawn based on the methodology presented in previous chapter. In addition to SPRC Conceptual model, numerical model is schematized in the Figure 4-21. The upper part of the figure represents the upstream of river, the lower part of the figure represents the downstream. While blue single sided arrows represents the estimated flow direction for SPRC model, blue double sided arrows represents the estimated flow can be two directional. Similarly, green single sided arrows represents the flow direction in numerical model. The flow direction is estimated by using elevation and slope information of the flood plain between the neighbor elements defined in the system diagram.

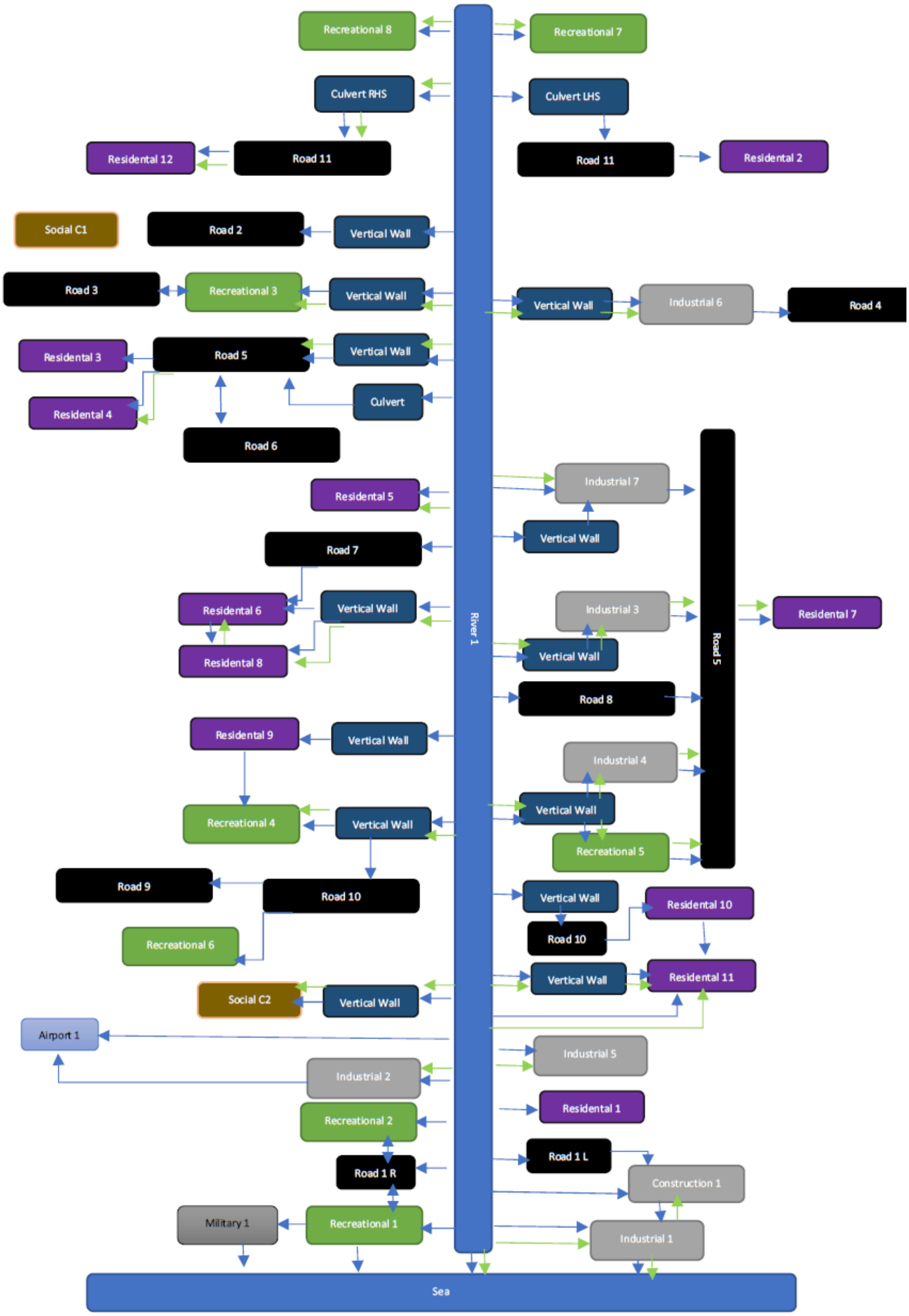

Figure 4-21 SPRC Diagram For River Flood

All the descriptions of numbered categories are alphabetically listed below;

Airport 1 = Atatürk Airport

Construction 1 = Ataköy 2 Site Construction

Industrial 1 = Industrial Facility (at Lat = 40.973 & Long = 28.849 degrees)

Industrial 2 = Industrial Facility (at Lat = 40.974 & Long = 28.840 degrees)

Industrial 3 = Yenibosna Center Neighborhood (Between Ayamama River and Road 5, Upstream)

Industrial 4 = Yenibosna Center Neighborhood (Between Ayamama River and Road 5, Downstream)

Industrial 5 = Biological Waste Treatment Plant

Industrial 6 = Mahmutbey Neighborhood (Between Ayamama River and Taşocağı Yolu Street)

Industrial 7 = Halkalı Center Neighborhood (Left Hand Side of Ayamama River)

Military 1 = Air Force Academy

Recreational 1 = Military Green Area

Recreational 2 = Unknown Recreational Area

Recreational 3 = Recreational Area at the intersection of O-7 and O-3 roads

Recreational 4 = Çobançeşme Garden (Right Hand Side of Ayamama River)

Recreational 5 = Çobançeşme Garden (Left Hand Side of Ayamama River)

Recreational 6 = Recreational Area at Çobançeşme Boulvard

Recreational 7 = Oruçreis Military Recreational Area, Left Hand Side of Ayamama River

Recreational 8 = Oruçreis Military Recreational Area, Right Hand Side of Ayamama River

Residental 1 = Ataköy 2-5-6

Residental 2 = Mahmutbey Neighborhood (Between Ayamama River and 2457th Street)

Residental 3 = Mehmet Akif Neighborhood

Residental 4 = Atatürk Neighborhood

Residental 5 = Halkalı Center Neighborhood (Right Hand Side of Ayamama River)

Residental 6 = İnönü Neighborhood

Residental 7 = Yenibosna Center Neighborhood

Residental 8 = Tevfikbey Neighborhood

Residental 9 = Kartaltepe Neighborhood

Residental 10 = Çobançeşme Neighborhood

Residental 11 = Ataköy 7-8-9-10

Residental 12 = Ziya Gökalp Neighborhood

River 1 = Ayamama River

Road 1 L = Rauf Orbay Street (Left Hand Side of Ayamama River Flow Direction)

Road 1 R = Rauf Orbay Street (Right Hand Side of Ayamama River Flow Direction)

Road 2 = O-7 Road (Latitude = 41.066983 , Longitude = 28.813927)

Road 3 = O-7 & O-3 Roads Interception

Road 4 = Taşocağı Yolu Street

Road 5 = Mahmutbey Yeşilköy Connection Road

Road 6 = Halkalı Street

Road 7 = Fatih Street

Road 8 = Değirmenbahçe Street

Road 9 = D-100

Road 10 = Çobançeşme Boulvard

Road 11 = O-7 Road (Latitude = 41.073049 , Longitude = 28.815187)

Social C1 = Mall of İstanbul Shopping Center and Life Center

Social C2 = CNR Fair Center

Both the most left and right hand side elements (directions are defined as going from upstream to downstream) are decided as the criteria in the methodology section; approximately 100-150 meters away from and 8-10 meters above the river. Starting from the upstream, the channel width is inadequate and elevation of banks are 1- 4 meters higher than the river bed, both “Recreational 7” and “Recreational 8” are marked as estimated flood area. The channel is in natural condition, therefore the recreational areas are both pathway and receptors. In numerical model, the river is flooded from both right and left hand sides.

In order to flood the “Road 11” water should pass the Culvert as pathway. Both left and right hand banks are 3 meter above the river bed, therefore both sides are marked as flood route. For left hand side of the river, Road 11 and Residental 2 are 7 meters above than banks, since the worst scenario is taken into considered, these are also marked as flow route, however, the flooded water in the numerical model didn’t follow this route. On the right hand side, Road 11 is almost at the same level with the culvert, and Residental 12 is 2 meters above the Road 11. So until Residental 12, river source passes through Culvert and Road 11 which act as pathways to Residental 12 receptor in SPRC model. In numeric model, water moves same as SPRC model. The main reason for flooding in this section is inadequate culvert capacity. The river floods and elevates to the right hand side. There is no flood occur on the left hand side so Residental 2 didn’t flood in the numerical model.

The next important point is Mall of Istanbul Shopping Center (Social C1). The vertical wall between the road and the river is 8 meters above the bed. It is assumed as the vertical wall acts as pathway to the Road 2 if water overflows this structure. Since shopping center is at way higher location than the river bed, in SPRC model Social C1 is not estimated as flood receptor. In numerical model, water depth remains at 7 meters, so there is no flood occurred at this point in hydraulic model. Any flood that has longer return period would flood the river at this point but the possibility that Social C1 will be flooded is very low.

In clover shaped connection, recreational area (Recreation 3) is 4-5 meter higher than river bed, and Road 3 is 10 meter higher than bed. Following the system diagram it is assumed that water flooded through the vertical wall to the recreational area, then continued to its way to Road 3. Since 10 meter water height is assumed as maximum, even if river floods to this area, the elevation and slope of Road 3 would limit the flow it will return back to recreational area. In hydraulic model, recreational area (Recreation 3) is flooded but it didn’t reach to Road 3. In the Figure 4-22, inundation of 500 year return period flood is observed in this section. Land usage and its SPRC corresponding elements are identified with elevations in the figure.

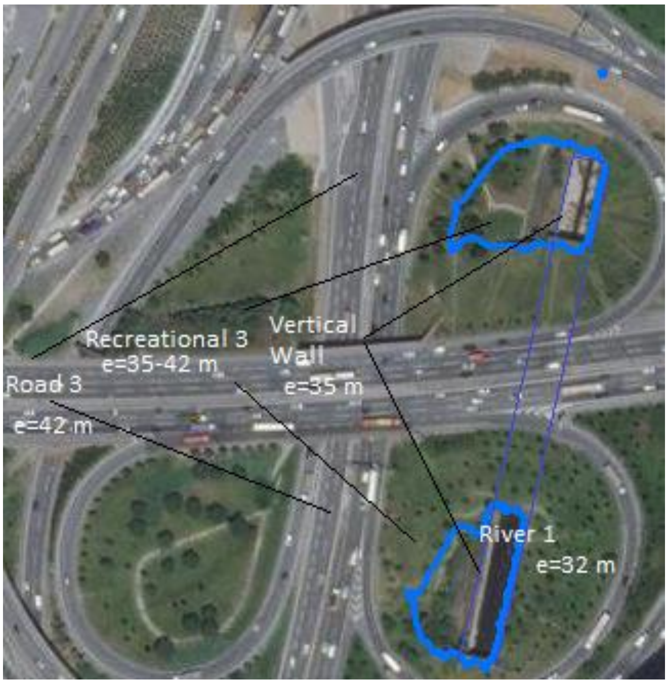

Figure 4-22 Elevations, Inundation and Land Use in Satellite View

On the left hand side Industrial 6 area is seen as an unprotected area, between the lowest point in the bed and the Industrial 6 area, only 4.5 meter vertical distance is measured. Flood should pass the vertical wall between Industrial 6 and river bed, and reach to Industrial 6. Since elevation of Industrial 6 is under 10 meters, it is defined as critical receptor in SPRC model. Therefore, if flood rises 4 more meters, it would reach to Road 4, but numerical model results show that water only inundates Industrial 6 and couldn't reach to Road 4.

On the right hand side, water should pass through the Road 5 to reach Residental 3 and Residental 4. Road 5 is 6.5 meters higher than river bed, Residental 3 and Residental 4 are lower than Road 5. So if the Flood passes Road 5, it definitely will inundate Residental 3 and 4 too. In SPRC model vertical wall is also added to diagram since water firstly should pass the vertical wall. In numerical model, river channel capacity is enough for the flow in the upstream, but when the river gets narrower, water flooded from Road 5 to Residental 4. Before closed section, the river passes through a culvert. It is thought that if the culvert opening is not enough, river will flood Road 5 again, but numerical model showed that section is wide enough for the modeled flow.

End of the closed section starts with a natural cross section, and the vertical distance to banks are around 5 meters. Neighbour elements are Residental 5 and Industrial 7, so the region is decided as highly risky area. In numerical model, these areas are also flooded. In the diagram, it can be seen that if the river floods through Road 7, it will pass through Residental 6 and reach Residental 8, but surprisingly, in the numerical model no flood occured on the Road 7, so it couldn't reach to Residental 6 and 8. However, after Road 7, river flooded on the right hand side from vertical wall, passed through Residental 8 and flushed back to Residental 6. This was the most unexpected flood zone where the SPRC and numerical models are not consistent at all in this area.

On the left hand side, both in SPRC and numerical models water passes through vertical wall, Industrial 3, Road 5 and reaches Residental 7. All these elements are both receptors as themselves but also pathways for all those elements after them. Eventhough Residental 9 is not on high elevation, just 5 meter above the river bed, no flood occurred in the numerical model, since channel width was large enough for the modeled flow. Thus, this pathway to Recreational 4 shown in SPRC system diagram is not completed in the numerical model. However, it directly flooded from vertical wall to Recreational 4 which is another pathway shown in system diagram (vertical wall to Recreational 4). The vertical wall is also expected to be a pathway for Road 10, Road 9 and Recreational 6. However, since Road 10 not flooded under flow conditions used in numerical model, automatically Road 9 and Recreational 6 stayed dry.

On the left hand side, as it is expected both in numeric and SPRC models, vertical wall was a flood pathway for Industrial 4 and Recreational 5. Flood continued to Road 5 from Recreational 5, in other words, Recreational 5 was receptor before, but now it is pathway for Road 5. Residental 10 is 8 meters higher than river bed, so it might flood, or not. In critical case, it was thought as flooded with correct pathways, but in the numerical model it didn’t flood under the model flow condition. However, in 2009, this neighborhood flooded. SPRC model is more realistic than numerical model at this point by showing all the possible links between the elements of floodplain regardless of flood scenarios.

Residental 11 is another critical place in the models, since it is near river bed with and without structural protection (vertical walls). In SPRC model, it is assumed that it will be flooded in both from natural bed and vertical wall, and numerical model validates it for the model flow condition. On the right hand side of the river, Fair Center (Social C2) is flooded as receptor with pathway of a vertical wall. From here to downstream, the vertical distances between the river bed and elements are not high, so all of the neighbor elements are thought as potential inundation area in SPRC model. However, only Industrial 2, Industrial 5 and Industrial 1 are flooded in numerical model for the flow condition. Since the river bed is wide enough to carry the flow, the numerical model results show no flood for this location.

River flood SPRC model presented 80 relationship, and 38 of them are consistent with the results of the numerical model which uses a specific flow scenario. The reasons of the difference can be said as; the SPRC model shows all the possible elements and the links based on the worst possible scenario, in other words, the flood is expected at its maximum in each relationship. If longer return period of flow values are used in numerical model, the difference would be minimized. Another reason for the difference is that if the riverbed is wide enough, all expected flood routes disappear in the numerical model. Since the first pathway is eliminated, no receptor is exposed to flooding in this condition.

When HEC-RAS and River flooding SPRC models are compared, it can be said that SPRC model is conservative, but more practical as it delivers not only information about the area but information on the links between the elements.

4.3.2 Tsunami Case

Tsunami SPRC system diagram was constructed with the same methodology as River SPRC system diagram. The most critical elevation and distances are taken into consideration to determine links between elements of the floodplain. If any connection (pathway) is missing in the initial mapping part of SPRC model, these are also added while flow diagram is drawn. Since the coastal line and coastal zone is important for this diagram, most of these additions were revetment, vertical wall, jetty, etc. Main flood direction is from shore to inlands, but the flow also moves across the horizontal elements from left to right or right to left. These links can be decided by considering elevation differences, slopes and potential obstacles of two neighbors in SPRC system diagram. Flow signs and colors are used in same way with River SPRC model where green lines indicate numerical model results and blue lines indicate SPRC model.

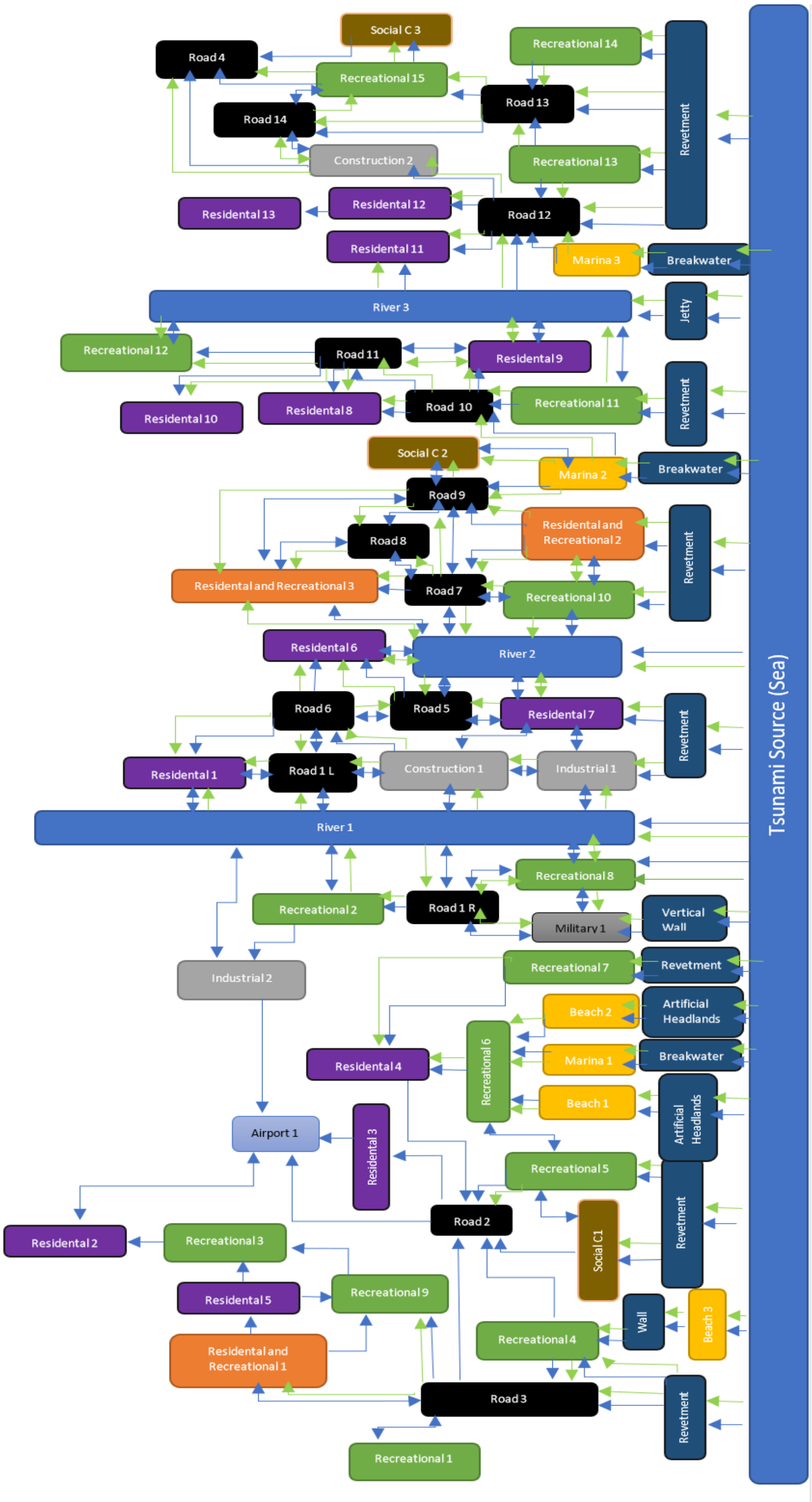

Figure 4-23 SPRC Diagram For Tsunami Flood

Detailed descriptions of numbered categories are listed below;

Airport 1 = Atatürk Airport

Beach 1 = Yeşilköy Çiroz Beach & Beach Protection Constructions

Beach 2 = Yeşilköy Beach (In front of Police Center)

Beach 3 = Florya Güneş Beach

Construction 1 = Ataköy 2 Site Construction

Construction 2 = Empty Construction Area

Industrial 1 = Industrial Facility (at Lat = 40.973 & Long = 28.849 degrees)

Industrial 2 = Industrial Facility (at Lat = 40.974 & Long = 28.840 degrees)

Marina 1 = Yeşilköy Marina

Marina 2 = Ataköy Marina

Marina 3 = Zeytinburnu Port

Military 1 = Air Force Academy

Recreational 1 = Park (No Name Info)

Recreational 2 = Unknown Recreational Area

Recreational 3 = Atatürk Forest (Upper Part)

Recreational 4 = Menekşe Park & Florya Beach Park

Recreational 5 = Florya Social Facility

Recreational 6 = Yeşilköy Beach Park

Recreational 7 = Yeşilköy Sport Center

Recreational 8 = Military Green Area

Recreational 9 = Atatürk Forest (Lower Part)

Recreational 10 = Empty Area (now Baruthane Park)

Recreational 11 = Aytekin Kotil Park

Recreational 12 = Veliefendi Racetrack

Recreational 13 = Kazlıçeşme Beach Park

Recreational 14 = Kocamustafapaşa Park

Recreational 15 = International Peace Park

Residental 1 = Ataköy 2-5-6

Residental 2 = Şenlikköy Neighborhood (Upper Part)

Residental 3 = Şenlikköy Neighborhood (Lower Part)

Residental 4 = Yeşilköy Neighborhood

Residental 5 = Basınköy Neighborhood

Residental 6 = Ataköy 5 Houses

Residental 7 = Ataköy 2 Houses (Near Çavuşbaşı River)

Residental 8 = Cevizlik, Sakızağacı and Yeni Neighborhoods

Residental 9 = Area Between Aksu Street, Çırpıcı River, Kenedy Street

Residental 10 = Kartaltepe Neighborhood

Residental 11 = Sümer Neighborhood

Residental 12 = Area Between Abay Street, Kennedy Street and Kazlıçeşme Beach Park

Residental 13 = Nuripaşa Neighborhood

Residental and Recreational 1 = Basınköy Neighborhood, Papatya Çiçeği Street

Residental and Recreational 2 = Yalı Ataköy

Residental and Recreational 3 = Area between Ali Rıza Efendi and Conk Bayırı Streets

River 1 = Ayamama River

River 2 = Çavuşbaşı River

River 3 = Çırpıcı River

Road 1 R = Rauf Orbay Street (Right Hand Side of Ayamama River Flow Direction)

Road 1 L = Rauf Orbay Street (Left Hand Side of Ayamama River Flow Direction)

Road 2 = Yeşilköy Halkalı Street

Road 3 = Basınköy İstanbul Street

Road 4 = Marmaray Rail Road Construction

Road 5 = Rauf Orbay Street (Right Hand Side of Çavuşbaşı River Flow Direction)

Road 6 = Adnan Kahveci Street

Road 7 = Rauf Orbay Street (Left Hand Side of Çavuşbaşı River Flow Direction)

Road 8 = Ali Rıza Efendi Street

Road 9 = Ataköy Galleria Boulevard

Road 10 = Kennedy Street (Right Hand Side of Çırpıcı River Flow Direction)

Road 11 = Aksu Street

Road 12 = Kennedy Street (Left Hand Side of Çırpıcı River Flow Direction Until Kazlıçeşme Beach Park)

Road 13 = Kennedy Street (Left Hand side of 100. Yıl Street, Kocamustafapaşa Park side)

Road 14 = 100. Yıl Street

Social C 1 = Aqua Florya Shopping Center

Social C 2 = Galleria Shopping Center & Sheraton Hotel & Dünyagöz Hospital

Social C 3 = Yedikule Animal Shelter

As it is stated in the methodology section, failure of all defence systems is considered in building the SPRC system diagram. In numerical model results, sea inundated to places up to 10 meters of elevation on the left hand side of the Ayamama River, on the right hand side, water inundated to 5 meters of elevation. Thus, SPRC system diagram area is limited to these places that have maximum of these elevations. After the extend is decided, elements are mapped. Since the source is selected at the South West side of the study area, flow direction is decided as South to North and West to East.

In Figure 4-23, the water firstly passes through the revetment and reaches Recreational 4 and Road 3. Since Recreational 4 is connected to Road 3 again, flood is considered to pass there. Then, water is considered to pass Residential and Recreational 1, Recreational 1, Road 2 and Recreational 9. In other words, Road 3 is the receptor while focusing on Recreational 4, Revetment and Road 3 frame. But it becomes a pathway for the frame of Recreational 9, Recreational 1, Road 2 and Residential and Recreational 1. Therefore, it can be inferred that one element can be both receptor for different elements, and meantime can also be pathway for other elements.

In SPRC system diagram, water is expected to reach up to Airport 1, Residential 2 and Industrial 2 as these locations have highest elevation points below 10m. But in numerical model, water reached to Residential and Recreational 1 and Residential 4. This means that in numerical model, Residential and Recreational 1 and Road 2 is the farthest flooded area and they prevented water to pass through the next element. The final receptors in the numerical model and SPRC model are different at this part of the system diagram. While constructing SPRC system diagram, specific areas are completely considered as one element, on the other hand in numerical models, elevation for each grid is considered separately. Therefore, while quality of the numerical model result depend on the grid quality, SPRC model result depends on the evaluation of elements with different parameters like elevation, slope, friction, voids between the minor elements (apartments, trees or other solid obstacles) as a lump sum approach. This difference leads to different results for numerical model and SPRC system diagram.

On the right hand side of Ayamama River, SPRC diagram and numerical model results are similar. After mapping of elements, connections are made with the same methodology as the left hand side. In this section, compared to left hand side more details are shown in terms of elements of floodplain (in other words, elements are defined at a higher resolution). Thus, consistency in SPRC and numerical model results is high in this section. This section shows that finer scale elements can provide more consistent results. Detailed risk analysis can be made with higher resolution using finer SPRC elements.

In Tsunami SPRC model, 139 connections are identified as flow propagation path. When the NAMI DANCE model results are integrated in the SPRC model, 116 of the connections are matched. This means more than 80% of the assumed flow paths are same with numerical model output. Although NAMI DANCE model results are only for the worst case defined in the literature, once again, SPRC system diagrams could provide a much larger network regardless of scenarios.

4.3.3 Intersection of Flood and Tsunami Cases

Both SPRC system diagrams (river and tsunami) are intersected and combination of these models at Ayamama River Mouth is developed as another SPRC system diagram which considers more than one source of flooding. In this model (Figure 4-24), blue arrows show the expected tsunami flood, orange ones represent expected river flood, green ones show results of flow direction in the output of NAMI DANCE model, and black ones represents the flow direction in the output of HEC-RAS model.

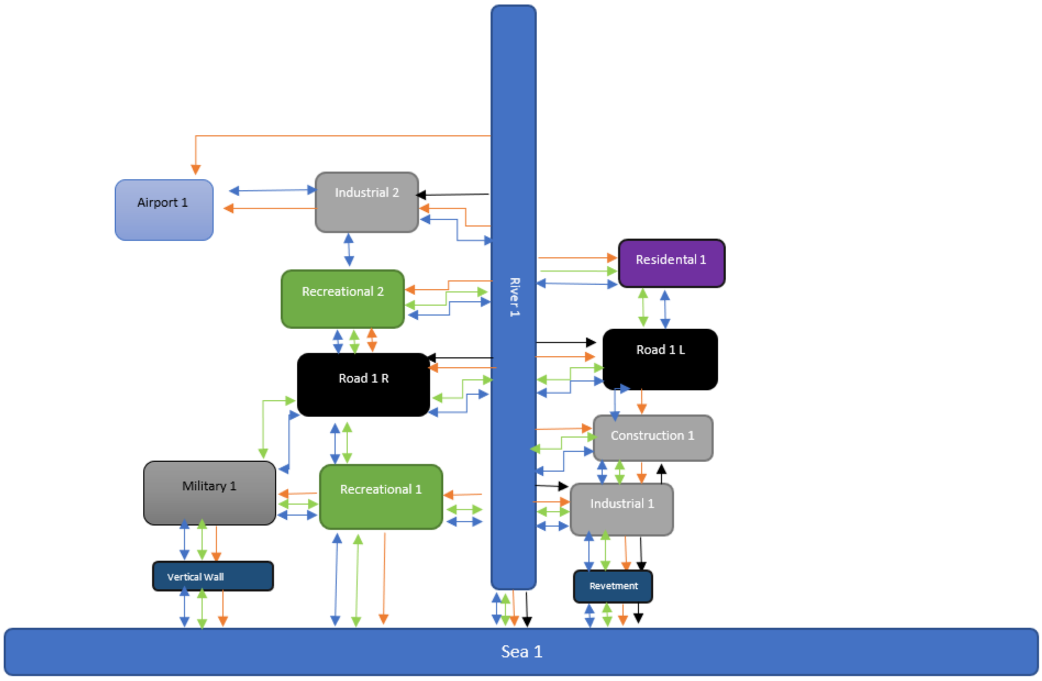

Figure 4-24 Intersection of SPRC models

List of the descriptions of elements that used in Figure 4-24 are listed below;

Airport 1 = Atatürk Airport

Construction 1 = Ataköy 2 Site Construction

Industrial 1 = Industrial Facility (at Lat = 40.973 & Long = 28.849 degrees)

Industrial 2 = Industrial Facility (at Lat = 40.974 & Long = 28.840 degrees)

Military 1 = Air Force Academy

Recreational 1 = Military Green Area

Recreational 2 = Unknown Recreational Area

Residental 1 = Ataköy 2-5-6

River 1 = Ayamama River

Road 1 L = Rauf Orbay Street (Left Hand Side of Ayamama River Flow Direction)

Road 1 R = Rauf Orbay Street (Right Hand Side of Ayamama River Flow Direction)

Sea 1 = Marmara Sea

In Figure 4-24, two different sources are defined which are Sea 1 and River 1. Sea 1 indicates the Tsunami source while River 1 indicates river flood source. In this section, elements are both exposed to these two sources. It can be seen that in this section, between River 1 and neighbor elements, no structural defense exists, and the river channel is in its natural form. On the other hand, Sea side is protected by vertical wall and revetment. Industrial 1, River 1 and both right and left hand sides of Road 1 are exposed to both river and tsunami floods in all model types. Industrial 1 and right hand side of Road 1 are affected both from sea side and river side. Thus, improvements for both sides should be made for these elements. However, left hand side of Road 1 is affected only by River source, so between Construction 1 and Road 1L, protection doesn't needed when numerical model results are considered. However, since SPRC method is more conservative than numerical models, a protection is needed at this location. For other elements, protection measures can be determined by importance of elements. For example, if flooding on Recreational 1 is not important, but Military 1 is important, protection measures should be taken between Vertical wall-Military 1 and Recreational 1-Military 1. In this case protection between Recreational 1 and Sea 1 is not needed. On the other hand, if Recreational 1 is decided as critical area, both between Military 1-Recreational 1, Sea 1- Recreational 1 and Recreational 1- River 1 protection is needed. This section does not show the most critical area, but shows the area that is exposed to 2 different sources. The most critical area can be just exposed to only one of tsunami and river source, this can be decided by different parameters (economical, neighbor, exposure ratio etc.) by the decision makers. SPRC system diagram provides an effective base for such decisions and enables the decision makers to consider different hazards at the same time.

4.4 Discussion On Utilizing The SPRC Method in Flood Management

When the hydraulic numerical model is observed, results are similar to past river flood events with minor differences. The 500 year return period flood inundates a total of 2269308.4 m2 area. This means, approximately 325 professional football field of area is flooded. The flooded areas are determined in a quantitative manner as flood area and flood depth by the numerical models as well as the duration of the flood event based on the specific event scenario. Time series assessment of the numerical model results also provide information about the propagation of the flood. Therefore, hdyraulic numerical models only provide information about the event probability and exposure components of risk esitmation. However, additional layers of information such as land use, data on buildings and roads (infrastructure) and other models are required to assess the flood risk including susceptibility and impacts. Any change corresponding to a protection measure needs to be defined in terms of input parameters of the hydraulic model such as elevation, friction, etc. The hydraulic model is needed to be run for any change to reflect the changes in the risk. In order to assess a variety of options under different scenarios, many model runs are required which is resource consuming.

On the other hand, SPRC system diagram of this study defines the Ayamama River flood as Source, each adjacent element to the river channel becomes receptor of the flood. When water passes through the next element, past receptor becomes new pathway and final receptor changes. This logic in the SPRC model allows us to see the all paths and all receptors in one view. If any protection action should decided to be taken, the most critical pathways can be chosen as protection paths. This approach could even provide one protection measure that may save larger areas of many elements of the floodplain. With the selection of conservative flood plain boundary, SPRC model enables to assess these options for all types of scenarios at the same time. Thus, SPRC system diagram provides this new information which helps to point out the management strategies for decision makers without the requirement of high computing resources.

In the upstream section of the Ayamama river system diagram, it can be seen that there is no defence structure between the river and the recreational areas. In this section, in order to protect recreational area, a river reclamation can be made. In order to prevent flooding at Residental 12, Road 11 and Residental 2, culvert before closed section of river should be widened. In order to prevent flooding at the Road 2, vertical wall height can be increased. For the Recreational 3 and Road 3, since the receptor is not residental area, and the flood only affects Road 3 at its extreme conditions, flood can be assumed to be spread in Recreational 3 area. So in this section, protection measurement may not be needed. On the other hand, vertical wall height should be increased to protect Industrial 6. If this area is not flooded, Road 4 is automatically protected due to this reclamation. For the Residental 3, Residental 4, Road 5, Road 6 group, an improvement for vertical wall and culvert would be adequate for protection. This group shows the importance of mapping elements, a simple protection can protect both elements in this group. Next, Residental 5 , Industrial 7 and Road 7 are seen as unprotected areas. Thus in order to protect these areas, a reclamation can be made here. However, this reclamation may not prevent Industrial 7 from flooding, as it has another pathway for flooding. It also should be improved for certain solution. Then, one of the pathways of Road 5 is eliminated. To protect Road 5, vertical wall heights along to Recreational 5 should be increased. This might be costly, so in this section, using hydraulic numerical model to calculate the optimum wall height would be required. However, SPRC model provides the information that a significant protection measure is needed to be taken. On the other side of the river, a protection should be placed to both Road 7 and Vertical Wall, so both Residental 6 and Residental 8 areas can be protected. For Residental 9 and Recreational 4 areas, pathways are vertical walls. So another protection measurement should be taken to vertical wall for these elements. On the downstream section of the diagram, inland elements are all unprotected, since the river channel is in natural condition. Thus; in this section, in order to protect this area, channel reclamation should be made. The discussion of SPRC model results provide the framework of protection or mitigation studies, therefore consequences can be minimized or eliminated.

Similar discussions also can be made for tsunami. Tsunami modeled in the study inundated 2992623.55 m2 land which is nearly 430 football fields. General protection approach of SPRC can also be applied here as well. The most critical coastal area can be determined and a hard protection or mitigation plan can be applied. SPRC model is useful in seeing where the flooding starts intensely and disperses through the land, and which pathways can be blocked. In tsunami sourced SPRC diagram, since movement is in both horizontal and vertical directions, protection measurement decision procedure is not same as river sourced SPRC diagram. In this diagram, the first pathways between the sea and the inland elements are shore protection elements that are revetments, artificial headlands, vertical walls, breakwaters and jetties. Therefore, as it is expected, modification of these structures along the shoreline based on tsunami scenarios can prevent inundation initially. However, as tsunami is a low probability event, depending on the importance of the elements and the receptors, local protection measurements can also be taken where part of the shore is permitted to be flooded and become pathways. Then, the critical pathways to the important receptors are assessed for protection measures in light of a tsuami event. In the tsunami system diagram of Bakirkoy coast, it can be seen that one pathway is connected to more than one receptor, and more than one pathway connects to one receptor. Therefore, following the routes for critical elements are needed. As an example, if residental 7 is considered, both revetment, River 1 and River 2 are the critical pathways. For another example, if Marina 3 is needed to be protected, breakwater should be improved as only pathway of that element.

SPRC system diagrams shows 50% more elements and links for River model and 20% more elements and links for Tsunami model. It can be said that SPRC model is conservative, but more practical as it delivers not only information about the area but information on the links between the elements. In order to make these comparisons, numerical models had to be analyzed at every time step to determine the propagation of flood among the elements of floodplain. This is very time consuming in the case of HEC-RAS and NAMI DANCE models whereas with SPRC system diagram approach, the same information can be determined based on limited data (elevation and slope) as well as previous observations. SPRC system diagram would only need to be prepared once regardless of scenarios and then these systems diagrams could be used to discuss the flood propagation, flood damage and any management options based on a variety of flood scenarios for rapid assessment. Inundation maps based on numerical models can be used as these flood scenarios integrated with SPRC system diagrams for a more detailed assessment as well.

In intersection of SPRC models, it can be seen that if a protection measurement is feasible for both sources or not. If a protection measurement is taken between recreational 1 and sea 1, it can prevent tsunami waves, but due to this protection, in the case of river flood, water will accumulate at this pathway and could pass through military 1. If a measurement would taken between military 1 and recreational 1, river flood does not pass through military 1, and even tsunami wave may not pass through recreational 1 from military side. If a measurement is taken between River 1 and Recreational 1, the river does not flood to Recreational 1, however, tsunami waves will pass to Road 1 R directly. As tsunami wave direction is considered,a protection that is taken to the left hand side of the river (flow direction is taken as positive) can both prevent tsunami and river flooding at the same time, however, on the right hand side, it may lead tsunami waves headway to inlands while river flood is prevented. This example shows how SPRC model can help to assess risks and the effect of protection measures or any outside changes in the flood plain for more than one type of flood source. To have a similar type of assessment would require modeling of two different numerical model runs for many scenarios that reflect the effect of any one of the options discussed here. However with SPRC model approach, it is possible to discuss the impacts of many protection measures albeit not quantitatively and then numerical modelling can be performed for a selected number of cases to quantify the risk or effectiveness of the measures.

In general, SPRC is useful in creating an effective understanding for flooding and floodplain. The results showed that SPRC model includes a larger inundation area than both numerical models areas. Even if one decides to take protection against flooding for a specific area, SPRC model is a guiding method itself. On the other hand, both numerical model results contain time depended outputs, SPRC model is not time depended. Therefore, if time depended solution is needed especially for mitigation, SPRC model is inadequate compared to numerical models.

CHAPTER 5

CONCLUSION

In this study, a HEC-RAS numerical hydraulic model, a NAMI DANCE numerical tsunami model, and SPRC conceptual models for both river flood and tsunami inundation are constructed in the Ayamama River region and Bakırköy Coasts of Istanbul. As the required data and resources were available for numerical modeling of the study area due to previous projects and literature, the inundation areas could be determined efficiently. However, risk analysis and protection studies of larger areas based on different numerical models with many scenarios would definitely require a lot of resources and detailed datasets that might be unavailable. Additionally, not all the assessments require the same level of resolution and the resources used in numerical models could actually become excessive. Therefore, another way of defining the flood plain could provide a possible solution. SPRC approach ideally placed as a descriptive conceptual model of floodplain could be useful to evaluate the flood system, inform subsequent quantitative risk analysis and facilitate understanding amongst diverse stakeholders (Narayan et al., 2014). Therefore, this study aimed to analyze the effectivenes and applicability of SPRC model for riverine and coastal floods at an urban area in Turkey, its advantages and disadvantages, and comparison of models.

At the end of the study, it can be seen that SPRC model is succesful for the study area with some advantages and limitations. When positive aspects are considered, most important feature is that the model is easily constructed. The system diagrams does not need high resolution data; rather a simple elevation map, sattelite images and expert opinion or data from historical events are enough to analyze the study area and construct the SPRC model. This aspect of SPRC also encourages integration of participation of different stakeholders and not only the technical experts. Another positive aspect is system diagrams are constructed regardless of specific hazard scenarios but actually cover many scenarios needed for numerical modeling. Once constructed, the SPRC model provides all pathways, receptors, and sources (if available in study) one by one with the corresponding links between these elements. Therefore, it is easy to discuss protection measures for specific points (elements of floodplain), so consequences can be minimized or eliminated regardless of scenarios. Additionally, the element based approach to define the floodplain provides a flexibility in selection of scale of assessment and helps to assess more than one source of hazard for the same area. The flexibility to define an element as pathway or receptor based on the scale of assessment is also an advantage of the SPRC model, as it enables to discuss the same element both in terms of consequence and as possible protection measure or weak link.

The SPRC model also has some limitations. While numerical models provide flood propagation information as time steps, SPRC model is independent from the time. Thus, if one receptor is flooded by two pathways, which is first and which is later cannot be understood from the model. This problem is also valid for one pathway, two receptor situation. In addition, SPRC model doesn’t provide a quantitative assessment of flood plain such as surface area that is inundated due to a souce. Rather, it gives general behavior information of the elements. In this study, without numerical models, SPRC gives a information on flood propagation among elements of floodplain for both river and coastal area, general paths and receptors can be seen from the model. However, when combined with the result of numerical models, SPRC model showed the possible inundation areas, flood pathways, and progress of flood itself for the modeled scenarios.

Comparison with results of numerical models showed that consistency between these models will increase as the variety and density of pathways are increased. More elements defined in the system diagram also provides more realistic results in SPRC model. Further improvements of the SPRC model could provide quantitative assessments related to risk such as a way to integrate probability of failure along the pathways. Additionally, a method to integrate quantitative assessment of changing inputs such as climate change into the SPRC model would enhance the advantages of the model significantly. In addition, an SPRC model that contains both storm and flood conditions can show the results for dependent events.

REFERENCES

Alpar, B., Yalçıner, A. C., Imamura, F., & Synolakis, C. E. (2001). *Determination of probable underwater failures and modeling of tsunami propagation in the Sea of Marmara. Proceedings of the International Tsunami Symposium 2001*.

Altinok, Y., Alpar, B., Özer, N., & Aykurt, H. (2011). Revision of the tsunami catalogue affecting Turkish coasts and surrounding regions. *Natural Hazards and Earth System Science*, *11*(2), 273–291. https://doi.org/10.5194/nhess-11-273-2011

Altınok, Y. (2005). Türkiye Ve Çevresinde Tarihsel Tsunamiler. *Tmh - TürkiyMühendislikHaberleri*, *2*(45), 25–32.

Ambraseys, N. ., & Finkel, C. F. (1991). Long-term seismicity of Istanbul and of the Marmara Sea region. *Terra Nova*, *3*(5), 527–539. https://doi.org/https://doi.org/10.1111/j.1365-3121.1991.tb00188.x

Arcement, G. J., & Schneider, V. R. (1989). *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*.

Aytore, B. (2015). *Assessment of tsunami resilience of ports by high resolution numerical modeling: a case study for Haydarpasa port in the sea of Marmara*.

Bahçeci, A. (2014). *Ayamama Deresi Havzası'nın Taşkın Analizi Modeli*.

Darmendrail, D., Bardos, P., Harris, R., & Quercia, F. F. (2002). *Sustainable management of contaminated land: an overview*. https://doi.org/10.13140/RG.2.2.20348.03204

Demir, A. (2010). *Şehir Taşkınları ve İstanbul*.

Durukal, E., Erdik, M., & Uçkan, E. (2008). Earthquake risk to industry in Istanbul and its management. *Natural Hazards*, *44*(2), 199–212. https://doi.org/10.1007/s11069-007-9119-0

Einfalt, T., & Keskin, F. (2010). *Analysis of the Istanbul Flood 2009*. *May*, 1–8.

Fang, X., & Prakash, K. (2005). Revisit of NRCS unit hydrograph procedures. *Proceeding of the ASCE Texas Section Spring Meeting in Austin*, *April*(1), 1–21. http://cleveland2.ce.ttu.edu/documents/copyright/F-AUTHORS/2005_0408_asce_tx/2005_0408_asce_tx.pdf%5Cnhttp://scholar.g oogle.com.my/scholar?q=Revisit+of+NRCS+Unit+Hydrograph+Procedures&btnG=&hl=en&as_sdt=0,5#

The Gebco_2014 Grid, version 20150318, www.gebco.net

General Directorate of State Hydraulic Works. (2015). Flow Observation Annuals. Available online at: https://www.dsi.gov.tr/Sayfa/Detay/744

Guidoboni, E., Comastri, A., & Traina, G. (1994). *Catalogue of the Ancient Earthquakes in the Mediterranean Area up to the 10th Century*. Istituto Nazionale Di Geofisica

Gülbaz, S., Kazezyılmaz-Alhan, C. M., Bahçeçi, A., & Boyraz, U. (2019). Flood Modeling of Ayamama River Watershed in Istanbul, Turkey. *Journal of Hydrologic Engineering*, *24*(1), 05018026. https://doi.org/10.1061/(asce)he.1943-5584.0001730

Hayir, A., Seseogullari, B., Kilinc, I., Erturk, A., Cigizoglu, H. K., Kabdasli, M. S., Yagci, O., & Day, K. (2008). Scenarios of tsunami amplitudes in the north eastern coast of Sea of Marmara generated by submarine mass failure. *Coastal Engineering*, *55*(5), 333–356. https://doi.org/10.1016/j.coastaleng.2007.12.001

Hébert, H., Schindelé, F., Altinok, Y., Alpar, B., & Gazioglu, C. (2005). Tsunami hazard in the Marmara Sea (Turkey): A numerical approach to discuss active faulting and impact on the Istanbul coastal areas. *Marine Geology*, *215*(1-2 SPEC. ISS.), 23–43. https://doi.org/10.1016/j.margeo.2004.11.006

HEC. (2016). *HEC-RAS River Analysis System Version 5.0*.

Keskiner, A. D. (2018). *Taşkin Hesaplarinda Kullanilan Sentetik Yöntemlerin Küçük Ölçekli Sulama Göletleri Alt Havzalarina Uyarlanmasi: Yaylalik Göleti Örneği*.

Keskiner, A. D., & Cetin, M. (2019). *Taşkın Hesaplarında Kullanılan Sentetik Yöntemlerin Küçük Ölçekli Sulama Göletleri Alt Havzalarına Uyarlanması : Yaylalık Göleti Örneği*. *December 2016*.

Koç, G., Petrow, T., & Thieken, A. H. (2020). Analysis of the most severe flood events in Turkey (1960-2014): Which triggering mechanisms and aggravating pathways can be identified? *Water (Switzerland)*, *12*(6). https://doi.org/10.3390/W12061562

Latcharote, P., Suppasri, A., Imamura, F., Aytore, B., & Yalciner, A. C. (2016). Possible worst-case tsunami scenarios around the Marmara Sea from combined earthquake and landslide sources. *Pure and Applied Geophysics*, *173*(12), 3823–3846. https://doi.org/10.1007/s00024-016-1411-z

Monbaliu, J., Chen, Z., Felts, D., Ge, J., Hissel, F., Kappenberg, J., Narayan, S., Nicholls, R. J., Ohle, N., Schuster, D., Sothmann, J., & Willems, P. (2014). Risk assessment of estuaries under climate change: Lessons from Western Europe. *Coastal Engineering*, *87*, 32–49. https://doi.org/10.1016/j.coastaleng.2014.01.001

NAMI DANCE (2016). NAMI DANCE Manual. Ankara, Turkey: METU. Available online at http://namidance.ce.metu.edu.tr/ pdf/NAMIDANCE-version-5-9-manual.pdf.

Narayan, S., Hanson, S., Nicholls, R. J., Clarke, D., Willems, P., Ntegeka, V., & Monbaliu, J. (2012). A holistic model for coastal flooding using system diagrams and the Source-Pathway-Receptor (SPR) concept. *Natural Hazards and Earth System Science*, *12*(5), 1431–1439. https://doi.org/10.5194/nhess-12-1431-2012

Narayan, S., Hanson, S., Nicholls, R. ., Clarke, D., Willems, P., Ntegeka, V., & Monbaliu, J. (2011). *Use of the Source – Pathway – Receptor Model for Assessment of Coastal Flood Systems*. *January*.

Narayan, S., Nicholls, R. J., Clarke, D., Hanson, S., Reeve, D., Horrillo-Caraballo, J., le Cozannet, G., Hissel, F., Kowalska, B., Parda, R., Willems, P., Ohle, N., Zanuttigh, B., Losada, I., Ge, J., Trifonova, E., Penning-Rowsell, E., & Vanderlinden, J. P. (2014). The SPR systems model as a conceptual foundation for rapid integrated risk appraisals: Lessons from Europe. *Coastal Engineering*, *87*, 15–31. https://doi.org/10.1016/j.coastaleng.2013.10.021

Nelson, S. A. (2018). *Mass Movements and Mass Movement Processes*. 1–6. http://www.tulane.edu/~sanelson/Natural_Disasters/masswastproc.htm

Nicholls, R., Zanuttigh, B., Vanderlinden, J. P., Weisse, R., Silva, R., Hanson, S., Narayan, S., Hoggart, S., Thompson, R. C., Vries, W. de, & Koundouri, P. (2014). Developing a Holistic Approach to Assessing and Managing Coastal Flood Risk. In *Coastal Risk Management in a Changing Climate*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-397310-8.00002-6

Örnek, M. A., Ersoy, M., & Seçkin, Y. Ç. (2016). Estimating Stormwater Runoff from the 3D-model of an Urban Area in Istanbul. *Journal of Digital Landscape Architecture*, *1*(1), 198–206. https://doi.org/10.14627/537612023

Özcan, O. (2017). Taşkın Tespitinin Farklı Yöntemlerle Değerlendirilmesi: Ayamama Deresi Örneği. *Doğal Afetler ve Çevre Dergisi*, *January*, 9–9. https://doi.org/10.21324/dacd.267200

Özeren, M. S., Çağatay, M. N., Postacioğlu, N., Şengör, A. M. C., Görür, N., & Eriş, K. (2010). Mathematical modelling of a potential tsunami associated with a late glacial submarine landslide in the Sea of Marmara. *Geo-Marine Letters*, *30*(5), 523–539. https://doi.org/10.1007/s00367-010-0191-1

Şen, N. (2015). *İstanbul Ayamama Deresi Taşkın Yatağı Yönetimi Planı*. İstanbul Teknik Üniversitesi.

Soysal, H., Sipahioglu, S., Kolcak, D., & Altinok, Y. (1981). Türkiye ve çevresinin tarihsel deprem kataloğu. *TUBİTAK Rapor No: TBAG 341*, 86.

T.C. Tarım Orman Bakanlığı. (2017). CORINE Project. Available online at: https://corine.tarimorman.gov.tr/corineportal

Thorne, C. R., Evans, E. P., & Penning-rowsell, E. C. (2007). Future flooding and coastal erosion risks. *Future Flooding and Coastal Erosion Risks*, *December 2014*. https://doi.org/10.1680/ffacer.34495

Tüfekçi, D. (2016). *Tsunami Risk Assessment Using GIS-Based Multi Criteria Decision Analysis At Bakırköy, İSTANBUL*. Middle East Technical University.

TUİK. (2020). *No TitleAdrese Dayalı Nüfus Kayıt Sistemi Sonuçları, 2019*. https://data.tuik.gov.tr/Bulten/Index?p=Adrese-Dayali-Nufus-Kayit-Sistemi-Sonuclari-2019-33705

Ündül, Ö., & Rul, A. T. U. (2006). The engineering geology of Istanbul, Turkey. *10th IAEG International Congress*, *392*, 1–13.

Usul, N. (2015). *Engineering Hydrology*. METU Press.

Yalçıner, A. C., Alpar, B., Altmok, Y., Özbay, I., & Imamura, F. (2002). Tsunamis in the Sea of Marmara: Historical documents for the past, models for the future. *Marine Geology*, *190*(1–2), 445–463. https://doi.org/10.1016/S0025-3227(02)00358-4

Yalçıner, A. C., & Süzen, L. (2020). *İstanbul İli Tsunami Eylem Planı Hazırlanması*.

Yucel, I. (2015). Assessment of a flash flood event using different precipitation datasets. *Natural Hazards*, *79*(3), 1889–1911. https://doi.org/10.1007/s11069-015-1938-9

APPENDICES

A. Maximum P Differences for the Stations

Table 5-1 Maximum P Differences for the Stations

	İstanbul Airport	Eyüp	Florya
Normal Distribution	0.240	0.102	0.074
Log-Normal (2 Parameters)	0.137	0.105	0.119
Log-Normal (3 Parameters)	0.138	0.100	0.074
Pearson Type-3 (Gama Type-3)	0.154	0.098	0.071
Log-Pearson Type-3	0.101	0.094	0.080
Gumbel	0.211	0.079	0.108

B. Gauge Data

Table 5-2 Gauge Data

Gauge Name	Latitude	Longitude	Gauge Name	Latitude	Longitude
gp1g	28.839624	40.957785	gp43g	28.858989	40.973421
gp2g	28.839906	40.958224	gp44g	28.860336	40.973703
gp3g	28.840314	40.9586	gp45g	28.861809	40.973703
gp4g	28.840972	40.959603	gp46g	28.86325	40.973703
gp5g	28.842037	40.96048	gp47g	28.864723	40.973484
gp6g	28.842507	40.961389	gp48g	28.865036	40.973421
gp7g	28.843196	40.962235	gp49g	28.865349	40.971823

Table 5-2 Gauge Data (continued)

gp8g	28.843635	40.962893	gp50g	28.865287	40.969786
gp9g	28.843729	40.963614	gp51g	28.865381	40.968345
gp10g	28.844042	40.964334	gp52g	28.865663	40.967812
gp11g	28.844481	40.964804	gp53g	28.866007	40.967342
gp12g	28.84492	40.96565	gp54g	28.86654	40.966935
gp13g	28.845296	40.966152	gp55g	28.868107	40.96681
gp14g	28.846048	40.966465	gp56g	28.86936	40.966935
gp15g	28.846455	40.966998	gp57g	28.870864	40.966778
gp16g	28.845797	40.96775	gp58g	28.872149	40.966904
gp17g	28.845797	40.96847	gp59g	28.873747	40.96681
gp18g	28.847113	40.970789	gp60g	28.874593	40.966904
gp19g	28.847865	40.971165	gp61g	28.846921	40.972524
gp20g	28.848586	40.97057	gp62g	28.847675	40.9721
gp21g	28.849557	40.969818	gp63g	28.846169	40.97111
gp22g	28.850685	40.968846	gp64g	28.844932	40.969986
gp23g	28.851218	40.968721	gp65g	28.843741	40.96857
gp24g	28.851186	40.96941	gp66g	28.844483	40.969357
gp25g	28.849902	40.970632	gp67g	28.853251	40.976124
gp26g	28.849244	40.971635	gp68g	28.852082	40.975517
gp27g	28.848304	40.972826	gp69g	28.853543	40.975202
gp28g	28.847144	40.97411	gp70g	28.839214	40.958754
gp29g	28.845672	40.975708	gp71g	28.840439	40.960424
gp30g	28.843854	40.977557	gp72g	28.841665	40.962206
gp31g	28.842538	40.978999	gp73g	28.842778	40.963877
gp32g	28.841003	40.980377	gp74g	28.843447	40.965436
gp33g	28.85222	40.969598	gp75g	28.84456	40.966884
gp34g	28.851907	40.970476	gp76g	28.84456	40.968555
gp35g	28.850998	40.971353	gp77g	28.84456	40.969446
gp36g	28.85034	40.972324	gp78g	28.845785	40.970894
gp37g	28.850779	40.972951	gp79g	28.846454	40.972341
gp38g	28.852314	40.97317	gp80g	28.848793	40.973566
gp39g	28.854007	40.973703	gp81g	28.850686	40.974346
gp40g	28.855354	40.973703	gp82g	28.851354	40.975014
gp41g	28.857077	40.973703	gp83g	28.85269	40.974903
gp42g	28.858143	40.973703	gp84g	28.853805	40.97468