DETERMINATION AND COMPARISON OF FLOOD MITIGATION MEASURES WITH DISTINCT RIVER BASIN CHARACTERISTICS

FARKLI KARAKTERİSTİKLERDEKİ AKARSU HAVZALARINDA TAŞKIN TEDBİRLERİNİN BELİRLENMESİ VE KARŞILAŞTIRILMASI

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ABSTRACT

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Sungurlu River is located northeastern part of İstanbul. Sungurlu River disembogue into the Black Sea where Ağva Town is located. This small town is already a tourist attraction for people from İstanbul and also has a great potential for increase in touristic attractions. Therefore, modifications in riverine environment could have detrimental social and economic impacts on the town, which makes nature-based solution (NBS) a supportive measure for flood risk management for study area. In this study, Sungurlu River and Ağva Town is analyzed in regards of flood risk and locations have flood hazard is identified. Hydraulic modelling is completed with HEC-RAS software with full two-dimensional flood modelling. High resolution LiDAR based DEM data, hydrologic data and river bathymetry are obtained from administrations, which increased the accuracy of this study significantly. As per results of the flood hazard analysis, three flood mitigation alternatives were proposed, one with traditional grey infrastructure, other one with only NBS and the last one is a hybrid solution.

Performance of these alternatives were evaluated with multi-criteria analysis. As a result of the evaluation, it was concluded that the most suitable alternative for the study area is only traditional and hybrid solutions.

Keywords: Flood risk management, Nature based solutions, HEC-RAS, Sungurlu River, 2D Flood modelling, Multi criteria analysis

ÖZET

FARKLI KARAKTERİSTİKLERDEKİ AKARSU HAVZALARINDA TAŞKIN TEDBİRLERİNİN BELİRLENMESİ VE KARŞILAŞTIRILMASI

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Sungurlu Nehri, İstanbul'un kuzeydoğusunda yer almaktadır. Sungurlu Nehri, Ağva Kasabası'nın bulunduğu yerden Karadeniz'e dökülmektedir. Bu küçük kasaba, İstanbullular için halihazırda turistik bir cazibe merkezidir ve aynı zamanda turistik faaliyetlerin artma potansiyeline sahiptir. Bu nedenle, nehir ortamındaki değişikliklerin kasaba üzerinde zararlı sosyal ve ekonomik etkileri olabilir. Bu da çalışma alanı için taşkın risk yönetiminin doğal tabanlı çözümler ile desteklenmesini bir gereklilik haline getirmektedir. Bu çalışmada Sungurlu Nehri ve Ağva İlçesi taşkın riski açısından incelenmiş ve taşkın tehlikesi olan yerler tespit edilmiştir. Çalışma alanında HEC-RAS yazılımı kullanılarak iki boyutlu hidrolik taşkın modellemesi yapılmıştır. İdarelerden temin edilen yüksek çözünürlüklü Dijital Yükseklik Modeli (DEM) verisi, hidrolojik veriler ve nehir batimetrisi bu çalışmanın doğruluğunu önemli ölçüde artırmıştır. Tehlike analizinin sonuçlarına göre sadece geleneksel, sadece doğal tabanlı ve hibrit olmak üzere üç adet taşkın tedbir senaryosu önerilmiştir. Bu senaryoların performansları ise çoklu karar verme metodu ile değerlendirilmiştir. Değerlendirme sonucunda çalışma alanı için en uygun senaryonun sadece geleneksel ve hibrit çözüm olduğu sonucuna ulaşılmıştır.

Anahtar Kelimeler: Taşkın risk yönetimi, Doğal tabanlı çözümler, HEC-RAS, Sungurlu Nehri, 2B Taşkın modellemesi, Çoklu karar verme metodu

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ABBREVIATIONS

APSFR	Area with Significant Flood Risk
BC	Benefit-Cost
BCS	Benefit-Cost Score
CBA	Cost-Benefit Analysis
CIS	Cultural Impact Score
CN	Curve Number
CORINE	Coordination of Information on the Environment
DC	District of Columbia
DEM	Digital Elevation Model
DSİ	State Water Works
EAC	Expected Annual Cost
EAD	Expected Annual Damage
EAS	Economic Assessment Score
EEA	European Environmental Agency
EIS	Environmental Impact Score
EKAP	Electronic Public Procurement Platform
ENAS	Environmental Assessment Score
EU	European Union
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HS	Health and Safety
IPCC	Intergovernmental Panel on Climate Change

İSKİ	İstanbul Water and Sewerage Administration
ISLS	Improvement in Social Life Score
JRC	EU Commission Joint Research Centre
LiDAR	Laser Imaging Detection and Ranging
LULC	Land Use/Land Cover
MCA	Multi-Criteria Analysis
MCAS	Multi-Criteria Analysis Score
MCS	Measure Cost Score
NBS	Nature Based Solutions
NNC	National Nonstructural Committee
NSE	Navier-Stokes Equation
PFRA	Preliminary Flood Risk Assessment
RPIS	Risk on Public Institutions
RRP	Reduction of Risk on the People
SAS	Social Assessment Score
SEIS	Social and Economic Impact Score
SWAT	Soil Water Assessment Tool
SWE	Shallow Water Equations
USACE	US Army Corps of Engineers
USD	United States Dollar
WCD	World Commision of Dams
WHO	World Health Organization
WMO	World Meteorological Organization

1. INTRODUCTION

1.1. General Remarks

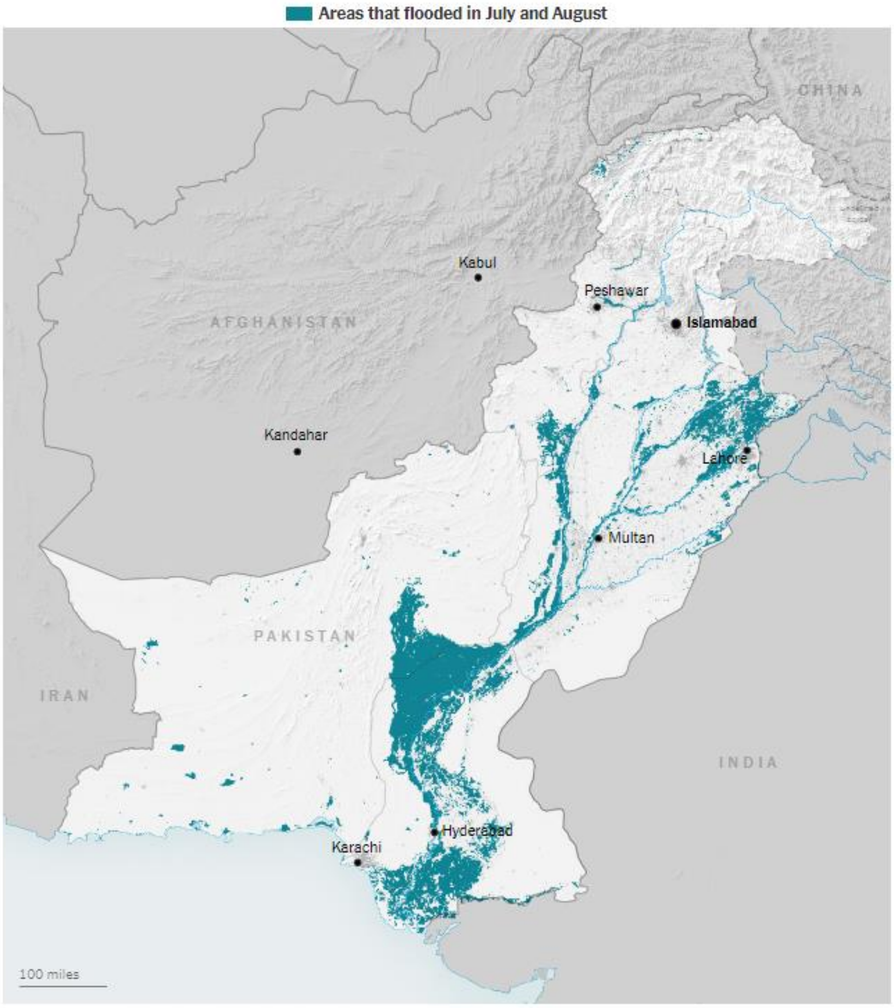
Floods are always one of the most destructive and frequent disasters that result in loss of lives and damage to economic assets [1]–[3]. Floods are defined as submergence of land, which is usually dry, with water [4]. There is growing evidence that floods and flood-related disasters are the most frequent cause of devastation for economies and people around the world when compared to any other types of disasters [5], [6].

The main causes of floods are anthropogenic factors such as excess urbanization and climate change [7]. According to the report of the International Panel on Climate Change [8], the adverse effects of climate change will worsen, and it is expected to see an increment in extreme weather events in the coming decades. The latest report of IPCC in 2021 suggests that heavy rainfalls are becoming more severe due to global warming [9]. Therefore, floods will be more frequent and more devastating than ever before. On 14 and 15 July 2021, an extreme flood event affected Germany, Belgium, Netherlands, and Luxembourg. The flooding resulted in 184 fatalities in Germany and 38 in Belgium [10]. Moreover, the flooding also caused considerable damage to the infrastructure [11]. Flooded areas in Germany and Belgium during the 2021 flood event are presented in Figure 1.1 and Figure 1.2.

Figure 1.1 Flooding of Kordel, Germany (July, 2021) [12]

Figure 1.2 Flooding of Verviers, Belgium (July, 2021) [11]

After the monsoon season in Pakistan started in 2022, floods took place, and more than 1600 people died due to floods. The estimated emergency recovery requirement because of a flood event is predicted as 816 million USD, according to the 2022 Revised Flood Response Plan of Pakistan [13]. Flooded areas of Pakistan in the 2022 flood event are pictured in Figure 1.3, while flooding of residential areas in Pakistan is given in Figure 1.4.



Source: UNOSAT analysis of Suomi NPP satellite data, July 1 to Aug. 31 • By Agnes Chang

Figure 1.3 Flooded Areas in Pakistan During July and August 2022 [14]

Figure 1.4 Flooded Residential Area in Dera Allah Yar, Balochistan Province, Pakistan [14]

To prevent floods or reduce the adverse effects of floods, flood management plans were prepared or are being prepared all over the world. According to the “European Union Flood Directive”, all members and candidate states should prepare flood management plans. Moreover, these plans should be updated every six years by considering changes in the hydrological regime and morphological changes resulting from alterations in the environment and human activity [15].

Flood management plans, which are considered non-structural measure itself, often involves a determination of possible flood risks and mitigation measures. These measures are often structural and non-structural ones that can prevent damage or reduce the adverse effects of flooding. This is a straightforward process in terms of flood management. Traditional measures and interventions often focused on structural measures (gray infrastructures) such as dams, pipes, canals, tunnels, dikes, etc. These measures are implemented with hard-engineered materials such as concrete and steel. As a result, many governments and communities trust such structures to protect them from floods, and in case of failure, they often find themselves underprepared to cope with the adverse effects. Several studies suggest that such infrastructure has not been effective in achieving adequate flood protection, cost-effectiveness, and environmental sustainability [16].

However, in recent years, nature-based solution (NBS) has recently gained importance and received increasing attention from engineers and researchers as a flood management strategy (journal of cleaner production). Urbanization process is often accompanied by excess impervious layers due to the construction of new buildings, roads, industrial facilities, etc. [17].

The NBS concept emerged from seeking an innovative solution to manage the natural system in a way that can balance the benefits for both nature and society. The main objective of the NBS is to integrate flood measures with ecology and nature so that impact of floods will be reduced. At the same time, damage to the environment and ecosystem can be prevented. There are lots of studies that examine the applicability of NBS. Due to the social and economic development, as well as increment in population, infiltration and storage capacity of land surface, decrease as a result of decrement in vegetation and pervious layers. Therefore, highly populated built-up areas are more prone to the risk of flooding. Nature-based solutions (NBS) are defined as solutions that are focused on nature and ecosystem to provide economic, social, and environmental benefits [18].

The NBS program of the World Bank was established in 2017. However, World Bank started to courage NBS in 2012. From 2012 to 2018, 681 risk management projects were financed by World Bank, approximately 52.87 billion USD, 76 of which utilize NBS as project subcomponents (Figure 1.5) [19]. Moreover, in the USA, DC water utilized the NBS program by employing hybrid infrastructure to minimize urban flood hazards. The hybrid approach involves bioretention or rain gardens, permeable pavement, etc.

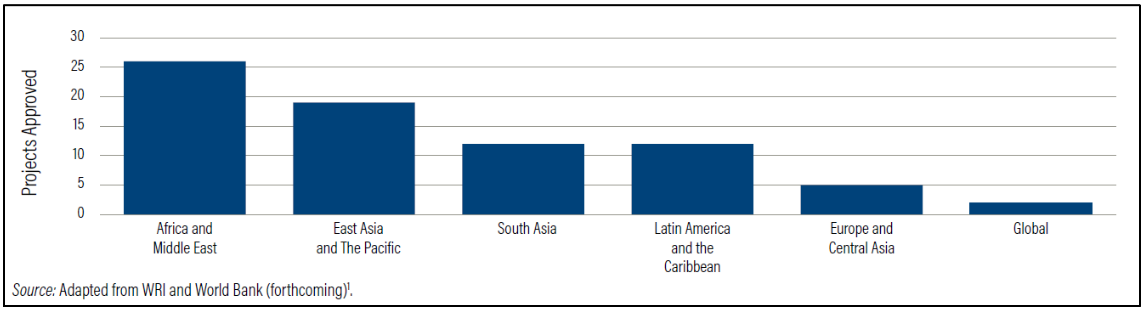


Figure 1.5 Number of disaster risk management plans approved by World Bank includes NBS [19]

Therefore, by considering the increasing risk of flood due to anthropogenic factors and changing climate, flood risk all over the world is increasing. It is more important today to provide NBS, integrated with environment and ecology, with gray structural measures to reduce flood risk and prevent economic loss.

This study focused on examining the effect of NBS solutions with and without gray ones on reducing flood risk. For this purpose, an area with flood risk in Türkiye is selected to implement and examined the effect of NBS on preventing floods or reducing flood hazards.

1.2. Objective of the study

Emerging flood risks are the primary concern of the latest decades. Conventional structural solutions (also called gray infrastructure) were implemented to prevent/reduce the adverse effects of floods. However, the aforementioned structures have a maximum service life of 100 years if they are kept well-maintained [20]. Moreover, failure of these structures poses a greater risk, especially for the areas located downstream of the measure. Therefore, the applicability and feasibility of NBS with and without conventional measures are examined within the scope of the study. Potential cons and pros of NBS measures are examined in detail for the selected area located in the northwest of Türkiye by implementing a hydraulic model. The performance of NBS and gray infrastructure for Sungurlu River and Ağva Town is analyzed and compared with three different alternatives and a multi-criteria selection method.

1.3. Outline of the thesis

Chapter 2 covers a wide range of information about structural and non-structural measures as well as NBS. Moreover, brief information about the hydraulic modeling procedure, creation of hazard maps, determination of flood control measures according to the EU Flood Directive and MCA methods to select the best alternative for flood risk mitigation are given. These are basic steps of flood risk management for a certain area.

Chapter 3 presents the study area, governing equations of fluid flow for hydraulic modeling, input data required for hydraulic modeling, and hydraulic modeling procedure with HEC-RAS software. Also, hazard assessment, selection of measures, and MCA procedures were given in this chapter.

In chapter 4, the current situation of the selected area and the alternatives with both traditional measures and NBS solutions were examined. Chapter 5 presents the conclusion and recommendation for further studies.

2. LITERATURE REVIEW

2.1. Introduction

In this chapter, a brief summary of hydraulic modeling and governing equations and a detailed description of flood mitigation measures, namely, structural, non-structural measures, as well as NBS are given.

2.2. Hydraulic Model

The motion of fluid is often described by 3D Navier-Stokes Equations (NSE) that are derived by considering the differential analysis of fluid particles and conservation of mass and momentum equations. Moreover, solving NSE requires the determination of an appropriate turbulence model. In the case of surface or flood flows, the horizontal disturbances of flow are much larger than the vertical ones, so by assuming hydrostatic distribution and taking the depth average of NSE, shallow water equations (SWE) come into the scene.

A hydraulic model of free surface flows and floods can be achieved by solving 2D depth-averaged non-linear SWE showed that the most appropriate way of numerical modeling of flood flows is to solve shallow water equations [21]. Several numerical schemes were introduced or validated by the researchers to examine the applicability of SWEs to real-life cases [22]–[24]. Furthermore, state-of-the-art software for solving free-surface flows, such as DHI-MIKE, TELEMAC, HEC-RAS was introduced.

Within the scope of this study, the modeling of surface flow was implemented by constructing a hydraulic model via HEC-RAS. HEC-RAS was developed by U.S Army Corps of Engineers and it is widely accepted and used software all over the world. Hydraulic modeling procedure of the flood management plans of Turkey, implemented by the General Directorate of Water Management of Turkey, requires hydraulic modeling of floods by HEC-RAS. Governing equations of fluid flow are examined in Chapter 3.4.

2.3. Structural Measures Against Flood (Gray Infrastructures)

Structural measures, also considered as gray measures, are physical modifications that are implemented to reduce the damaging levels of flood wave propagation. Structural measures include dams and reservoirs, channel modifications, levees or floodwalls [25].

- Dams and reservoirs
- Embankments (levees, dykes)
- Floodwalls
- Bypass and diversion channels
- Channelization
- River corridor rehabilitation and restoration

A brief explanation of each structural measure is given in the following sub-sections.

2.3.1. Dams and Reservoirs

Dams and reservoirs are built along the valleys or rivers to store, regulate and divert water for various purposes such as irrigation for agriculture, hydropower generation, human and industrial use, as well as attenuation of flood peaks. Therefore, most of the dams serve more than one purpose.

The main mechanism of dams and reservoirs with flood control purposes is to store flood volume fully or partially and delay or attenuate flood peaks so that the settlements located downstream of the dam or reservoir can be prevented from extreme events. If a dam has a flood control purpose, there exists a volume/space within the reservoir to store impending floods. Generally, small to medium floods within the catchment can be stored by the reservoir, suggesting full protection downstream while the partial volume of extreme floods can be stored in the reservoir volume and conveyance of peak floods and volume can be delayed and attenuated due to the reservoir.

Most of the dams are built considering multiple purposes and flood management purpose may be significant only for a few days or weeks in a year. Potential conflicts between flood management objectives, which require additional volume in a reservoir, and hydropower and irrigation, which requires keeping storage capacity as full as possible, make it difficult to operate a multiple-purpose reservoir. While allocating water for various uses, the need to maintain environmental flows should also be addressed. This should not only be guided by the percentage of the total flows released but also by the need for the variability of outflows in downstream of a storage reservoir to be mimicked in order to maintain near-pristine conditions [26]–[28]. Moreover, breaching of reservoirs can pose significant flood threat to the downstream settlement.

2.3.2. Embankments

Embankments are the oldest and most common flood protection structures. Embankments (also referred to as levees or dykes) are mainly constructed mainly from earth materials or compacted soil and used to confine stream flow within the specified area along the stream or to prevent flooding due to sea waves or tides. Embankments should be resistant to hydrostatic pressure of floods, erosion, piping failure and seepage. A representation of levee system is presented in Figure 2.1.

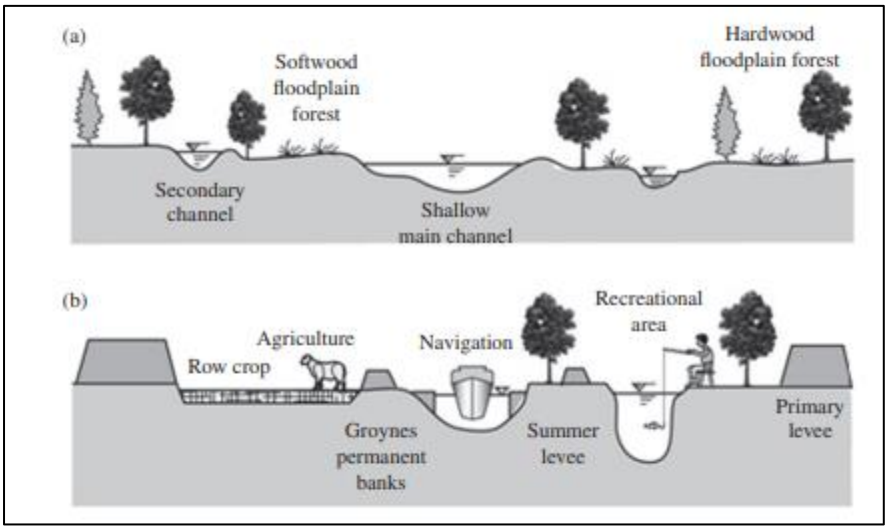


Figure 2.1 Double Leveed Floodplain Environment [29]

Levees restrict flow conveyance of a river. As a result, higher water levels and limited flood attenuation can be observed [29]. Disrupted conveyance of flow ends up with various effects on both the ecology of the channel and its floodplain. Moreover, construction of embankments close to main channel decreases the natural heterogeneity of the floodplain and prevents formation of wetlands. Therefore, nature of the environment can be adversely affected. Restriction of conveyance of water to the floodplain can also have adverse effects on groundwater recharge and therefore on ecological and economic benefits of it. Furthermore, due to the lack of sediment and nutrient transport because of the restricted flow, the fertility of floodplains can also be reduced.

The environmental impacts of embankments should be considered before the decision for construction is made [26].

2.3.3. Floodwalls

Floodwalls are engineering structures designed to prevent encroachment of floodwaters. Floodwalls are typically constructed of reinforced concrete and form a barrier against flood inundation. Therefore, they protect structures from hydrostatic and hydrodynamic load as well as debris and mudflow originating from floods [30]. The most common types of floodwalls are;

- Gravity,
- Cantilever,
- Buttress and,
- Counterfort

Schematic representation for floodwall is presented in Figure 2.2.

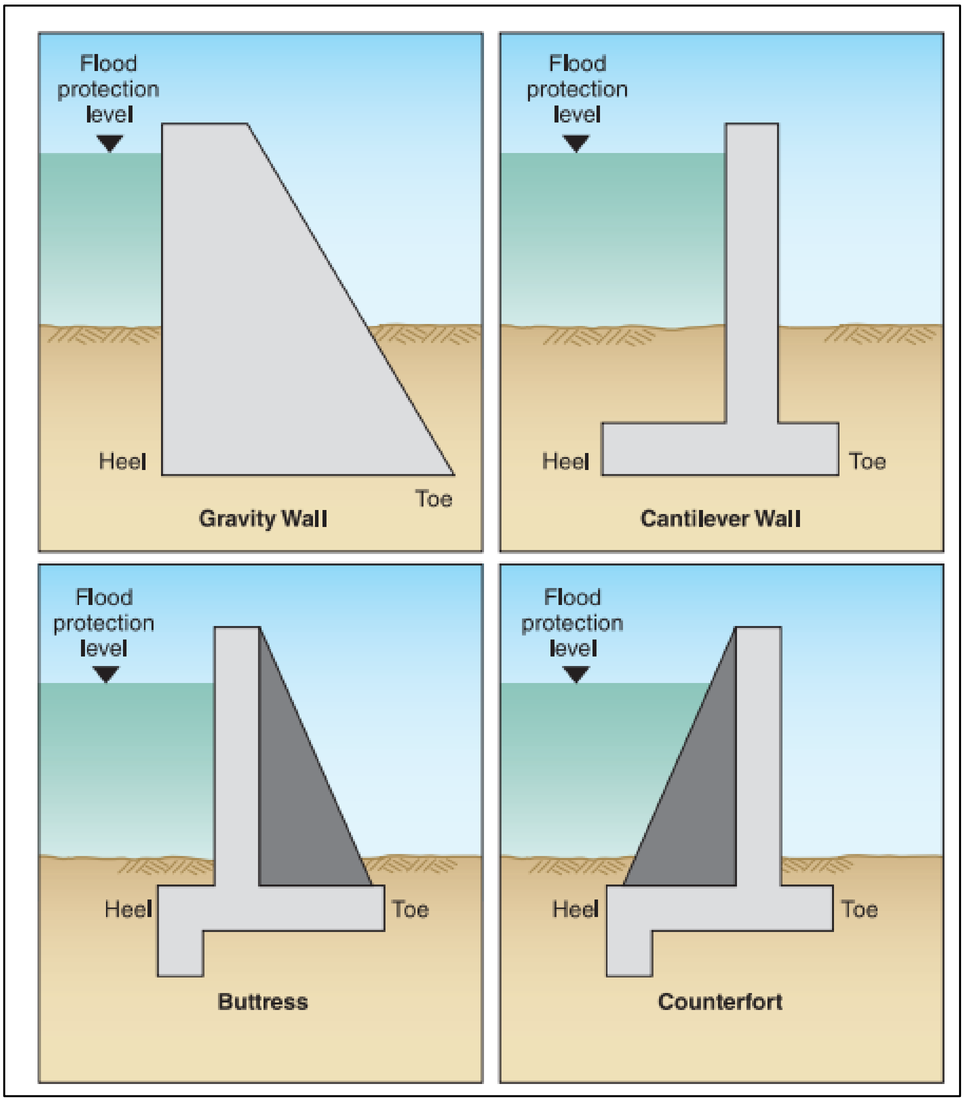


Figure 2.2 Gravity, Cantilever and Counterfort Floodwalls [30]

Gravity Floodwalls: Structural stability of gravity floodwalls are provided by its weight considering the effective positioning of the mass of the wall at its base. A gravity floodwall resists overturning primarily because of the material of its construction material. Therefore, they are extremely heavy to be overturned by a force exerted by flood. Construction and design of gravity floodwalls are relatively simple compared to other types of floodwalls. However, construction of them requires massive amount of materials which is considered as disadvantage [30].

Cantilever Floodwalls: They are the most common types of floodwalls due to the economic considerations through design and construction phases. Cantilever floodwalls are often constructed of reinforced concrete or concrete block with embedded steel bars in the core walls. Structural stability of these structures often achieved by the soil, weight of the base and wall itself [30].

Buttress and Counterfort Floodwalls: They are similar to cantilever walls except from the existence of transverse support wall. Counterfort walls have transverse support wall on the toe side while buttressed floodwalls have transverse support on the heel side [30].

2.3.4. Bypass and Diversion Channels

If an area requires protection, bypass channels divert discharge from the upstream of a river and discharged the flow into the same river or natural drainage system. Flow within the bypass and diversion channels are regulated by gates. The magnitude of flood can be decreased in the bypassed area; however, possibility of flooding at the downstream area significantly increases [31]. Moreover, diversion channels can increase possibility of flooding in the receiving drainage system. Increasing risk of flooding at the receiving environment or at the downstream area can be prevented by implementing detention and retention basins. Implementation of bypass and diversion channels requires careful examination of sediment transport. For example, if floodwaters are drawn from the river by bypass channels without sediment load of floodwaters, channel capacity of bypassed river can decrease due to the excess sediment load. On the other hand, conveyance of floodwaters with sediment can reduce capacity of bypass channel. Transportation of floodwaters with sediment via bypass or diversion channels causes new equilibrium to be established. However, if the flow is diverted at all stages considering the low flows, habitats and vegetation in the bypassed reach of the river are likely to be adversely affected. With reduced flows in the main stem of the river, streamside vegetation can encroach into the river channel, thereby changing its physical characteristics. Such altered flow conditions often favor exotic species, which places greater survival pressures on native species. A bypass channel has no appreciable impact on the quality of the water in the river or diverted floodwaters [26]. Schematic representation of bypass and diversion channels are pictured in Figure 2.3.

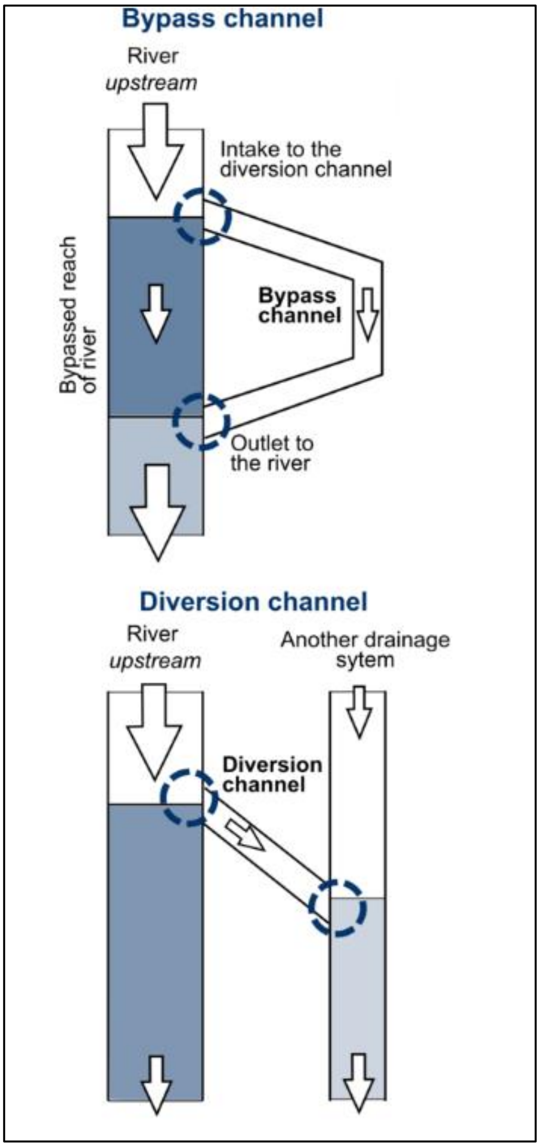


Figure 2.3 Schematic Representation of (a) Bypass Channel, (b) Diversion Channel

2.3.5. Channelization

The main aim of channelization is to increase the depth of flow within the river by increasing conveyance capacity, which allows navigation or/and reduces the impact of flooding or inundated area. In addition to the increased conveyance capacity, flow is confined within the single channel and friction is reduced. Reduction of friction is achieved by straightening, widening, deepening, or/and lining the channel. Existence of large wood pieces embedded in river bed cause backwater flow which is the main driving force of sediment accumulation and vegetation. Flow and sediment deposition patterns can change after removing these kinds of materials.

Implementation of channelization simplifies the channel form and floodplain environment by straightening and homogenizing the channel and disconnecting it from side channels. Another important alteration brought by channelization is the decreased roughness, which causes water to flow more rapidly, resulting in increased scour.

Channelization may have negative impacts on the environment such as the elimination of bars, riffles and pool complexes that are crucial for certain aquatic organisms. Lining of river cross sections prevents organisms from living on stream sediments. In order to reduce the adverse effects of channelization techniques such as porous pavement, and soft lining, soil bioengineering should be considered [26].

2.3.6. River Corridor Rehabilitation and Restoration

River corridor rehabilitation and restoration is often involving various activities with degraded river in order to convert it to its natural condition. The full recovery or returning river to its original state is impossible. However, limited works are implemented to restore river corridors.

The most common procedure for enhancing, rehabilitating and restoring river corridors is enhancing riparian zones by planting grasses, bushes and trees; stabilizing stream banks, removal of dams and other man-made structures and allowing fish and other living organisms to live within rivers.

Riparian zone or vegetation is defined as the special zones that require more humidity and water in the ecological system. Therefore, natural environment of riparian zone should be considered while planning interventions on fluvial systems. Measures that take riparian zones into consideration should address following criteria:

- Keeping a structure of vegetation of different ages that allows the presence of both shrub and tree layers
- Periodic cutting and selective thinning of adult trees that present problems of stability, and elimination of invading species in favor of autochthonous species and, possibly, valued species
- Keeping shrubby vegetation where possible, since it can bend easily during floods and does not obstruct bridge sections [32].

2.4. Non- Structural Measures Against Flood

Non-structural measures are modifications implemented to reduce the damages caused by flood wave propagation without significantly altering the nature or extent of the flooding by changing the use of floodplains or by accommodating existing uses to the flood hazard. Non-structural measures include modifying homes, businesses, and other facilities to reduce flood damage by elevating the structure or removing them from the floodplain. The remaining land can be used for ecosystem restoration, outdoor recreation, or natural open space. Flood warning systems are also considered non-structural measures. National Nonstructural Committee (NNC) of the USA defines non-structural measures and the difference between structural ones as: “Non-structural measures differ from structural measures in that they focus on reducing the consequences of flooding instead of focusing on reducing the probability of flooding.” [33]. When flood control and protection work and other types of measures fail or are insufficient to prevent flooding, these non-structural measures become effective in mitigating flood impacts on society and the environment.

The non-structural flood measures can be divided into physical non-structural and nonphysical non-structural measures. Each type of non-structural measure has its sub-measure. Each sub-measure is briefly explained below.

Physical non-structural measures

- Elevation
- Relocation
- Buyout/acquisition
- Dry flood proofing
- Wet flood proofing

Nonphysical non-structural measures

- Flood warning systems
- Flood insurance
- Floodplain mapping
- Flood emergency preparedness plans
- Land use regulation
- Zoning

- Evacuation plans
- Risk communication

2.4.1. Elevation

Elevation measure requires raising the buildings or structures so that flow depth of extreme floods causes no significant threat. Elevating structures often involve by foundation walls, piers, piles etc. [33].

2.4.2. Relocation

Relocation implies relocating a structure to another place that is free of flood hazard [33].

2.4.3. Buyout/Acquisition

Buyout involves elimination of flood damage by allowing inhabitants to locate another place that is free of flood hazard [33].

2.4.4. Dry flood proofing

Dry flood proofing involves implementing waterproofing compounds, impermeable sheeting or other materials to prevent the entry of flood waters into buildings/structures. Dry flood proofing can be beneficial for small to medium floods or shallow/low-velocity floods [33].

2.4.5. Wet flood proofing

Wet flood proofing involves entrance of flood water into structures. However, they provide protection to vulnerable items via relocating.

Flood proofing measures also involve removing goods, equipment and harmful industrial, agricultural and domestic chemicals, beyond the area subject to flooding or out of contact with inundation area, by constructing high ground or small embankments. Existing facilities for drinking water supply have the potential to get contaminated. The sewerage disposal and treatment infrastructure located in the flood plains can cause nuisance and spread diseases and pollution, affecting the health of the population. Provision should be made for the protection of such infrastructure. Both dry and wet flood proofing are considered as an important measure because they not only reduce the damage due to flooding but also prevent negative impacts of flood to the environments such as preventing spreading harmful pollutants [26].

2.4.6. Flood Warning Systems

According to NNC, flood forecasting and early warning systems have been the most commonly used and accepted non-structural measures since the latter half of the 20th century. They alert inhabitants living in flood prone areas and provide opportunity to reduce or prevent damage to the property as well as keeping human beings away from flood hazard [33]. The effectiveness of a flood warning system is a function of the accuracy, timeliness and outreach of the forecast as of the response behavior and preparedness. Inflow forecasts for reservoirs, detention basins, bypass channels, etc. play an important role in flood peak alleviation. It is important to draw reservoir operation guidelines covering various scenarios and effect managed flood releases based on these forecasts [26].

2.4.7. Flood Insurance

Flood insurance is considered as non-structural measure and provides assistance for recovery [33]. It should be supported by floodplain zoning or floodplain mapping program [26].

2.4.8. Floodplain Mapping

Floodplain mapping is another non-structural measure defining inundation boundaries as well as flow depth and velocity within flood-prone areas [33]. Floodplain mapping is one of the main outputs of flood management plans in Turkey and the main tool for developing both structural and non-structural measures.

2.4.9. Flood Emergency Preparation

Flood emergency preparation provides emergency preparedness by identifying hazards, risks and vulnerabilities. It also provides evacuation plans and routes and preparation for evacuation centers [33].

2.4.10. Land Use Regulations

Land use regulations are considered an important measure for reducing flood risk. As mentioned before, excess urbanization cause flooding and land use changes are mainly caused by urbanization. Changing land use and resulting increment of impervious layers has significant impacts on the magnitude of flood and the arrival of flood peaks to the settlement areas. Regulation of land use by policy or decision-makers reduces adverse consequences of floods by increasing infiltration capacity and shortening flood duration [26].

2.4.11. Zoning

Flood zoning helps for reducing flood risk. Determination of areas prone to significant flood risk and risk-free areas allows decision-makers to determine restricted or development areas. This is considered as long-term planning measure [33].

2.4.12. Evacuation Plans

Evacuation plans are the outputs of detailed hydrologic and hydraulic calculations or modeling that determines flood-prone areas, evacuation routes and evacuation places. When used with a flood warning system, it is an important tool for preventing loss of lives and reducing flood damage [33].

2.4.13. Risk Communication

Risk communication is defined as an educational tool, such as workshops, presentation, hand-outs etc., to inform the community and reduce the adverse effects of flooding [33].

2.5. Nature-Based Solutions

Nature-based solutions for flood risk management focus on decreasing flood risk for a particular area with measures copied, supported or inspired by nature. During the early 2000s, NBS first stated to be applied for climate change adaptation and to protect biodiversity, but its use quickly spread into other areas. NBS contributes to the improvement of water quality, supports climate change adaptation, increases the quality of life by creating recreational areas and supports biodiversity. The aim of NBS is alteration of the use of land to increase permeability, water retention capacity and enhance evapotranspiration. As a result of these effects, flood peak values and flood hazard decreases. However, the required space for the application of NBS is relatively larger than gray infrastructure measures. Therefore, NBS sometimes cannot be effective for extreme events or requires much greater space, and creating those space is impossible for already urbanized areas. On the other hand, using NBS with gray infrastructure is becoming to be a common practice throughout the world. In that way, the dependency on gray infrastructure is decreasing and NBS is creating flexibility for climate change adaptation.

Most of the time, NBS requires a holistic approach to basin management. Since the measures need more space, upscaling from the point of the flood hazard should be considered. In Figure 2.4, an example of sponge city approach can be seen. To be able to achieve this measure, upstream of the basin should be supported by wetlands, detention basins and land use changes. In the downstream part, city should be arranged as a permeable layer to slow down the propagation of flood waters with the help of extended time for peak flow arrival.

This field still lacks knowledge and experience, so further research is needed to improve the effectiveness of NBS methods [34].

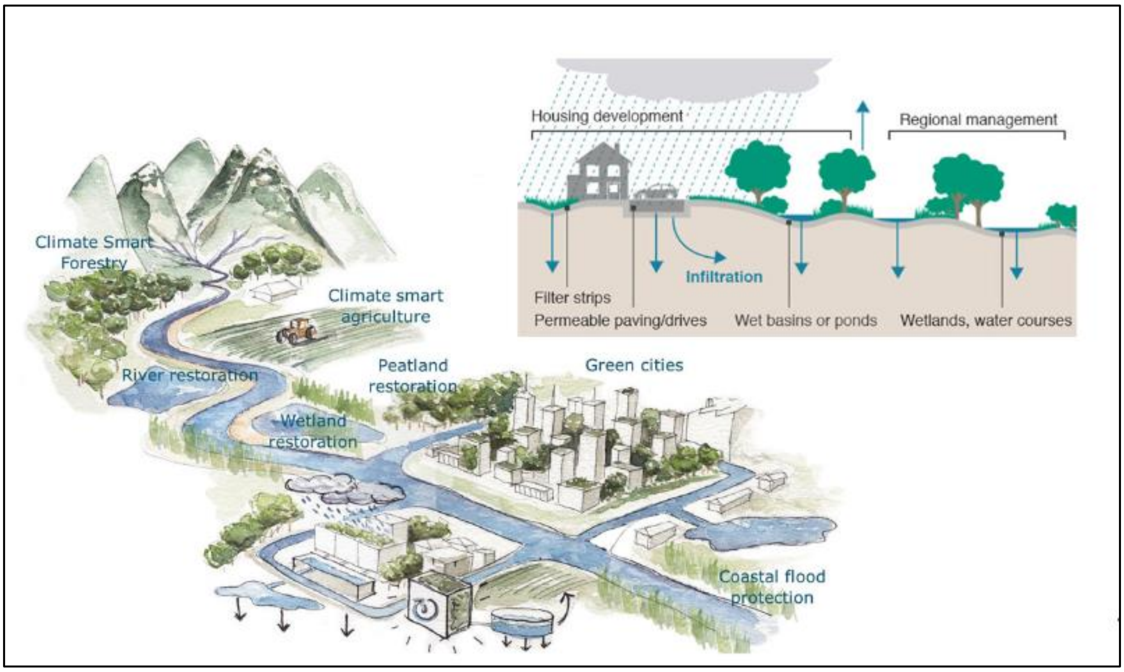


Figure 2.4 Sponge city concept as an NBS [34]

Some common NBS practices are explained below:

- Detention basin
- Retention Basin (wetlands)
- Afforestation
- Ecological River Restoration
- Land use / Land Cover changes
- Sponge city concept

2.5.1. Detention and Retention Basins

Detention and retention basins are defined as natural excavations that are constructed for temporarily storing flood waters and reducing flood peaks by regulating discharge of extreme events. The primary difference between these two is that the detention basin has a controlled flow outlet that releases water into man-made channels while stored water within the retention basins infiltrates into the ground and evaporates. Moreover, detention basins keep stored water for a few days depending on the capacity, while stored water in retention basins can be kept for months.

It is often assumed that detention and retention basins do not alter the sediment and organic matter composition of the river. However, if water is stored in these basins for a long period of time, it results in increasing temperature, decreasing dissolved oxygen and eventually eutrophication [26].

2.5.2. Afforestation

Afforestation is the establishment or reestablishment (reforestation) of the forest regions to increase the infiltration and roughness of the basin. As a result of these effects, flood event duration increases, which leads to lower peak flows and hazard. In addition to the decrease of flood hazard, afforestation increases biodiversity, decreases carbon dioxide concentration, creates recreational areas for people and increases water quality. The effects of afforestation as a measure have still not been demonstrated clearly yet. The reason for this is the different approaches in hydrology and hydraulics. In hydrology, land use is commonly evaluated with CN number; on the other hand, forest areas are represented with high roughness zones in hydraulics [34]. These two coefficients act differently in the modeling and flood assessment. Therefore, the effect of afforestation should be researched more and there should be more applications to observe its effects.

2.5.3. Ecological River Restoration

Ecological river restoration consists of various ecological, physical, spatial and management measures and practices. Modified rivers, most of the time, prevent the connection between the soil layer, and this leads to isolation between groundwater and river. Also, artificial river arrangements result in more severe downstream flood events by routing the water through the basin, even though it seems successful in preventing flood hazard for a certain region. Ecological river restoration also aims to restore the natural state of the river to recover river habitat and biodiversity. Even though all these advantages, ecological river restoration projects require land acquisition and land use change. Therefore, for densely urbanized areas, this measure could be difficult to be implemented [34].

2.5.4. Land use / Land Cover changes

Land use/land cover (LULC) changes are the measures that aim to decrease the flood hazard by increasing the perviousness of the basin, storing water upstream or changing the riverine environment to increase roughness to decrease discharge rates of the rivers by increasing friction with riparian zones. Actually, LULC includes all the measures such as afforestation, river restoration, detention basins, retention basins etc., because all these measures require land use changes. To be able to consider LULC as an NBS, spatial changes should aim to recover the natural state of the land [34].

2.5.5. Sponge City Concept

The current pattern of urbanization during past decades resulted in loss of permeable soil layers. In literature, for certain areas, a 30% of increase in impermeable surfaces in the urbanized area results in 100% increase in flood hazard when comparing the state before the urbanization [35]. The aim of the sponge city concept is to increase the permeability of the urbanized areas, direct run-off water into the ground or collect it in detention basins and small ponds instead of discharging it to the sewerage system. After the collection of the rainwater, stored water could be released in a controlled way, or it can be used for irrigation or other purposes after water quality checks [36]. Also, the sponge city concept includes the increase of green areas in the city, so it helps to decrease the average temperature of the urbanized area, decrease CO_2 emissions, increase biodiversity and provide recreational zones for people living in the city.

2.6. Flood Risk Management Under EU Flood Directive

Flood risk management is a phenomenon that starts from identifying flood risk to its elimination. There are several directives for flood risk management in different parts of the world. In this chapter, “EU Flood Directive 2007/60/EC” which EU member states have to follow is introduced for flood risk management.

EU Flood Directive requires all EU countries to analyze all flood-prone areas that could have significant flood risk, create maps of flood extent and assets under flood risk, and take measures to decrease flood risk [15].

The aim of the EU Flood Directive is reducing the impact of flooding to people, assets, environment and social life. According to the directive, this aim could be achieved by incorporating the following elements to the flood risk management programs.

1) **Prevention**: Includes preventive measures to avoid impact of flooding. These measures are land use changes, avoiding construction of buildings and industries where flood risk exists.
2) **Protection**: Reducing the impact of flooding for a specific location by taking structural and/or non-structural measures.
3) **Preparedness**: Informing the population about flood risk and increasing the preparedness to floods of people
4) **Emergency response**: Development of emergency response plans in case of a flood
5) **Recovery and lessons learned**: Recovering to the conditions before flood event by mitigating social and economic impacts on the people

In Figure 2.5, the general process of flood risk management planning according to EU Flood Directive was given.

Figure 2.5: Phases of Flood Risk Management As Per EU Flood Directive [15]

Article 4 of the Floods Directive requires all Member States to undertake a Preliminary Flood Risk Assessment (PFRA) for each river basin district, unit of management of the portion of an international river basin district, or unit of management lying within their territory. The aim of PFRA is the identification of areas with probable flood risk by using already available data.

After the identification of Areas with Significant Flood Risk (APSFR) in the PFRA phase, more data are collected to increase the accuracy of the flood hazard and risk analysis. After the collection of data, flood hazard and risk maps are prepared to determine precise locations of areas have a flood risk.

EU Flood Directive recommends taking sustainable and non-structural flood control measures with limited or no negative impact on the environment and society. Therefore, EU member states and states that follow this directive are obliged to avoid gray infrastructure measures as much as possible. Also, NBS is getting more popular throughout the world since NBS provides sustainability, environmentally positive effects, and good social and economic benefits with great climate change adaptation.

However, EU Flood Directive Article 4(7) allows taking gray infrastructure measures when there is no other option. When there is no room for NBS, or when the implementation of the gray infrastructure is justifiable over NBS or non-structural measures, then traditional structural measures could be taken. Mostly these kinds of areas are narrow valleys where there is no enough space for NBS.

After the selection of possible measures for an area with significant flood risk, the most favorable option should be selected according to the objectives of the country regarding flood risk management. To be able to select the best flood measure alternative, a multi-criteria analysis (MCA) should be carried out. In the literature, a variety of MCA methods exist. MCA also includes cost-benefit analysis (CBA), by that way MCA can assess economic terms as well as non-monetary terms. For flood-prone areas where only one type of measure is insufficient to eliminate residual flood risk, different types of flood measures should be combined to manage flood risk. This makes the MCA more important when selecting the best option with a transparent process and compatible with predetermined objectives. MCA methodology could differ and MCA weights are subjective according to the objectives of the country and public opinion. In addition, MCA allows the involvement of non-monetary terms, especially relating to social and environmental impacts of probable measure alternatives [37].

There are pros and cons of different MCA methods. A summation of different methods is given in Table 2-1. Administrations and project implementers should decide on the suitable method according to their priorities and the data availability.

Table 2-1 Characteristics of different multi-criteria methods [37]

Method	Information	Result	Transparency	Computation	Costs
Weighted Summation	Quantitative	Performance scores/ranking	High	Simple	Low
Ideal Point Method	Quantitative	Distance to target/ranking	Medium	Simple	Low
Evaluation by Graphics	Qualitative, Quantitative and Mixed	Visual presentation	High	Simple	Low
Outranking Method	Quantitative	Ranking/ incomplete ranking	Low	Very complex	Medium

Method	Information	Result	Transparency	Computation	Costs
Analytical Hierarchy Process (AHP)	Quantitative	Performance scores/ranking	Low	Complex	Medium
Regime Method	Qualitative, Quantitative and Mixed	Ranking/ probability	Low	Very complex	Low
Permutation Method	Quantitative	Ranking	Low	Very complex	Medium
Evamix Method	Mixed	Ranking	Low	Simple	Low

For this study, the weighted summation method was used for MCA, since the available data is qualitative and the performance of the measures was needed with high transparency. The method selected could differ by the needs of decision makers.

After the selection of the best measures to be taken for specific APSFRs, one more prioritization should be carried out according to the institutional capacity and urgency of the measure. After this last prioritization, a flood risk management plan could be written with a summary of measures, which includes all selected measures with urgency to be implemented.

A public consultation process should be carried out after the first draft of flood risk management plans to include all stakeholders in the process. The reason for this procedure is the inclusion of local knowledge and opinion in the planned projects. In this process, if possible harmful effects to society realized, then the selected projects should be reconsidered. After the consensus is established regarding the planned measures, then the final version of the flood risk management plan could be published and this plan should be implemented for six years according to EU Flood Directive.

The next cycle of the flood risk management plan should include the lessons learned during the six years of the implementation period.

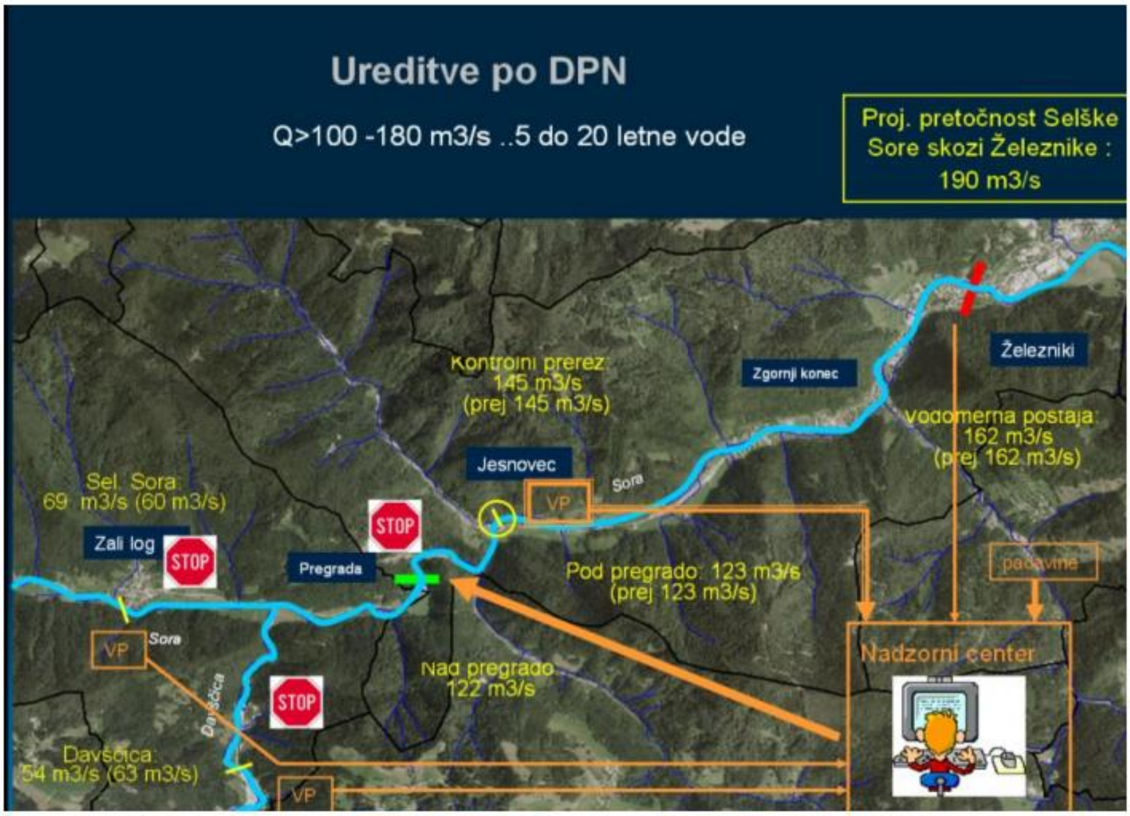
2.7. Example Implementation of EU Flood Directive in Selška Sora River, Slovenia

Throughout Selška Sora River in Slovenia, an example application of flood risk management with hybrid solutions is in progress, which includes gray and NBS together. The population and economic assets through Selška Sora River Basin are prone to pluvial flood risk since the characteristics of the basin are narrow valleys could create high discharges in a short time. Gray infrastructure had to be included in the project since the valley is narrow and in some parts of the basin there is no room for NBS, especially to prevent high discharges. The process for eliminating flood risk in this region is carried out in two phases. In phase one, ecological river restoration, reconstruction of two dams, equalizing the height of the floodwalls, land use arrangements, and increasing the height of the roads where necessary. All the planned measures are demonstrated in Figure 2.8. Also, flood insurance is done as a non-structural measure. The community living in this region is informed about every step of the project, so public opinion is included in the planned projects too. This also enabled the increase in public awareness against floods, which is envisaged by EU Flood Directive [38].

In the second phase, a dam (Suša Dam) with 20 meters crest height and 1 million m^3 capacity will be built. The location of the dam is located on Selška Sora River in Slovenia, near Železniki Town. The purpose of this dam is only flood control, therefore dam designed is as a dry dam. According to the calculations, which are verified from the flood event that happened in 2007, after 190 m^3/s discharge of Selška Sora River, the flood reaches to hazardous level and leads to damages in Železniki Town and small residential areas around Železniki. Therefore, this dam is designed to allow flows until 190 m^3/s. After this threshold, the dam starts to regulate discharge and work as a flood control structure by storing water. The design of dams should be carried out carefully since one small design mistake results in catastrophic damages. Thus, during the design phase of Suša Dam, a physical model was built at the University of Ljubljana to validate the design of the energy dissipation structure where the outflow of the dam (Figure 2.6). The first reason why a physical model is built is to check the stability of the structure. The second reason is the water that the dam is discharging has solid particles because of a quarry located upstream of the dam. According to the physical model results, the energy dissipation structure had to have sealing and the only core layer is not enough to maintain stability.

The discharge rate is constantly observed by three stream gauges and if the thresholds are exceeded, the retention process begins automatically (Figure 2.7).

Figure 2.6 Physical model of Suša Dam built at the University of Ljubljana (Photo was taken during a technical study visit at 26/10/2022)



Ureditve po DPN

Q>100 -180 m3/s ..5 do 20 letne vode

Proj. pretočnost Selške Sore skozi Železnike : 190 m3/s

Figure 2.7: Conditions for the beginning of the retention process of Suša Dam [38]

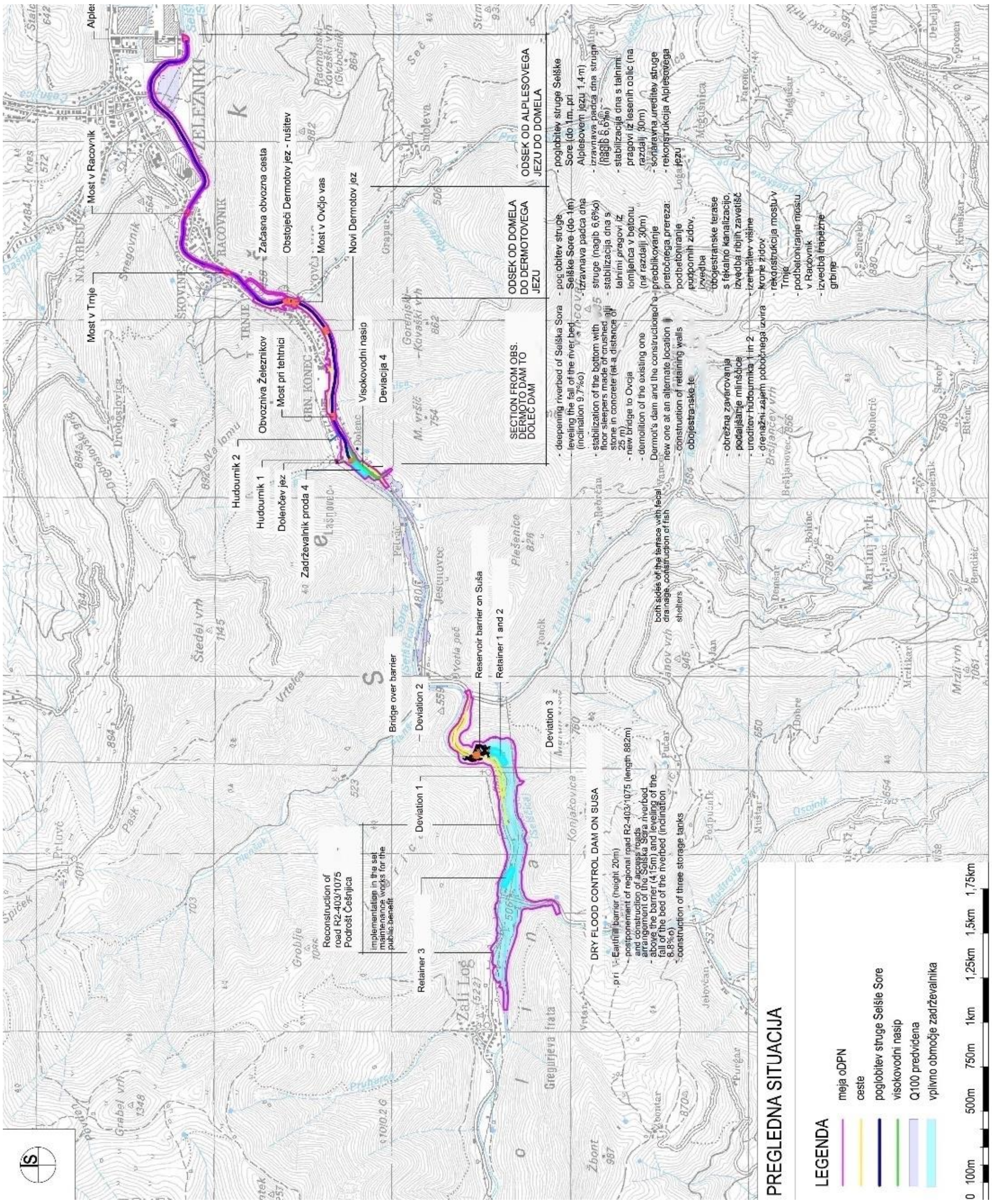


Figure 2.8 Planned measures for Selška Sora River Basin [38]

Other than the construction of a dam as a flood mitigation measure, the riverbed of Selška Sora River is rearranged to increase the capacity.

Where the riverbed could be widened between Alples Dam and Domel, the riverbed is planned to be returned to its natural state since in this area there is enough space to apply this NBS approach. In Figure 2.9, a typical cross-section of this measure is given.

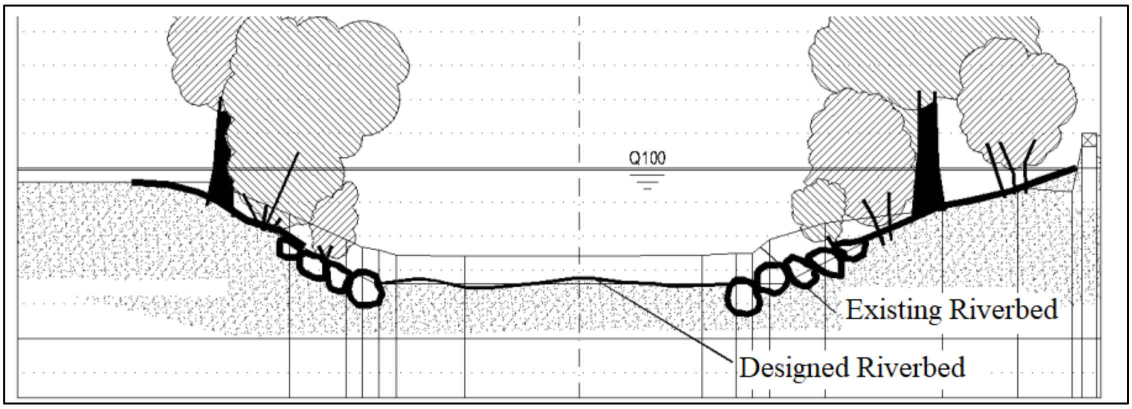


Figure 2.9: Typical cross-section between Alples Dam and Domel [38]

However, between Domel and Dermot Dam, due to the narrowness of the river bed in its current state, the bed is surrounded by a river wall on both sides, so the expansion of this section is not possible. Even though the flood discharges were reduced from the construction of the dam located upstream, it is seen that flood safety can only be increased by deepening the riverbed and equalizing the height of the crown of the bank walls. In Figure 2.10, a typical cross-section of this measure is given.

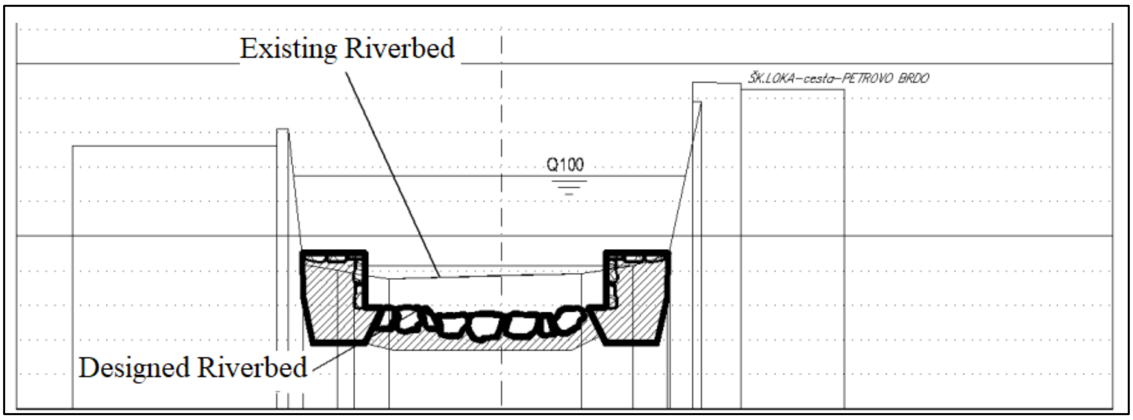


Figure 2.10: Typical cross-section between Domel and Dermot Dam [38]

Also, to facilitate the fish passage from this section, the bottom of the riverbed is stabilized and floor sleepers made of crushed stone are used and the bottom level is lowered by 20 centimeters at a width of 4 meters.

The measures were implemented and will be implemented for Selška Sora River Basin demonstrates that NBS and gray infrastructures could be used as complementary to each other wherever these measures are suitable to use. Topography, geology, and hydrologic regimes of the study area change the measures to be taken.

All project documentation could be reached from the project website (http://www.poplavna-varnost.si/zelezniki/dokumentacija-2/) [38].

2.8. Summary

Structural and non-structural measures against flood inundation are examined in this chapter. Structural measures are well-understood and designed engineering structures aiming to improve flow conditions. Structural measures often cause environmental changes which can be harmful to habitats, vegetation, ecology, and water characteristics. Moreover, failure of these structures, such as breaching of a dam, may cause catastrophic floods. On the other hand, non-structural measures often require the implementation of early warning systems, management plans, etc. These measures often aim to reduce the impact of floods. Moreover, as the name implies, NBS is often considered as a structural measure that has no or insignificant adverse effects on the environment and ecology. As a result, implementing flood measures requires a multi-disciplinary approach that considers the environment and ecology while aiming to minimize the adverse effects of floods.

“Living with floods” – an age-old practice in many parts of Asia – recognizes that while it is not possible to eliminate floods, their negative impacts can be reduced through an understanding of flood risks, by working towards holistically modifying this risk-generation process in a manner and by minimizing settlement in areas subject to flooding. This strategy, in conjunction with non-structural measures such as land use planning, flood forecasting, and warning and emergency planning, can help keep the adverse impact on the environment to a lower level. The concept of “living with floods”, rather than fighting them, is the most effective way of preserving ecosystems [26].

3. MATERIALS AND METHODS

3.1. Introduction

For the flood hazard assessment, after the hydrologic assessment and determination of the boundary flow conditions, hydraulic modeling should be carried out to create detailed flood hazard mapping. In this chapter, boundary conditions and inputs of 2D hydraulic modeling, procedures, and methods of hydraulic modeling are explained in detail. For hydraulic modeling, a full 2D HEC-RAS model was used in this study. This model requires the inputs given below:

- Hydrologic and topographical boundary conditions
- Digital Elevation Model (DEM)
- Land use data

The study area is introduced in Chapter 3.2. Required input data for 2D hydraulic modeling is explained in Chapter 3.3. The governing equations and modeling approach for 2D hydraulic modeling are explained in Chapter 3.4.

2D hydraulic model results are water depth, velocity, volume of water in a specific area, and other variables that could be iterated from the model output. After the hydraulic modeling, flood hazards can be determined from the output data. In the literature, there are several methods for different conditions. The selected flood hazard assessment method for this study is explained in detail in Chapter 3.6.

After obtaining hazard maps and calculation of damages and cost of the proposed measures, MCA was carried out. The following MCA methodology was explained in Chapter 3.8.

3.2. Study Area

The study area, Ağva District, is located in the northeastern part of the Asian side of İstanbul. The latitudinal coordinates of the study area are 40^{o}54’40N to 41^{o}06’23N, and longitudinal coordinates are 29^{o}53’34E to 30^{o}01’33E. This area covers Ağva Town center in the downstream part of the Sungurlu River, and the upstream section covers forest and agricultural areas. The mouth of the Sungurlu River flows into the Black Sea after flowing through the east side of the Ağva Town center. The climate of the Ağva region is hot and humid in summer and mostly snowy, cold, and rainy in winter. The annual precipitation is around 850 mm according to meteorology stations near the study area. The daily average temperature during the summer months is 28 ^{o}C; during winter, it is 5.4 ^{o}C. The catchment area of the Sungurlu River subbasin is 327 km^{2}. The maximum elevation in the basin is 460 meters, and the minimum elevation is 0 meters.

The population of Ağva District is 2101 people, according to the most recent data from the Turkish Statistical Institute from 2021. This district has touristic places such as hotels and restaurants through the left bank of the Sungurlu River and there is a beach located on the Black Sea coast. There is another river on the west side of the town center. Therefore, the town center is prone to the risk of flooding. The location of the study area is shown in Figure 3.1.

Figure 3.1 Study Area

3.3. Input Data

3.3.1. Hydrological Data

One of the most important input data for the 2D hydraulic modeling is hydrologic data, which is the location and amount of flood event discharge. The accuracy of the hydrological data is important since it directly affects the inundation area and hazard mapping. Designs of the measures that will be carried out for an area at risk are done according to hazard mapping. When the flooded area is overestimated, the measures will cost much more than needed and lead to spending resources of the administration more than it should be. This situation could result in a longer implementation period for other planned measures and decrease in the institutional capacity of the administrations. When the flooded area is underestimated, that leads to ineffective measures and sometimes results in more damage than the previous state where the measure is implemented if these measures are grey infrastructures. Also, after the extreme flood event, these measures are damaged and need maintenance.

Hydrological data for this study is taken from İstanbul Water and Sewerage Administration (İSKİ) Master Plan project, Existing Creek Interim Report in 2019. In the mentioned project, hydrological studies were carried out with Soil Water Assessment Tool (SWAT) rainfall-runoff model using high-resolution data, some of them are DEM with 10 meters of the resolution, land use, soil classes, data from stream gauging stations, etc. The locations of subbasins are given in Figure 3.2.

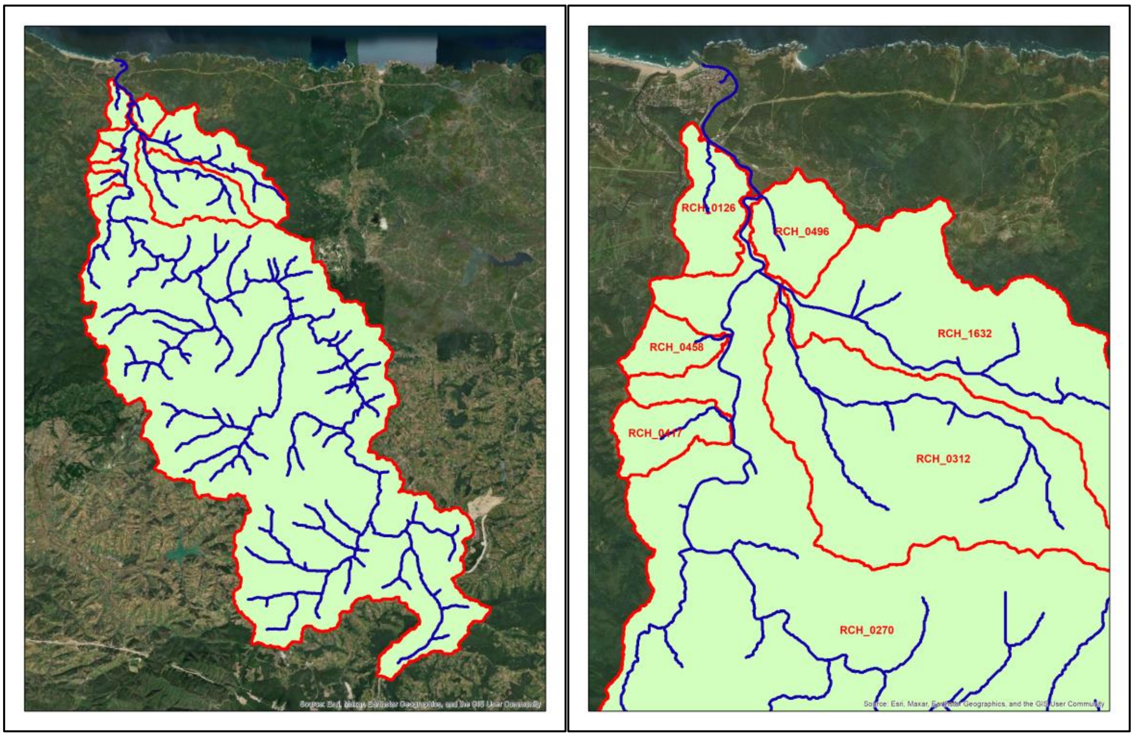


Figure 3.2: Subcatchments of Sungurlu River

The maximum run-off values of the outlet of the subcatchments are given in Table 3-1.

Table 3-1: The maximum run-off values of the outlet of the subcatchments

Subcatchment Name	**Maximum Run-off (m^3/s)**			
	Q_{10}	**Q_{100}**	**Q_{500}**	**Q_{1000}**
RCH_0126	8.9	23.9	34.3	38.8
RCH_0270	217.3	459.2	626.6	698.7
RCH_0312	32	81.8	116.2	131
RCH_0417	7.6	20.7	29.8	33.7
RCH_0458	6	16.7	24.2	27.4
RCH_0496	9.3	24.8	35.6	40.2
RCH_1632	32.5	85.3	121.7	137.4

Flow hydrographs are given in Annex 1 in table and graph format.

3.3.2. Digital Elevation Model (DEM)

Digital elevation model (DEM) is a bare ground topographic surface layer in a spaced grid raster format. During the processing of DEM data, trees, buildings, and other surface objects are excluded from the data. The source of DEM could be a free source, like USGS DEM. However, the resolution of these free data is usually not enough to represent the topography for flood risk assessment studies. Since this freely available data is not enough for flood assessments, administrations create their data using the LiDAR technique. With this technique, high-resolution DEM data could be created up to centimeter accuracy. DEM data is one of the most important data that affects the inundation area as well as hydrological data. It can be stated that the 2D hydrologic models are as good as the DEM used in the model since topographical changes directly affect the inundation area. Besides the resolution of the DEM, the up-to-datedness of the DEM is also important. Especially for urbanized areas, the extent of the city expanses and land use changes. These kinds of changes lead to changes in topography as well. Therefore, flood risk management plans should be updated every six years according to EU Flood Directive (2007/60/EC) [15]. In summary, the accuracy and correctness of the DEM data are important to have realistic results from 2D hydraulic modeling.

For this study, outside the city center, 1x1 meter accuracy LiDAR DEM data has been used. Inside the Ağva Town center, the LiDAR data accuracy is 10x10 centimeters. Inside the Sungurlu River, a bathymetric survey was conducted and points collected through the Sungurlu River were superposed into the final DEM data. The order of the superposed DEM data is given in Table 3-2. In Figure 3.3, the DEM used in the hydraulic flood modelling is given.

Table 3-2: Order of superposed DEM data

Order	**DEM Data**
1	River bathymetry
2	10 cm resolution LiDAR data available for Ağva town center
3	1-meter resolution LiDAR data available for the whole study area

The data is obtained from the Republic of Türkiye Ministry of Agriculture and Forestry, General Directorate of Water Management.

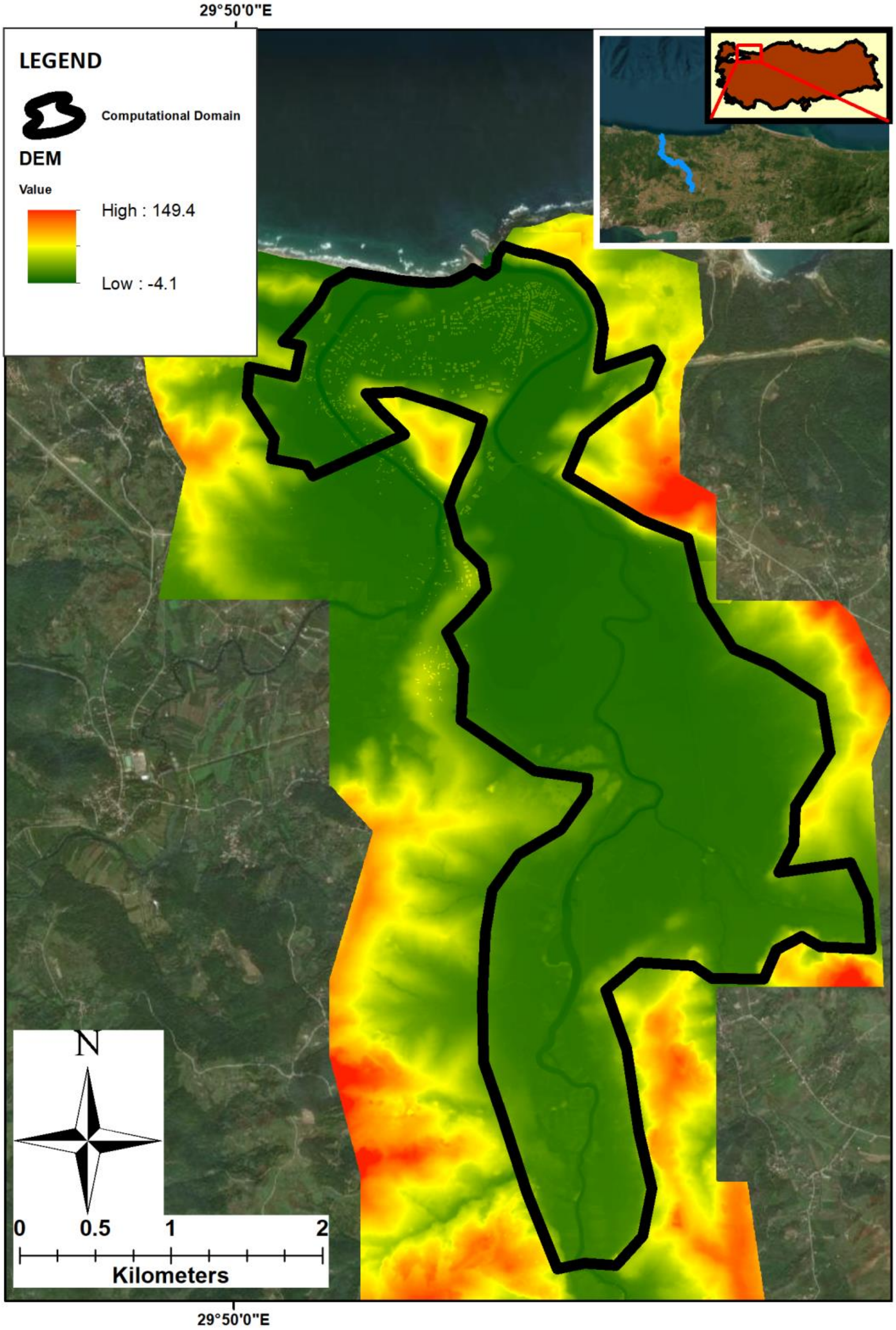


Figure 3.3: Digital Elevation Model used in the flood model

3.3.3. Land Use Data

Land use data is an important input data for the 2D hydraulic modeling since the roughness of the 2D floodplain is determined by this data. Manning constant is used as the roughness method in this study. Usually, roughness is used as the main calibration parameter for flood models, but no calibration data were available for the study area. Therefore, Sentinel-2 Land Cover data was used in this study to determine roughness. Sentinel-2 Land Cover has been selected for this study since it has a 10 by 10 meters resolution and has better accuracy than CORINE 2018 data, which has 100 by 100 meters of resolution. For the location of Sungurlu River, the Manning’s roughness value is determined as 0.035 by looking at the pictures taken from the site during the bathymetric survey is conducting [39]. River is close to its natural state and was not modified so much. From Figure 3.4, the typical river environment of Sungurlu River could be seen.

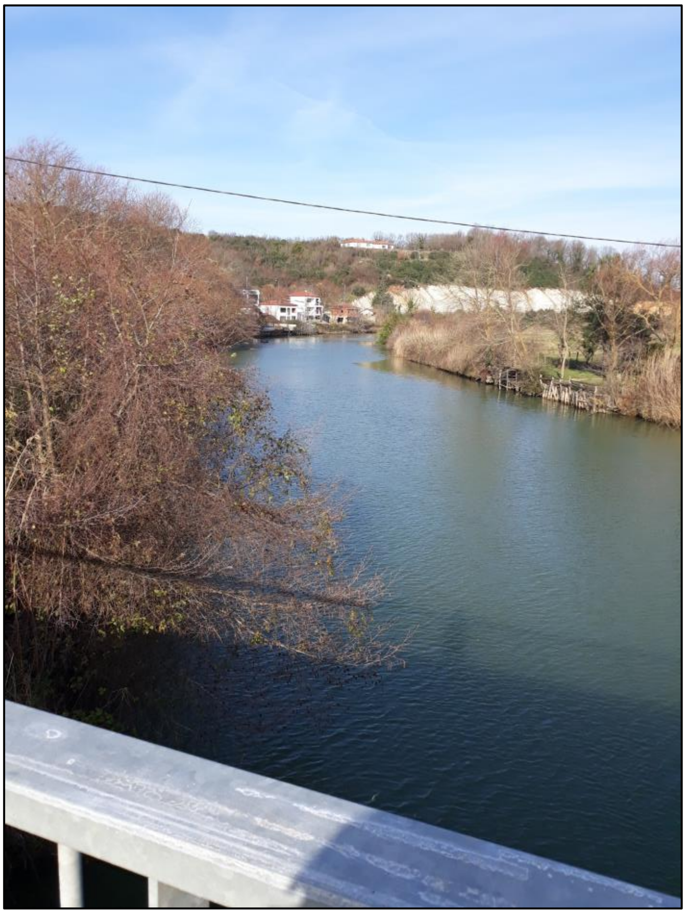


Figure 3.4: Sungurlu River

For the other areas, Sentinel-2 Land Cover data gave land use data in 5 different categories for the study area (Figure 3.5). In Table 3-3, these categories and determined roughness values according to State Water Works (DSİ) especially for the region determined as a result of more than 60 years of observation and with average values of several studies.

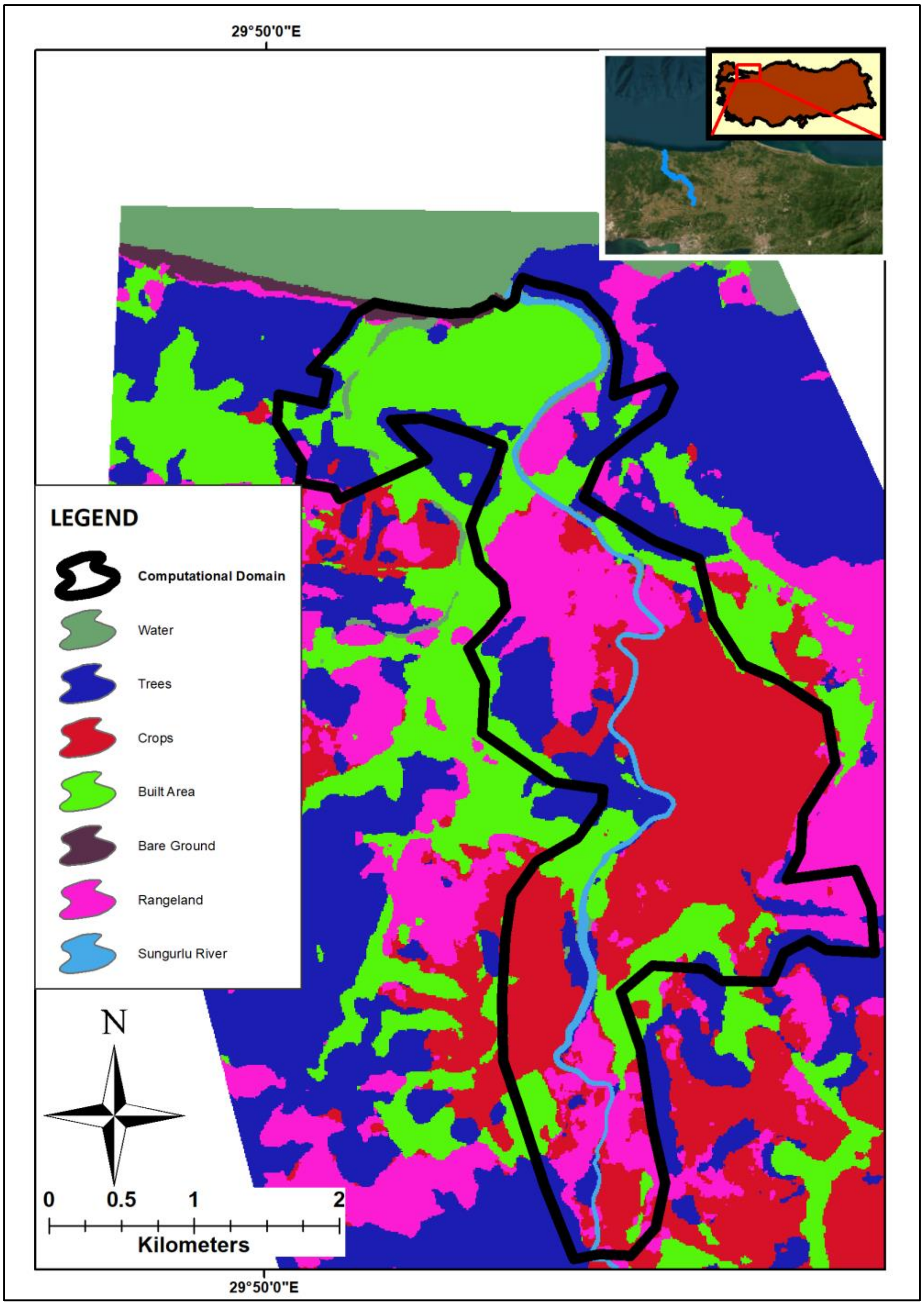


Figure 3.5: Land use layer created from Sentinel-2 land use data

Table 3-3: Variation of surface roughness with respect to land cover for the computational domain [40], [41]

Class Name	Description	Manning Coefficient
Water	Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built-up features like docks.	0.04
Trees	Any significant clustering of tall (~15-m or higher) dense vegetation, typically with a closed or dense canopy.	0.1
Crops	Human planted/plotted cereals, grasses, and crops not at tree height.	0.03
Built Area	Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing.	0.02
Bare Ground	Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation.	0.035
Rangeland	Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses, a mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within forests that	0.035

Another kind of land use data is used to determine economic and social impact assessment for this study in Ağva Town. This data includes building polygons with its purpose of use (residential, commercial, cultural objects etc.) and the location of the roads. Also, building polygons obtained from this data were used in modeling procedure of the urbanized area (see Chapter 3.5).

For multi-criteria analysis, a monetary value is assigned according to the method explained in Chapter 3.8.1, and each polygon that has residential use has assumed to have certain number of residents. Details of this assumption are given in Chapter 3.8.2. This data was obtained from the Republic of Türkiye Ministry of Environment, Urbanization and Climate Change. Figure 3.6 represents this data.

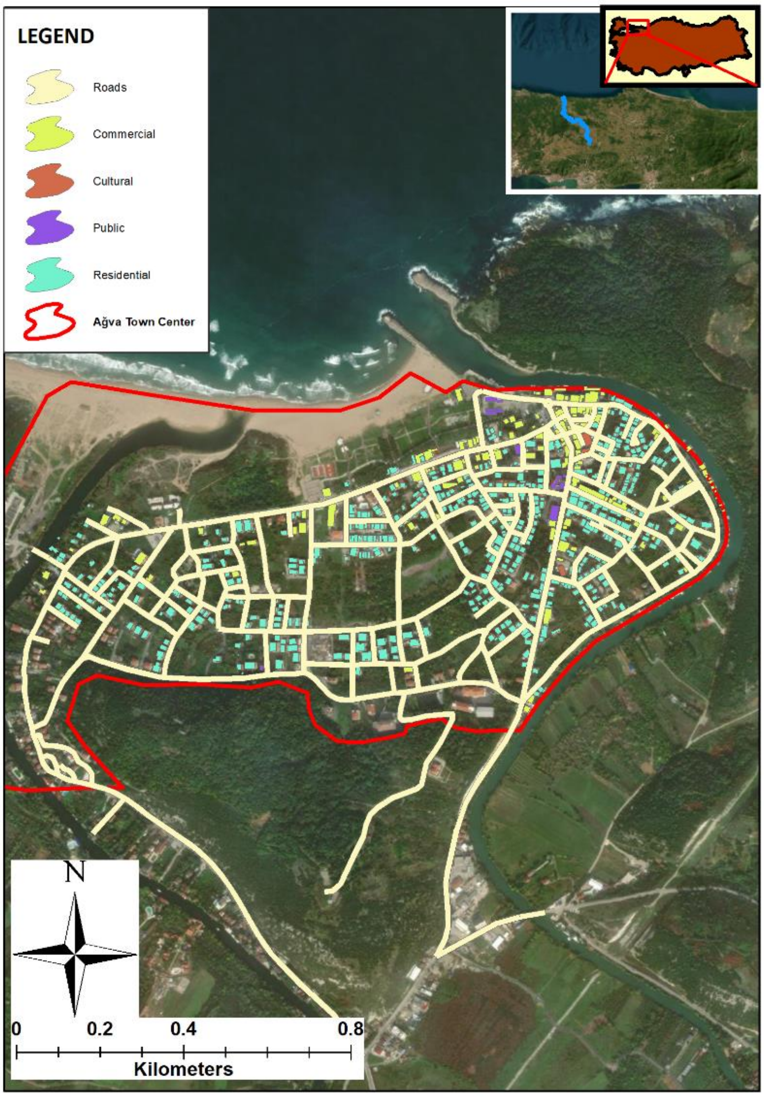


Figure 3.6: Building and road polygons that used in MCA

3.4. Governing Equations in 2D Hydraulic Flood Modelling

Fluid motion is described by Navier Stoke's equations. If the vertical disturbances are small compared to the horizontal ones, then the fluid flow can be described by depth-averaged shallow water equations which can be summarized as follows [42];

$$\frac{\partial \mathrm{h}}{\partial \mathrm{t}}+\frac{\partial(\mathrm{hu})}{\partial \mathrm{x}}+\frac{\partial(\mathrm{hv})}{\partial \mathrm{y}}=\mathrm{q} \tag{1}$$

$$\frac{\partial \mathrm{u}}{\partial \mathrm{t}}+\mathrm{u}\frac{\partial \mathrm{u}}{\partial \mathrm{x}}+\mathrm{v}\frac{\partial \mathrm{u}}{\partial \mathrm{y}}-f_c\mathrm{v}+\mathrm{g}\frac{\partial Z_s}{\partial \mathrm{x}}-\frac{1}{h}\frac{\partial}{\partial \mathrm{x}}\left(\upsilon_{t,xx}\mathrm{h}\frac{\partial \mathrm{u}}{\partial \mathrm{x}}\right)-\frac{1}{h}\frac{\partial}{\partial \mathrm{y}}\left(\upsilon_{t,yy}\mathrm{h}\frac{\partial \mathrm{u}}{\partial \mathrm{y}}\right)=\frac{\tau_{b,x}}{\rho R}+\frac{\tau_{s,x}}{\rho h} \tag{2}$$

$$\frac{\partial \mathrm{v}}{\partial \mathrm{t}}+\mathrm{u}\frac{\partial \mathrm{v}}{\partial \mathrm{x}}+\mathrm{v}\frac{\partial \mathrm{v}}{\partial \mathrm{y}}-f_c\mathrm{u}+\mathrm{g}\frac{\partial Z_s}{\partial \mathrm{y}}-\frac{1}{h}\frac{\partial}{\partial \mathrm{x}}\left(\upsilon_{t,xx}\mathrm{h}\frac{\partial \mathrm{v}}{\partial \mathrm{x}}\right)-\frac{1}{h}\frac{\partial}{\partial \mathrm{y}}\left(\upsilon_{t,yy}\mathrm{h}\frac{\partial \mathrm{v}}{\partial \mathrm{y}}\right)=\frac{\tau_{b,y}}{\rho R}+\frac{\tau_{s,y}}{\rho h} \tag{3}$$

where u and v are the velocities in the x and y coordinates, g is the gravitational acceleration, Z_s is the water surface elevation, $\upsilon_{t,xx}$ is the horizontal eddy viscosity, $\tau_{b,x}$ is the bottom shear stress, R is the hydraulic radius, $\tau_{s,x}$ is the wind stresses, h is the water depth, and f_c is the Coriolis parameter.

It should be noted that diffusion wave approximation of shallow water equations can be preferred if the flow is dominated by gravity and frictional forces (i.e. gradually varied flow). However, throughout this study, shallow water equations are considered as governing equations of fluid flow because of long and meandering river beds and time-dependent high amounts of discharges.

3.5. 2D Flood Modelling Procedure

For 2D flood modeling of HEC-RAS 6.3.1 software, the input data should be preprocessed to be compatible and accepted by the software. For preprocessing procedures, ArcGIS 10.7 GIS software was used. The first step is the determination of the needs of the software to be able to analyze. These requirements are the preparation of the DEM file in raster format, 2D computational domain in shapefile format, 2D roughness layer in raster format, and introduction of the boundary conditions to the software.

For the preparation of the DEM terrain, the input file is already prepared in “.tif” raster format. Although DEM represents the terrain, it does not include buildings. Buildings are represented in polygon shapefile. The height of the buildings was assigned to the building polygons. Buildings were added to the DEM in GIS and introduced to HEC-RAS as terrain. The buildings of Ağva town can be seen in the northern part of Figure 3.7.

HEC-RAS requires a 2D domain as a polygon shapefile. The 2D domain perimeter had been determined as the inundation area should not touch the boundaries (except where the outlet boundary condition is located). It is important to have realistic results without bouncing the water to the borders of the 2D domain. Also, any part of the 2D domain should not be outside the terrain DEM data. The determined 2D perimeter is shown in Figure 3.7.

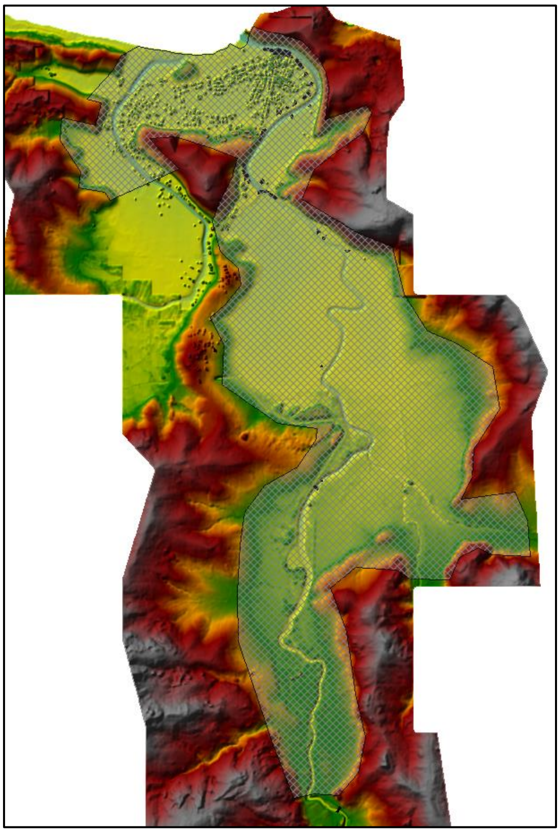
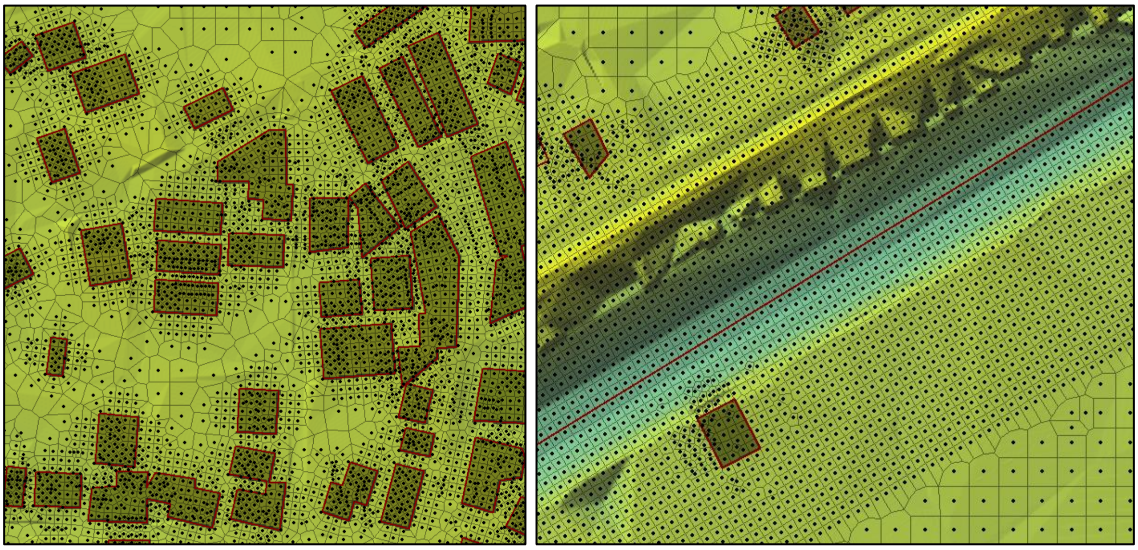


Figure 3.7 Determined computational 2D domain for the model. In the northern part, buildings of Ağva town could be seen

After this step, the already prepared roughness layer mentioned in Section 3.3.3 was introduced into the model and Manning coefficients were assigned for each category.

The elevation values of the buildings are available in building polygon data and superposed into the DEM layer. This creates abrupt changes in the DEM, which could lead to mistakes in the computational domain created by meshes. To eliminate this error, a shapefile that includes the buildings is introduced to HEC-RAS as breaklines. Also, the thalweg of the river is introduced as breaklines to represent the river in more detail. These representations could be seen in Figure 3.8.



(a) (b)

Figure 3.8 (a) Buildings were defined with DEM modification and breaklines. (b) Breakline inside the river to make meshes perpendicular and more detailed inside the river.

These procedures explained until now made the creation of mesh possible. In the model, it observed the elevation values of the possible inundated area between 0 to 10 meters. Therefore, mesh size was determined as 8 meters if the area is not affected by breaklines. Spacings through breaklines for buildings and inside the river were 3 meters, and these values are sufficient to represent every detail of the real-world conditions for a model of that size.

Also, the domain should include the structures such as bridges and culverts. These structures were introduced into the model by using 2D connection feature of HEC-RAS. The model includes 4 structures, and the data of these were obtained from a field survey.

For the north side of the model, Black Sea should be the outlet boundary condition. Thus, the sea outlet is defined as outlet boundary condition. Inflow boundary conditions were obtained from a hydrological study. The hydrological boundary conditions were introduced in the model as “Flow Hydrograph” option.

After the procedure explained above, the model is ready to run. 1 second time step was determined to be used after a trial-and-error procedure. Greater and lower time steps were tried for the model, but greater and lower time steps than 1 second resulted in stability problems. Also, the solving method was selected as SWE-ELM (original/faster).

3.6. Flood Hazard Calculation and Quantification

After obtaining the flood depth and velocity data from the hydraulic modeling, the determination of the flood hazard is important to decide both structural and non-structural measures as results indicate the locations where the hazard risk is severe. In the literature, there are several methods to quantify flood hazards. According to the study of Smith et al. [43], flood hazard could be determined by the multiplication of water depth and velocity. Spatially distributed flood depth and velocity data are obtained from the model outputs and this enables the creation of flood hazard mapping for the study area in six hazard classes. Flood hazard classes determined by this study are given in Table 3-4 and Figure 3.9. This method is selected for flood hazard assessment in this study since this method validated the hazard by considering the stability of people, vehicles, and structures with real data. Also, Yılmaz et al. (2022) implemented a proposed methodology for the historical event in Barsem, Tajikistan and it was found that assessment of flood hazard even if the flow is non-newtonian gives reliable results [44].

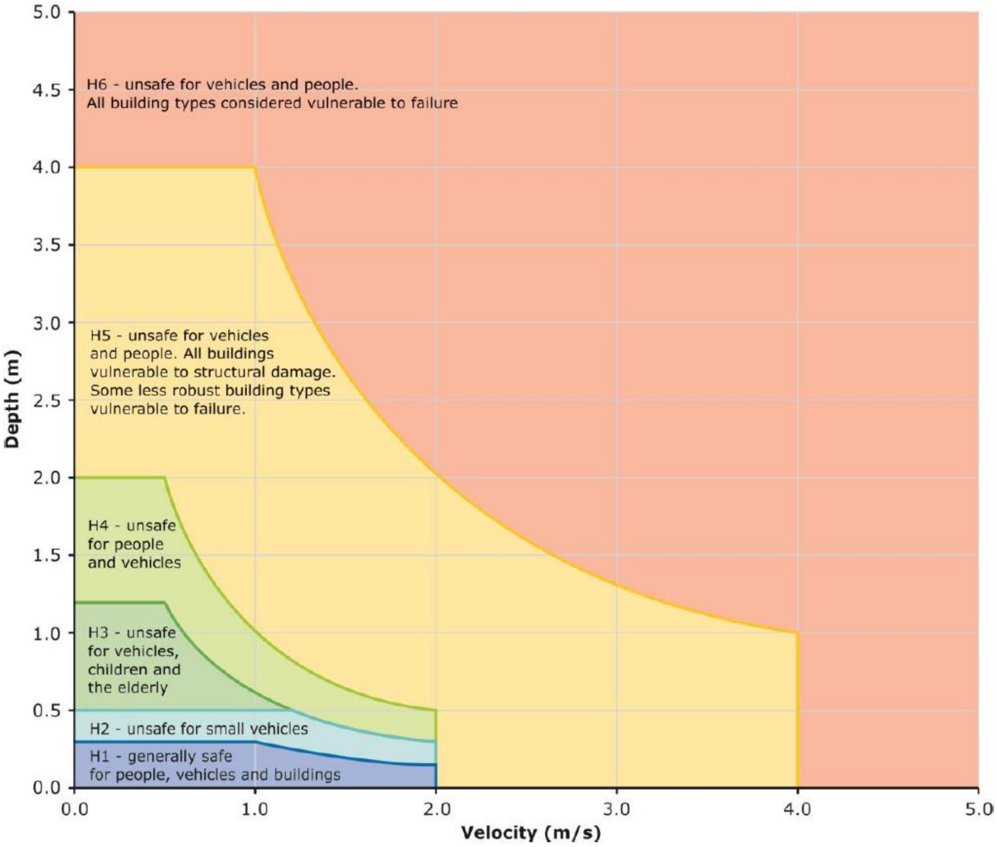


Figure 3.9: Flood Hazard Curves [43]

Table 3-4: Flood Hazard Curves - Vulnerability Thresholds [43]

Hazard Classes	**Description**	**Limiting V (m/s)**	**Limiting D (m)**	**Classification Limit (m^2/s)**
H1	Generally safe for vehicles, people and building	2	0.3	D*V ≤ 0.3
H2	Unsafe for small vehicles	2	0.5	D*V ≤ 0.6
H3	Unsafe for vehicles, children and the elderly	2	1.2	D*V ≤ 0.6
H4	Unsafe for vehicles and people	2	2	D*V ≤ 1
H5	Unsafe for vehicles and people. All buildings vulnerable to structural damage.	4	4	D*V ≤ 4
H6	Unsafe for vehicles and people. All building vulnerable to failure	-	-	D*V ≥ 4

3.7. Determination of Flood Risk Mitigation Measures

After the preparation of flood hazard maps, high-hazard zones are determined. The aim of having measures against flooding is to reduce the possible damage due to flood events. In this study, NBS measures are considered instead of grey infrastructures to protect against ecological and socially harmful impacts that could be emerged from grey infrastructures. A good measure should have these features listed below. A measure should:

- protect or enhance biodiversity by not creating impervious layers,
- solve the problem of flooding for design discharges,
- be compatible with climate change adaptation,
- be efficient and selected from a variety of alternatives,
- compatible with EU Flood Directive and local directives,
- not have a harmful social impact on the population living in the area.

When selecting the measures to accomplish these prerequisites listed above for the study area, several measures were used to solve the flooding problem. These measures are summarized in Table 3-5.

Table 3-5: Designed measures to solve the flooding problem in Ağva Town

Measure Number	Measure
1	Increase the height of the road next to Sungurlu River in Ağva town
2	Detention Basin designed upstream

The alternatives given in Table 3-6 were applied to the hydraulic model with the procedure of hydraulic modeling and flood hazard assessment was repeated for each alternative.

Table 3-6: Flood measure assessment alternatives

Alternative Number	Alternative
1	(1)
2	(2)
3	(1) + (2)

The reasons why these measures were selected are explained in Chapter 4.

3.8. Multi-Criteria Analysis for Selection of the Most Suitable Alternative

In the next step after the selection of probable measures and alternatives, the best alternative for the project implementers should be selected. This selection should include economic, ecological, and social assessments, and other criteria if the necessary data is available for further assessment. As mentioned in Chapter 2.6, there are several MCA methods to decide the most suitable alternative for a specific region.

In this study, economic data is available for damage which allows for cost-benefit analysis (CBA). Also, population data is distributed to residential polygons to get a rough estimate of the affected population from flood events. Social impacts are determined as an increase in life quality by creating recreational areas and this assessment couldn’t be carried out quantitatively. Even though the exact impact is unknown, this assessment is converted into negative/neutral/positive classification. Cultural objects are assessed as separate and if it is flooded, then the measure was considered as ineffective for cultural impacts. Flood risk on public institutions was assessed the same as cultural objects, however damage to public institutions has both economic and socially harmful impacts. If a public instuition such as a school, hospital and emergency services take place, these services stop for a certain period with economic damage. By considering the data type available, the weighted summation method is suitable for this study. The reason is data is in quantitative form, this method retains high level of transparency, simple to apply and has a low cost.

In Table 3-7, the summary table of applied methodology for MCA is given.

Table 3-7: Summary of proposed MCA for social, economic, and environmental assessment

<table>
<tr><th colspan="2">Criteria</th><th rowspan="2">Unit</th><th colspan="5" rowspan="2">Quality and Score (0-100)</th><th rowspan="2">Score type</th></tr>
<tr><th>Main Criteria</th><th>Sub-Criteria</th></tr>
<tr><td rowspan="3">Social Impact</td><td>Health and Safety</td><td>%</td><td>≥80 (100)</td><td>≥65-80< (75)</td><td>≥50-65< (50)</td><td>≥40-50< (25)</td><td><40 (0)</td><td>Add</td></tr>
<tr><td>Improvement in social life</td><td>-</td><td>Positive impact on society (100)</td><td colspan="2">Neutral impact on society (50)</td><td colspan="2">Negative impact on society (0)</td><td>Add</td></tr>
<tr><td>Cultural Impact</td><td>-</td><td>Full protection for cultural items (100)</td><td colspan="2">Partial protection for cultural items (50)</td><td colspan="2">No protection for cultural items (0)</td><td>Add</td></tr>
<tr><td rowspan="2">Economic Impacts</td><td>Measure Benefit/cost ratio</td><td>-</td><td>≥2 (100)</td><td colspan="2">≥1–2< (50)</td><td colspan="2">1< (0)</td><td>Add</td></tr>
<tr><td>Measure Cost</td><td>M€</td><td colspan="2"><1 (Max)</td><td colspan="3">>=1 (1.00)</td><td>Multiply</td></tr>
<tr><td>Social and Economic Impacts</td><td>Reduction of Flood Risk on Public Institutions</td><td>-</td><td>Full protection for public institutions (100)</td><td colspan="2">Partial protection for public institutions (50)</td><td colspan="2">No protection for public institutions (0)</td><td>Add</td></tr>
<tr><td>Environment Impact</td><td>Improvement in biodiversity</td><td>-</td><td>Positive impact on biodiversity (100)</td><td colspan="2">Neutral impact on biodiversity (50)</td><td colspan="2">Negative impact on biodiversity (0)</td><td>Add</td></tr>
</table>

MCA score was calculated with the formula given below:

$$MCAS = (SAS + EAS + SEIS + ENAS) \tag{4}$$

Where MCAS is the MCA score, SAS is the social assessment score, EAS is the economic assessment score, SEIS is the social and economic impact score, and ENAS is the environmental assessment score.

The weights of each item in MCA depends on the objectives of the country, institutional capacity and opinion of public, decision-makers and project implementers. For flood risk management plans, the weights of the MCA should be decided after a public consultation process. Data should be collected through questionnaires and meetings with project beneficiaries.

Since there is no data exist for the study area, actual weights for the study area are uncertain. Therefore, three weight options were used in this study. In Table 3-8, the weights of the three options were given. Option 1 gives priority to a decrease in social impact. Option 2 gives equal priority to social, economic, and environmental risk degradation and Option 3 is giving priority to economic risk mitigation.

Table 3-8: The change of scoring for the various weighted condition of criteria

Criteria		**Score Range**		**Max- weighted scoring**		
Main Criteria	**Sub-Criteria**	**Min**	**Max**	**Option 1**	**Option 2**	**Option 3**
Social Impact	Health and Safety	0	100	0.3	0.1	0.13
	Improvement in Social Life	0	100	0.05	0.07	0.05
	Cultural Impact	0	100	0.05	0.05	0.05
	Total for SAS			**0.4**	**0.22**	**0.23**
Economic Impact	Measure Benefit/cost ratio	0	100	0.3	0.18	0.4
	Measure Cost	1	1.3	1.3	1.3	1.3
	Total for EAS			**0.39**	**0.23**	**0.52**
Social and Economic Impact	Risk on Public Institutions	0	100	0.1	0.22	0.1
	Total for SEIS			**0.1**	**0.22**	**0.1**
Environment Impact	Improvement in biodiversity	0	100	0.11	0.33	0.15
	Total for ENAS			0.11	0.33	0.15
Total for MCAS				**1.00**	**1.00**	**1.00**

3.8.1. Economic Assessment

The formula can compute the ratio of benefit over cost as:

$$BC = \frac{EAD_b - EAD_a}{EAC} \tag{5}$$

where BC is benefit-cost ratio, EAC is the expected annual cost, EAD is the expected annual damage and a and b are the symbols before and after the measure implementation. The expected annual damage of floods is computed from the following formula:

$$EAD = \int_0^1 D(p)dp \tag{6}$$

Where $D(p)$ is the damage monetary value in the exceedance probability of p. p is calculated as the risk of the flood event with T return period of the flood as the following formula:

$$p = \frac{1}{\mathrm{T}} \tag{7}$$

In practice, only limited return periods are used for annual expected damage calculation. The exceedance probability is calculated for 10, 100, 500, and 1000-years floods in this project. In Table 3-9, p is the difference of sequential exceedance probability between one and zero.

Table 3-9 Probability exceedance for flood risk

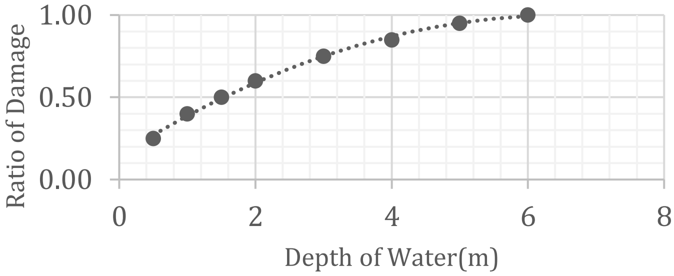
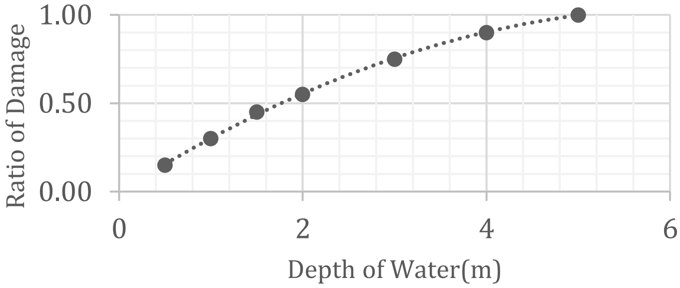
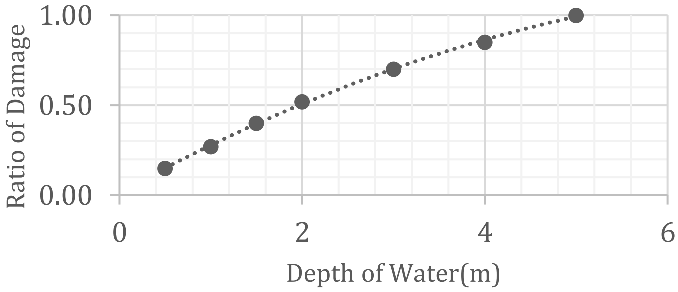
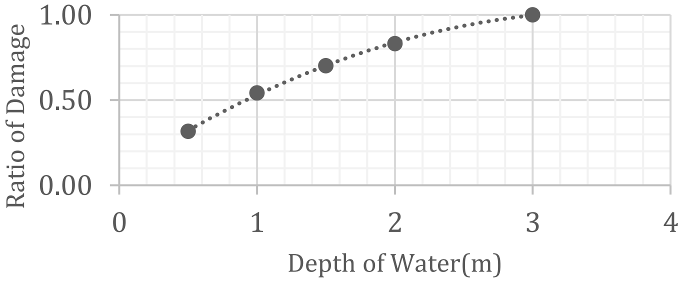
T (Years)	**p**
10	0.100
100	0.010
500	0.002
1000	0.001

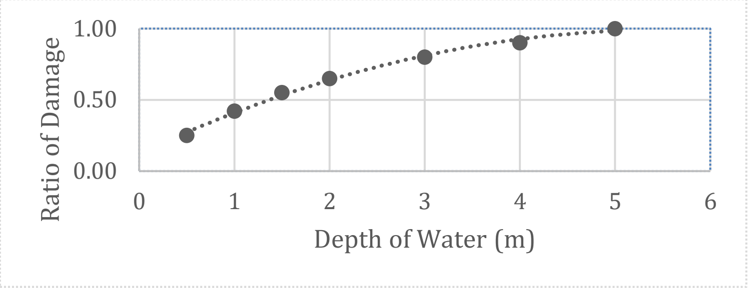
Determination of direct flood damage for a specific return period T or p ($D(p)$) is commonly done using depth-damage curves as the following equation:

$$R = \frac{D(p)}{Dmax} = f(h(p)) \tag{8}$$

Where $Dmax$ is the maximum damage on the object, R is the coefficient of damage, and $h(p)$ is the depth of flow in the object affected by the flood with an exceedance probability of p. Because of the lack of locally observed data about the depth-damage function for the study area, a global dataset from EU Commission ***Joint Research Centre*** (**JRC**) [45] contains the curves and maximum damage values for various assets and land use classes is used here. The categories of economic damage include residential facilities (houses and apartment buildings), industrial facilities, transportation, infrastructure, and agricultural areas. The ratio of depth-damage is extracted from the dataset for European countries and used the best-fitted function as shown in Table 3-10. Additionally, the unit price of various economic classes is extracted for Türkiye and presented in Table 3-11 from the same global dataset. All the unit prices represented in the dataset are from 2010. Therefore, data is projected to 2022 by using consumer price index inflation obtained from World Bank and European Central Bank databases [46].

Table 3-10 Depth-Damage Ratio Curves for Assets in European Countries [45]

Assets Type	**Depth-Damage Ratio Function Curve**
Residential buildings $R = -0.0201h^2 + 0.2617h + 0.1447$ For h>6 m R=1 h: Depth of water(m)	
Commercial buildings $R = -0.0263h^2 + 0.3319h - 0.0041$ For h>4 m R=1 h: Depth of water(m)	
Industrial buildings $R = -0.0167h^2 + 0.2787h + 0.0158$ For h>5 m R=1 h: Depth of water(m)	
Transportation $R = -0.0734h^2 + 0.5273h + 0.0769$ For h>3 m R=1 h: Depth of water(m)	

Assets Type	**Depth-Damage Ratio Function Curve**
Infrastructure R = $-0.0286h^2 + 0.3154h + 0.1219$ For h>5 m R=1 h: Depth of water(m)	

Since there is no agricultural area exists within the Ağva Town center, and the only aim of this study is eliminating flood risk in the populated area, the agricultural function was not given in Table 3-10.

Table 3-11 Unit Price for economic damage categories

	Max Damage Structure	**Max Damage Content**	**Total**
	€/m^2, 2010, projected to 2022	**€/m^2, 2010, projected to 2022**	**€/m^2, 2010, projected to 2022**
Residential	202.8	101.4	304.2
Commercial	219.3	219.3	438.6
Industrial	148.9	223.3	372.2
Transportation	218.2	-	218.2
Infrastructure	7.26	-	7.26

Unit prices for public institutions could not be calculated because of the range variety of properties in these structures. Therefore, the number of affected public institutions was considered in the MCA methodology of this study.

Expected annual cost (EAC) is calculated by dividing the cost of the measure by the service life of the measures proposed in the alternative [47].

$$EAC = \frac{C}{N} \tag{9}$$

Where C is the cost of the measures, and N is the service life of the measures proposed in the alternative.

After obtaining the BC for a specific alternative, this value should be normalized to be compatible with MCA methodology. If an alternative has BC value higher than 2, this alternative was considered highly profitable, so it gets 100 points from BC criterion of the MCA. If the BC is in between 1 and 2, it gets 50, and below 1 value is an infeasible alternative from an economical point of view, thus zero points were given to these alternatives.

The cost of the flood control measure is affecting its implementation period and allocates the budget of institutions that will fund the measure. Even though the benefit/cost ratio is high for a measure, its implementation could take a long time. Also, it leads to delays in other critical flood measures to be taken because of lack of budget or institutional capacity. Therefore, in the MCA procedure, this criterion should be considered, especially for countries that have a limited budget for flood control measures. For alternatives with a cost over 1 million Euros, the multiplication factor for the economic assessment of MCA is given as the maximum. If the alternative cost is over that threshold, the multiplication factor was set as 1.

Economic assessment score (SAS) can be calculated from the formula below:

$$EAS = \mathrm{W_{BC}} * \mathrm{W_{MC}} * (BCS) * (MCS) \tag{10}$$

where $\mathrm{W_{BC}}$ is the weight for BC ratio, BCS is the benefit/cost score, $\mathrm{W_{MC}}$ is the measure cost weight and MCS is the measure cost score.

3.8.2. Social Assessment

Health and safety of people include impacts such as risk to life or serious injury, stress, anxiety (mental health and livelihood) and other health effects [37]. Reduction of risk on inhabitants is an important criterion of MCA since it represents impacts on social and economic damage as well as the health of inhabitants where flood event is happens. Even though it could be converted into monetary values some of the regions have enough data, in Türkiye it is uncertain to assess a monetary value per person affected by floods because of the lack of data. Hazard classes could be useful to determine whether the people in the flooded area are affected or not, since every flooded region is not necessarily able to affect health and safety if it has a low hazard class. In this study, if the hazard class is equal or greater than H2, then the population in this region is considered risky from the health and safety criterion.

For each alternative for flood risk mitigation, the reduction ratio of flood risk on people for each flood discharge is calculated with a similar methodology as EAD calculation.

The formula can compute the ratio of alternative effectiveness of reduction of risk on the people (RRP) as:

$$RRP = \frac{\int_0^1 A_b(p)dp - \int_0^1 A_a(p)dp}{\int_0^1 A_b(p)dp} \tag{11}$$

where $A(p)$ is the number of people at risk in the exceedance probability of p and a and b are the symbol before and after the measure implementation.

p is calculated as the risk of the flood event with T return period of the flood according to Equation 7. p is determined according to Table 3-9.

The value of RRP value is converted to “Health and Safety (HS)” criterion of MCA according to the classification given in Table 3-12.

Table 3-12: Conversion of RRP score to HS

RRP			
Upper limit	Lower Limit	Classification	HS
1	0.8	Very High Efficiency	100
0.8	0.65	High Efficiency	75
0.65	0.5	Moderate Efficiency	50
0.5	0.4	Low Efficiency	25
0.4	0	Not Efficient	0

For social assessment, one non-quantitative and one quantitative MCA criteria were defined in addition to the quantitative value of RRP. One of them is the improvement in the quality of life of residents and tourists by creating new recreational zones with flood measures. This criterion cannot be assessed quantitatively, therefore scoring of this criterion is converted into positive, neutral, and negative impact which 100, 50, and 0 points were given to improvement in social life score (ISLS), respectively. The second one is the protection of cultural items such as historical places, religious facilities, etc. Monetary value could not be assessed for these structures and damage to these structures was evaluated as several items prevented from flood risk. If flood risk on cultural items was prevented, a 100 score was given to the cultural impact score (CIS). 50 score was given to partially effective alternatives, and if the alternative is ineffective on flood risk for cultural items, then this alternative gets a zero score.

The social assessment score was computed with the following formula:

$$SAS = \mathrm{W_{HS}} * (HS) + \mathrm{W_{ISLS}} * (ISLS) + \mathrm{W_{CIS}} * (CIS) \tag{12}$$

Where W_{RRP} is the weight of reduction of risk on the people score, W_{ISLS} is the weight of improvement in social life score, W_{CIS} is the weight of cultural impact score.

For the analysis in this study, because of the lack of data about the number of residents living in a certain building, population data of Ağva Town is distributed to the residential polygons. In this method, areas of the polygons, a number of floors of the residential buildings were considered. The formulation given below was applied to every residential building polygon.

$$n_{res,i} = \frac{\mathrm{A_i} * \mathrm{F_i}}{\sum_{i=0}^{i=t} A_i * F_i} * N \tag{13}$$

Where n_{res} is the number of people living in residential buildings, $\mathrm{A_i}$ is the area of the building polygon, $\mathrm{F_i}$ is number of floors of the building polygon, t is the total number of building polygons and N is the total population of the urbanized area represented with polygons.

3.8.3. Social and Economic Assessment

Flood risk on public institutions were taken into account as both economic and social impact since the services given by school, hospital and emergency services have probability to be interrupted by flood. When the population cannot reach these services, especially health and safety services, could lead to an increase in a number of people affected by flooding. Also, the economic damage that emerged from flooding could be high regarding other properties because of probable expensive properties in use in these kinds of facilities.

The social and economic impact score was computed with the following formula:

$$SEIS = \mathrm{W_{SEIS}} * (RPIS) \tag{14}$$

Where W_{RPI} is the weight of reduction of risk on public institutions, and RPIS is score of risk on public institutions.

RPIS is given 100 score if the damage to public institutions was prevented totally. If an alternative has partial prevention from flood risk, then it takes a score of 50 and gets zero if there is no prevention.

3.8.4. Environmental Assessment

Besides economic and social criteria, environmental impacts are important when assessing flood risk mitigation measures. Increase in biodiversity could be provided by creation of new wetlands and this could feed the groundwater. Probable positive impacts of flood control measures were mentioned in Chapter 2.5. The aim of NBS is to increase environmental benefits as well as flood risk.

In this study, the retention basin measure was assumed to have positive impact on the environment since this measure creates new wet areas and recreational zone where this land wasn't used and classified as rangeland. The proposed gray measure was considered as no impact on the environment as this measure is relatively small measure that has 120 meter long of renovation of the road and increasing the height of the road.

As in social assessment, this evaluation could not be done quantitatively. Therefore, if an alternative has positive/neutral/negative impacts on the environment, gets 100/50/0 points respectively.

The environmental impact score was computed with the following formula:

$$ENAS = \mathrm{W_{ENAS}} * (EIS) \tag{15}$$

Where ENAS is the environmental assessment score, $\mathrm{W_{ENAS}}$ is the weight of environmental assessment and EIS is the environmental impact score.

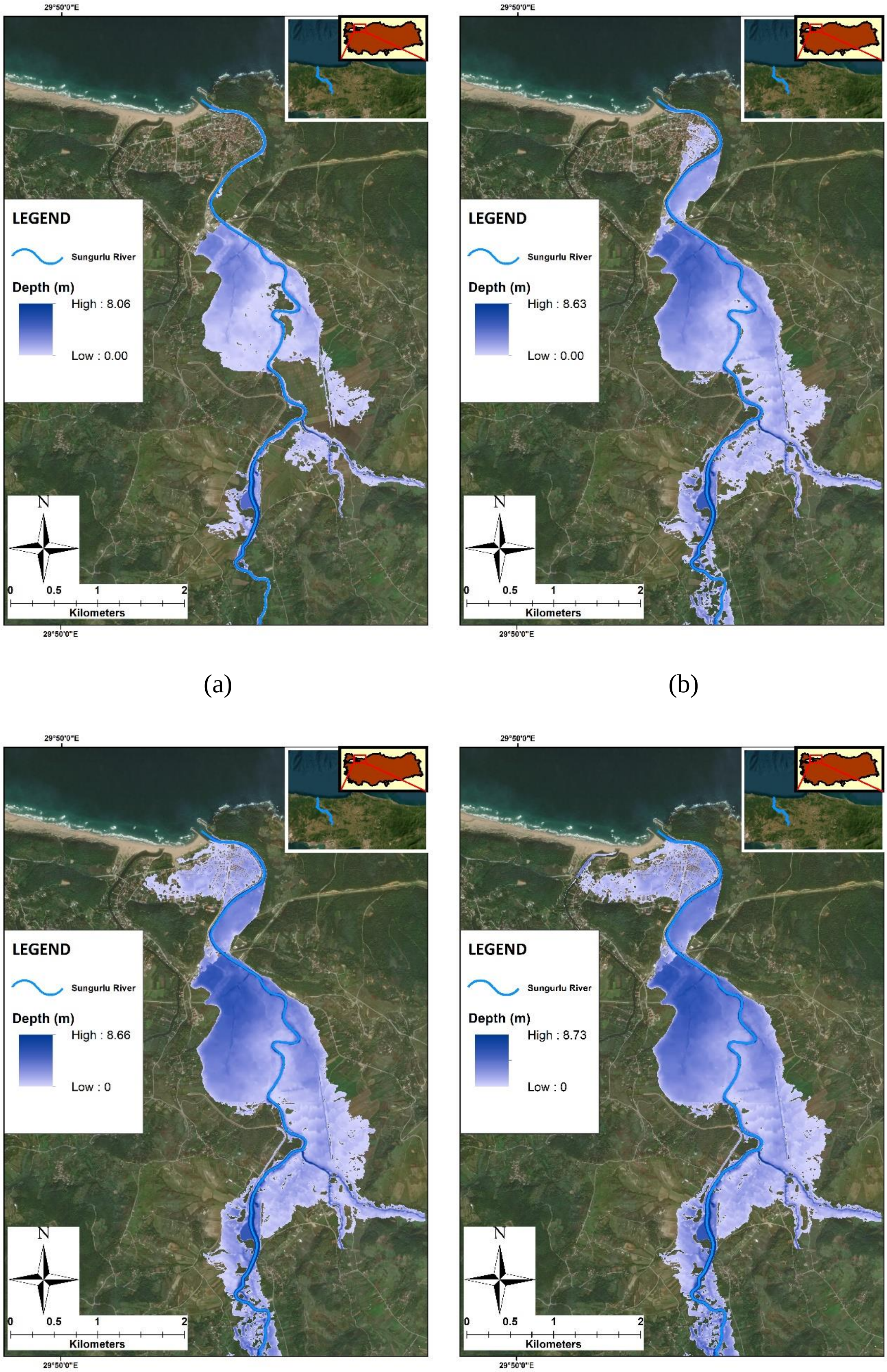
4. RESULTS AND DISCUSSION

4.1. Flood Modeling and Creation of Flood Mapping

The methodology explained in Chapter 3 was carried out for hydraulic modeling for the study area. The model includes 313071 meshes with average 32.22 m^2 cell area. Inside the river, breaklines has 2-meter mesh spacing and for near the building polygons, 3-meter mesh spacing was used in the model. The computer that the model is ran has Ryzen 5 5600H (6 core, 3.3 GHz), 8 GB of RAM and NVIDIA RTX 3050 GPU. Even though the runtime changes by discharges and alternatives, the runtime of 1000-year frequency flood event in existing condition is 7 hours 33 minutes and 29 seconds.

As the first step, the current situation regarding flood risk was examined. According to the results, for 10-year frequency discharge, it could be seen that there is no flood risk for the urban area. According to the flood modelling results, after 100-year frequency, the urbanized area is under flood risk. Maximum water depth, velocity, and hazard maps of flood events could be seen in Figure 4.1, Figure 4.2, and Figure 4.3 , respectively.

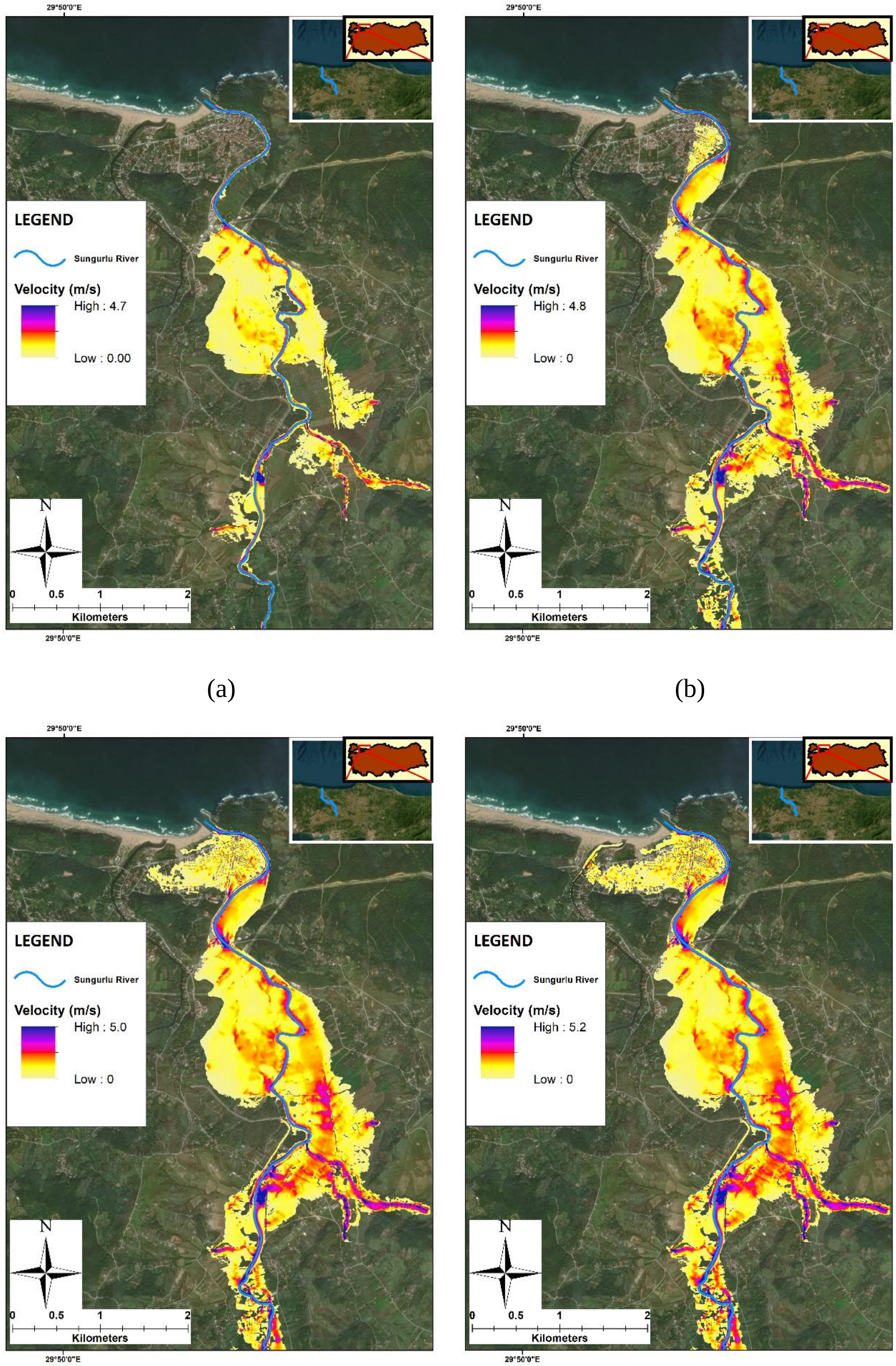
Hazard maps created for four discharges demonstrated that the urbanized area is in flood hazard risk for more than 100-year frequency (Q_{100}) flood events. Even though the hazard level for the Q_{100} event is not so significant as Q_{500} and Q_{1000} events, in some parts there is an H3 hazard level, and this could lead to casualties for children and give damage the properties. For Q_{500} and Q_{1000} events, a significant part of the city has H3, H4, and H5 flood hazard levels, which means even structural damage to buildings is possible and casualties from flood events are quite probable.



(a) (b)

(c) (d)

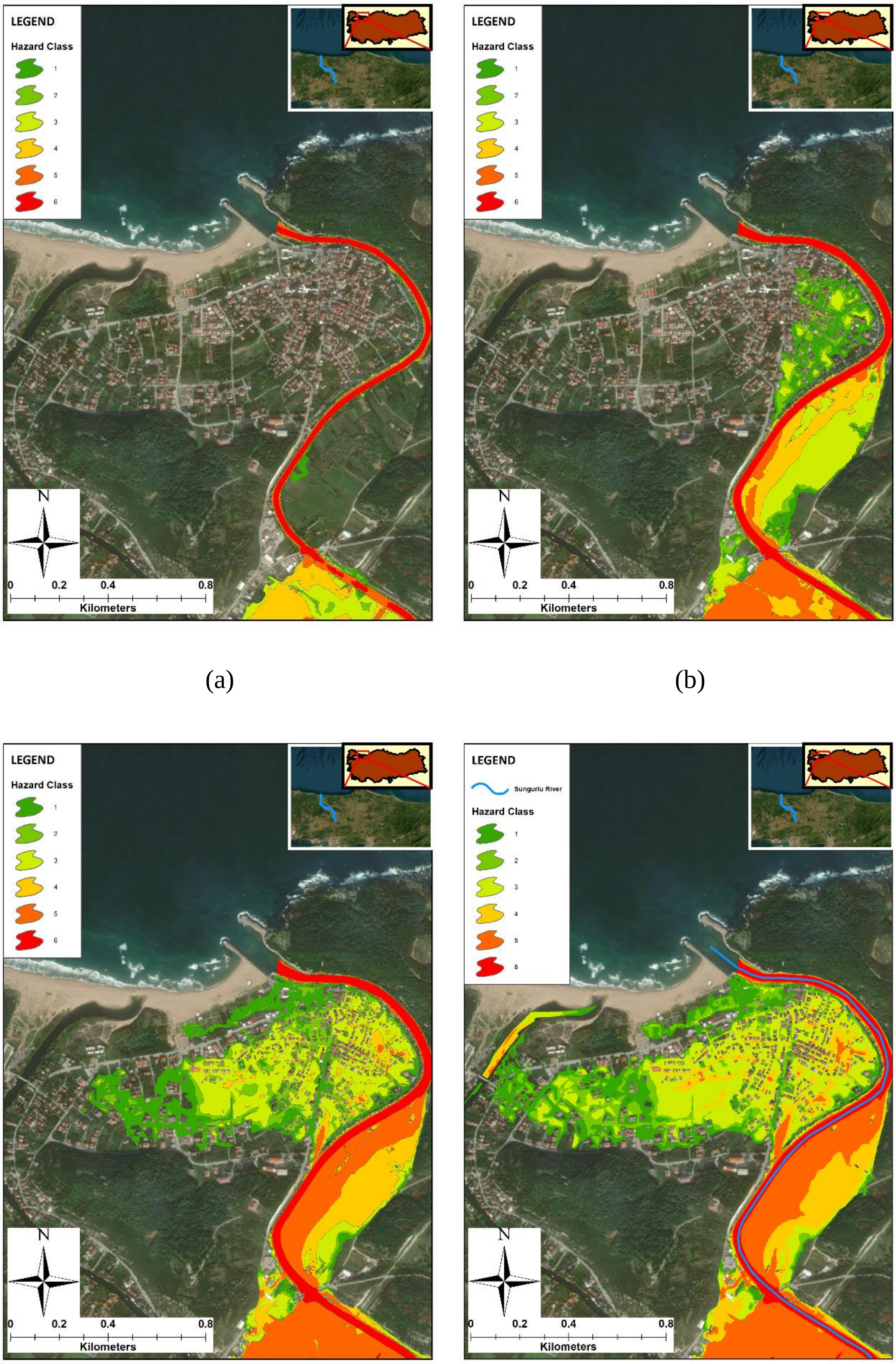
Figure 4.1 Maximum flow depth for (a) 10, (b) 100, (c) 500 and (d) 1000-year frequency flood events



(a) (b)

(c) (d)

Figure 4.2 Maximum flow velocity for (a) 10, (b) 100, (c) 500 and (d) 1000-year frequency flood events



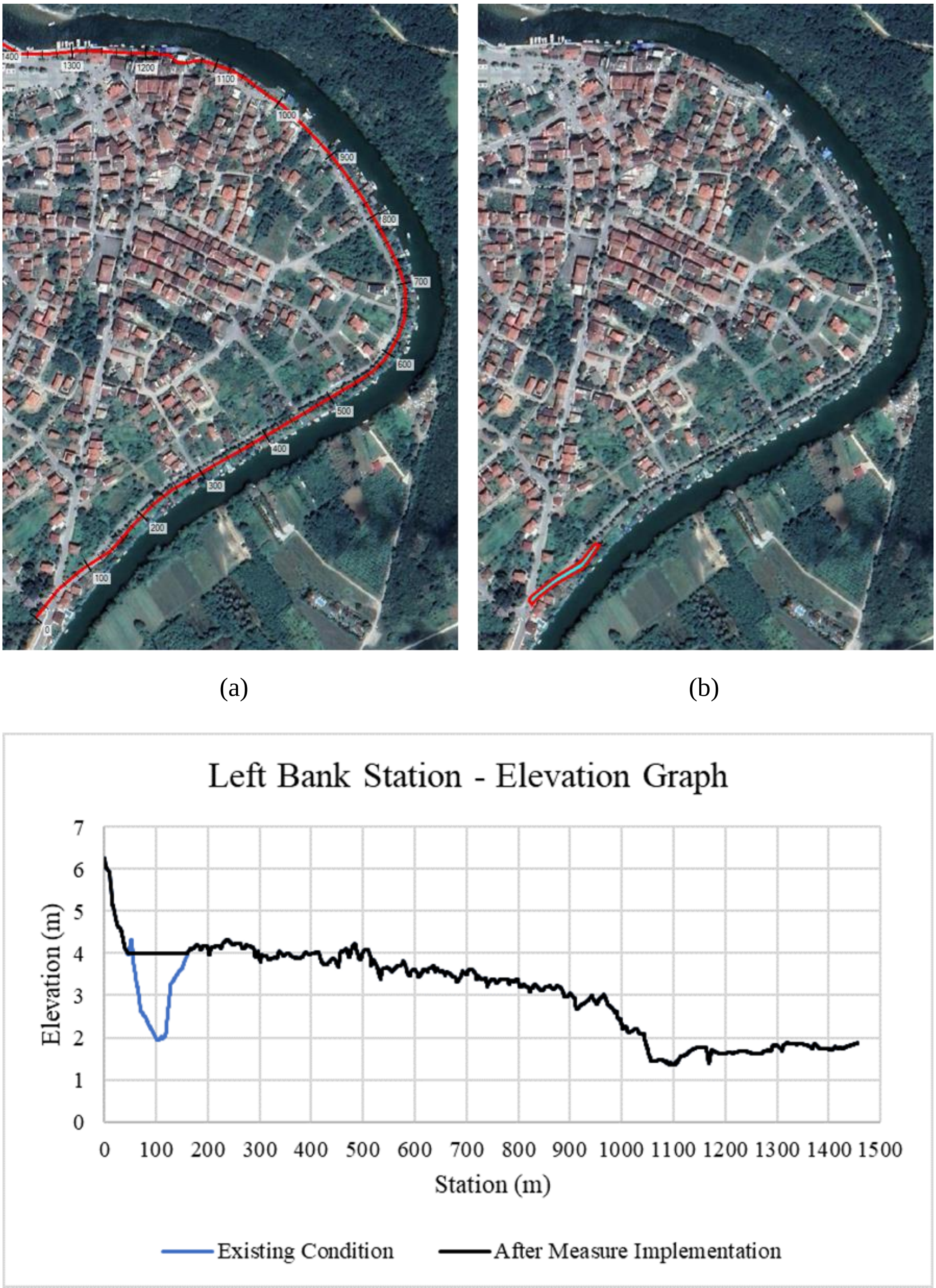
(a) (b)

(c) (d)

Figure 4.3 Maximum hazard map for (a) 10, (b) 100, (c) 500 and (d) 1000-year frequency flood events

After further investigation of the flood propagation during all results, it was seen that one part of the left bank of the Sungurlu River is lower than the other parts throughout the urbanized area, which enables flood to enter the town center. The elevation profile of the left bank of the Sungurlu River in the urbanized area could be seen in Figure 4.4(c). Figure 4.4(c) shows that around the station distance of 100 meters, the left bank's elevation decreases slightly below 2 meters. This low elevation part leads to water propagation towards the city center.

As an effective flood protection measure without any social impact, increasing the left bank of the Sungurlu River to 4 meters by increasing the road elevation next to the river is determined as a flood mitigation measure. The location of the measure is given in Figure 4.4(b). The length of the levee is 120 meters. Also, the location of the embankment is not in the touristic part of the city. Therefore, even though this measure is classified as gray infrastructure, the implementation does not have any social impacts or harmful effects on touristic activities. In Figure 4.4(c), the elevation profile of the left bank of the Sungurlu River after the implementation of the measure is represented.

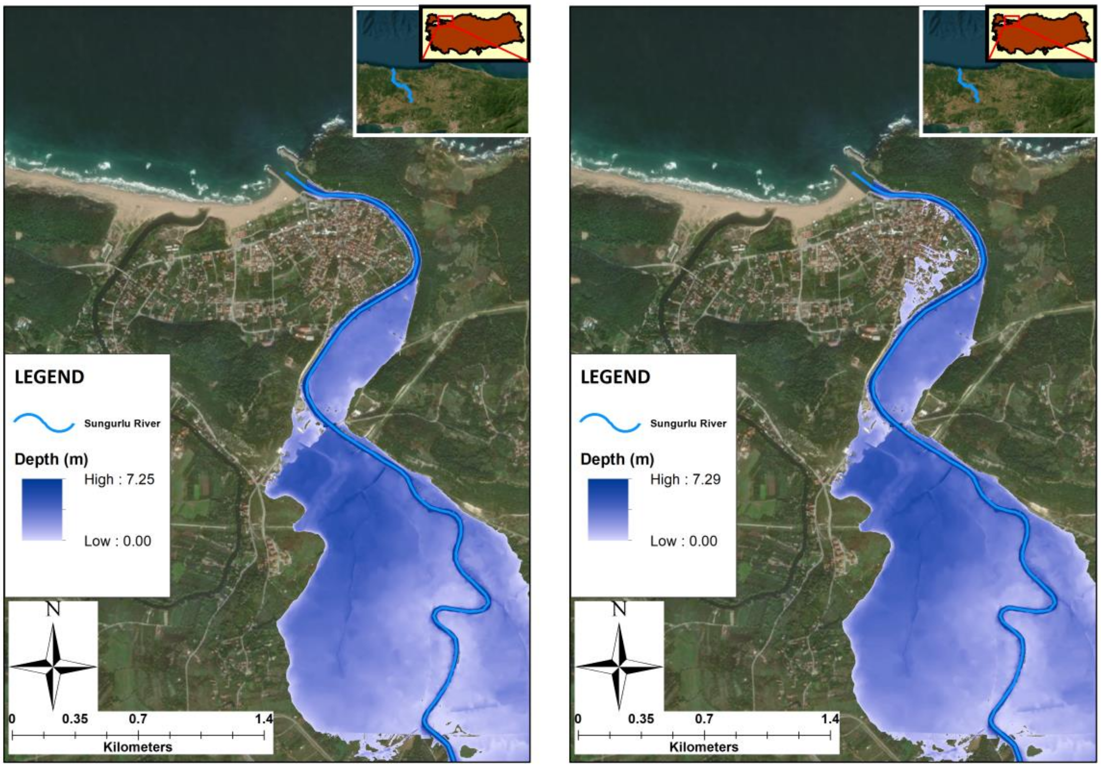


(a) (b)

(c)

Figure 4.4 (a) Profile line from left bank of Sungurlu River through Ağva Town, (b) location of the proposed measure, (c) elevation profile for the left bank of Sungurlu River in the existing condition and after measure implementation

Another analysis was carried out to see the effect of the measure. This case named as Alternative 1. This measure is quite effective and prevents the existing flood risk in the urbanized area for up to Q_{500} flood event and results of this analysis could be seen in Figure 4.5(a). Also, for the Q_{1000} flood event, the measure is quite effective and prevents the flood hazard significantly. In Figure 4.5(b), results of analysis for Q_{1000} flood after implementation of the measure is represented.



(a) (b)

Figure 4.5 Maximum flow depth map of Alternative 1 for (a) Q_{500} and (b) Q_{1000} flood events

The proposed measure in Alternative 1 has good performance with low cost and low social and environmental effects. Therefore, this measure is decided as a no-regret measure.

Even though design criteria for flood control measures could differ from country to country, according to “Flood and Sediment Control Directive, Resmi Gazete No:30763” [48], 1000-year frequency flood should be considered when eliminating the risk of flooding for urbanized areas. Thus, the residual flood risk for Ağva Town after the implementation of Alternative 1 should be assessed.

Increasing the height of the embankment for the whole left bank of the Sungurlu River in Ağva Town is against the objectives of the EU Flood Directive since this measure could have harmful social impacts. Hotels and restaurants are located throughout the left bank of the river. Flood protection with walls would have harmful effects on these touristic places and could bring social impacts to the population. Therefore, an NBS proposed located upstream of the Sungurlu river where the rangeland is located in the study area. The location of the rangeland is given in Figure 4.6.

Since the aim of the NBS is preventing flood hazards emerging from discharges from Q_{1000}, the volume of the water is too much to be stored. Therefore, the retention basin option was not effective in preventing flood hazards. Water should have been discharged in a controlled way because the capacity of the riverbed is enough for Q_{500}. With that information, the creation of a detention pond is determined as a flood mitigation measure.

During the design, the land use map was investigated as a first step. The land use map showed that the left bank of the river in the upstream part is a perfect place for the detention basin location. The first reason is this land is classified as rangeland, and there is no need for expropriation of the land Figure 4.6. This also means there will not be any loss of agricultural land, which is both the economic and social adverse impact of a flood measure.

Another reason is that the selected area has flat terrain, and a dam with an average height of 1.62 meters and a length of 2600 meters can hold 3,55 million m^3 of water. In Figure 4.6, the top view and location of the detention pond dam could be seen and in Figure 4.7, the elevation profile of the designed dam is given. Also, this measure stores excess water before the flooding of agricultural land located on the right bank of the river, so effective for lower discharges than Q_{1000}. However, the analysis with Alternative 2 did not give effective results as Alternative 1 because of the insufficient channel capacity where the designed measure for Alternative 1 is located. In Figure 4.8(c), the inundation area of the Q_{1000} flood is given after implementing the detention pond measure (Alternative 2). However, even though the low height of the left bank of the river, the detention pond was sufficient to eliminate flood risk for the Q_{100} flood event by itself (Figure 4.8(a)).

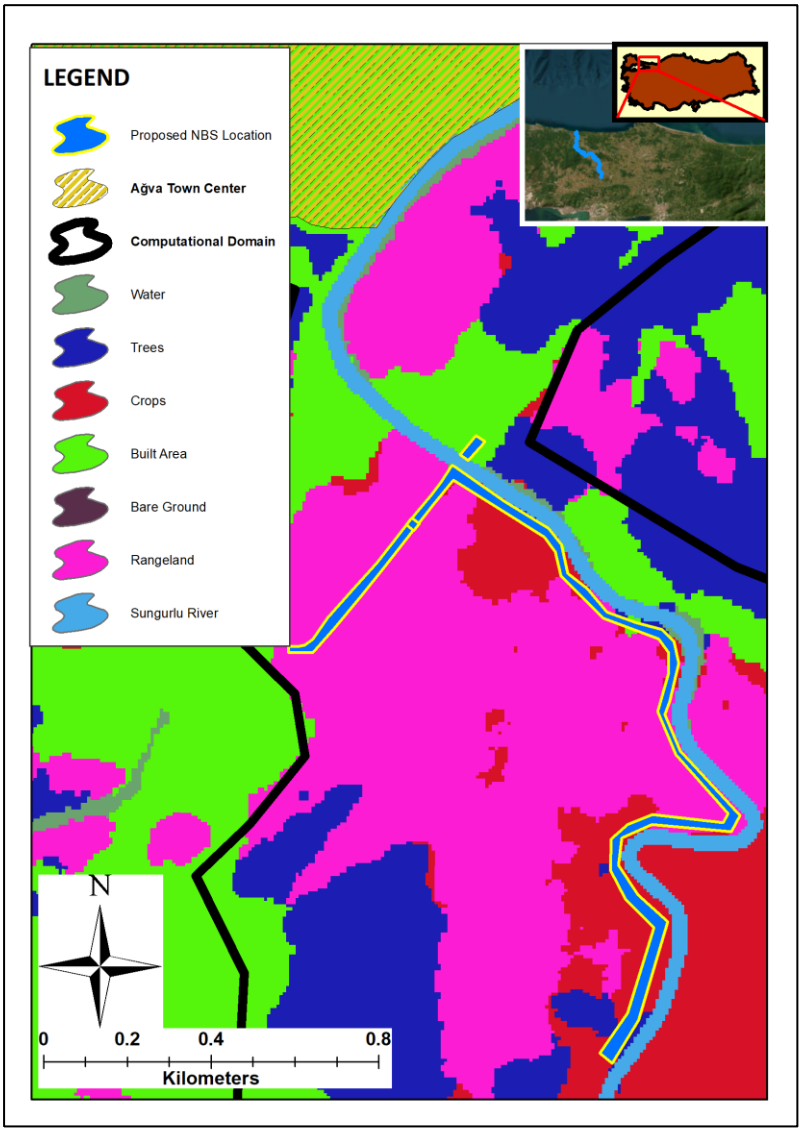


Figure 4.6 Location of the detention basin (Left bank of the Sungurlu River, classified as rangeland, represented with pink color)

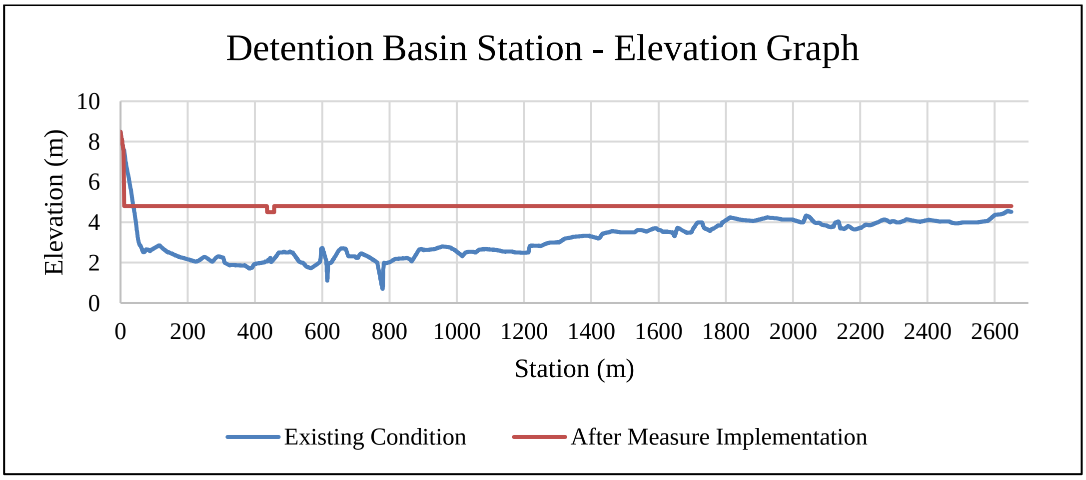
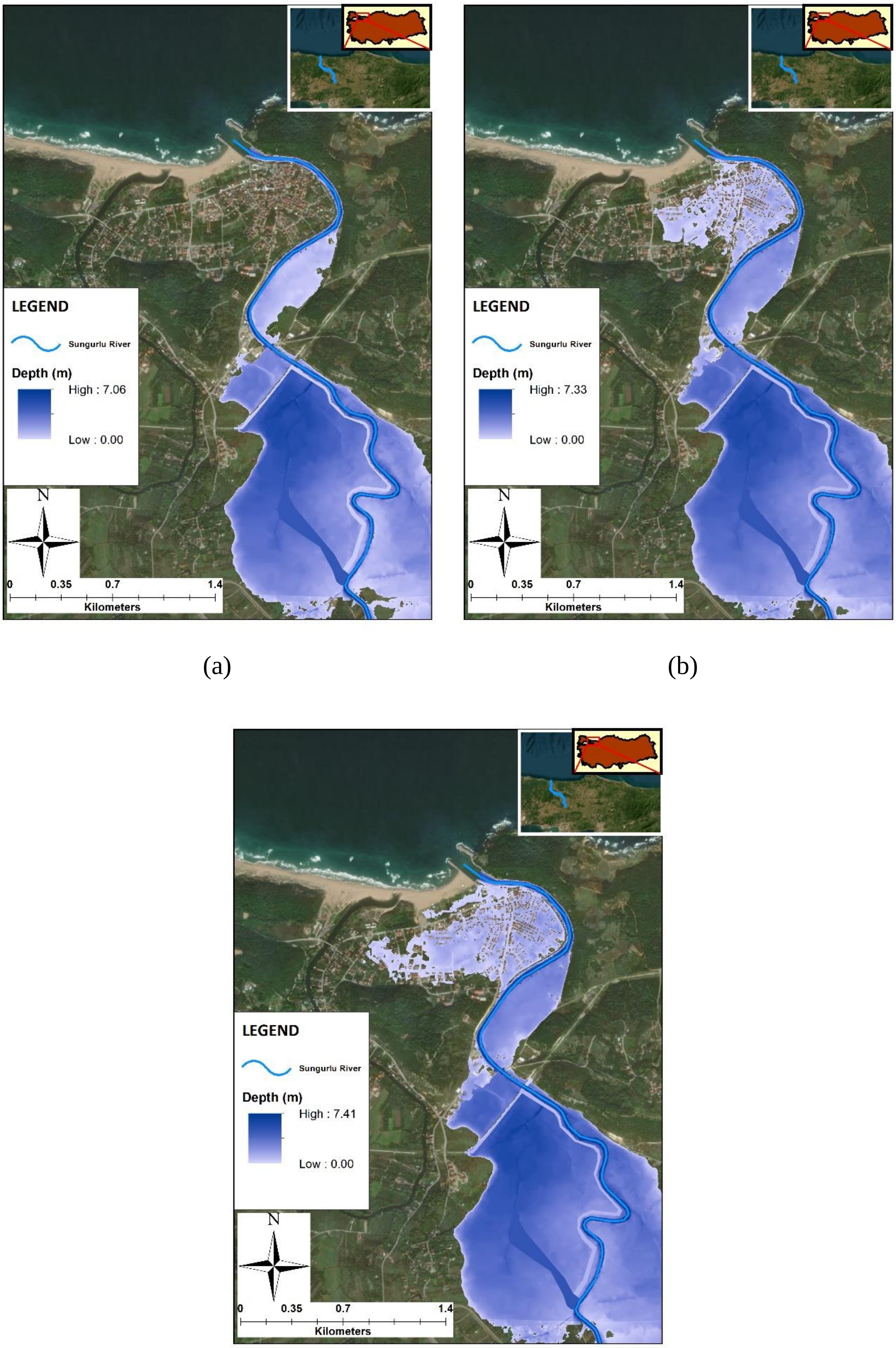


Figure 4.7 Elevation profile of the detention basin dam



(a) (b)

(c)

Figure 4.8 Maximum flow depth map of Alternative 2 for (a) Q_{100} (b) Q_{500} and (c) Q_{1000} flood events

Analysis showed that both alternatives are insufficient to mitigate flood risk in the urbanized area for the Q_{1000} event by itself. The proposed measures in Alternatives 1 and 2 were combined and the analysis of Alternative 3 was carried out. As per the analysis results, there was no flood risk left in the urbanized area with Alternative 3. In Figure 4.9, an inundation map of the Q_{1000} event for Alternative 3 is given.

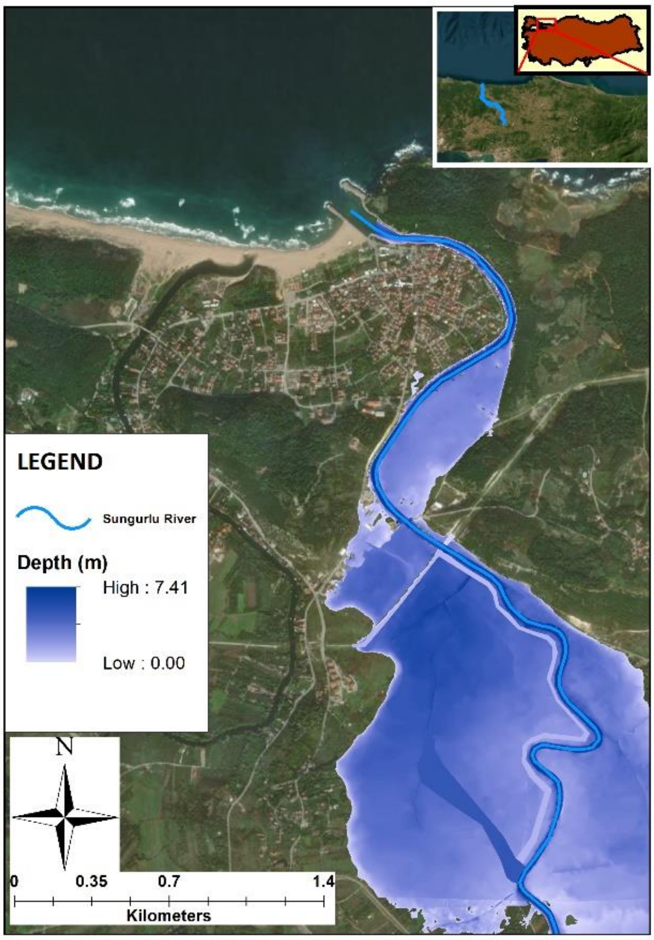


Figure 4.9 Maximum flow depth map of Alternative 3 for Q_{1000} flood events

In Figure 4.10, it could be seen that flood peak for Q_{1000} flood is decreased from 533 m^3/s to 494 m^3/s, which is 7.3% decrease. Flood peak time was reached with Alternative 1 and Alternative 3 at 6 hours and 10 minutes and 6 hours and 35 minutes, respectively. Flood peak time increased by 25 minutes, and this could be useful time gained for further early warning system designs. In Figure 4.10, the outflow hydrograph of the Alternative 1 and 3 are given.

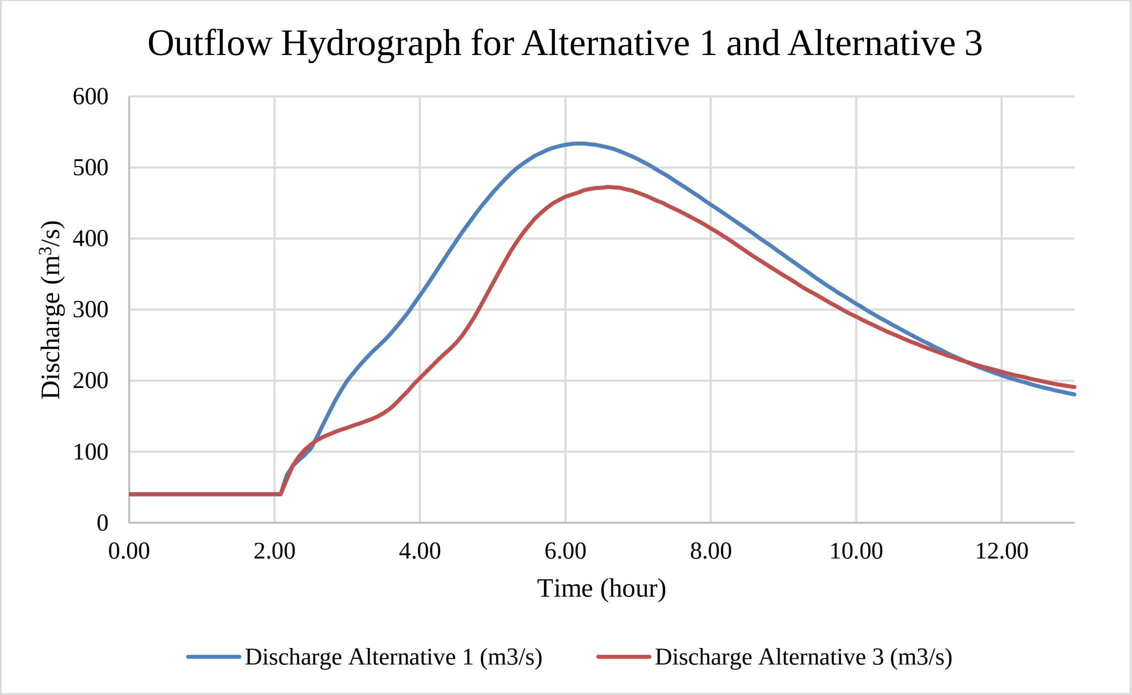


Figure 4.10 Comparison of outflow hydrograph with Alternative 1 (blue) and Alternative 3 (red)

Table 4-1 and Table 4-2 represent the performance of the alternatives for flood events higher than 100-year frequency. 10-year frequency flood analysis was not carried out for alternatives because there was no flood risk in the existing situation. According to Table 6, Alternative 1 prevented all existing flood risk until Q_{500}, and 89.3% of the inundation area for Q_{1000} event. Also, Alternative 1 prevented 95.5% of the high-hazard areas for Q_{1000} (Table 4-2), which makes Alternative 1 a non-regret measure with low cost and high efficiency.

According to the analysis results, it was observed that Alternative 2 performed poorer than Alternative 1. Alternative 2 eliminated all flood risk for Q_{100} event and decreased the high-hazard zone area by 57.5%. Even though this lower performance, the detention pond proposed for Alternative 2, delayed the arrival time of peak flood and increased the time for a future early warning system design. In addition, this zone will be used as a recreational area, and social and economic benefits should be kept in mind of this measure.

Alternative 3 provides a total solution for the flood problem of Ağva Town and hazard from Q_{1000} flood is prevented.

Table 4-1: Inundation area and percentage of decrease in the inundated area with flood measures

	Inundation Area (m^2)			**Reduction in Percentage**		
Alternative	**Q_{100}**	**Q_{500}**	**Q_{1000}**	**Q_{100}**	**Q_{500}**	**Q_{1000}**
Existing	93325.6	419694.0	527896.3	0	0.0%	0.0%
Alternative 1	0	0	56246.7	100.0%	100.0%	89.3%
Alternative 2	0	273774.3	422698.9	100.0%	34.8%	19.9%
Alternative 3	0	0	0	100.0%	100.0%	100.0%

Table 4-2: The amount of areas that have hazard class H3 or higher and the percentage of decrease in these areas

	>= H3 Hazard Class Area (m^2)			**Reduction in Percentage**		
Alternative	**Q_{100}**	**Q_{500}**	**Q_{1000}**	**Q_{100}**	**Q_{500}**	**Q_{1000}**
Existing	18825.8	211010.5	285575.1	0.0%	0.0%	0.0%
Alternative 1	0	0	12881.0	100.0%	100.0%	95.5%
Alternative 2	0	89744.1	215621.2	100.0%	57.5%	24.5%
Alternative 3	0	0	0	100.0%	100.0%	100.0%

4.2. MCA for Analyzed Alternatives

4.2.1. Social Assessment

Social assessment is consisting of health and safety of people, improvement in social life, cultural impacts, and risk on public institutions, partially.

The number of people affected by flood events, RRP, and health and safety MCA scores for all alternatives were calculated and represented in Table 4-3.

Table 4-3: Health and Safety criterion scores of MCA

	Number of Affected People				
Alternative	**Q_{100}**	**Q_{500}**	**Q_{1000}**	**RRP**	**MCA Score**
Existing	194	924	1047	-	-
Alternative 1	0	0	83	0.98	100
Alternative 2	0	649	930	0.54	50
Alternative 3	0	0	0	1.00	100

Results are showing that except for Alternative 2, all alternatives got the maximum score. Even though Alternative 3 showed 100% effectiveness, it is obvious that the measure proposed for Alternative 1 is preventing a majority of flood damage on health and safety of people.

On the other hand, Alternatives 2 and 3 have the probability to increase the quality of life of the residents in the town or increase the tourist attraction after the implementation of NBS including the creation of recreational zones. The measure proposed in Alternative 1 does not have any impact, neither positive nor negative on social life. Therefore, Alternative 1 gets 50, and Alternative 2 and 3 gets 100 for the ISLS criterion of MCA.

The number of cultural items under risk of flooding and CIS of alternatives is given in Table 4-4.

Table 4-4: Number of affected cultural items and CIS for alternatives

	Number of Affected Cultural Items			
Alternative	**Q_{100}**	**Q_{500}**	**Q_{1000}**	**CIS**
Existing	0	1	3	-
Alternative 1	0	0	0	100
Alternative 2	0	1	3	0
Alternative 3	0	0	0	100

Table 4-4 demonstrates Alternative 2 is ineffective to the risk for cultural items located in an urbanized area of Ağva Town. Other alternatives are preventing all the risk on cultural items, thus getting 100 CIS.

4.2.2. Economic Assessment

Economic direct costs for the alternatives were calculated as per the methodology explained in previous chapters. Calculated direct costs were represented in Table 4-5.

Table 4-5: Direct cost of flood damage for alternatives with different discharges

		Direct Damage (€)			
	Damage Type	**Existing**	**Alternative 1**	**Alternative 2**	**Alternative 3**
Q_{100}	Residential	411,079	0	0	0
	Commercial	0	0	0	0
	Transportation	496,110	0	0	0
	Infrastructure	13,905	0	0	0
	Total	921,094	0	0	0
Q_{500}	Residential	5,637,608	0	2,652,677	0
	Commercial	93,581	0	27,007	0
	Transportation	6,182,294	0	2,520,139	0
	Infrastructure	163,962	0	68,436	0
	Total	12,077,445	0	5,268,259	0
Q_{1000}	Residential	7,025,086	173,756	5,734,982	0
	Commercial	196,770	0	94,290	0
	Transportation	9,057,192	827,737	6,326,833	0
	Infrastructure	238,789	22,181	167,844	0
	Total	16,517,838	1,023,673	12,323,949	0

From the costs given, EAD could be calculated. However, the cost of the proposed measures should have been determined to calculate the BC ratio. Research had been carried out to determine the cost of measures suitable to Türkiye prices by using the Electronic Public Procurement Platform website (EKAP) [49]. After this research, it is determined that the cost of increment of the road for the proposed place is 50,000€ and the building of a retention basin in the proposed design and a recreational zone cost 2,100,000€. It should be kept in mind that these values are rough estimates and could be changed according to inflation and some unforeseen factors that were not considered in this study.

For this study, 20 years of service life is considered for road embankment measure since, as a common approach, the service life of roads is considered as 20 years [50]. The lifespan for NBS proposed is determined as 100 years, since well-designed, well-constructed and well-maintained, and monitored embankment and concrete dams can easily reach 100 years of service life [20]. However, the common approach is considering this time as 50 years to be on the safe side, since it is uncertain whether the dam will be well maintained or not. 70% of the dams that USACE manages are over 50-year service life [51].

EAC of Alternative 1 and 2 was calculated according to Equation 1. However, the measures that Alternative 3 includes are both implementations of Alternative 1 and 2, so the EAC of Alternatives 1 and 2 were summed to obtain the EAC of Alternative 3.

W_{MC} value is 1.3 for only Alternative 1, since it has a cost lower than 1 million Euros and is easy to implement without consuming so much institutional capacity.

Table 4-6 represents the summary of the economical assessment of MCA.

Table 4-6: Results of economic assessment of MCA

	Existing	**Alternative 1**	**Alternative 2**	**Alternative 3**
EAD	49,884	1,024	26,971	0
Benefit	-	48,860	22,912	49,884
Direct cost of the measures	-	50,000	2,100,000	2,150,000
EAC	-	2,500	42,000	44,500
MCS	-	1.3	1.0	1.0
BC	-	19.54	0.55	1.12
BCS	-	100	0	50

4.2.3. Social and Economic Assessment

As mentioned in Chapter 3.8.3, flood risk on public institutions was considered as both social and economic impact. Table 4-7 is representing several public institutions at risk of flooding for the existing situation and each proposed alternative.

Table 4-7: Number of Public Institutions Under Flood Risk for each alternative and SEIS values

	Number of Public Institutions Under Flood Risk			
Alternative	**Q_{100}**	**Q_{500}**	**Q_{1000}**	**SEIS**
Existing	0	1	9	-
Alternative 1	0	0	0	100
Alternative 2	0	0	1	50
Alternative 3	0	0	0	100

All alternatives except Alternative 2 prevented flood risk on public institutions. Therefore, Alternative 2 got 50 SEIS and other alternatives got 100 from this criterion of MCA.

4.2.4. Environmental Assessment

NBS solution with retention basin proposed in this study was considered as it has a positive impact on biodiversity and other environmental benefits explained in Chapter 2.5. The increment of road elevation measures has no impact on the environment since the impact area of this measure is negligible. Therefore, Alternative 1 got 50, and Alternative 2 and 3 got 100, ENAS, respectively.

4.2.5. Selection of the Best Alternative with MCA

All the scores needed for MCA were determined in previous chapters. The summary table of applied MCA scores was given in Table 4-8.

Table 4-8: Summary of MCA scoring

	Alternative	**Alternative 1**	**Alternative 2**	**Alternative 3**
Social Impact	**Health and Safety**	100	50	100
	Improvement in Social Life	50	100	100
	Cultural Impact	100	0	100
Economic Impacts	**Measure BC ratio**	100	0	50
	Measure Cost	1.30	1.00	1.00
Social and Economic Impacts	**Reduction of Flood Risk on Public Institutions**	100	50	100
Environmental Impact	**Improvement in biodiversity**	50	100	100

Scores represented in Table 4-8 are multiplied with the weights of three different options determined in Chapter 3.8. Every option has different aims for flood risk management, so project implementers could pick the right method after public consultation and flood risk management objectives.

Table 4-9: MCA scores for alternatives and weight options

Options	**MCA Score**		
	Alternative 1	**Alternative 2**	**Alternative 3**
Option 1 – Social Benefits Importance	85.5	49.0	84.0
Option 2 – Equal Importance	80.4	56.0	86.0
Option 3 – Economic Benefits Importance	90.0	31.5	68.0

Results in Table 4-9 are demonstrating that Alternative 1 is the best alternative to select for flood risk management of Sungurlu River when both the objective is economic and social benefits. Only Alternative 3 is the best option to pick if equal weights would be given to MCA scoring.

4.3. Summary

In conclusion, Alternative 1 is a good option for short-term and no-regret flood control since in the existing condition, the urbanized area is at risk of flooding from 100-year frequency flood event. For further protection, the detention basin can decrease the flood risk significantly and delay the flood peak time, which makes Alternative 3 the best option for total protection against the Q1000 flood event.

Furthermore, the area where the proposed detention basin could be evaluated as a recreational zone to increase tourist attraction and social benefits.

Even though the proposed hybrid solution prevented all the flood risks equal to or greater 1000-year event, CBA and MCA analysis demonstrated that alternatives with NBS measure have low BC ratios for the study area.

Although the results demonstrate some decision-making, there are uncertainties that should not be negligible and require further data collection and studies. The uncertainties in this study originate from Manning roughness coefficient and hydrologic data since no validation process was carried out because of a lack of measured data. Also, the impact of Göksu River, which belongs to another catchment area located on the west side of Ağva Town, should be assessed when deciding the optimum alternative for implementation.

In addition, during measure selection phase, interdisciplinary approach should be followed and the solutions should be optimized. For instance, the design of the detention basin could be improved or floodwall could be a better option than increasing road height.

Also, it should be noted that this study represents the current situation when the data was obtained. Conditions in topography and land use could be changed in the future.

5. CONCLUSIONS

In this study, Sungurlu River was evaluated regarding flood risk to Ağva Town. For this assessment, data required for the hydraulic flood modeling is prepared. Hydrologic assessment outputs were obtained from administrations and this data was used as an input boundary condition for the hydraulic model. Sentinel-2 satellite data was used for the determination of the land use, and DEM data was collected by the Republic of Türkiye Ministry of Agriculture and Forestry, General Directorate of Water Management in LiDAR format with 0.5 by 0.5 meters of resolution. Flood measure projects are prone to be useless if the analysis data is not representing real-world conditions. This study is important for decision-makers since data with high accuracy is used in this thesis. After carrying out hydraulic flood modeling with obtained data, it came out that the urbanized part of Ağva Town is under equal and over flood risk of Q_{100} flood event.

After consideration of the study area and according to the results of flood hazard mapping, the left bank of the Sungurlu River is lower than it should be 120 meters where the river enters the urbanized area. To eliminate the flood risk that emerged from this situation, a gray infrastructure that increases the elevation of the left bank to 4 meters for the mentioned part of the river is proposed and analyzed. It was seen that this measure effectively prevents the flood risk up to the Q_{500} flood event and significantly decreases the flood risk for the Q_{1000} event. Further gray infrastructure measures could not be taken for the urbanized area since the social impacts are great and these kinds of measures will modify the riverine environment would result in a significant decrease in tourist attraction to Ağva Town. Therefore, the NBS solution that utilized the upstream part of the river is considered. As an NBS solution, the implementation of a detention basin is analyzed in this study. The reason for deciding on this measure is the floodplain of Sungurlu River just upstream from Ağva Town has the necessary prerequisites for a detention basin. This terrain is flat and it is classified as rangeland. Therefore, this land does not need to be expropriated for the implementation of the measure, which is quite an amount of saving from the project budget. Also, this measure is designed to be worked after the Q_{100} design floods. The reason for this design project’s area will be used as a recreational zone for increasing tourist attraction in the town, which is beneficial in regard to social impacts.

Results of all three alternatives and MCA demonstrated that the implementation of Alternative 1, increasing road height to 4 meters for 120 meters in the determined part of the left bank of the Sungurlu River should be taken as an urgent, non-regret measure since this measure eliminates flood risk for the Ağva Town up to Q_{500} event. In Alternative 2, the implementation of the detention basin only is seen as not so much effective as in Alternative 1 and 3 since the level of the left bank of Sungurlu River where the proposed measure is located is too low. However, the detention basin decreased the flood arrival time and peak flow, giving people more time to evacuate zones with great hazard risk. In Alternative 3, implementation of both measures gave really good results to prevent flood risk up to (or more) Q_{1000} event by decreasing flood peak discharge and arrival time of the peak flow.

As a result, NBS measures are working effectively for the study area to eliminate flood risk of 1000-year probability when supported with gray infrastructure. The benefit of the NBS in the study area is questionable and depends on the objectives of the flood risk management of the administration and public opinion. If the aim is preventing the 1000-years probability flood risk no matter effectiveness according to the local law, Alternative 3 has to be taken. Otherwise, Alternative 1 is quite effective and the residual flood risk could be assessed by non-structural measures such as increasing public awareness where the residual risk exists or installation of an early warning system.

The effectiveness of NBS depends on the characteristics of the river basin and existing land use. This study proves that if traditional measures (grey) are supported by NBS, then the adverse effects of floods would be minimized with a lower budget and cause minimum damage to the environment, ecology, and society. To extend this study further, other nature-based solutions, as well as their optimum locations, should be examined, such as research carried out to automatize the selection of locations for detention basins [52].

For further studies, a survey could be conducted to determine weights by considering opinion of stakeholders to determine suitable weights.

Also, when assessing the EAD, EU JRC data is used. However, this data does not consider flow velocity when deciding the damage rate. Flow velocity or flood hazard could be included into this analysis.

For further studies, projection of the urbanization and tourism potential of Ağva Town could be assessed and the CBA and MCA analysis could be carried out with this projection.

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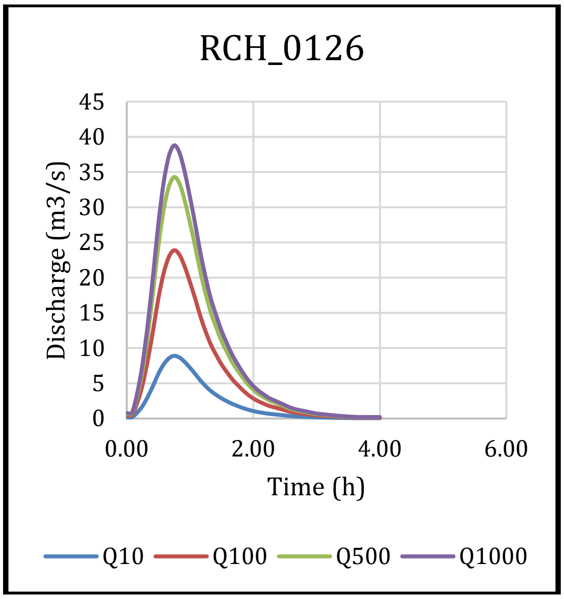
7. ANNEXES

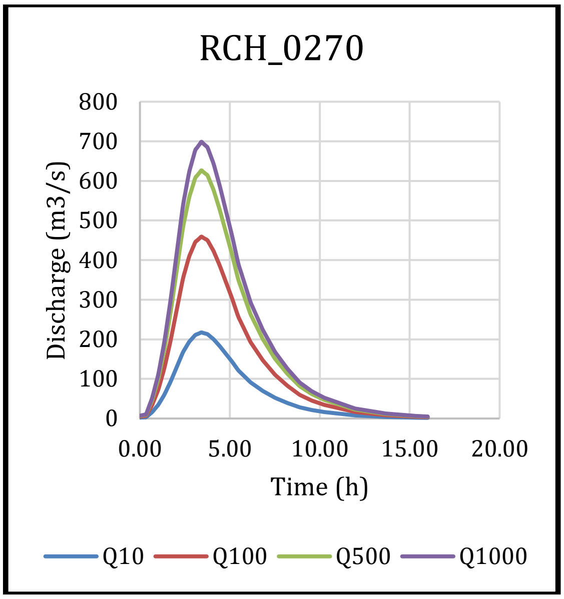
ANNEX 1 – Flow Hydrographs (Obtained from İSKİ Master Plan Project, Existing Creek Interim Report, 2019)

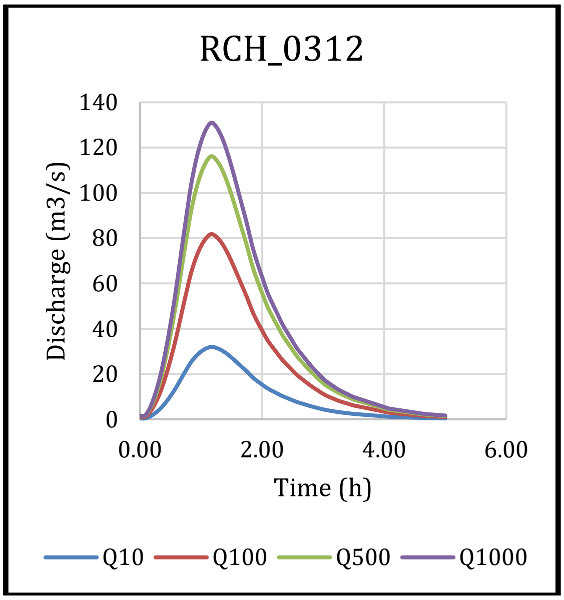
RCH_0126					RCH_0270				RCH_0312			
T (H)	**Q10**	**Q100**	**Q500**	**Q1000**	**Q10**	**Q100**	**Q500**	**Q1000**	**Q10**	**Q100**	**Q500**	**Q1000**
0.00	0.2	0.5	0.7	0.8	2.2	4.6	6.3	7.1	0.4	1.0	1.4	1.6
0.25	1.8	4.8	6.9	7.8	3.0	6.3	8.6	9.5	2.8	7.1	10.1	11.4
0.50	6.4	17.1	24.5	27.7	9.3	19.7	26.8	29.9	10.3	26.4	37.5	42.3
0.75	8.9	23.9	34.3	38.8	19.9	42.1	57.4	64.0	21.5	55.0	78.2	88.1
1.00	7.2	19.4	27.8	31.4	33.4	70.6	96.4	107.5	29.9	76.5	108.7	122.6
1.25	4.6	12.3	17.6	19.9	51.9	109.8	149.8	167.0	31.5	80.6	114.5	129.1
1.50	2.9	7.7	11.0	12.4	73.6	155.5	212.1	236.5	27.3	69.7	98.9	111.5
1.75	1.8	4.8	6.9	7.8	97.9	207.0	282.4	314.9	21.1	54.0	76.7	86.5
2.00	1.1	2.9	4.1	4.6	125.0	264.1	360.4	401.8	15.4	39.3	55.8	62.9
2.25	0.7	1.8	2.6	2.9	152.0	321.2	438.3	488.8	11.4	29.1	41.3	46.6
2.50	0.4	1.2	1.7	1.9	175.6	371.1	506.3	564.6	8.4	21.5	30.5	34.4
2.75	0.3	0.7	1.0	1.2	194.3	410.5	560.1	624.6	6.2	15.8	22.4	25.3
3.00	0.2	0.4	0.6	0.7	207.0	437.4	596.8	665.5	4.4	11.2	15.9	18.0
3.25	0.1	0.3	0.4	0.5	214.1	452.5	617.4	688.5	3.2	8.2	11.7	13.1
3.50	0.1	0.2	0.3	0.3	216.2	457.0	623.5	695.3	2.4	6.1	8.7	9.8
3.75	0.1	0.1	0.2	0.2	213.1	450.2	614.4	685.1	1.9	4.8	6.8	7.6
4.00	0.1	0.1	0.2	0.2	203.7	430.5	587.5	655.1	1.3	3.4	4.8	5.5
4.25	0.1	0.1	0.2	0.2	192.3	406.3	554.5	618.3	1.0	2.5	3.6	4.0
4.50	0.1	0.1	0.2	0.2	179.2	378.7	516.7	576.2	0.7	1.9	2.7	3.0
4.75	0.1	0.1	0.2	0.2	164.9	348.4	475.5	530.2	0.5	1.4	1.9	2.2
5.00	0.1	0.1	0.2	0.2	150.6	318.2	434.2	484.2	0.4	1.1	1.5	1.7
5.25	0.1	0.1	0.2	0.2	135.5	286.3	390.6	435.6	0.3	0.7	1.1	1.2
5.50	0.1	0.1	0.2	0.2	120.2	254.0	346.6	386.5	0.2	0.6	0.8	0.9
5.75	0.1	0.1	0.2	0.2	109.1	230.5	314.5	350.7	0.2	0.4	0.6	0.6
6.00	0.1	0.1	0.2	0.2	97.9	207.0	282.4	314.9	0.2	0.4	0.6	0.6
6.25	0.1	0.1	0.2	0.2	88.1	186.1	254.0	283.2	0.2	0.4	0.6	0.6
6.50	0.1	0.1	0.2	0.2	80.1	169.3	231.1	257.7	0.2	0.4	0.6	0.6
6.75	0.1	0.1	0.2	0.2	72.2	152.5	208.2	232.1	0.2	0.4	0.6	0.6
7.00	0.1	0.1	0.2	0.2	65.3	138.0	188.3	210.0	0.2	0.4	0.6	0.6
7.25	0.1	0.1	0.2	0.2	58.9	124.5	170.0	189.5	0.2	0.4	0.6	0.6
7.50	0.1	0.1	0.2	0.2	52.6	111.1	151.6	169.1	0.2	0.4	0.6	0.6
7.75	0.1	0.1	0.2	0.2	47.7	100.8	137.6	153.4	0.2	0.4	0.6	0.6
8.00	0.1	0.1	0.2	0.2	42.9	90.7	123.8	138.0	0.2	0.4	0.6	0.6
8.25	0.1	0.1	0.2	0.2	38.3	81.0	110.5	123.2	0.2	0.4	0.6	0.6
8.50	0.1	0.1	0.2	0.2	34.3	72.6	99.0	110.4	0.2	0.4	0.6	0.6
8.75	0.1	0.1	0.2	0.2	30.4	64.2	87.6	97.7	0.2	0.4	0.6	0.6
9.00	0.1	0.1	0.2	0.2	27.1	57.2	78.0	87.0	0.2	0.4	0.6	0.6
9.25	0.1	0.1	0.2	0.2	24.5	51.8	70.7	78.8	0.2	0.4	0.6	0.6
9.50	0.1	0.1	0.2	0.2	22.0	46.4	63.4	70.7	0.2	0.4	0.6	0.6
9.75	0.1	0.1	0.2	0.2	20.0	42.2	57.5	64.2	0.2	0.4	0.6	0.6
10.00	0.1	0.1	0.2	0.2	18.1	38.3	52.3	58.3	0.2	0.4	0.6	0.6
10.25	0.1	0.1	0.2	0.2	16.3	34.4	47.0	52.4	0.2	0.4	0.6	0.6
10.50	0.1	0.1	0.2	0.2	15.1	31.8	43.4	48.4	0.2	0.4	0.6	0.6
10.75	0.1	0.1	0.2	0.2	13.8	29.2	39.8	44.4	0.2	0.4	0.6	0.6
11.00	0.1	0.1	0.2	0.2	12.6	26.6	36.3	40.4	0.2	0.4	0.6	0.6
11.25	0.1	0.1	0.2	0.2	11.3	24.0	32.7	36.5	0.2	0.4	0.6	0.6
11.50	0.1	0.1	0.2	0.2	10.1	21.3	29.1	32.5	0.2	0.4	0.6	0.6
11.75	0.1	0.1	0.2	0.2	8.9	18.7	25.5	28.5	0.2	0.4	0.6	0.6
12.00	0.1	0.1	0.2	0.2	7.7	16.3	22.3	24.9	0.2	0.4	0.6	0.6

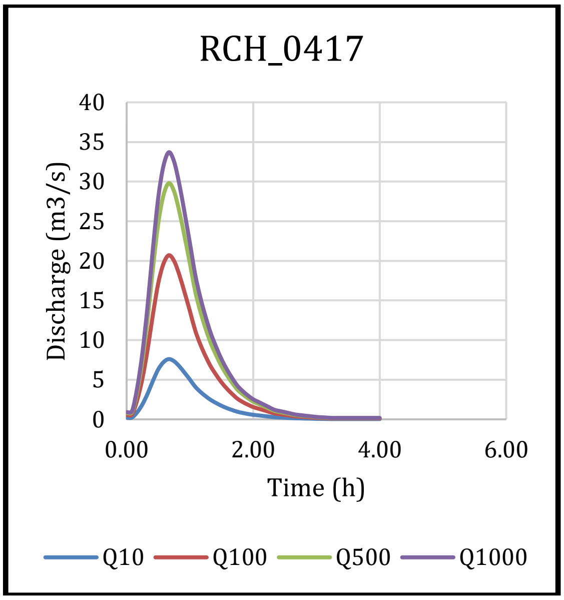
RCH_0417					RCH_0458				RCH_0496			
T (H)	**Q10**	**Q100**	**Q500**	**Q1000**	**Q10**	**Q100**	**Q500**	**Q1000**	**Q10**	**Q100**	**Q500**	**Q1000**
0.00	0.2	0.6	0.8	0.9	0.2	0.5	0.7	0.7	0.2	0.5	0.7	0.8
0.25	1.9	5.2	7.5	8.4	1.5	4.2	6.1	6.9	1.9	5.0	7.1	8.0
0.50	6.3	17.2	24.7	28.0	5.0	13.9	20.1	22.7	6.6	17.7	25.4	28.7
0.75	7.3	20.0	28.8	32.5	5.8	16.1	23.4	26.4	9.3	24.8	35.6	40.2
1.00	5.0	13.7	19.7	22.2	4.0	11.0	16.0	18.1	7.5	20.1	28.8	32.6
1.25	2.9	7.9	11.4	12.9	2.3	6.4	9.3	10.5	4.8	12.7	18.3	20.6
1.50	1.7	4.7	6.7	7.6	1.4	3.8	5.4	6.2	3.0	7.9	11.4	12.9
1.75	1.0	2.6	3.8	4.3	0.8	2.1	3.1	3.5	1.9	5.0	7.1	8.0
2.00	0.6	1.6	2.2	2.5	0.5	1.3	1.8	2.1	1.1	3.0	4.3	4.8
2.25	0.4	1.0	1.4	1.5	0.3	0.8	1.1	1.3	0.7	1.9	2.7	3.0
2.50	0.2	0.6	0.8	0.9	0.2	0.5	0.7	0.7	0.5	1.2	1.7	2.0
2.75	0.1	0.3	0.5	0.5	0.1	0.3	0.4	0.4	0.3	0.7	1.1	1.2
3.00	0.1	0.2	0.3	0.3	0.1	0.2	0.2	0.3	0.2	0.5	0.6	0.7
3.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.3	0.4	0.5
3.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.2	0.3	0.3
3.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
4.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
4.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
4.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
4.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
5.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
5.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
5.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
5.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
6.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
6.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
6.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
6.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
7.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
7.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
7.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
7.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
8.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
8.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
8.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
8.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
9.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
9.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
9.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
9.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
10.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
10.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
10.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
10.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
11.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
11.25	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
11.50	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
11.75	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2
12.00	0.0	0.1	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.2	0.2

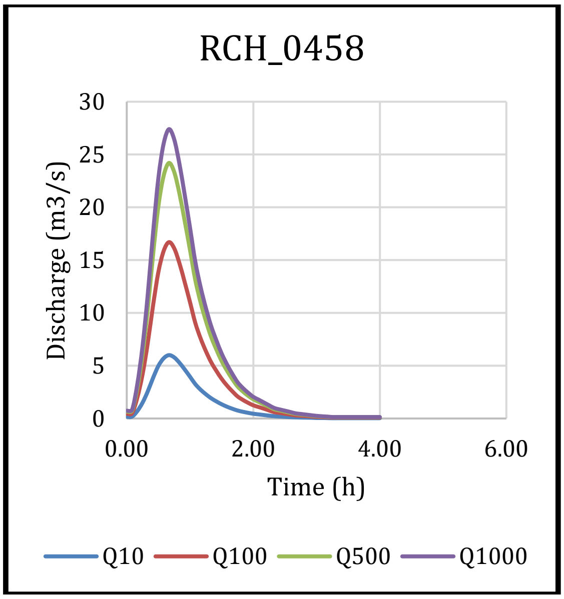
RCH_1632				
T (H)	**Q10**	**Q100**	**Q500**	**Q1000**
0.00	0.4	1.0	1.5	1.7
0.25	2.8	7.4	10.6	12.0
0.50	10.5	27.5	39.3	44.4
0.75	21.9	57.4	81.9	92.5
1.00	30.4	79.8	113.9	128.6
1.25	32.0	84.1	120.0	135.4
1.50	27.7	72.6	103.6	117.0
1.75	21.5	56.3	80.3	90.7
2.00	15.6	40.9	58.4	66.0
2.25	11.6	30.3	43.3	48.9
2.50	8.5	22.4	32.0	36.1
2.75	6.3	16.5	23.5	26.5
3.00	4.5	11.7	16.7	18.8
3.25	3.3	8.6	12.2	13.8
3.50	2.4	6.4	9.1	10.3
3.75	1.9	5.0	7.1	8.0
4.00	1.4	3.6	5.1	5.7
4.25	1.0	2.6	3.8	4.2
4.50	0.8	2.0	2.8	3.2
4.75	0.5	1.4	2.0	2.3
5.00	0.4	1.1	1.6	1.8
5.25	0.3	0.8	1.1	1.2
5.50	0.2	0.6	0.8	0.9
5.75	0.2	0.4	0.6	0.7
6.00	0.2	0.4	0.6	0.7
6.25	0.2	0.4	0.6	0.7
6.50	0.2	0.4	0.6	0.7
6.75	0.2	0.4	0.6	0.7
7.00	0.2	0.4	0.6	0.7
7.25	0.2	0.4	0.6	0.7
7.50	0.2	0.4	0.6	0.7
7.75	0.2	0.4	0.6	0.7
8.00	0.2	0.4	0.6	0.7
8.25	0.2	0.4	0.6	0.7
8.50	0.2	0.4	0.6	0.7
8.75	0.2	0.4	0.6	0.7
9.00	0.2	0.4	0.6	0.7
9.25	0.2	0.4	0.6	0.7
9.50	0.2	0.4	0.6	0.7
9.75	0.2	0.4	0.6	0.7
10.00	0.2	0.4	0.6	0.7
10.25	0.2	0.4	0.6	0.7
10.50	0.2	0.4	0.6	0.7
10.75	0.2	0.4	0.6	0.7
11.00	0.2	0.4	0.6	0.7
11.25	0.2	0.4	0.6	0.7
11.50	0.2	0.4	0.6	0.7
11.75	0.2	0.4	0.6	0.7
12.00	0.2	0.4	0.6	0.7

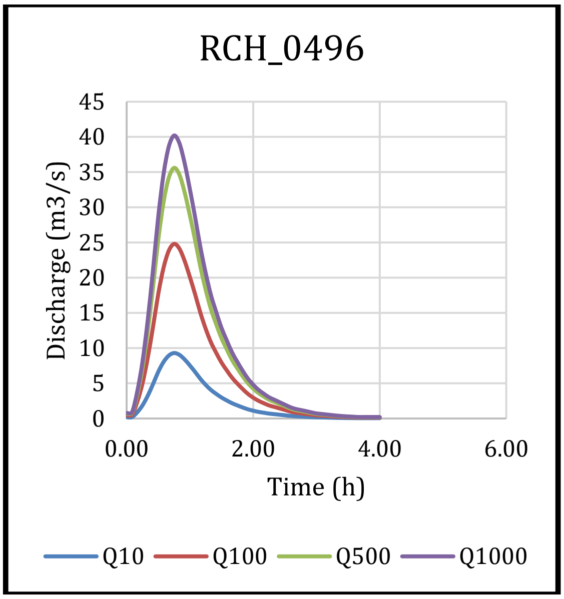

RCH_0126
Discharge (m3/s)
45
40
35
30
25
20
15
10
5
0
0.00
2.00
4.00
6.00
Time (h)
Q10
Q100
Q500
Q1000

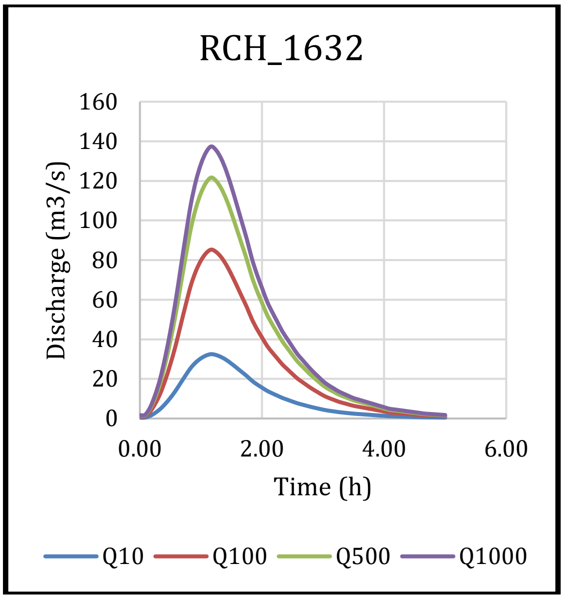

RCH_0270
Discharge (m3/s)
800
700
600
500
400
300
200
100
0
0.00
5.00
10.00
15.00
20.00
Time (h)
Q10
Q100
Q500
Q1000


RCH_0312
Discharge (m3/s)
140
120
100
80
60
40
20
0
0.00
2.00
4.00
6.00
Time (h)
Q10
Q100
Q500
Q1000


RCH_0417
Discharge (m3/s)
40
35
30
25
20
15
10
5
0
0.00
2.00
4.00
6.00
Time (h)
Q10
Q100
Q500
Q1000


RCH_0458
Discharge (m3/s)
30
25
20
15
10
5
0
0.00
2.00
4.00
6.00
Time (h)
Q10
Q100
Q500
Q1000


RCH_0496
Discharge (m3/s)
45
40
35
30
25
20
15
10
5
0
0.00
2.00
4.00
6.00
Time (h)
Q10
Q100
Q500
Q1000


RCH_1632
Discharge (m3/s)
160
140
120
100
80
60
40
20
0
0.00
2.00
4.00
6.00
Time (h)
Q10
Q100
Q500
Q1000