University
*of Ljubljana*
Faculty
*for Civil and Geodetic Engineering*

**FILMON GHILAY GHEBREBIMICHAEL**

# IMPACT OF CLIMATE INDUCED CHANGE IN FLOOD CHARACTERSTICS ON FLOOD DAMGE DAMAGE

MASTER'S THESIS

MASTER STUDY PROGRAMME FLOOD RISK MANAGEMENT

Univerza *v Ljubljani*

Ljubljana, 2022

University
*of Ljubljana*
*of Ljubljana*Faculty
Faculty
*for Civil and Geodetic*
*Engineering*

Candidate

# FILMON GHILAY GHEBREMICHAEL

## IMPACT OF CLIMATE INDUCED CHANE IN FLOOD CHARACTERSTICS ON FLOOD DAMAGE

Master's thesis no .: 551.58:556.166(497.4)(043.3)

**Mentor:**
doc. dr. Simon Rusjan
**Co-mentor:**
dr. Andrej Vidmar

**Commission member:**
Prof. Dr.Micha Werner

**Chairman of the Commission:**
izr. prof. dr. Natasa Atonasava

Ljubljana, 2022

Univerza *v Ljubljani*

*"This page is intentionally blank"*

## ERRATA

| Error page | Error bar | Instead | Let it be |
| --- | --- | --- | --- |

**ACKOWLEDGEMENTS**

First, I would thank the Almighty God who enabled me to reach this level, overcome various challenges, and witness success in my life.

My highly thank in this master thesis is to my research mentors, Dr. Simon Rusjan and Dr. Andrej Vidmar, for all the help, support, and active participation they gave me at every stage of writing my thesis.

The door of Professor Dr. Simon Rusjan's office was always open when I had a question or a concern about my research. He offered me the freedom to compose this thesis on my own, but he also provided me with full guidance, steering me in the right direction. I also want to thank Dr. Andrej Vidmar, for guiding me to have a more practical understanding of the thesis case study and for his valuable input on the thesis accomplishments.

I would also like to thank my family, who gave me valuable input, love, and lessons in my life to reach this level, and who supported me during every stage of my life and enabled me to look toward the future with hope and vision.I am also thankful to my friends and colleagues who were by my side and contributed to my success with morale and support.

Special thanks to the flood risk management group, who come from diverse backgrounds but ended up in a family and passed valuable experiences and enabled me to broaden my horizons and understanding of different parts of the world.

I would also like to thank all lecturers, professors, and coordinators in this master's program who gave valuable input and support during this master's program study.

## BIBLIOGRAPHIC-DOCUMENTALISTIC INFORMATION AND ABSTRACT

**UDC:** **551.58:556.166(497.4)(043.3)**
**Author:** **Filmon Ghilay Ghebremichael**
**Supervisor:** **Assist. Prof. Simon Rusjan, Ph.D.**
**Co-supervisor:** **Andrej Vidmar, Ph.D.**
**Title:** **Impact of climate induced change in flood characteristics on flood damage**
**Document type:** **Master thesis**
**Notes:** **72 xp., 7 tab., 28 fig. 2 eq., 88 ref.**
**Keywords:** **climate change, Vipava river, fluvial flooding, hydraulic modelling, KRPAN model, expected annual damage,**

**Abstract**

Global climate change is anticipated to result in changed precipitation characteristics and an increase in the frequency of extreme weather events, which can lead to catastrophic flood damage. Results of the climate change studies in Slovenia foresee a considerable rise in the average air temperature, changes in the frequency of precipitation characteristics, and an increase in the occurrence of extreme weather events. According to climate change scenarios RCP 2.6, RCP 4.5, and RCP 8.5, the average annual peaks of Slovenian rivers will rise by 20 to 40% by the end of the century at almost all water stations (ARSO, 2021). The Vipava river catchment is an area located in western Slovenia; the area is vulnerable to river flooding and has been subjected to several flood events in recent years which could be associated to changes in the precipitation as one of climate change's effects

Detailed flood damage analysis has not been conducted for the Vipava river catchment, and accurate estimation of flood damage is crucial to quantifying the actual flood risk and evaluating the cost-effectiveness of flood mitigation measures. Flood damage assessment for the Vipava river catchment was conducted in this study by considering different flood scenarios. The flood damage potential was investigated based on the designed flood event data adapted to specific flood scenarios related to anticipated impact of climate change and the presence of exposure/vulnerability elements. Hydraulic modeling using Hec Ras software is used to identify the flood polygons in the study area for current and climate-driven flood scenarios. The output of the hydraulic model is used as an input to KRPAN software to determine the flood damage potential in the study area.

According to the results of the hydraulic model, extensive floodplain areas along the studied Vipava river section are inundated, primarily covering agricultural land and buildings. The cost of both residential and non-residential buildings constitutes the majority of the projected flood damage for the specified flood return periods. The building's overall expected annual damage under the pessimistic RCP 8.5 scenarios is expected to reach around 1.3 million by the end of the century, In case of low probability events with 100- and 500-year return periods, the cost of the building's flood damage ranges from 4.5 million euros to 6 million euros. The total expected annual damage in the Vipava river catchment ranges from 0.97 million euros for the current situation to 1.97 million euros for the most pessimistic high-impact scenario. The study clearly shows that the economic impact of future flood scenarios is expected increase substantially In view of the local character of the exposure elements, the residential properties and non-residential properties were demonstrated to face the greatest consequences of an expected climate change induced changes in the river flood characteristics

## BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

| | |
|---|---|
| **UDK:** | **551.58:556.166(497.4)(043.3)** |
| **Avtor:** | **Filmon Ghilay Ghebremichael** |
| **Mentor:** | **izr. prof. dr. Simon Rusjan** |
| **Somentor:** | **dr. Andrej Vidmar** |
| **Naslov:** | **vpliv podnebno povzročenih sprememb značilnosti poplav na škodo zaradi poplav** |
| **Tip dokumenta:** | **magistrsko delo** |
| **Obseg in oprema:** | **73 str., 7 pregl., 28 sl., 2 en., 88 pril.** |
| **Ključne besede:** | **podnebne spremembe, rekae Vipavae, fluvialne poplave, hidravlično modeliranje, model KRPAN, pričakovana letna škoda,** |

Izvleček:

Pričakuje se, da bodo globalne podnebne spremembe povzročile povečane količine padavin in pogostejše ekstremne vremenske pojave, ki lahko povzročijo katastrofalno škodo zaradi poplav. Meritve iz študij podnebnih sprememb v Sloveniji kažejo precejšen dvig povprečne temperature zraka, spremembo pogostosti padavin in večjo pojavnost ekstremnih vremenskih pojavov. Glede na študije podnebnih projekcij scenarijev RCP 2.6, RCP 4.5 in RCP 8.5 bodo povprečne letne konice slovenskih rek do konca stoletja skoraj na vseh vodomernih postajah narasle za 20 do 40 % (ARSO, 2021). Povodje reke Vipave je območje v jugozahodni Sloveniji, ki je občutljivo na poplavljanje rek in je bilo v zadnjih letih izpostavljeno hudourniškim poplavam, ki so jih povzročile ekstremne konične pretoke zaradi sprememb v padavinskem režimu, ki je eden od učinkov podnebnih sprememb (Magjar et. sod., 2021).

V porečju Vipave še ni bila izvedena analiza poplavne škode, natančna ocena poplavne škode pa je ključnega pomena za količinsko opredelitev dejanskega tveganja in oceno stroškovne učinkovitosti omilitvenih del. Ocena poplavne škode za porečje reke Vipave je bila izvedena v tem študija za različne scenarije poplav. Možnost poplavne škode je bila raziskana na podlagi načrtovanih podatkov o poplavnih dogodkih, prilagojenih specifičnim scenarijem poplav in elementom izpostavljenosti/ranljivosti. Hidrodinamične simulacije, izvedene na podlagi obsega poplavljanja in porazdelitve globine vode, se uporabljajo kot vhodni podatki za model KRPAN za oceno gospodarske škode, ki jo povzročijo poplave. Ocene škode na podlagi šestih povratnih obdobij so bile uporabljene za izdelavo krivulj škode in verjetnosti ter izračun skupne pričakovane letne škode zaradi poplav (EAD), ki jo povzročijo scenariji poplav zaradi podnebja.

Po rezultatih hidravličnega modela je bilo poplavljeno precejšnje območje poplavne ravnice reke, ki zajema predvsem kmetijska zemljišča in objekte. Stroški tako stanovanjskih kot nestanovanjskih stavb predstavljajo večino predvidene škode zaradi poplav za navedena

povratna obdobja poplav. Skupna pričakovana letna škoda stavbe po RCP 8.5 pesimističnih scenarijev doseže okoli 1,3 milijona do konca stoletja, za dogodke z nizko verjetnostjo s 100- in 500-letnimi povratnimi obdobji pa se stroški škode zaradi poplav stavbe gibljejo od 4,5 milijona evrov na 6 milijonov evrov. Skupna pričakovana letna škoda v povodju reke Vipave se giblje od 0,97 milijona evrov za trenutno stanje do 1,97 milijona evrov za najbolj pesimističen scenarij velikih vplivov. Študija jasno kaže, da se pričakuje, da bodo gospodarski učinki prihodnjih poplavnih scenarijev postali dragi, glede na lokalni značaj pa se je izkazalo, da se bodo stanovanjske in nestanovanjske nepremičnine soočale z največjimi posledicami povečanja konic pretoka reke.

## TABLE OF CONTENTS

# LIST OF FIGURES

**LIST OF TABLES**

*"This page is intentionally blank"*

# INTRODUCTION

This section briefly introduces the topic to be addressed in this study. The study's motivation and the primary methodologies followed to achieve the objectives are highlighted below. The main objectives, as well as the significance of the study, are also addressed briefly.

## 1.1 Research Motivation

Global floods have had a significant negative impact on society's economy and affected billions of people. Fluvial floods rank among the most socially and economically catastrophic natural disasters since 1980, killing more than 200,000 people and resulting in direct economic losses of $790 billion (Arrighi et al., 2018). A statistical review of historical flood records from all over the world reveals a tendency toward increased flooding over the 20th century, and according to global-scale simulations, a warmer climate will make river flooding more frequent in the future (Xu et al., 2019). According to current climate models, increasing temperatures will exacerbate the Earth's water cycle and increase evaporation ("Nasa," n.d.). As evaporation rises, storms will occur more frequently and be more intense, and areas affected by storms will probably experience more precipitation and a greater risk of flooding ("Nasa," n.d.). Numerous studies also examined global predictions of increases in flood frequency caused by climate change (He et al., 2022). For instance, Arnell et al. (2019) reported that at 1.5 °C and 4 °C of rising temperatures, the global average probability of the 50-year return period fluvial flood rises from 2 to 2.4 and 5.4 percent correspondingly. Thus, future flood risks will rise due to the increase in the global water cycle caused by climate change, which will intensify flood damage (Alfieri et al., 2017). Therefore, evaluating fluvial flood hazards under climate change scenarios is crucial for developing flood risk mitigation strategies and measures (Yin et al., 2021).

The assessment of economic flood damage is becoming more and more crucial as flood risk management becomes the main principle for flood protection programs in Europe (Merz et al., 2010). Since 1980, river flooding in Europe has resulted in over 4,700 fatalities and more than €150 billion in direct economic losses (Alfieri & Feyen, 2017). The risk will certainly rise in the future, attributable to climatic and socioeconomic factors. As a result, reliable research studies are required to examine the risk of river flooding under possible future climatic conditions and to assess potential adaptation measures.

The current river flooding trend has also impacted Slovenia. Floods in Slovenia over the past ten years have averaged roughly €120 million yearly losses, and the annual estimate rises to over €150 million if the direct loss is added to the indirect loss, which includes lost revenue from economic activities, company failure, damaged public infrastructure, and long-term effects (Kučić, 2018). The estimated cost of the damage from the 2010 flood was €190 million and €255 million in 2014, and nationwide property losses from the floods were nearly $1.8 billion during the preceding 25 years ( Kučić, 2018).

The Vipava River catchment is one of several Slovenia places at risk of flooding. Floods were common along the whole river corridor; in 2010 and 1998, significant flood occurrences resulted in significant flood damage. The region had disastrous floods due to a change in the region's precipitation pattern, one of the impacts of climate change (Magjar et al., 2021). The primary purpose of this study is to assess flood damage in the Vipava river catchment while considering climate change's effects. This study will investigate the potential flood damage in the lower Vipava valley's flood-prone region. Flood damage analysis will be carried out for selected flood scenarios related to the anticipated impact of climate change in the study area. The flood damage potential was investigated based on the designed flood event data adapted to specific climate-driven flood scenarios, and exposure/vulnerability elements. A hydrodynamical simulation was performed to define flood polygons and other characteristics of floods in the river basin. The hydraulic modeling was conducted using Hec-RAS software to define the presence of the flood hazard with different flood return periods. The simulation results from the hydraulic modeling were used to assess the flood damage in the study area using the KRPAN model. KRPAN enables the calculation of flood damage estimates by sectors which is applicable to the entire Republic of Slovenia's territory.

Flood damage analysis plays a significant role in proper flood protection measurements in the Vipava river valley; calculating the total projected flood damage while considering future climate change is a crucial step for adopting effective flood protection measurements. The primary objective of this study is to estimate the flood damage potential in the study area, considering the impact of climate change. However, future research could conduct a cost-benefit analysis of planned flood protection measures following flood damage analysis.

## 1.1 Objectives

The study objective encompasses the following details:

- Evaluate the climate change impacts on river discharge in the study area;
- Conduct hydraulic modeling to define flood polygons in the study area;
- Determine the flood extent and flood depth distribution of the climate-driven flood scenarios to be used as input to the KRPAN model for flood damage analysis.;
- Assess each sector's flood damage potential in the study area based on the climate-driven flood inundation scenario results of RCP 2.6, RCP 4.5, and RCP 8.5;
- Create a damage probability curve for each flood scenario based on the selected return periods;
- Estimate the total expected annual flood damage for each climate-driven flood scenario.

## 1.2 Research questions

According to the problem formulation, the following research questions will be addressed in this study:

- What impact does climate change have on the maximum river discharge rates?

- How will the current situation and several hypothetical representative concentration pathways, including RCP 2.6, RCP 4.5, and RCP 8.5, impact the flood extent and depth of the fluvial floods and the related economic damage in the Vipava river catchment?
- Which floodplain areas along the studied Vipava river section are most severely affected during an extreme flood scenario?
- Which economic sectors and types of land use are most affected by the expected climate change impact on river flooding?
- How do the different flood scenarios affect the expected annual damage from the fluvial floods in the Vipava river catchment?

## 1.3 Practical Value of the study

The thesis results will present a thorough analysis of different flood scenarios on the economic damage due to flooding as one of the crucial elements of climate change adaptation. A systematic flood damage analysis will provide a detailed understanding of the potential flood damage in the study area, as there has been no systematic evaluation of flood damage conducted for the Vipava river catchment. Moreover, as the climate change projections for the Vipava river basin published by the Slovenian Environment Agency under scenario A1B show a 2% rise in precipitation for winter months until 2030, flood damage analysis for different flood scenarios will help to understand how flood inundation and damage could vary under climate change scenarios in the lower vipava river valley. This study will also contribute to a database of KRPAN application model for flood damage estimation. KRPAN has been used in several studies to estimate flood damage potential for several case studies in Slovenia. The investigation of flood damage for the Vipava river catchment with KRPAN will be an additional database to the software application in flood damage assessment.

# 2. LITERATURE REVIEW

This section summarizes the literature review of the study objectives. An overview of climate change projection, hydraulic modeling with Hec-Ras, and flood damage analysis relevant to the study objectives and methodologies are discussed in this chapter. A background on fluvial flood risk and climate change impact is also briefly highlighted

## 2.1 Climate change Impacts and Fluvial Flood Risk

Beyond the impacts of natural climatic variation, human-induced climate change has had various adverse consequences, such as more frequent and intense extreme events (Pörtner et al., 2022). Floods result in thousands of deaths and enormous economic losses each year. Globally, floods caused about 220,000 lives and more than $1 trillion in direct economic losses between 1980 and 2013 (He et al., 2022). Several climatic factors, notably precipitation and temperature trends, affect floods (Bates et al., 2008). Numerous climatic trends relevant to floods have been observed, demonstrating the continuous effects of climate change. The global climate system is warming, and this conclusion is confirmed by observations of rising air temperatures across all regions during the past 50 years, with a 0.65°C increase in the world average temperature (Kundzewicz et al., 2010). Given that increasing temperatures allow more water to evaporate from the land and oceans, changes in the frequency of intense precipitation events may impact how frequently rivers flood.

Sauer et al. (2021) noted that since the 1980s, more extreme daily precipitation events had been seen than expected in a stagnant climate (12 percent increase between 1981 and 2017), and this trend has been associated with anthropogenic global warming. Ionita and Nagavciuc (2021) stated that under a high-end climate scenario, climate change might triple the direct damage of floods over the twenty-first century if no mitigation measures are implemented. Furthermore, a 2-degree-centigrade increase in global warming could cause a 170 percent increase in flood damage compared to the current situation, and a 4-degree-centigrade rise could cause a 580 percent increase in flood risk in countries holding 73 percent of the world's population (Ionita and Nagavciuc, 2021).

Climate change would also likely intensify precipitation and prolong dry periods in Europe. In most of Europe, heavy daily precipitation is projected to rise by up to 35% in the twenty-first century ( Kučić, 2018). In its comprehensive study of the physical science of climate change, the IPCC also concluded with high confidence that this is a growing trend in Europe, particularly for winter flooding ("UN Environment Programme," n.d). The IPCC also noted that since the middle of the 20th century, socioeconomic damage from floods has intensified due to increased exposure and vulnerability. As a result, with the population growth and economic development in flood-prone areas, the effects of future fluvial floods will increase (Yin et al., 2021).

A fluvial flood occurs when a river surpasses its natural banks and covers an ordinarily dry area. Depending on the geographic environment, river floods occur in various ways (Arnell & Gosling, 2016). According to Blöschl et al. (2015), river flood characteristics are influenced by processes in all three compartments. The first is the atmosphere, the source of precipitation; the second is catchments, which are regions of land, soil, and groundwater; and the third category consists of the river system. Any alterations to these processes will result in changes to the floods themselves. River flooding may be caused by rain that falls on ground that is already saturated or by rain that exceeds the soil's capacity for infiltration, and the soil saturation in these circumstances determines the extent of the flood. As a result, the impact of climate change on a flood's characteristics varies throughout space based on the process that creates it (Arnell & Gosling, 2016).

## 2.2 Climate change projection

The future climate will be determined by global warming caused by the release of greenhouse gases and natural climate variability (Fletcher,2018). The projected climatic extremes change significantly impacted by the emission scenarios' pathways and greenhouse gas /aerosol forcing ratios (Wang et al., 2017). The IPCC-AR5 defined four projected greenhouse gas emission pathways for the twenty-first century to serve as guidelines for designing mitigation and adaptation policies (Fletcher,2018). These include a very high greenhouse gas emission scenario (RCP 8.5), two intermediate scenarios (RCP 4.5 and RCP 6), and a stringent mitigation scenario (RCP 2.6). Scenarios in which humans fail to engage in efforts to limit greenhouse gas emissions led to pathways ranging between RCP 6.0 and RCP 8.5. 5 (Fletcher,2018).

Climate change caused by greenhouse gas emissions will diverge between scenarios up to and beyond 2100. (Change, 2014). The choice of emissions scenarios considerably impacts the expected level of climate change by the middle of the twenty-first century (Fletcher, 2018). Such predictions, also known as projections, are typically made by scenario assessments, in which the causes of floods are modeled mathematically. (Blöschl et al. 2015). Climate models provide essential insights into future global climate, and while their ability to predict regional and localized climate remains limited, it is improving as computer computing power increases. (Fletcher, 2018). In addition to the uncertainty caused by a lack of precise future greenhouse gas emissions, future climate simulations are riddled with two other sources of uncertainty (ARSO, 2021). The first is caused by the inherent variability of the climate. Another source of uncertainty is the methods we use to study the future climate, specifically climate models. The basic conclusion gained from climate change science is that the hydrological cycles are anticipated to accelerate with global warming. However, climate models cannot reproduce the fine details of observed precipitation, which is the primary input data to hydrological systems (Kundzewicz et al., 2010). However, such estimates are required, even if their accuracy and dependability are severely constrained. Researchers are expected to arrive at more credible estimates with more data and better tools; currently, the outputs are mostly model and scenario-dependent (Kundzewicz et al., 2010).

## 2.3 Analyzing the impact of climate change on river discharge

Climate change can affect society and the environment by changing river flows, particularly unusual peaks or low flows (Nouri et al., 2021). In this aspect, variations in climatic indices, such as temperature and precipitation, directly affect streamflow and thus indirectly contribute to changes in flow regimes (Li et al., 2013). Since extreme precipitation events are occurring more frequently and with higher intensity, scientists are relating changes in the atmosphere to changes on the surface, as determined by soil moisture and river discharge. (Wu, 2018). In this case, precipitation and river runoff projections related to climate change are essential sources of information for predicting flood discharge (Nohara et al., 2006). Hydrological models commonly use input from climate models to analyze potential impacts on river flow (Kay et al., 2021). Future climates, for example, are projected using atmosphere-ocean general circulation models (GCMs) driven by greenhouse gas emission scenarios, with the output being changed in climate variables such as temperature and precipitation through time and space (Wu, 2018). The effects on river discharge can also be assessed using hydrological models that use GCM outputs to generate estimates of streamflow, runoff, and soil moisture (Wu, 2018). Regional or watershed impact assessments necessitate a finer geographical scale than those produced by GCMs or other large-scale climate models; in such cases, a statistical and dynamical downscaling technique of regional climate models (RCM) is utilized (Wu, 2018; Quilbe et al., 2008).

## 2.4 Simulating Flood Hydrographs Using Dimensionless Hydrographs

Analyzing the hydrologic response of a rainfall event in a watershed requires the development of a unit hydrograph. Most of the time, the hourly stream flow measurements required to derive a unit hydrograph are not always available. Therefore, methods for determining unit hydrographs must be developed. These techniques are based on theoretical or empirical formulations that connect the watershed parameters of a watershed with the timing and peak discharge of hydrographs, commonly known as synthetic unit hydrograph (SCS). In SCS, discharge is a percentage of the peak discharge, and the time step is a percentage of the unit hydrograph's rise time. The dimensionless synthetic unit hydrograph for the study basin can be used to estimate the unit hydrograph by determining the peak discharge and the lag time for excess rainfall at a given time (Kaffas & Hrissanthou., 2014).

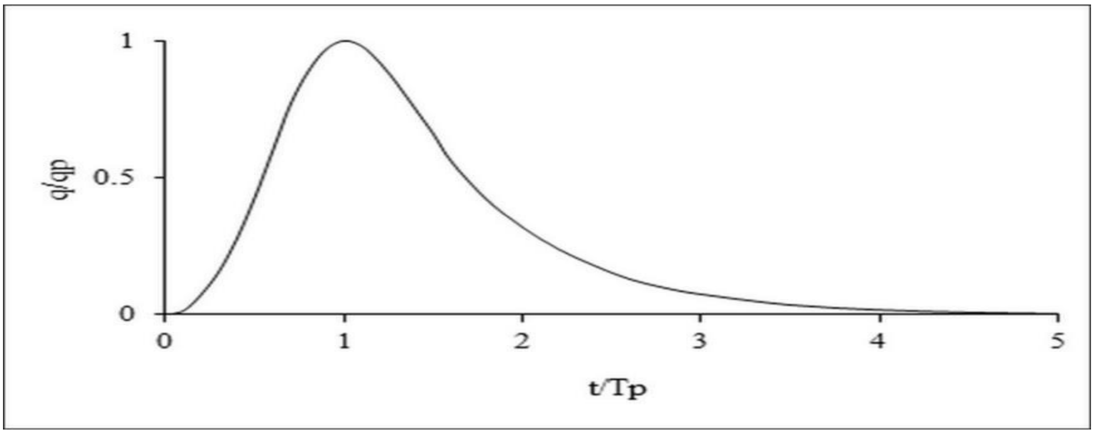



Figure 1: Dimensionless SCS synthetic unit hydrograph (Kaffas and Hrissanthou,2014)

## 2.5 Using Hec Ras for 1D-2D Hydraulic modeling

The hydraulic model basically depicts the events that occur during a flood (Cook, 2008). Using hydraulic modeling, observed or simulated discharge is transformed into flood extent and depth. Numerous flood models that use various hydrological techniques have been created during the past few decades. One of the popular tools for hydraulic modeling is Hec Ras, and according to a review of the literature, Hec Ras is among the most widely used flood modeling software (Zainalfikry et al., 2019). Modeling of sediment movement, water temperature, and quality, as well as simulations of 1D and 2D flow, are all functions of the model (Dasallas et al., 2019). The HEC-RAS model is free and easy to use for simulating flood patterns and other hydraulic aspects in the river basin. Most government and business agencies recognize this software's output, and add-on packages allow it to interact with or be connected with other hydrological applications ( Mbajiorgu, n.d ). The features mentioned above, advantages, and high accuracy for floodplain mapping necessitated the selection of this model in this study.

The Hec-Ras fundamental calculation method for steady and unsteady flow is based on a one-dimensional energy equation and the implicit finite difference technique ( Mbajiorgu, n.d ). The advantages of the finite-volume approach utilized in HEC-RAS are attributed to its geometric flexibility and conceptual simplicity (Ongdas et al., 2020). Building the model geometry and output post-processing is made simple by Hec-GeoRas and ArcView GIS' seamless connection with the GIS program ArcView. The cross sections and the river geometric data can be produced using GeoRAS, and it is possible to transfer surface water data from Hec-RAS back into ArcView to produce flood inundation maps (Ongdas et al., 2020).

Hydraulic modeling can be classified as 1D, 2D, or coupled 1D–2D model. 1D can model represents flow in the river. Although 1D model can be effective in computation, it has modeling drawbacks. Such drawbacks include the inability to model flood wave lateral diffusion and sensitivity to cross-section position and orientation (Cook, 2008). The accuracy and precision of 2D models are better for simulations of complex flows. However, 2D models also need many processing data, making real-time flood forecasting challenging (Cook, 2008). The latest advancement in flood inundation modeling is the use of a combined one-dimensional main channel model and a two-dimensional floodplain model. Coupled 1D and 2D hydraulic modeling enable the representation of channel flow in 1D and the modeling of flood plains in 2D (Dasallas & An, 2019). One of the most significant features of coupled 1D/2D models is the direct interaction between the 1D and 2D flow elements at each time step to properly determine the peak floodwater depth at each model grid unit (Vozinaki et al., 2017). 1D–2D connections are frequently modeled with lateral weir equations, wherein the flow is computed based on the difference in water level.

## 2.6 Estimation of flood damage

Accurate flood damage estimation is essential for calculating actual risk and assessing the cost-effectiveness of flood protection strategies which require significant investment (Arrighi et al., 2018). Over the last ten years, academics have emphasized developing a flood defense system and implementing policies to prevent the risk of flood. However, in recent years, the importance of conducting flood damage assessments has become much more acknowledged (Mushar et al., 2019). Floods can cause damage to property, physical injury and death, animal mortality, and environmental pollution, among other things. A flood can affect both tangible and intangible properties directly or indirectly. Direct damage occurs when floodwater directly contacts assets, including buildings, people, properties, and other environmental items. The damage that arises after a certain period due to direct damage is known as indirect damage (Mushar et al., 2019).

| | Direct loss | Indirect loss |
|---|---|---|
| Tangible | Structural damage<br>Cars<br>Infrastructure<br>Livestock<br>Crops<br>Evacuation and rescue operations<br>Clean up costs | Disruption to transport<br>Business interruption<br>Temporary housing of evacuees<br>Loss of industrial production |
| Intangible | Lives and injuries<br>Diseases<br>Loss of memorabilia and pets<br>Damage to cultural or heritage sites<br>Ecological damage<br>Inconvenience | Stress and anxiety (PTSD)<br>Disruption of living<br>Loss of community<br>Reduced land values<br>Undermined trust in public authorities |

Table 1: A description of damage classifications and some examples ((Olesen et al., 2017))

Many studies have also shown that direct, tangible damage is the most significant damage category. This is because it is the most well-understood damage class and has also been widely used in flood damage assessment studies (Hammond et al., 2015). According to Hammond et al. (2015), the most crucial flood characteristics influencing the degree of flood damage are the flood depth, velocity, duration, and water contamination level. Among these, flood depth is the essential characteristic for damage assessment. The degree of damage also depends on how resilient the elements exposed to floods are. As a result, it is crucial to consider the structure's quality in the evaluation if possible (Olesen et al., 2017; Thieken et al., 2008).

The flood damage can be categorized into a wide range of groups depending on sectoral entities. The main damage classes are buildings, agriculture, businesses, and public infrastructure. These categories could be further divided into subcategories depending on the details of the damage analysis and the exposure characteristics (Olesen et al., 2017). Public infrastructure damage includes various possibly impacted structures and categories such as water supply networks, sewerage networks, electrical lines, roads, and railways (Merz et al., 2019). Damage to agriculture includes loss of agricultural products such as crops and meadows and damage to farm infrastructure (Dutta et al., 2003).

The depth and damage functions are used to estimate flood damage. The empirical and synthetic methods are two methods that have been commonly applied (Mushar et al., 2019). The empirical model is created using data gathered after the flood event. Some of the models that apply the empirical models are the commercial sector flood loss estimation model (FLEMOcs), the flood loss function for Australian residential structures (FLFArs), and the Flood loss estimation model for the private sector (FLEMOps) (Mushar et al., 2019). A synthetic-based model, on the other hand, is a model that integrates land use characteristics, item categories, and questionnaire data. The Hazards U.S. Multi-Hazard (HAZUS-MH), the Flemish model, and (FLEMOps) are some of the flood damage estimation models for tangible damages (Gerl et al., 2016). The applications of these models can be distinguished by their inputs and scope. For instance, FLEMOps primarily focuses on estimating the direct damage to residential buildings and properties with respect to flood depth (Kefi et al., 2018). HAZUS-MH includes three different applications (earthquake, wind, and flood). The U.S. uses this program to calculate direct and indirect tangible damages (Kefi et al., 2018). Geographic information systems (GISs) have also recently been used by particular academics to assess flood risks and damage on a wide scale. GIS is useful software for mapping flood risk zones and analyzing risk (Kefi et al., 2018).

## 3. CASE STUDY AREA

The location of the study is in southwest Slovenia and is a part of the Vipava river basin. The Vipava river runs across western Slovenia and northeastern Italy. The river spans 49 km in total and 45 kilometers in Slovenia, covering an area of 598 $k.m^2$. The valley is primarily formed of alluvial sediments in which the soil is very fruitful, and the mountain regions enclosing the river have a sedimentary rock with an impervious nature. The river originates in the small town of Vipava, at the bottom of a steep slope of Mount Nanos, where a series of springs fall into the river bed in the shape of an inverted delta. In addition to these source springs, the torrent Bela, the Hubelj River, Branica Creek, and Moilnik Creek are tributary rivers that discharge into the Vipava river. During heavy precipitation, the Hubelj River discharges high water into the Vipava River.

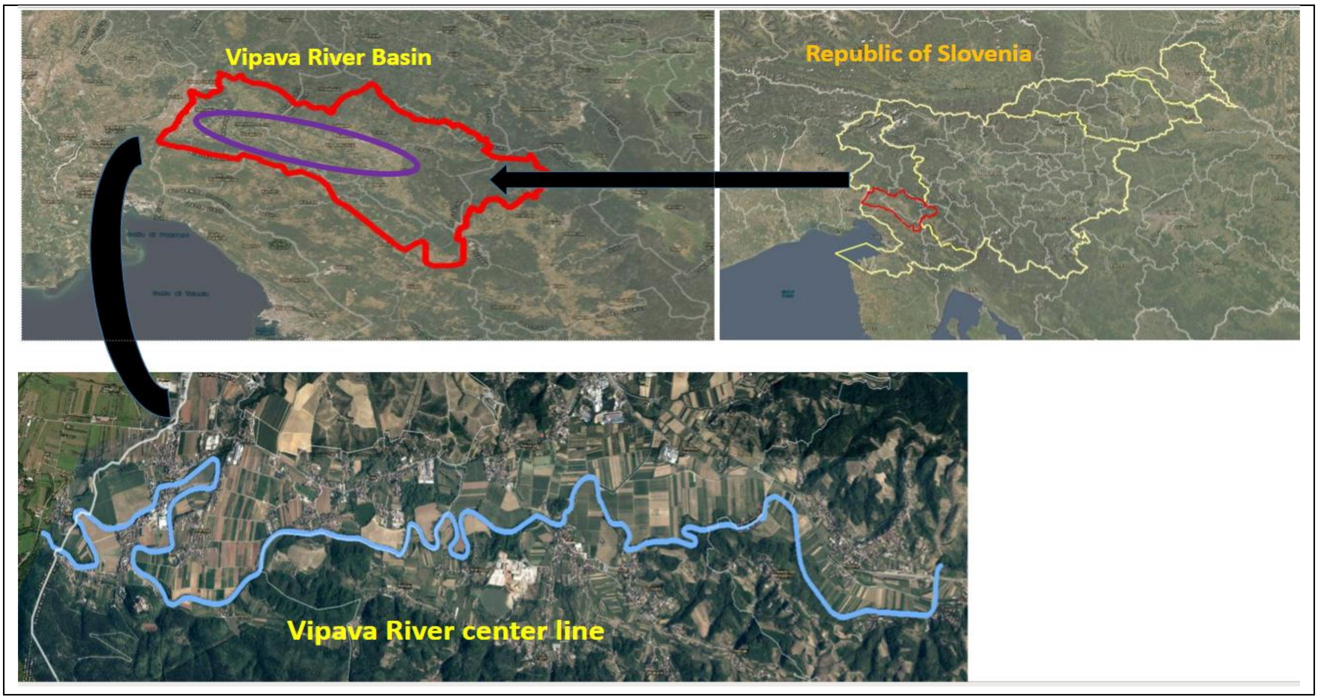



Figure 2: Location of the Vipava river study area in Slovenia

The study site in this research along the Vipava river is 19.5 k.m long and is characterized by meandering bends, as represented in figure 2. The Vipava River has characteristics of a pluvial or pluvial-nival flow regime. The river has a low and persistent flow during the summer and two high flows in early spring and autumn. Due to the snowfall from the mountains in late winter, there is a relatively short but noticeable flow (Magjar et al., 2021). The river flow also varies significantly due to the geomorphic character of the watershed.

### 3.1 Flood hazard in lower Vipava river valley

Floods were common along the Vipava river basin. The primary causes of this are the hydrological characteristics of Vipava and the valley's topography. There have been several interventions made in the Vipava river. These include widening and deepening the river channel and straightening the river where it meanders. The Vipava River's regulations and measures have improved flood protection in the basin's upper reaches. However, because of a quicker runoff toward the basin's lower region, floods have become more frequent, and several catastrophic floods have happened in recent years due to extreme rainfall events, one of climate change's impacts (Magjar et al., 2021). Below is a description of the major flood events in the Vipava river catchment.


Figure 3: In September 2010, a flood reached the bridge deck, and many streets were closed due to the flooding.

There were heavy flood events that occurred in the Vipava river basin. In the town of Vipava in October 1998, 35 homes and a water treatment facility were inundated. The event also led to the inundation of homes and post offices in Podnanos and the Mayor's Road. In September 2010, the river inundated the areas along the valley downstream. The flood incident significantly impacted the cities of Miren and Rence. The city's road network, as well as homes, vineyards, vegetable farms, and orchards, were inundated by the river flood. In Rence, the flooding incident for the first time reached the bridge deck (Figure 3), and the new bypass road was also partially flooded. According to some estimation, the water was deeper than the river's maximum recorded water depth by 70 cm. The river's discharge was assessed to be a 100-year flood event.

### 3.2 Climate change impact on Vipava valley

The Vipava River basin has a Mediterranean climate with warm, dry summers and moderate winters (Klemenčič et al., n.d). The higher region of the valley has around 2000 mm/year of average annual precipitation, whereas the lower region has around 1500 mm/year. The Vipava River catchment has been subjected to torrential floods caused by extreme peak discharges during heavy rainfall. The Euro-Mediterranean region's climate change scenarios indicate an increase in annual air temperature and a rise in the frequency of extreme events like floods and drought. According to a hydro-meteorological study conducted in Slovenia, small changes in rainfall's temporal and spatial distribution can lead to floods, and according to Slovenian Environment Agency climate change projections from 2008, scenario A1B shows that by 2030, the average annual temperature in the basin could rise by about 1.3°C (Magjar et al., 2021). Temperature increases can lead to higher precipitation in winter

# 4. RESEARCH METHODOLOGY

This chapter briefly describes the methodological framework followed in this study to achieve the research objectives. The procedures used in this study concern assessing flood damage caused by river flooding while considering the possible impact of climate change in the Vipava river catchment. The details of the methodology adopted and the data set applied in each section of the methodological framework are explained below.

## 4.1 Methodological framework

The methodologies used in this study to achieve the research objectives are illustrated in the diagram below. The methodological framework of the diagram illustrates the procedures adopted to estimate the flood damage potential in the Vipava river catchment. The procedures include data acquisition for the study area from various sources, hydraulic modeling of the Vipava river catchment using the Hec Ras software, climate change impact analysis based on the official report of the ARSO (Slovenia Environmental Agency), and flood damage analysis using the KRPAN model.

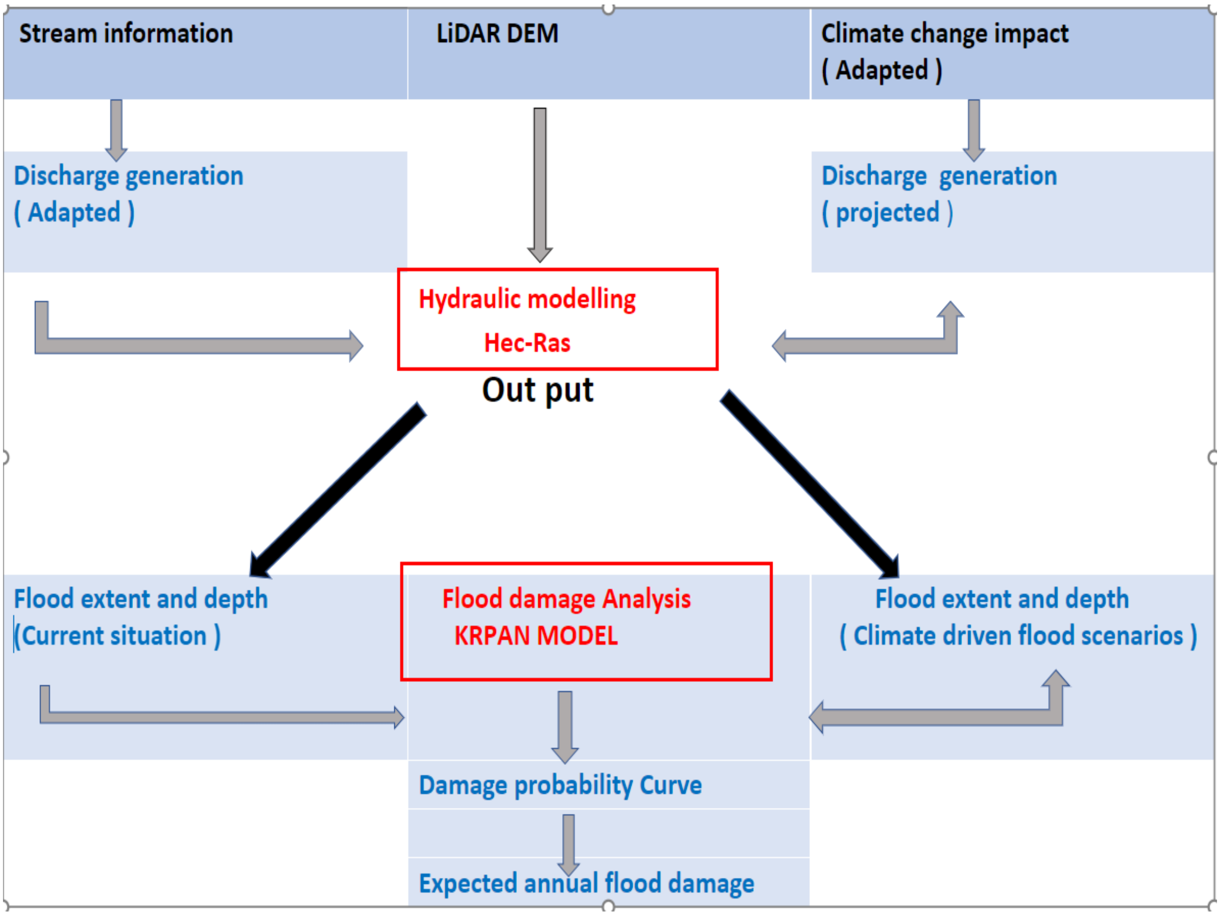



Figure 4: Methodological frame work

### 4.2 Data acquisition

The information for this study's data was compiled from various Slovenian ministries and government agencies, most of which are freely accessible online. The required data and sources for this study are listed below. High-resolution (1 m) Lidar data, hydrological data, and climate projection data were adopted from the Slovenian environmental agency. Online sources were also used to obtain geospatial data covering population, building registrations, public infrastructure, and land use maps.

| List of Data | Source |
|---|---|
| **Climate change projection** | ARSO |
| ➢ Regional data | |
| **Hydrological Data** | |
| ➢ Yearly data | |
| **Terrain Data (LiDAR DEM)** | Ministry of the environment and spatial planning |
| ➢ (1m resolution) | |
| **Registry of buildings** | |
| ➢ Scale 1: 1000 | |
| **Orthophoto** | |
| ➢ Scale: 0.25 m | |
| **Land use data** | Ministry of Agriculture, Forestry and Food |
| ➢ Scale: 1:5000 | |
| **Population data** | Slovenian statistical office |
| ➢ Scale:100 m by 100 m grid | |
| **Cultural heritage** | Ministry of culture |
| ➢ Scale: 1: 5000 | |

Table 2: The required data with its sources

### 4.2.1 Elevation data

The Ministry of Environment and Spatial Planning provided high-resolution LiDAR data for the Vipava river catchment for this study. LiDAR is a remote sensing process that utilizes an airplane outfitted with a laser that measures its distance from the surface. The airplane is also equipped with advanced GPS technology, allowing for precisely determining the aircraft's location. The target area's points are all identified by three-dimensional coordinates (latitude, longitude, and elevation), and this data is referred to as terrain layers (Alzahrani, 2017). Good lidar data quality is essential for the accuracy of hydrodynamical simulations and flood modeling (Stoleriu et al., 2020). The 1m-by-1m LiDAR resolution data used in this study could therefore enhance the accuracy with which floods are modeled.

### 4.2.2 Land use

Data on land use were taken from various sources as demonstrated in table 2. The study area in the Vipava river catchment has 14 % of forest, 74 % agriculture, 9% built up area, and 2 % water as demonstrated in Figure 5.

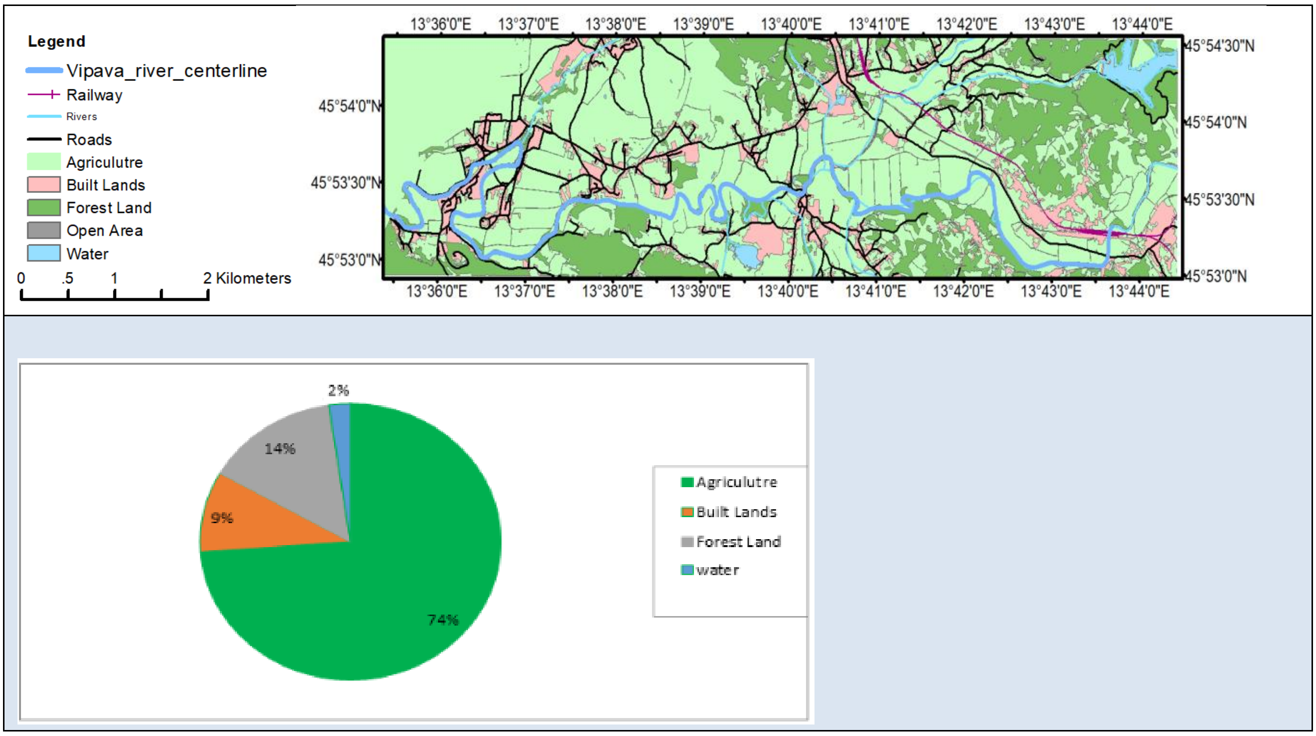



Figure 5: Land use classification and Land use Map in the study area

### 4.2.3 Hydrological data

The Slovenian Environmental Agency conducted a detailed hydrological investigation of the Vipava River and used the results of that analysis in this study. The used hydrological analysis result in this study refers to Miren Water Station. The Miren Water Station contribution hinterland is estimated to be 588 km2.

The rating curves (Q / H curves) at the Miren water station were utilized for the hydrological analysis in the study conducted by ARSO (Figure 6). In this hydrological analysis, the maximum flows were calculated using Q/H curves based on the highest recorded water levels for the year. The maximum flows of various return periods were assessed using probabilistic analysis by considering Log- Pearson III distribution.

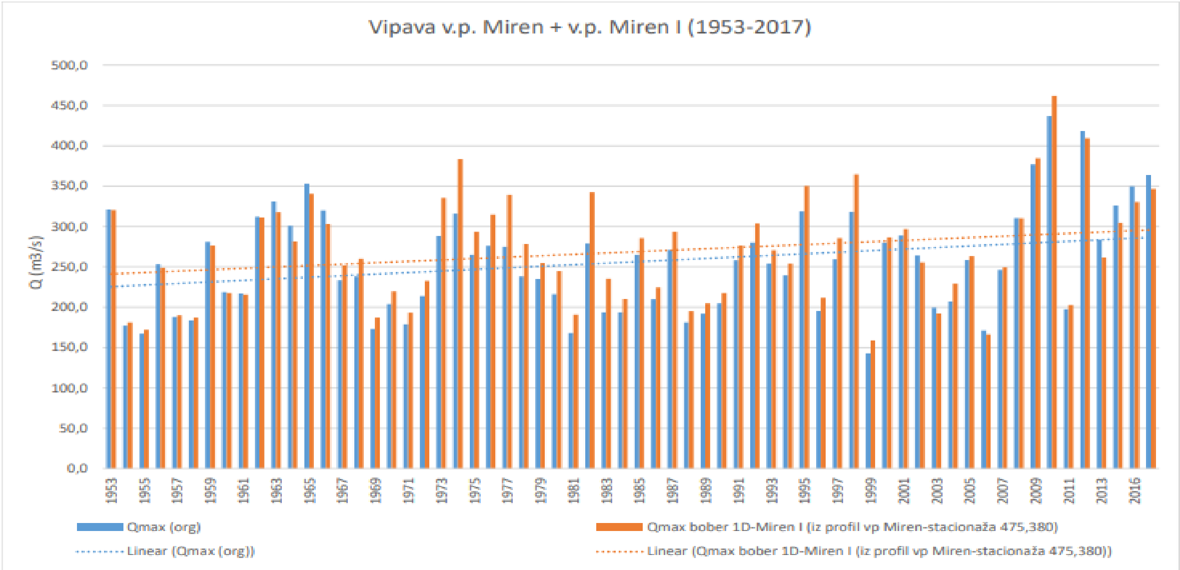



Figure 6: Vipava river flow for the period of 1953 to 2017 at Miren water station (Source: Slovenian Environmental Agency)

### 4.2.4 Climate change projection data

The ARSO climate project analysis for the territory of Slovenia was used for the climate impact study on the Vipava river flow. The climate projection analysis prepared by ARSO includes the changes in the maximum, minimum, and average changes in river flow for Slovenia. The general prediction in a change of annual peak referring to the water meter station in the Vipava region was used in this study. ARSO used a climate model from Euro-Cordex simulation data and a regional climate model to analyze the impact of climate change, and NAM hydrological model used to analyze the hydrological characteristics (Environmental Agency of the Republic of Slovenia (ARSO), 2021).

## 4.3 Climate change Impact Analysis

The climate change impact analysis for the Vipava river flow was adopted from the official report prepared by ARSO on Climate Change Assessment for Slovenia in the 21st Century. ARSO conducted a comprehensive analysis of the impacts of climate change on temperature, precipitation, and river flow in Slovenia. This study is based on the findings and conclusions of ARSO about the effects of climate change on changes in river discharges during the 21st Century at water stations which are part of the state hydrological monitoring, taking into account possible scenarios for greenhouse gas emissions.

The study foresees that the average annual peaks in Slovenia will rise by 20 to 30 percent under all emission scenarios (RCP 2.6, RCP 4.5, and RCP 8.5 compared to 1981 to 2010). For a high impact scenario (RCP 8.5), the increase will be between 20 and 40 percent at almost all water meter stations in Slovenia by the end of the Century (Environmental Agency of the Republic of Slovenia (ARSO), 2021). The report shows climate projections on how the discharge varies for maximum, minimum, and average flow for the water stations in Slovenia by considering three scenarios, namely RCP 2.6, RCP 4.5, and RCP 8.5.

The RCP2.6 scenario represents a strong climate action scenario in which carbon emissions are drastically reduced. In this case, the global temperature may be limited to no more than 2 °C global mean surface temperature (IPCC 2014). IPCC refers to RCP4.5 as an intermediate scenario, assuming that the radiative forcing will be 4.5 W/m2 in 2100. According to this scenario, greenhouse gas emissions will peak around 2040 and subsequently decline to half of 2050 levels by 2100, resulting in a projected 2-3 °C increase in global temperature by that year. Emission rates are anticipated to keep increasing even after 2100 in the high concentration scenario RCP8.5. This scenario refers to the current emission trajectory with just minimal climate action, which is projected to cause global warming of more than 4 °C (GMT) (IPCC 2014; Prütz, 2021).

Figure 7 below shows climate projections' impact on the river flow for the water stations in Slovenia for discharge of a 100-year return period. As shown in the Figure, the study covers the periods of 2010–2040, 2040–2070, and 2070–2100.

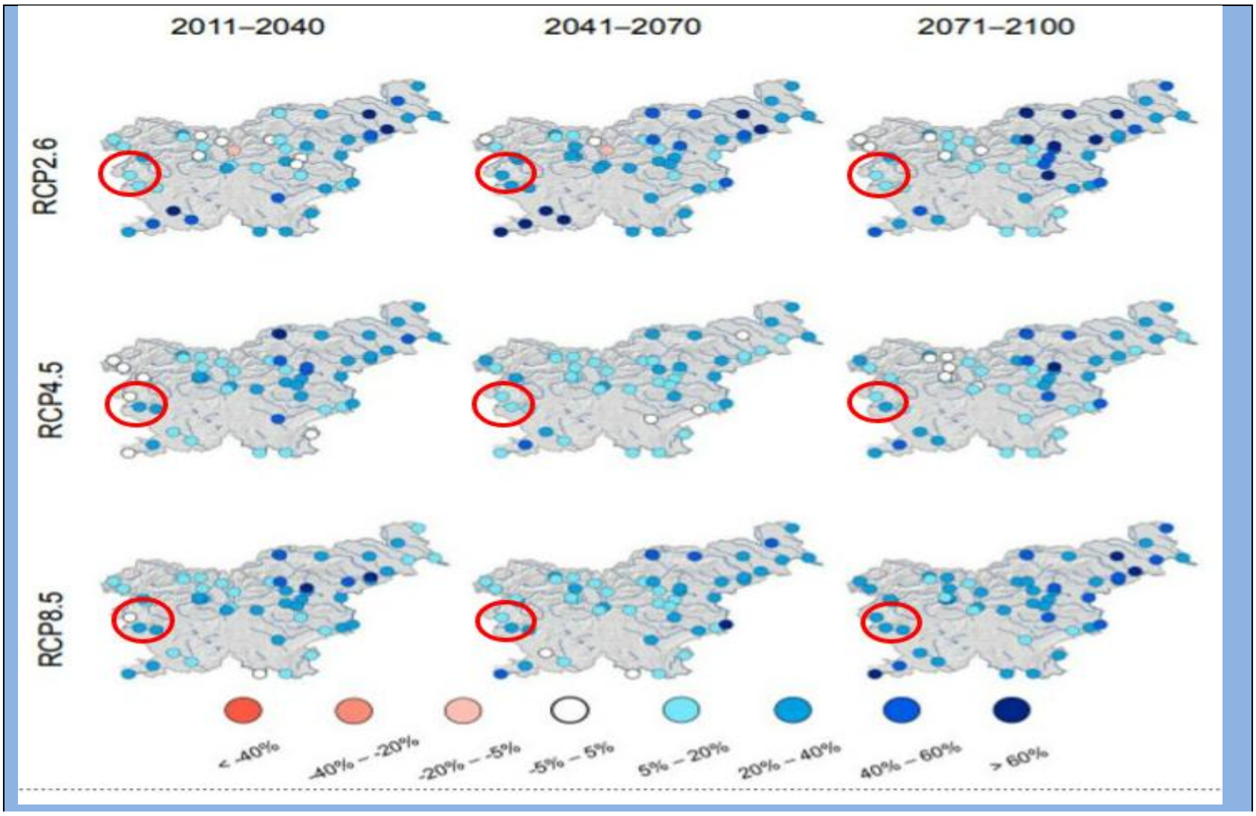



Figure 7 : Mean relative change in large flows with a 100-year return period in three projection periods compared to 1981-2010 for scenarios RCP2.6, RCP4.5 and RCP8.5 according to the Pearson distribution of the third type (source: ARSO)

The red circle refers to the water stations in the lower Vipava river valley, and its corresponding rate of change in discharge can be read in table 3. As seen from the diagram, the change is as low as 5 % change and as high as 40 % change in discharge. This range of values gives a broad estimate of the minimum and maximum change in the river flow to account for this study. In addition, it is crucial to consider all three RCP emission scenarios when determining how the river's peak flow would change, as each scenario represents how the climate may change in the twenty-first century based on various factors.

In this study, without additional available data and detailed projections about the climate change impact on flood characteristics, we assumed that the percentage change also represents a general change in the peak discharge. However, it targets the maximum and minimum levels of the ARSO projection and a fair distribution of the middle peak change discharges. Therefore, related to climate change impact analysis toward the end of the century, the following changes in high discharges have been associated with the particular RCP scenario (Table 3).

| **Climate projection scenario** | **RCP 2.6** | **RCP 4.5** | **RCP 8.5** | **RCP 8.5** |
|---|---|---|---|---|
| **Mean relative change in high discharges** | 5% | 10 % | 20 % | 40 % |

Table 3 : Selected percentile changes in large flow of the Vipava river according to the presumed climate change impact

## 4.4 Design flow hydrograph using synthetic hydrograph

In order to assess flood damage, it is common practice to choose a set of standardized flood scenarios that correspond to specific exceedance probabilities. The flood scenarios are planned for a high probability scenario with an exceedance probability of 0.2–0.1, while medium- and low-probability floods could correspond to exceedance probabilities of 0.02-0.01 and 0.002-0.001 and return periods of 50–100 and 500, respectively, in accordance with the EU Flood Directive recommendations (2007/60/EU) (Pistrika, 2010) .

The return period and the corresponding values are obtained from ARSO's official study report of hydrological analysis on the Vipava river and are listed in the table below. The statistical analysis of the discharge data from the Miren water station (the most downstream water station) was considered in hydraulic simulations.

| **Return period ( years)** | **Discharge ( $m^3/s$)** |
|---|---|
| **5** | 324 |
| **10** | 363 |
| **20** | 399 |
| **50** | 445 |
| **100** | 478 |
| **500** | 555 |

Table 4: Discharge values for different return periods at the Miren water station - Vipava Miren and Miren I (1953- 2017 ) (Source: ARSO)

The hydraulic model requires an input flow hydrograph for upstream boundary conditions; hence, this study uses a synthetic flow hydrograph to generate the flood model. (Ukumo, 2022). The discharges for the return periods of 5, 10, 20, 50, 100, and 500 years were considered. The flow hydrograph for the present climate and four scenarios of future climate change are shown in Figure 9, with return periods of 5, 10, 20, 50, 100, and 500 years. The depicted hydrographs' magnitude shows the highest fluctuation at their peak. According to the considered impact of climate change projections, the flood stream flow significantly increased between the RCP2.6 and RCP8.5 scenarios. Under the RCP8.5 scenario, the 500-year flood, which is a maximum discharge of 725, is especially high. The Synthetic SCS Dimensionless Unit Hydrograph method generates the flood hydrograph.

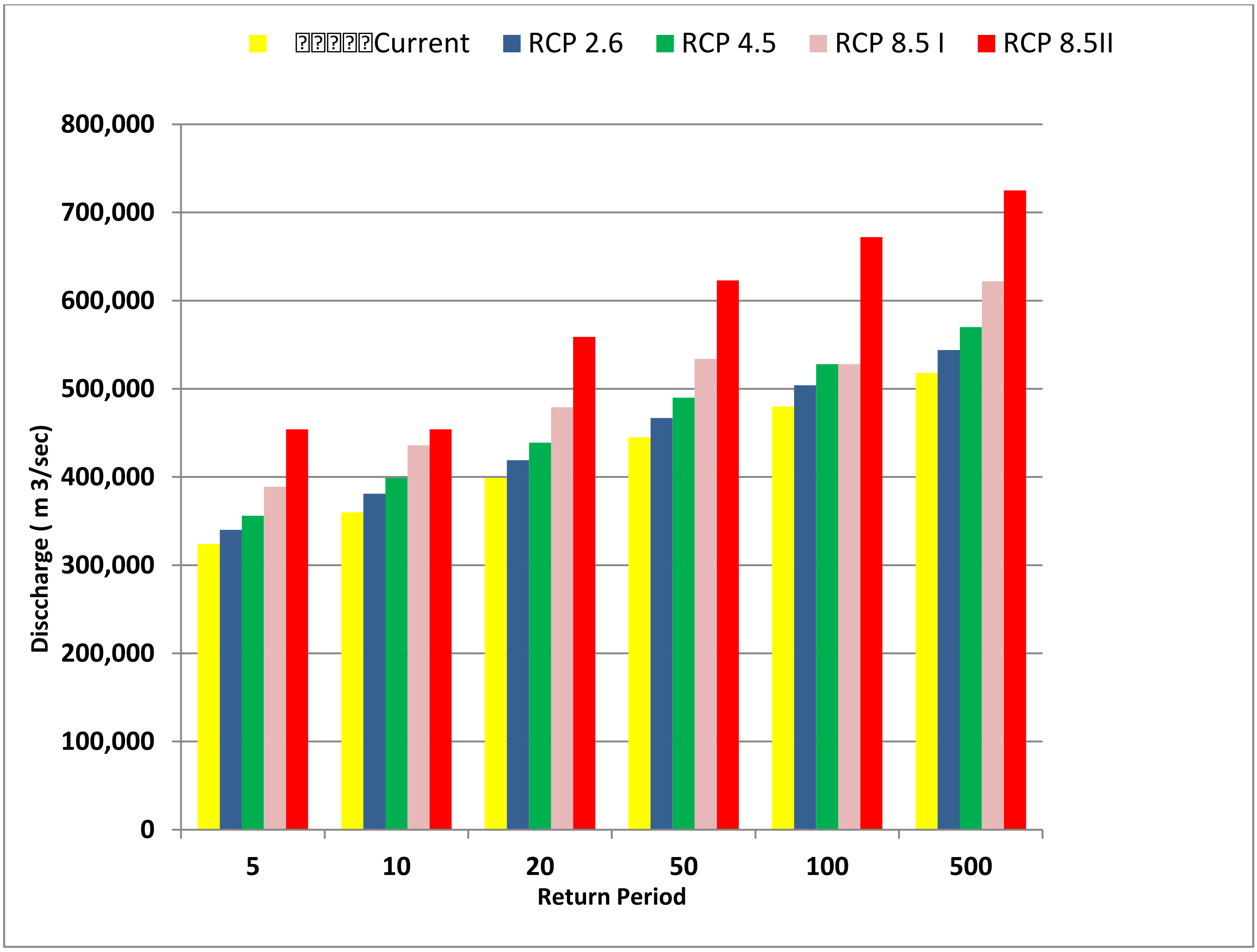
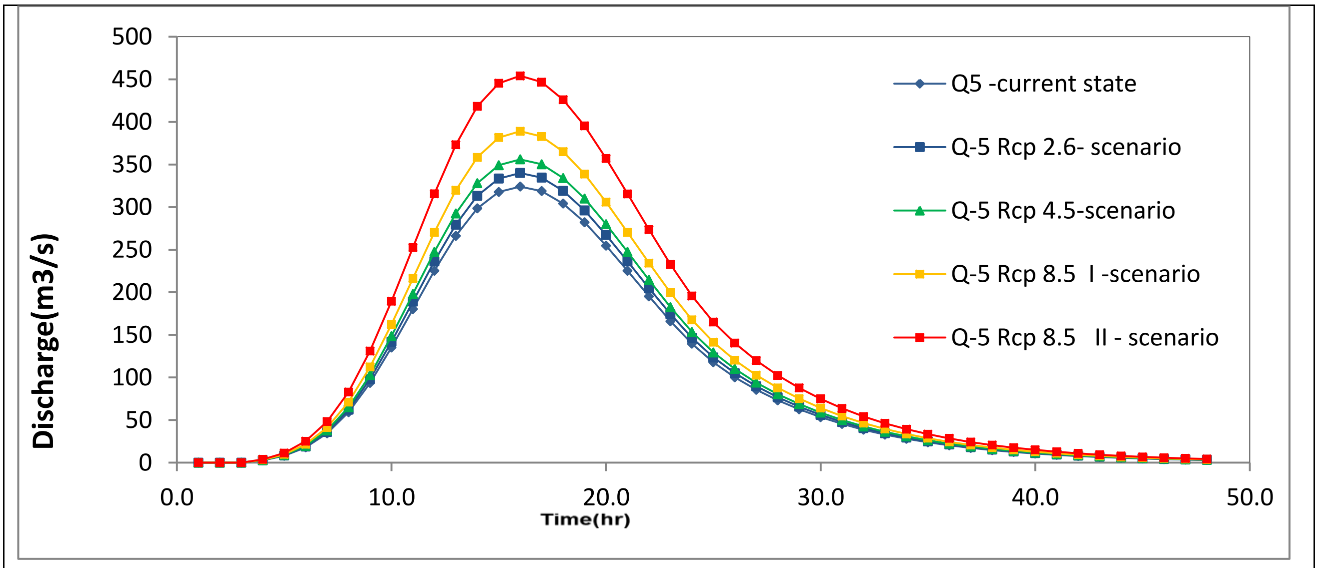
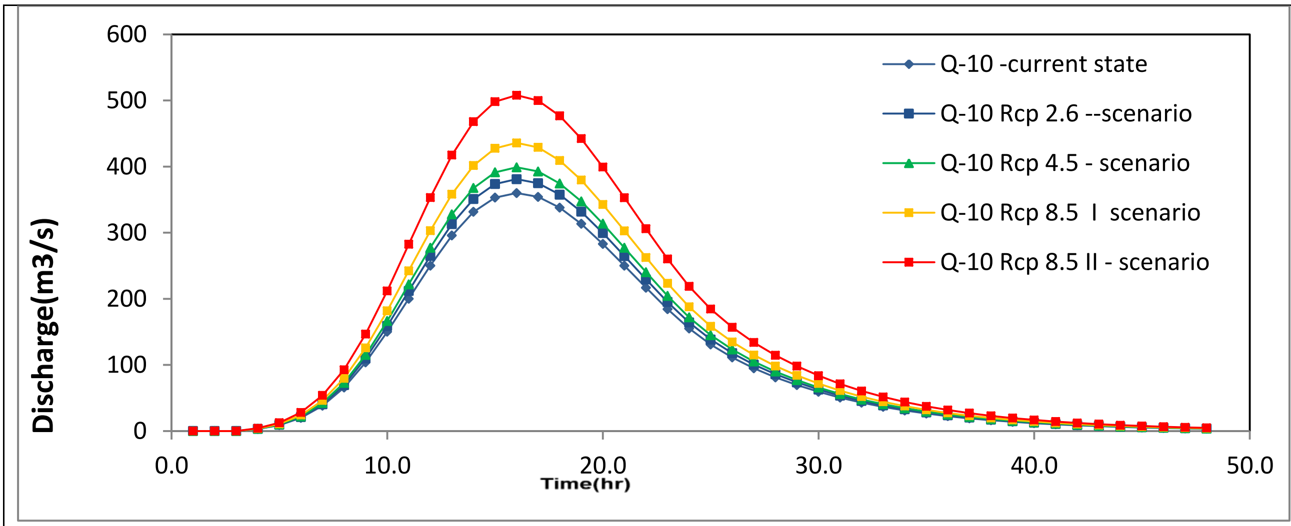


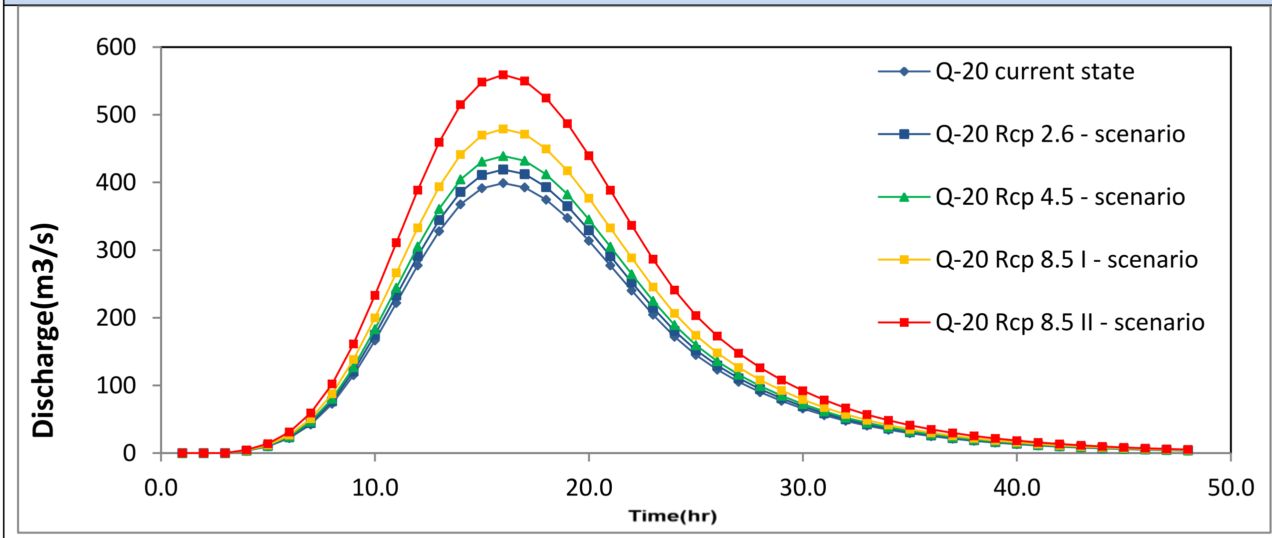

Figure 8: Maximam discharge for the current and climate driven flood scenarios



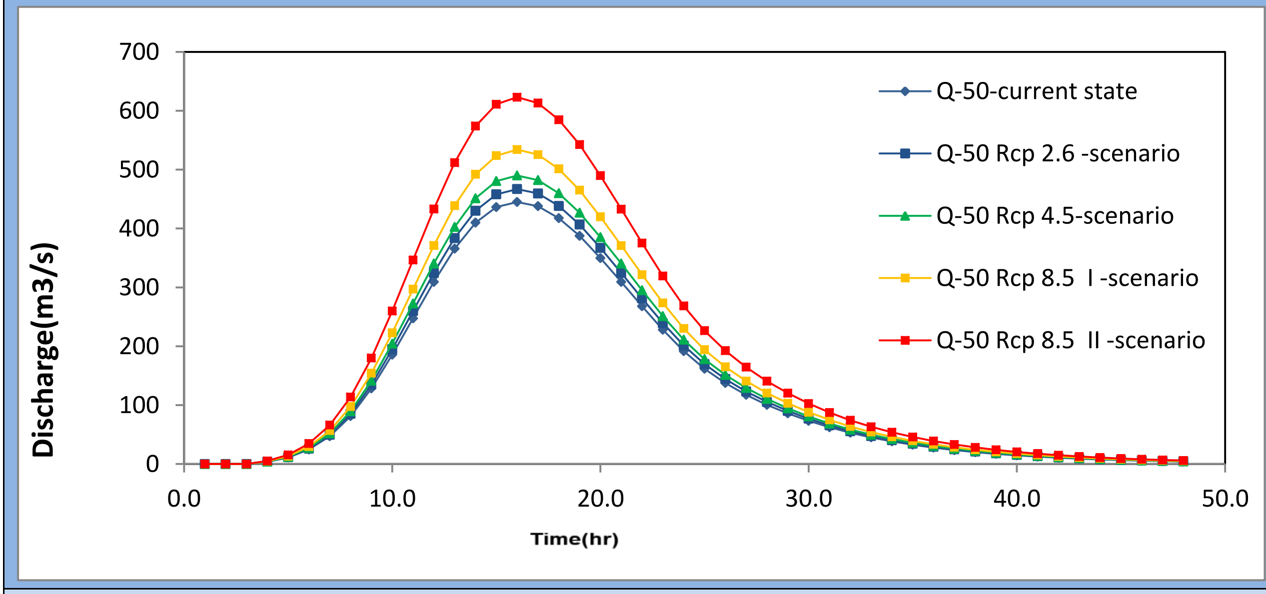

A) Synthetic flow hydrograph scenario 5-year return period



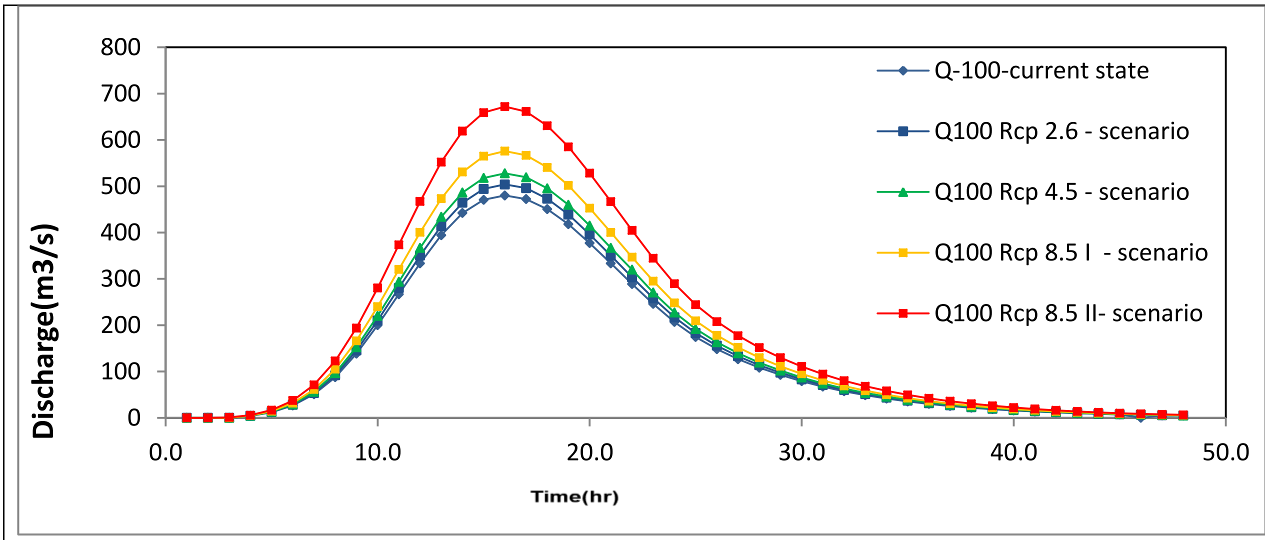

B)Synthetic flow hydrograph scenario 10-year return period



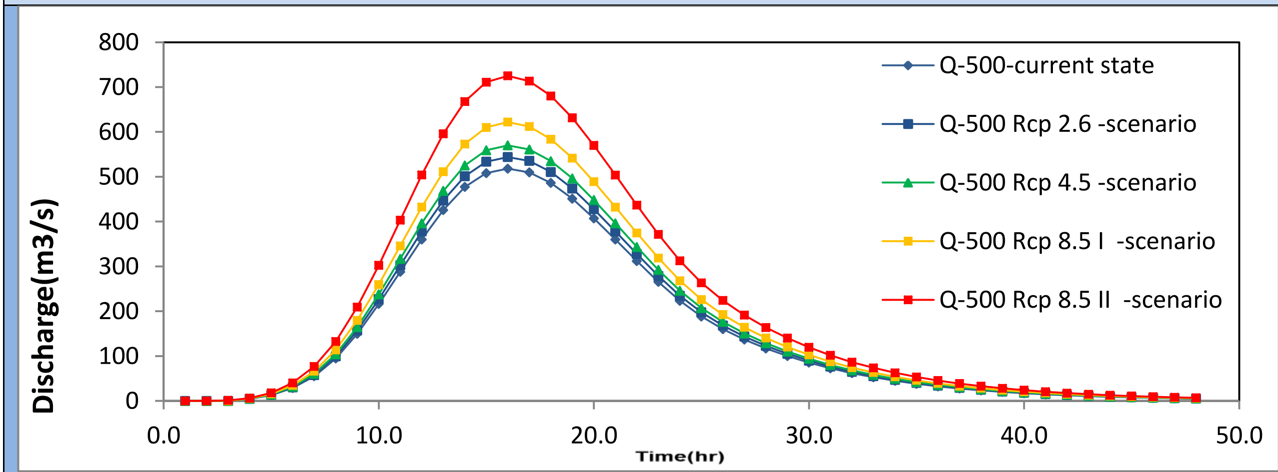

C)Synthetic flow hydrograph scenario 20-year return period




D )Synthetic flow hydrograph scenario 50-year return period




E )Synthetic flow hydrograph scenario 100-year return period




F ) Synthetic flow hydrograph scenario 500-year return period

Figure 9: Synthetic flow hydrograph for current and climate driven flood scenarios

## 4.5 Hydraulic modeling

In this study, a combined 1D and 2D hydraulic model was prepared to define the flood polygons in the study area. High-resolution LiDAR data of 1m-by-1m grid size and ground survey data of the river cross-section were used as input to Hec Ras for the model setup. A lateral structure was created to connect the 1D and 2D portions of the river system (Figure 10). First, the 2D in the study area is delineated by creating a mesh size of 10 m by 10 m grid size cell. Following that, a lateral structure, upstream and downstream boundary conditions, Manning roughness of the 2D area, and other model parameter values were defined to initialize the modeling. Several steps were taken during the hydraulic model setup process to determine the proper hydraulic and numerical parameter settings. These steps included adjusting the mesh size, computation time step, weir width, and coefficient values to create a numerically and hydraulically stable model. The model in this study was not calibrated with other actual flood events, but the model simulation results for different return periods compared to Slovenia's official hazard map, and the extent of the flood was similar. Moreover, the high-resolution LiDAR data and ground survey data used in the model could also enhance the quality of the model.

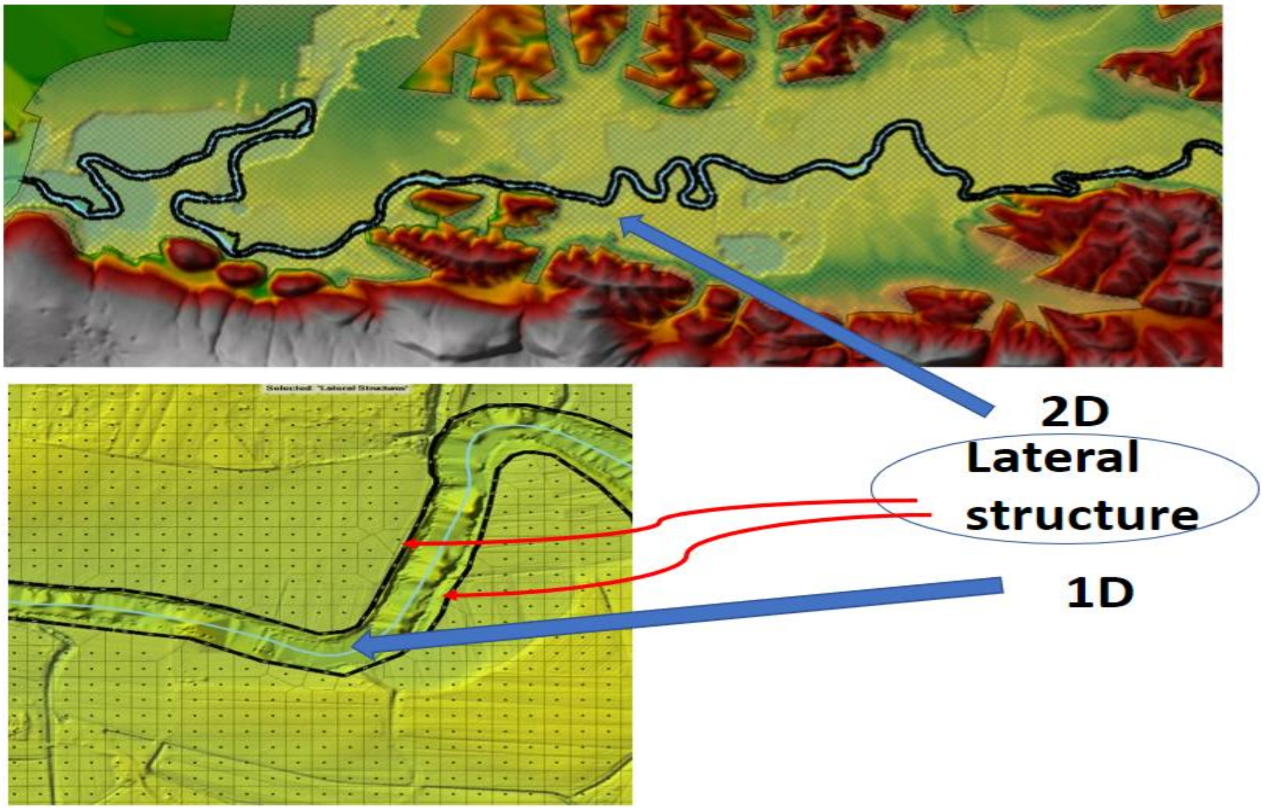



Figure 10: 1D-2D Model set up in the study area

### 4.5.1 Elevation data

The DEM information utilized in this analysis is composed of the ground survey data for the river and the Lidar DEM from the flood plain. LiDAR can portray the terrain accurately, but it cannot properly characterize the bathymetry of the channel. This is due to LiDAR waves being unable to penetrate into subsurface terrain along rivers, which can cause models to be inaccurate (Podhoranyi and Fedorcak, 2014). Thus, field survey data cross-sections and LiDAR data were integrated to include actual terrain beneath the water's surface in the channel, combining the accurate river geometry into flood analysis.

### 4.5.2 Cross-section data

For hydraulic modeling, accurate cross-sectional data is necessary because river bathymetry determines the flow's characteristics (Betsholtz & Nordlöf, 2017). Cross-sectional data is a collection of points with coordinates for elevation, longitude, and latitude measured in the field. It is advisable to take measurements to record significant bathymetric changes. This includes areas where the flow passes below bridges, culverts, or other structures that may involve major accelerations (Betsholtz & Nordlöf, 2017). Cross-sectional data for this study was provided as a shapefile by the Slovenian Water Agency (DRSV), who has conducted hydrological and hydraulic studies in the river catchment. A total of 222 cross sections were used in this for the hydraulic modeling

.

### 4.5.3 Lateral weir structure

A lateral structure was added to the model spanning both sides of the river ( left and right bank) . A weir equation connects the 1D and 2D portions of the model.

$$dQ = C(yws - yw)^{2/3}\, dx \qquad (1)$$

Where yws is the water surface height, yw is the elevation of the lateral structure, and C is the weir coefficient, dQ represents the flow through the lateral structure over the length dx.

### 4.5.4 Boundary condition

A synthetic flow hydrograph used as upstream boundary condition in the modeling. The synthetic flow hydrographs presented in Figure 9 used as in put in the upstream boudnary for each flood scenarios. The average slope of the channel at the downstream section of the Vipava River used as normal depth for downstream boundary condition.

### 4.5.5 Mesh design and manning rougness

A mesh size of 20 m by 20 m was used in the model and as lidar data have high accuracy this grid size cell can produce a good model result. This mesh size was established considering the computational time as well as stability of the model.Regarding the land use characteristics, the Vipava river catchment has 14 % of forest, 74 % agriculture, 9% built up area, and 2 % water as shown in figure 5. The Manning's roughness coefficient values for the 2D model was used based on each land use characteristic. The Manning values with the respective land use are displayed in the table below.

| Codes and items | Manning's N |
|---|---|
| 1211 -- Wineyard | (0.08) |
| 1500 -- Trees and shrubs | |
| 1221 - - Intensive orchard | |
| 1222 - -Extensive orchard | |
| 1230 - - Olive grove | |
| 1190 - Greenhouse | |
| 1300 - - Permanent (Perennial) grassland | 0.04 |
| 1600 - - Uncultivated agricultural land | 0.045 |
| 1410 - - Overgrown land | 0.04 |
| 1100 - - Field or garden | 0.05 |
| 1180 - - Perennial plants in arable land | 0.05 |
| 1240 - - Other permanent (perennial) | |
| 2000 - - Forest | 0.12 |
| 1420 - - Forest tree plantation (0.08 | |
| 1800 - Agricultural land overgrown with forest trees | |
| 4210 - - Reeds | 0.06 |
| 4220 - - Other marshy lands | |
| 3000 - - Built-up and related land | 0.12 |
| 5000 - - Dry open land with special vegetation cover | 0.03 |
| 7000 - Voda - Water | 0.35 |
| 6000 -Open land without or with insignificant vegetation cover | 0.03 |

Table 5: Land uses and used Manning values in the model

## 4.6 Flood damage Estimation

As mentioned in the literature section, flood damage is commonly divided into direct and indirect impacts. In this study, only direct flood damage will be evaluated, and potential flood losses will be estimated for the current and future flood scenarios. Typically, depth-damage functions are used to estimate flood damage, and this method is widely accepted (Smith, 1994). The application of stage-damage curves, which relate flood depth with the anticipated adverse effects, is typically used to evaluate flood damage and flood consequences, which, in the case of tangible damage, are calculated in terms of economic cost (Thieken et al., 2016).

Various methodologies have been developed in Europe and around the world for assessing flood damage and differ fundamentally depending on whether the damage estimation is based on data collected from previous flood events (empirical data) or synthetic data (Vidmar et al., 2019). Some of the models that have been widely used for flood damage assessment include FLEMO in Germany, Multi-Coloured Manual in the United Kingdom, and HAZUS-MH in the United States. These have been used in various studies to analyze flood damage. In the case of Slovenia in 2017, the Ministry of the Environment and Spatial Planning acknowledged the need to use advanced methodologies for flood damage analysis, particularly to take into account the most recent data, which includes cultural heritage, public infrastructure, and watercourses, (Vidmar et al., 2019). In consideration of this, the improved methodology known as KRPAN was developed for flood damage assessment. KRPAN is an abbreviation for "Cumulative Calculation of Flood Damage and Analyses." The KRPAN methodology was applied in this study to evaluate the climate change-related flood damage in the lower Vipava river valley. The standard application of KRPAN uses the procedures and data input described in the section below..

### 4.6.1. Introduction to KRPAN Application on estimation of flood damage

KRPAN enables the calculation of flood damage estimation by sectors, and the method is applicable to the entire Republic of Slovenia's territory. The KRPAN model can be used to estimate flood damage for sectors such as agriculture, buildings, businesses, people, the environment, and public infrastructure. The procedures and applications are based on relevant data that is publically available, or that has been acquired from the relevant ministries, including data that belongs within the category of personal data (Vidmar et al., 2019).

Figure 11 shows the conceptual flow chart for the KRPAN model application. The model receives data on the exposure to the elements in flood-prone locations through one of the GIS software (e.g., Arc GIS or Saga). The hydraulic simulation result provides data to the model on the flood depth and inundation boundary. As part of the data preprocessing, the output file of the hydraulic model is vectorized, and the topological compatibility of the hydraulic model with the KRPAN model is also checked in this study. The KRPAN database contains all the necessary data for the generated flood assessment, including information on exposure elements, The kRPAN database needs to be updated frequently enough to ensure an up-to-date flood assessment. The krpan, krpaL, krpaK, krpaP, and krpaV modules of the application contain land use data information.

The Building Cadastre, Register of Spatial Units, Real Estate Register, Land Use, and Central Residential Register are in krpaP and the Intangible Cultural Heritage of Slovenia is represented as KrpaK, and both these are represented as polygons input into the model application. The line input to the model includes the krpaL and krpaV, where krpaL is the mode for cadaster of public infrastructure and krpaV hydrology. eCentral Residential Register, Slovenian Business Register, IPPC, and SEVESO are all represented as points in the application's model, known as krpaK.

The KRPAN model is a console software; therefore, it is accessed through a text-only computer interface (command-line interface, CLI). This type of application is preferable to a graphical user interface program since the computation of expected flood damage is difficult due to the huge amount of data required to be handled in the background (GUI) (Vidmar et al., 2019). Google Earth and other open-source GIS and CAD software can present a project's results, and it is initially necessary to categorize input data into polygons, lines, and points to use KRPAN with GIS tools.

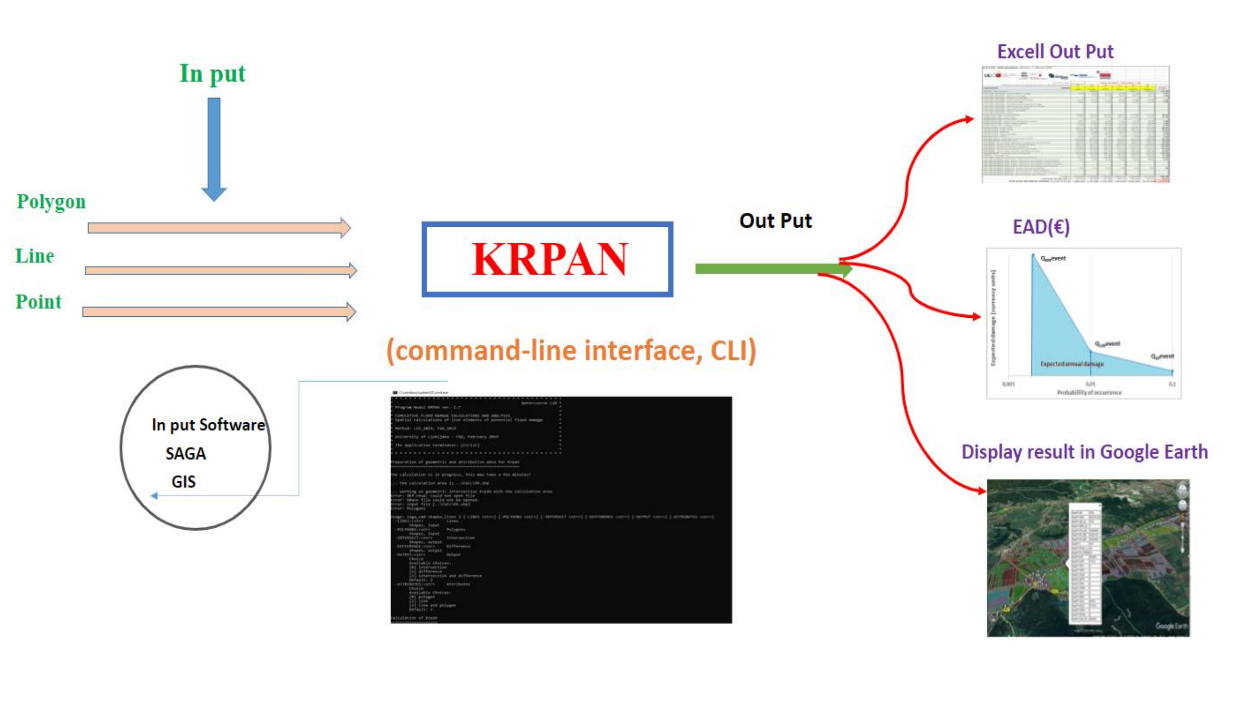



Figure 11: Flow chart illustrates KRPAN Applications for flood damage assessment

### 4.6.2 Estimation of flood damage

n this study, a flood damage assessment of the land uses in the study area (building, cultural heritage, environment, agricultural, public infrastructure, and business sectors) was analyzed. The damage cost is determined for each sector using a straightforward calculation that takes into consideration the strength, duration, and dimensions of the anticipated flood event with various return periods, as well as the exposure, susceptibility, and values of the vulnerable objects in the sectors.

- **Damage to property (buildings, public infrastructure, and agriculture)**

The property damage assessment includes damage to buildings, agriculture, and public infrastructure. The damage analysis for these categories was conducted using the methodology described above. The method also includes the expense of cleaning urban and other outside surfaces near the buildings and actual damage to cars. Intangible damages from housing replacement are also quantified for residential buildings. For various flood event magnitudes, the average projected damage to watercourses is calculated based on the damages registered in the AJDA application developed by the Slovenian Administration for Civil Protection and Disaster Relief (Vidmar et al., 2019). The average of the documented damages in AJDA is used to calculate the tangible damage to public infrastructure, and a higher vulnerability factor is assigned for important components where it is plausible for the infrastructure to collapse.

- **Damage to the environment, cultural heritage, and business entities.**

Damages to cultural heritage include both tangible and intangible damage. Tangible damage is determined by the average amount of damage documented in the AJDA application, and intangible damage is determined by adding another factor to the amount of tangible damage (Vidmar et al., 2019; Dassanayake et al., 2012).

Evaluating the environment takes into consideration the factors and values used to determine the environment's aesthetic value and the services that depend on biodiversity. According to the average reported damages during previous events, damages to equipment, machinery, stocks, and revenues are divided into four company size classes.

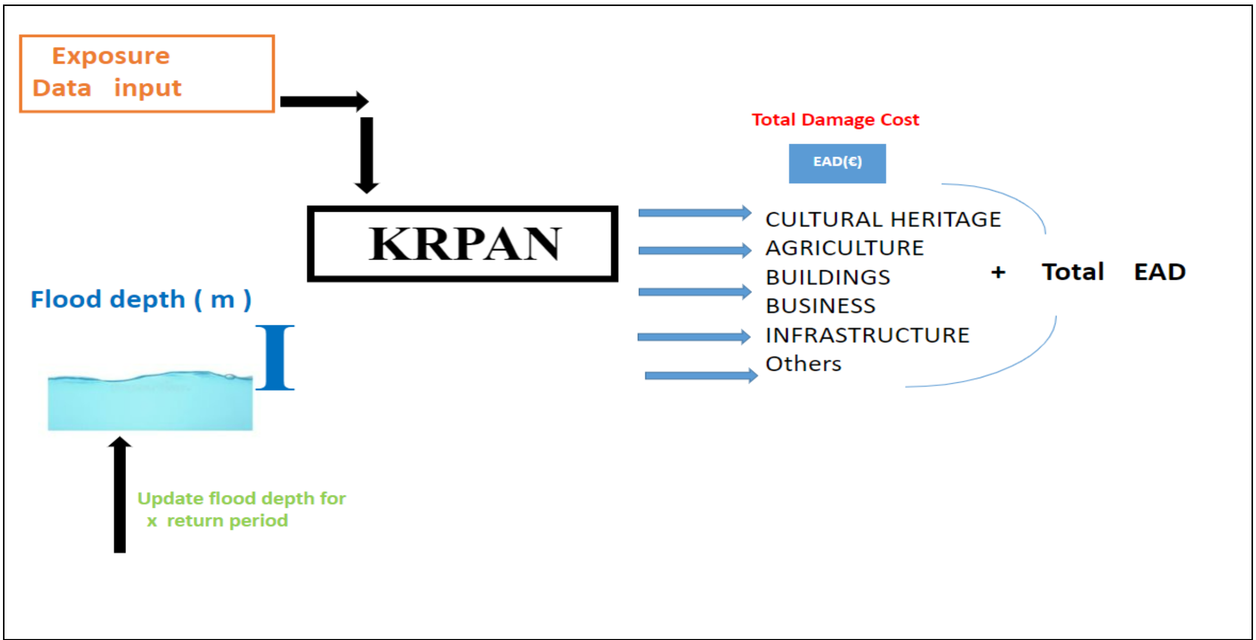



Figure 12: The applied Procedure for flood damage assessment

The estimated damage (ED) of a flood event with a return period of T is determined using the following equation for each sector at a specific location.

$$ED = S*D*E*Vu*Va \tag{2}$$

Where $S$ stands in for the event's strength, referring to the flood depth and velocity, $D$ is the dimension representing the size of the exposed feature in a given area, $E$ is the likelihood that an element will be present in a given area at a particular time, $Vu$ is a term for the individual element's vulnerability, and $Va$ is the economic value of the item in a given area.

KRPAN model calculates the expected annual damage by defining the damage cost as a function of the exceedance probability. Figure 13 is an illustration of this type of function. The expected annual damage is determined by the area under the curve.

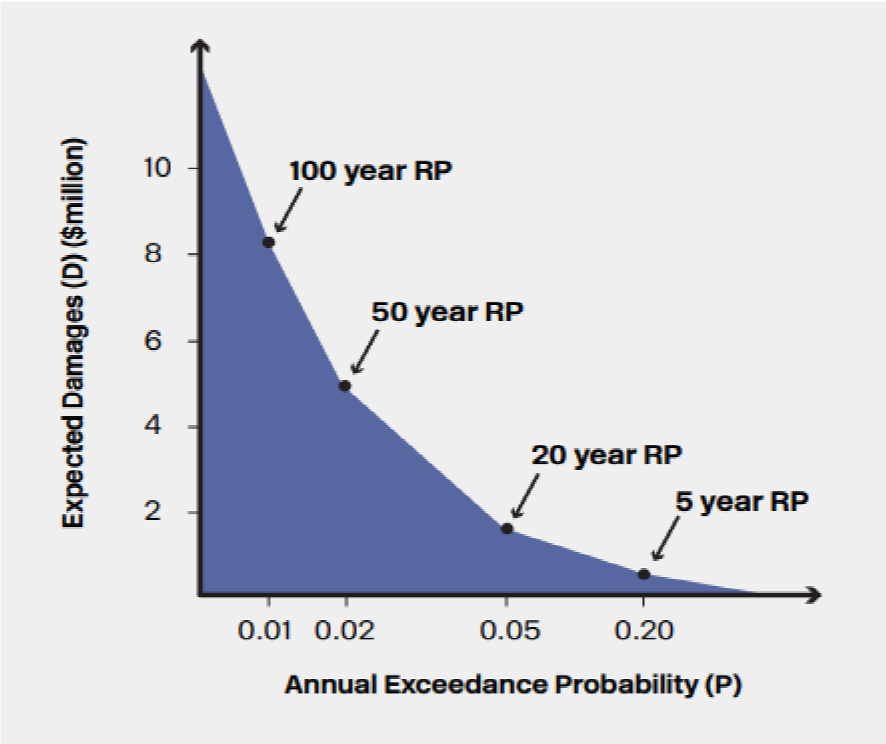



Figure 13: Expected Annual Damage is shown as a function of the annual exceedance probability p, which is the inverse of a given event's Return Period (Olesen et al., 2017).

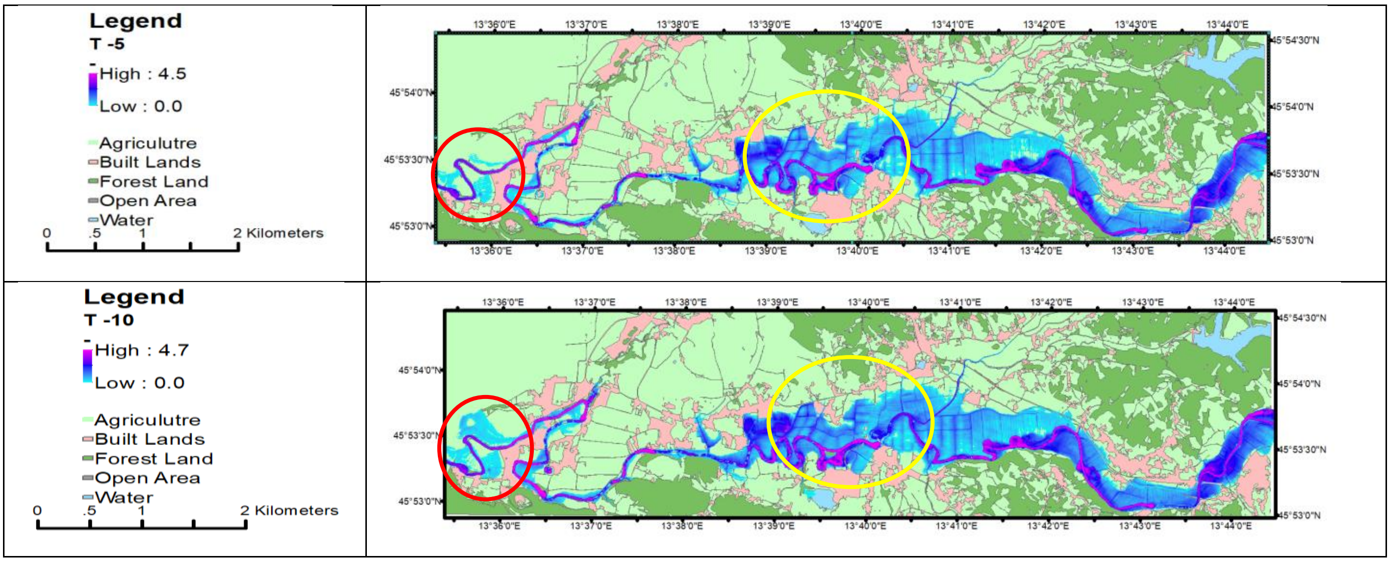
# 5. RESULT AND DISCUSSION

This chapter presents the result of the hydraulic modelling and flood damage estimation conducted in the study. The result of the flood inundation analysis, as well as the direct damage estimation and significant findings briefly discussed while addressing their implication for the study area.

## 5.1 Flood Plain Mapping

In consideration of climate change, simulations were conducted for the present and future scenarios of flooding. Thirty simulations were conducted, with six simulating the current flood and 24 simulating the projected flood driven by climate change. These scenarios and their respective flood inundation maps are represented in this section, along with the potential changes in the total inundated area and maximum flood depth.

The simulation results for return periods of 5, 10, 20, 50, 100, and 500 years are presented in Figure 14. The highest depth of flood water for the 500-year return period is 5.8 meters, whereas the maximum depth of flood water for the 5-year return period is 4.5 meters. The flood map shows that the extent of the flood varies as the return period increases, with the inundation area around the town of Miren becoming significantly larger for higher return periods. The red circles indicate the area surrounding the town of Miren that has a high potential for flooding, and the extent of flooding varies significantly in this region based on considered flood peak return periods. In addition, the flood extent varies substantially along the sides of the river's meandering course, as depicted by the yellow circle. This flood simulation result for the current condition is used as the base scenario to investigate further the flood simulation results and related flood damage for the climate-driven flood Scenarios.



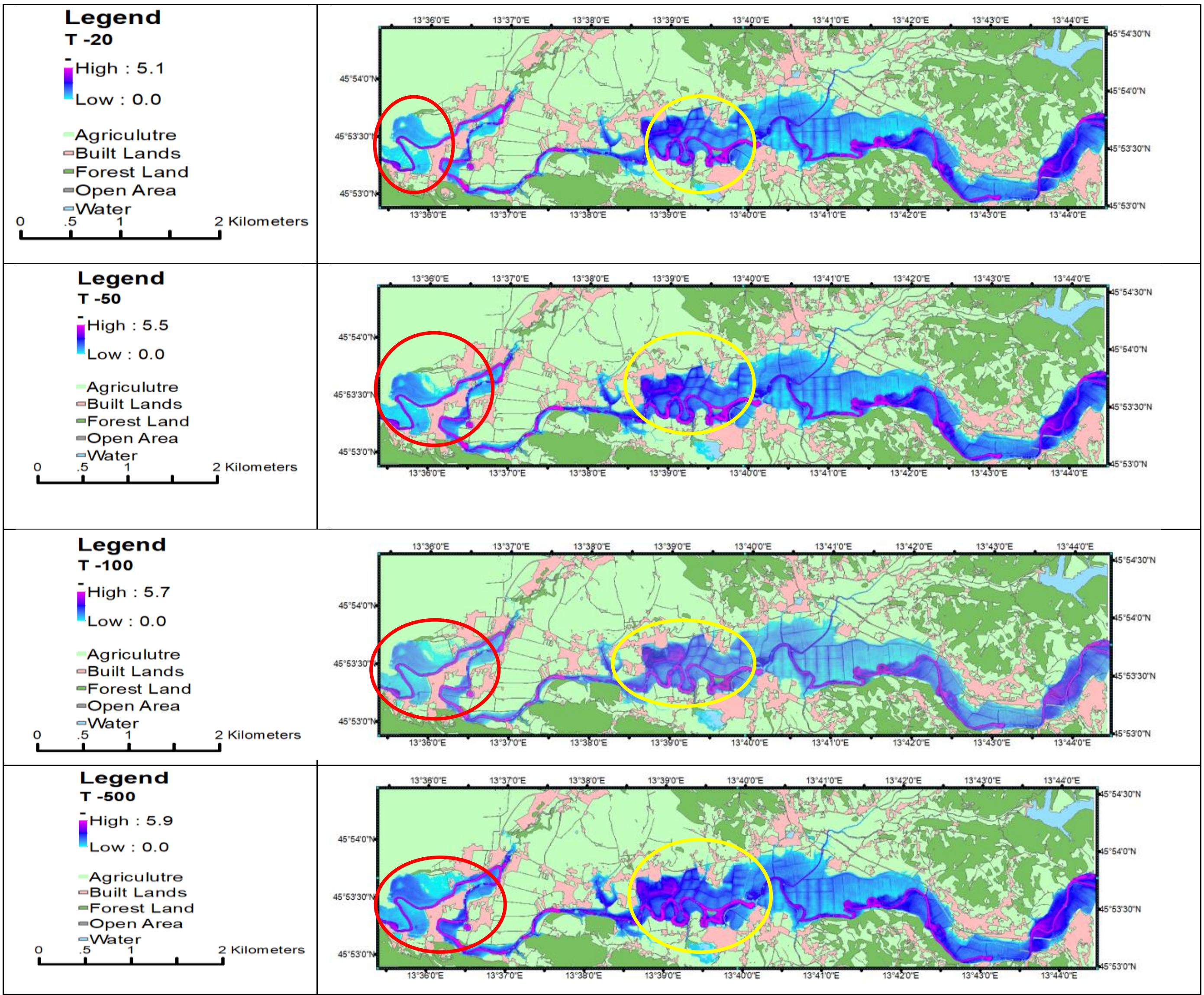



Figure 14 : Flood simulatio Results for the current state of the six return periods selected in this study

## 5.2 Projected Change in Flood Plain Mapping

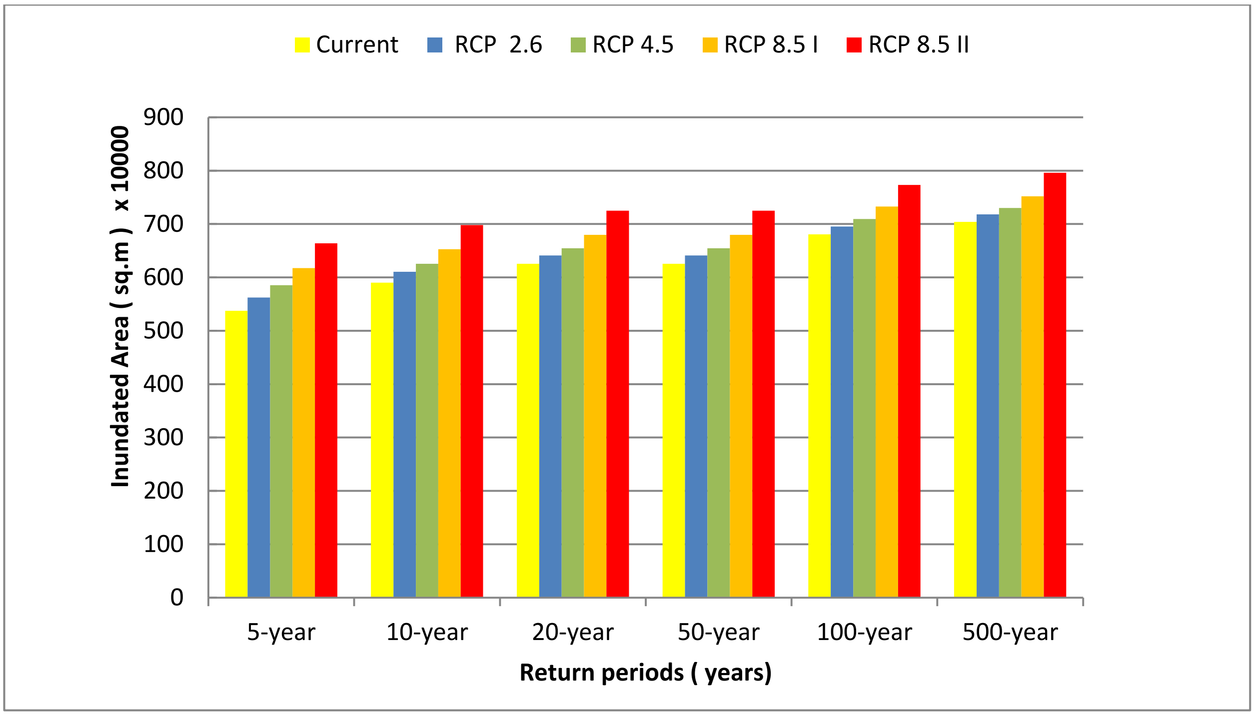



Figure 15: Inundated areas in the study area for a series of flood scenarios

| Climate scenario | 5-year | 10-year | 20-year | 50-year | 100-year | 500year |
|---|---|---|---|---|---|---|
| RCP 2.6 | 5% | 3% | 2% | 2% | 2% | 2% |
| RCP 4.5 | 9% | 6% | 5% | 5% | 4% | 4% |
| RCP 8.5 I | 15% | 11% | 9% | 9% | 8% | 7% |
| RCP 8.5 II | 23% | 18% | 16% | 16% | 14% | 13% |

Table 6: Percentage increase in inundation extent for all flood scenarios with respect to the current state

Table 6 demonstrates the percent change in the inundated area for all scenarios with respect to the baseline condition. As illustrated in the table, the 5-year return period shows a higher variation in the inundated area for flood scenarios. It varies by 5%, 9%, 15%, and 23% for RCP 2.6, 4.5, and 8.5, respectively. This shows that the climate change impact on flood inundation in the area will have a higher impact for the 5-year return period than the other return periods. Furthermore, for RCP 2.6, the difference in inundation area between the mentioned return periods is small, indicating that in the range of 2% to 5%, the 5% change refers to the change in the 5-year return period

In the RCP 4.5 scenario, the change in the inundation is relatively more significant than in RCP 2.6, which is a 4 % increase for a 500-year return period and a 9 % increase for a 5-year return period. For the most pessimistic scenarios considered in this study, RCP 8.5 I and RCP 8.5 II show the highest increase in the flood extent compared to RCP 2.6 and RCP 4.5. The highest increase in flood extent was observed in the case of RCP 8.5 II, which is a 23 % increase in flood extent for a 5-year return period.

As noted above, the highest increase in flood extent was observed for the 5-year return period compared to the other return periods. The hydraulic simulation result for a 5-year return period is presented in Figure 16 below. According to the outcome of the simulation, the current state inundation area is 5.62 km2, 5.85 km2, 6.17 km2, and 6.63 km2 for RCP 2.6, RCP 4.5, and RCP 8.5, respectively.

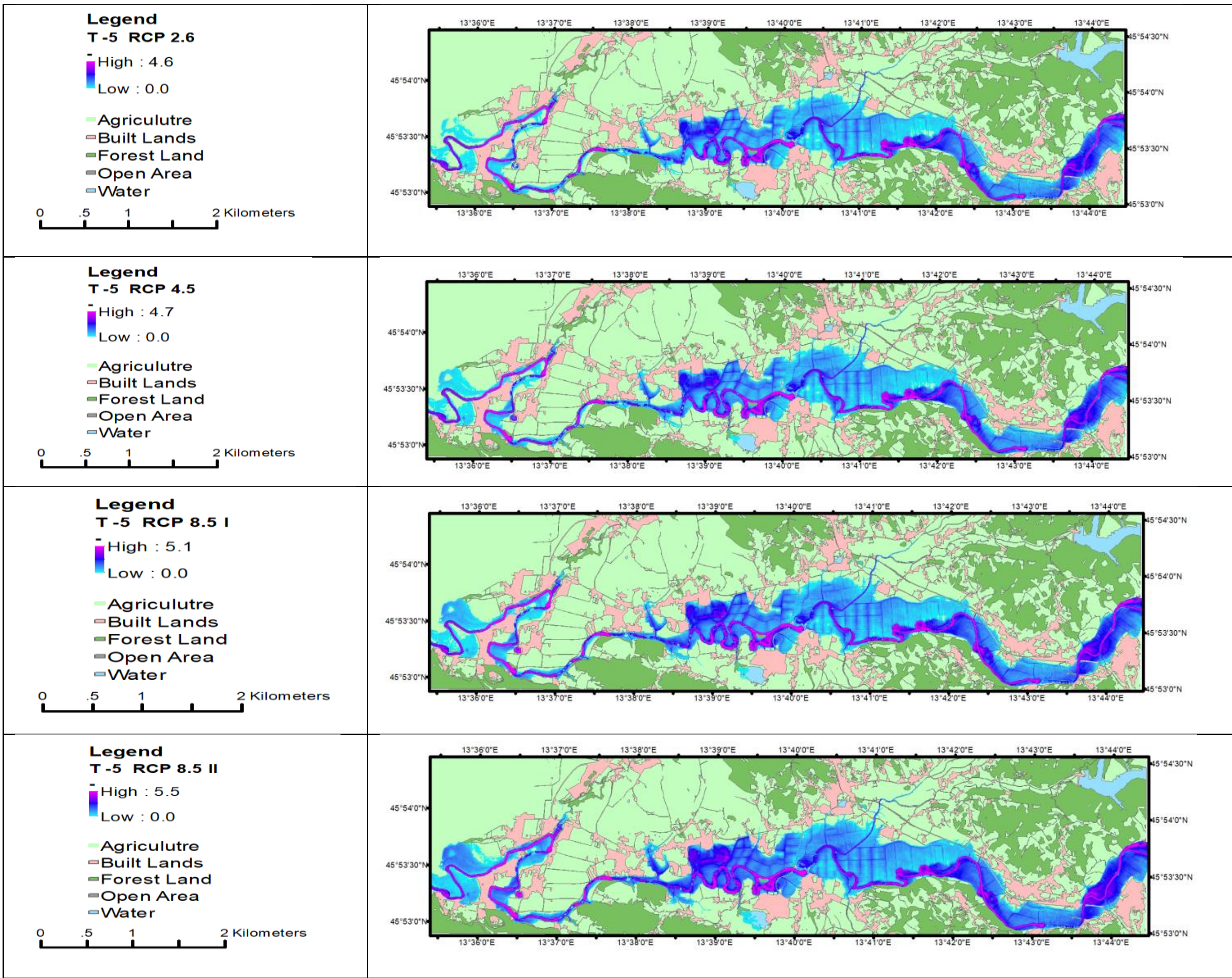


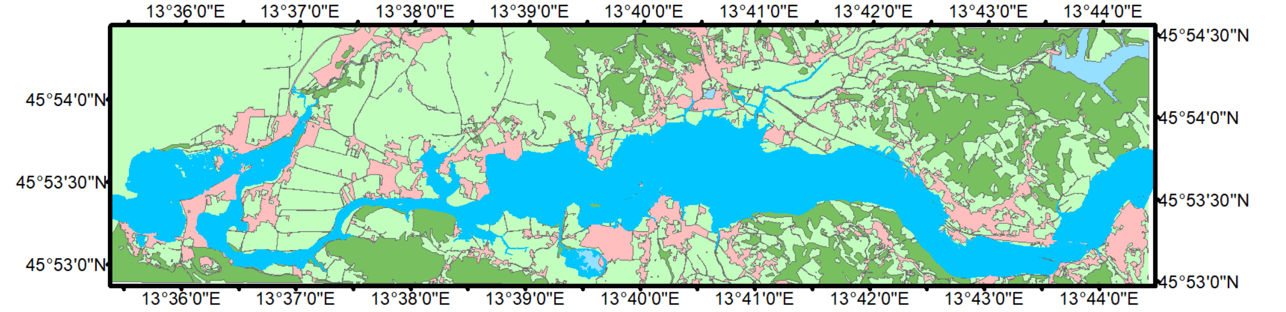

Figure 16 : Simulation result for T - 5

Table 7 shows this study's maximum water depths associated with river floods. According to the results, the river maximum flood depth increases significantly for RCP 8.5 and RCP 4.5 scenarios. The maximum increase in maximum flood depth observed for a 500-year return period high-impact scenario with a 50% increase over the current state. This can cause a devastating flood. The inundation area in this scenario is factored in by 20% of the current. This scenario substantially impacts the flood plain along the studied river section; the simulation result is shown in Figure 18, which demonstrates the flood extent to T 500.

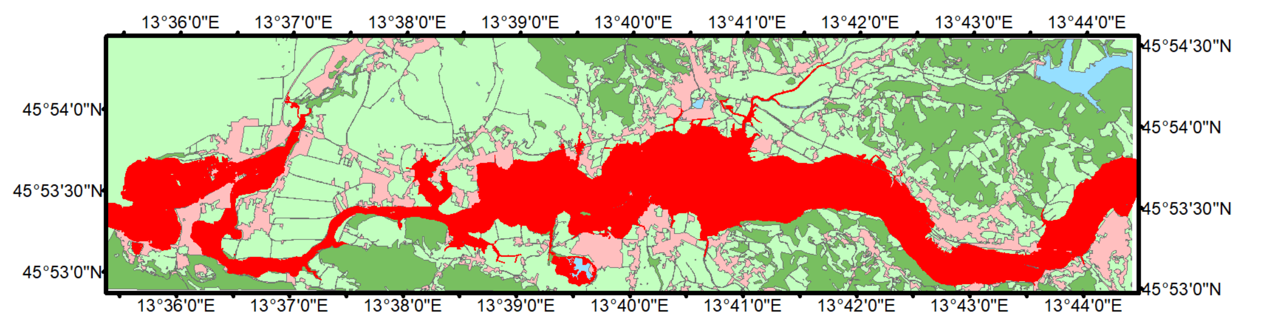
| Return period (years ) | **Maximum Water Depth (m)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Current** | **RCP 2.6** | | **RCP 4.5** | | **RCP 8.5 I** | | **RCP 8.5 II** | |
| 5 | 4.5 | 4.5872 | 3% | 4.7 | 5% | 5.1 | 14% | 5.5 | 24% |
| 10 | 4.7 | 4.9 | 12% | 5.2 | 15% | 5.4 | 21% | 5.8 | 30% |
| 20 | 5.2 | 5.2 | 19% | 5.5 | 22% | 5.7 | 27% | 6.1 | 36% |
| 50 | 5.5 | 5.6 | 25% | 5.8 | 28% | 5.9 | 33% | 6.3 | 42% |
| 100 | 5.7 | 5.8 | 30% | 5.9 | 32% | 6.1 | 37% | 6.5 | 46% |
| 500 | 5.9 | 6.0 | 34% | 6.1 | 37% | 6.3 | 42% | 6.7 | 50% |

Table 7: Maximum flood depth of the hydraulic simulation result

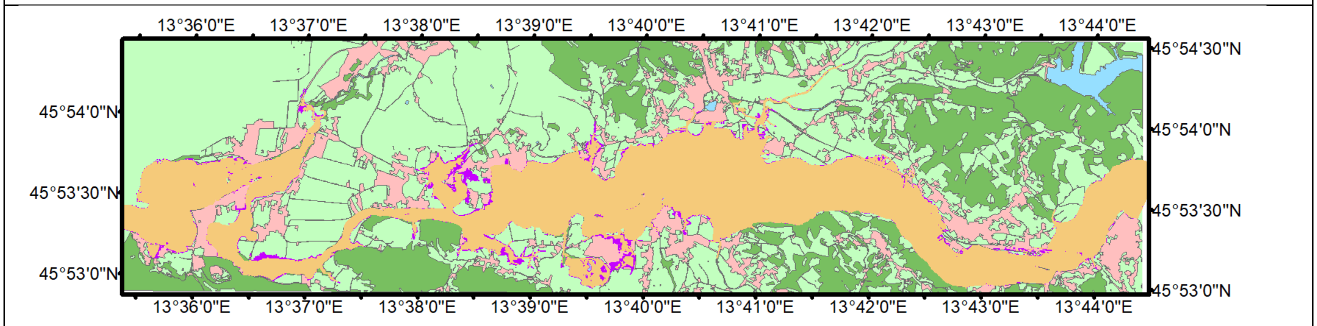
The hydraulic model result shows a more significant variation around the town of Miren, a settlement that is prone to flooding. The flood simulation for the present and future showed that the flood affects the town of Miren on both the east and west sides of the river. For the 100-year simulation, as shown in Figure 17, it is observed that the flood first flows to the west of the side of the river before spreading eastward into the neighborhoods and channeling through the town's road network, where the flood flow is directed along the road to the north. Figure 17 shows the flood extent for a 100-year return period flood for current and future scenarios. The simulation result is similar to the Slovenian water agency report of the flood pattern in the vicinity of the town of Miren. Vipava River starts to overflow the area on the left bank of the bridge at around 400 $m^3$/s and the road in Miren at about 340 $m^3$/s.



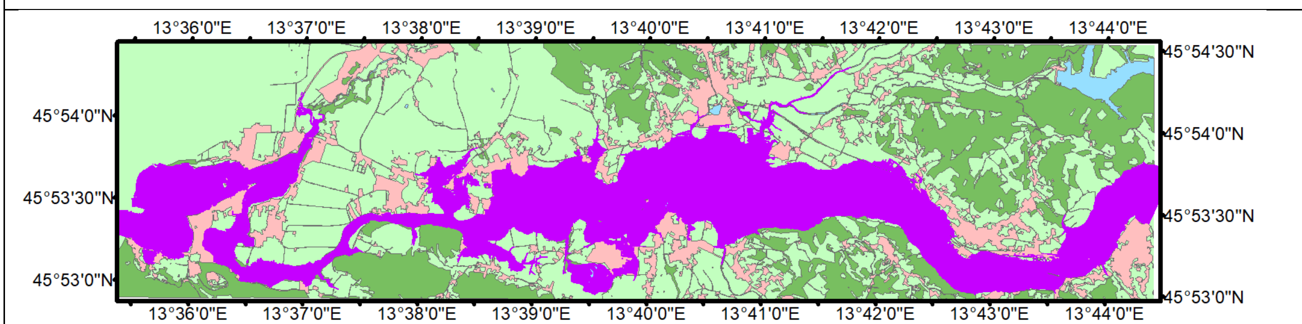

A. RCP 2.6




B: RCP 4.5

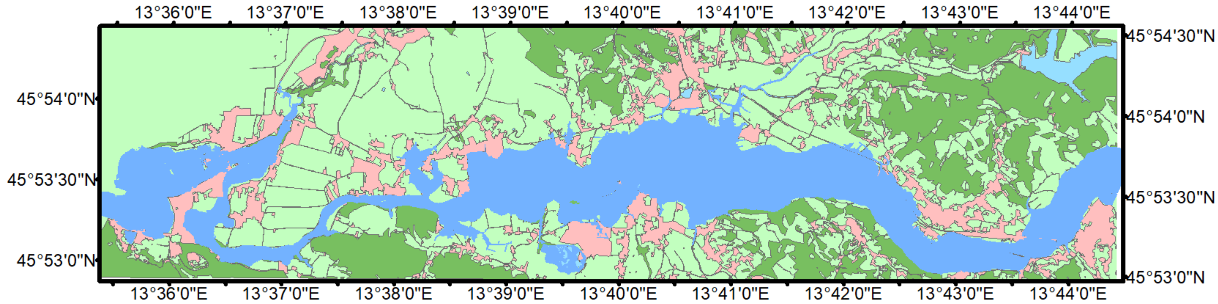



C: RCP 8.5 I

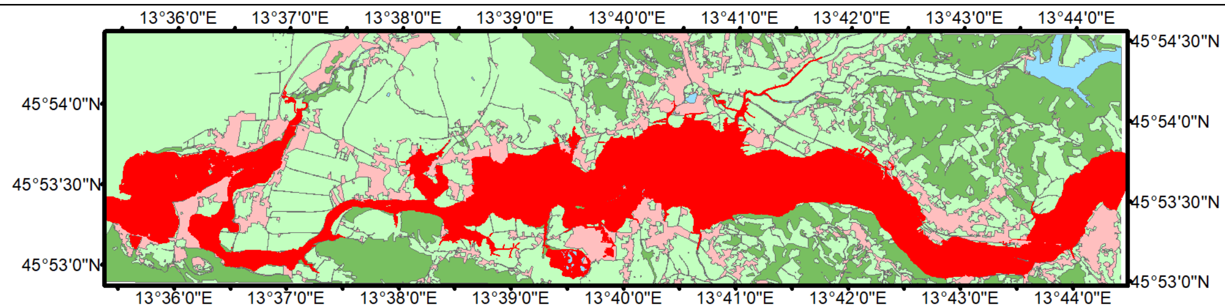



D. RCP 8.5 II

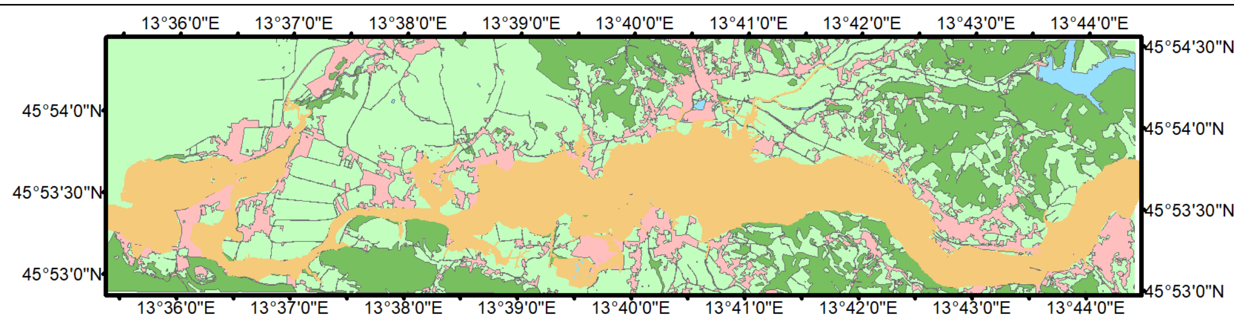
Figure 17 : Simulation Result for T -100 years



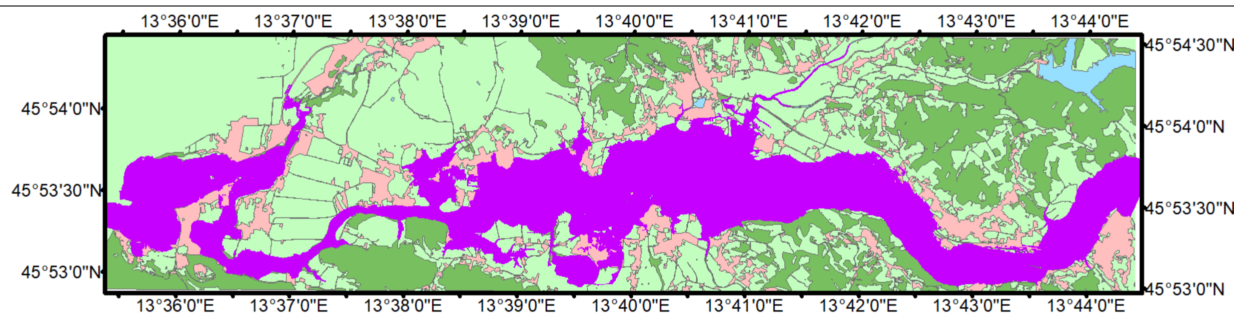

A. RCP 2.6




B: RCP 4.5




C: RCP 8.5 I




D: RCP 8.5 II

Figure 18: Simulation Result for T -500 years

### 5.3 Estimation the potential flood damage in the lower Vipava river valley

The flood extent and depth information from the hydraulic modeling outputs was used as the primary input in the KRPAN model to calculate the flood damage cost in Vipava river catchment .The result of the KRPAN model provides a breakdown of the expected damage caused by simulated flood events to different sectorial entities in the study area. The cost of flood damage to residential and non-residential buildings, public infrastructure, water courses, and agriculture, business, and traffic passengers is analyzed in this study. A damage probability curve was prepared for all the flood scenarios, and the total expected annual damage was calculated. The total expected damage for the selected scenarios ranges from 0.97 million euros for the current state to 1.97 million euros for the most pessimistic emission scenario. The building sector in the Vipava river catchment is the category most affected by flood damage in all scenarios, accounting for more than 50% of all flood damage inflicted in the study area. Agriculture, watercourse, and public infrastructure are the other categories with the highest flood damage among the sectoral entities in the study area.

#### 5.3.1 Expected Annual Damage

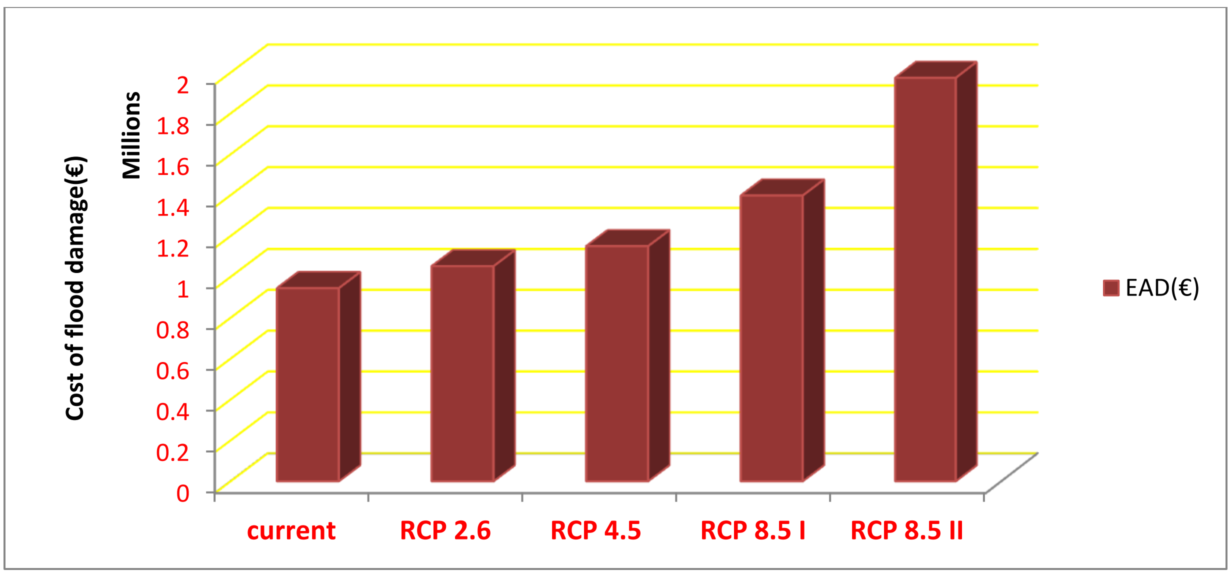



Figure 19 : Total Expected Annual Flood Damage for different flood scenarios

As explained in the methodology section, EAD is an essential element of flood damage assessment because it can give a tangible and brief image of the expected annual damage in the studied section of the Vipava valley, considering the current and future scenarios. The total expected damage of all four scenarios shows a gradual increase in flood damage for RCP 2.6 and RCP 4.5 scenarios, but the increase in EAD for the low probability of high impact RCP 8.5

scenario is high. According to the result, the total expected damage ranges from 0.97 million euros for the current situation to 1.97 million euros for the most pessimistic emission scenario, which refers to a 40% rise in the discharge peaks. In this case, the cost of the damage is increased by a factor of 2.08 compared to the current situation. A 20% increase in the flood peak equals 1.398 million and is 1.47 times greater than the EAD in the current situation. The estimated 5% and 10% increases in river peak discharge will increase overall predicted damage costs by 1.11 and 1.21 times higher than the current condition.

### 5.3.2 Damage to Agriculture and Public infrastructure

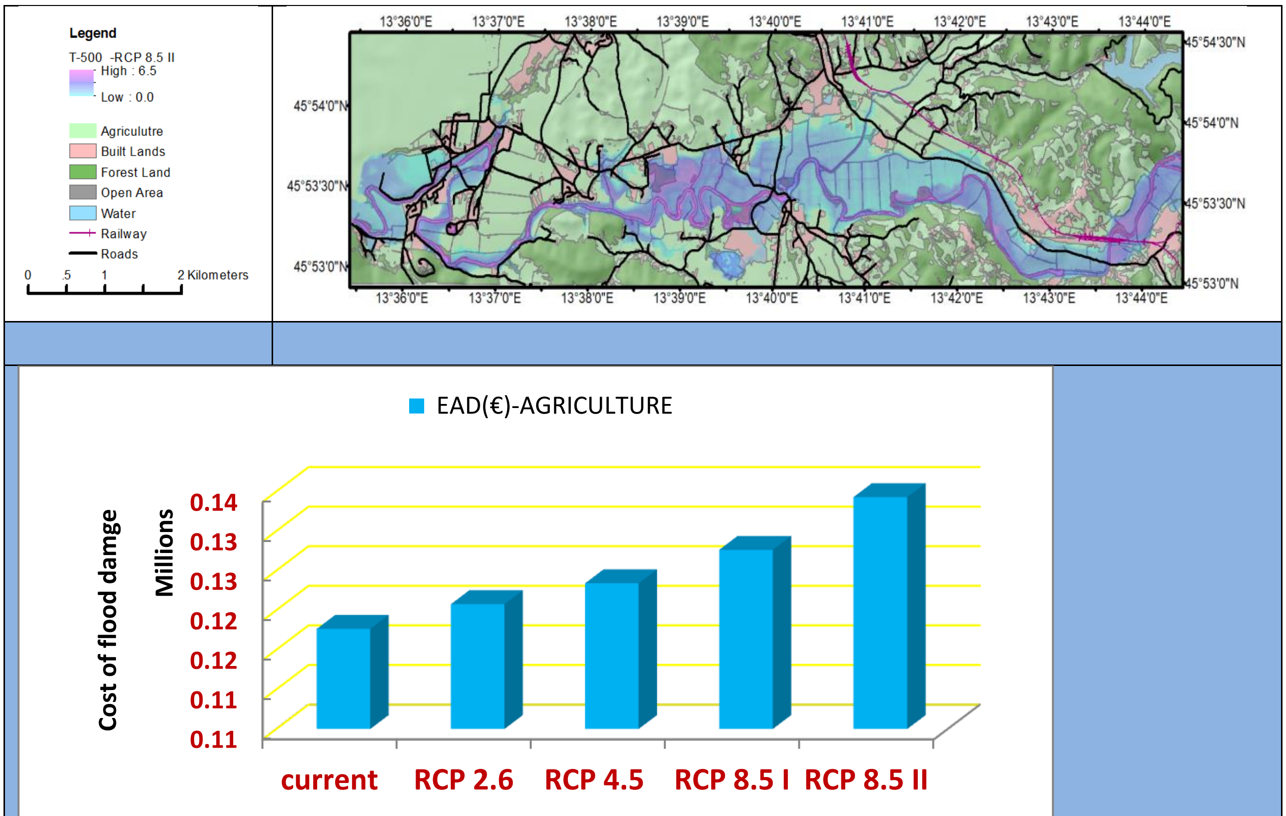



Figure 20: The result of hydrodynamic simulation results from the high-impact scenario T-500 RCP 8.5 II demonstrates the affected land use in the study area (upper) and expected annual damage to the Agricultural sector for all scenarios (lower)

The expected annual damage to the agricultural sector ranges from 0.11-million-euro for the current state to 0.13-million-euro for the high-impact pessimistic scenario. The agricultural damage subcategories in the study area include crops, meadows, fields, arable land, and forest. Arable land and crops are the most affected subcategories of the agricultural flood damage, for example, accounting for 51 % and 37 % of the flood damage costs, in the case of the high-impact scenario of a 500-year return period. Figure 20 shows a simulation result of the flood hazard map for a high-impact scenario of T-500. As seen in the hydrodynamical simulation result, a significant agricultural land use area in the floodplain flooded. The flood damage cost caused by this low-probability event and a high-impact scenario of 500 year return period is 0.13 million euros.

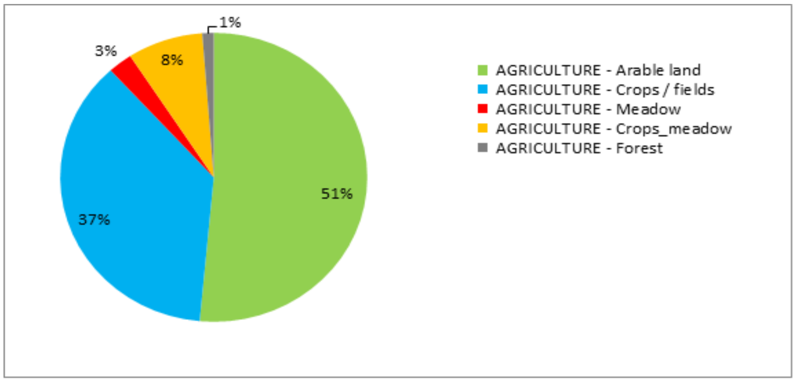



Figure 21: Agricultural sector sub-category's share of flood damage for T -500 RCP 8.5 II scenarios

The cost of flood damage to agriculture does not show a significant difference with repsect to climate-driven flood scenarios. The increase in the cost of flood damage from the current state to the pessimistic scenario is only by 14 %, ranging from 0.11 to 0.13 million euros, and this is because agricultural products can be fully damaged whether exposed to a higher flood depth or less water depth. This can be depicted from Figure 20, which demonstrates the total damage cost to the agricultural sector for the different flood scenarios.

The public infrastructure in the study area includes local roads, national roads, forest roads, a water supply network, and a sewerage network. The national road is the most severely damaged sub-category of public infrastructure. As illustrated in Figure 20, there is a network of roads crossing the river at different points, and these roads are vulnerable to flooding during extreme flooding. The bridges that cross the river are part of the road more vulnerable to flood damage.

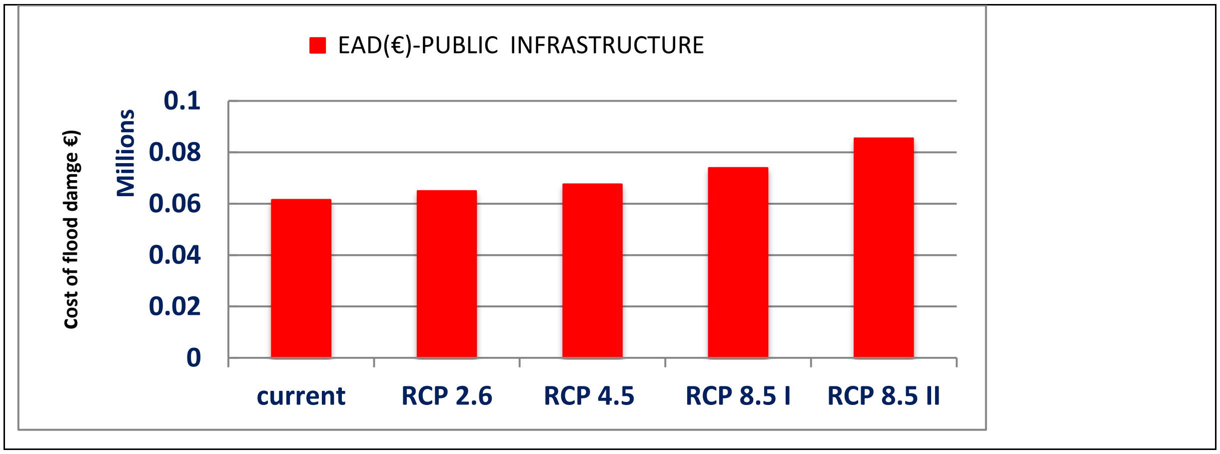



Figure 22: Expected annual damage to public infrastructure for all scenarios

### 5.3.3 Damage to Building

The residential and non-residential building categories have the highest flood damage share among the sectoral entities in the study area .The flood damage analysis result shows the expected annual damage of this sector increases significantly with the RCP scenarios. Flood damage increases by 2.5 for RCP 8.5 of the pessimistic scenarios, reaching around 1.3 million by the end of the century, corresponding to the increase in the maximum river discharge peak by 40%.

The xpected annual damage of the building for current state ranges from 4.5 million euros to 6 million euros for 100 year and 500 year return period, as illustrated in the Figure 23. The residential portion of the building also has the highest share of the cost of flood damage compared to the non-residential building.Residential buildings account for 43 percent of total flood damage to buildings in the current state.The flood inundation maps for all scenarios show that the building classes located downstream of the studied river section are the most vulnerable to flood damage. As illustrated in the Figure 25, residential and non-residential buildings exist in the town of Miren. As the inundation and topographic maps shows, several buildings in the river floodplains are inundated.

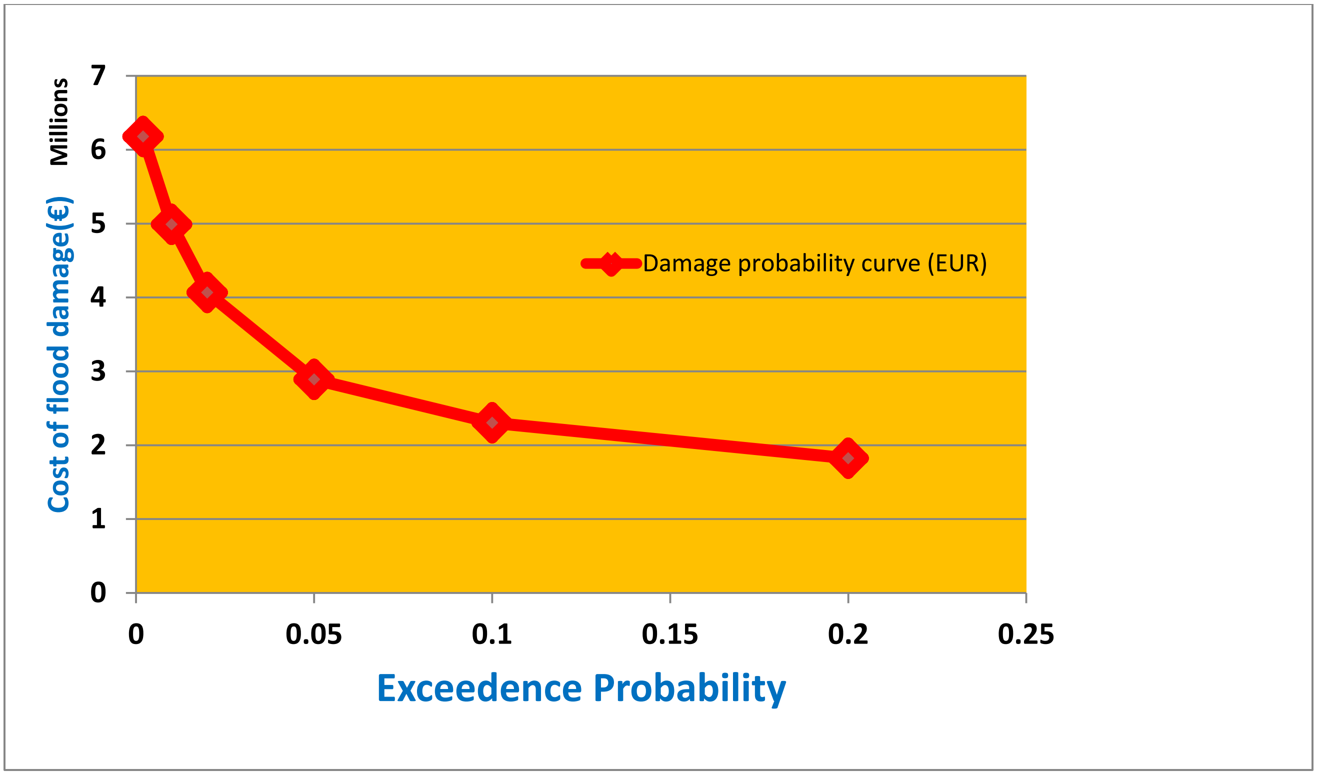



Figure 23: Total Expected annual damage of the building for current state

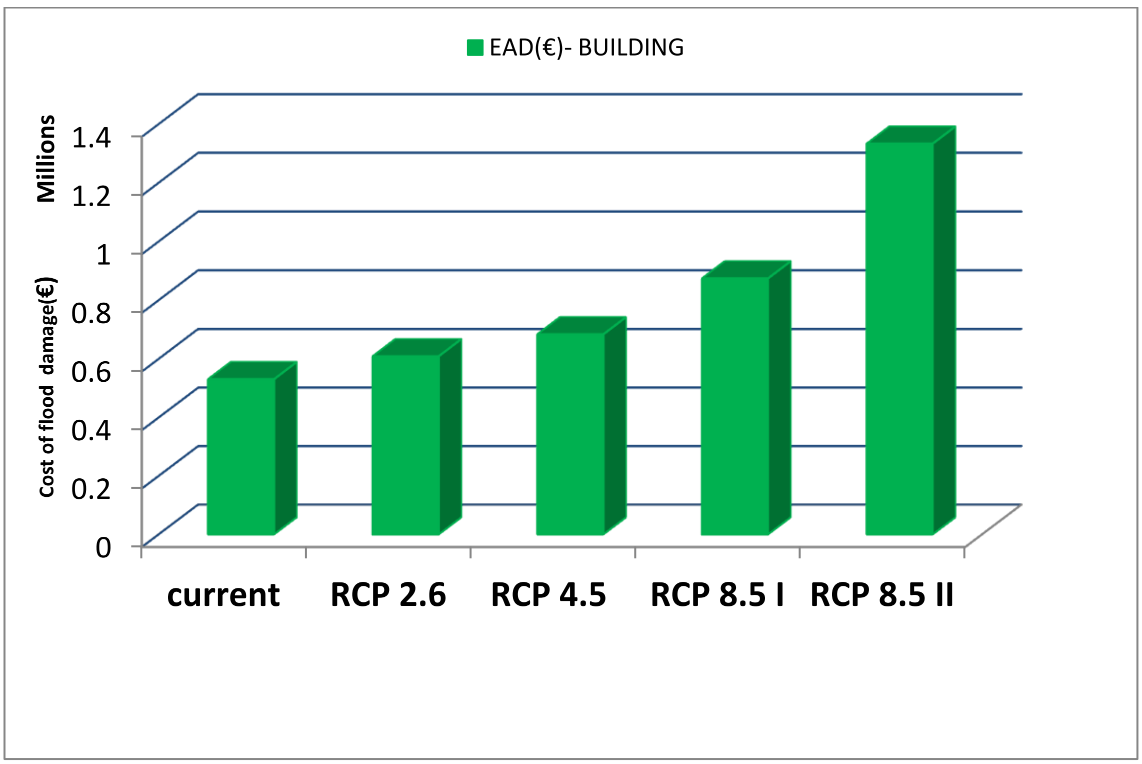



Figure 24: Expected annual damage to building sector for all scenarios

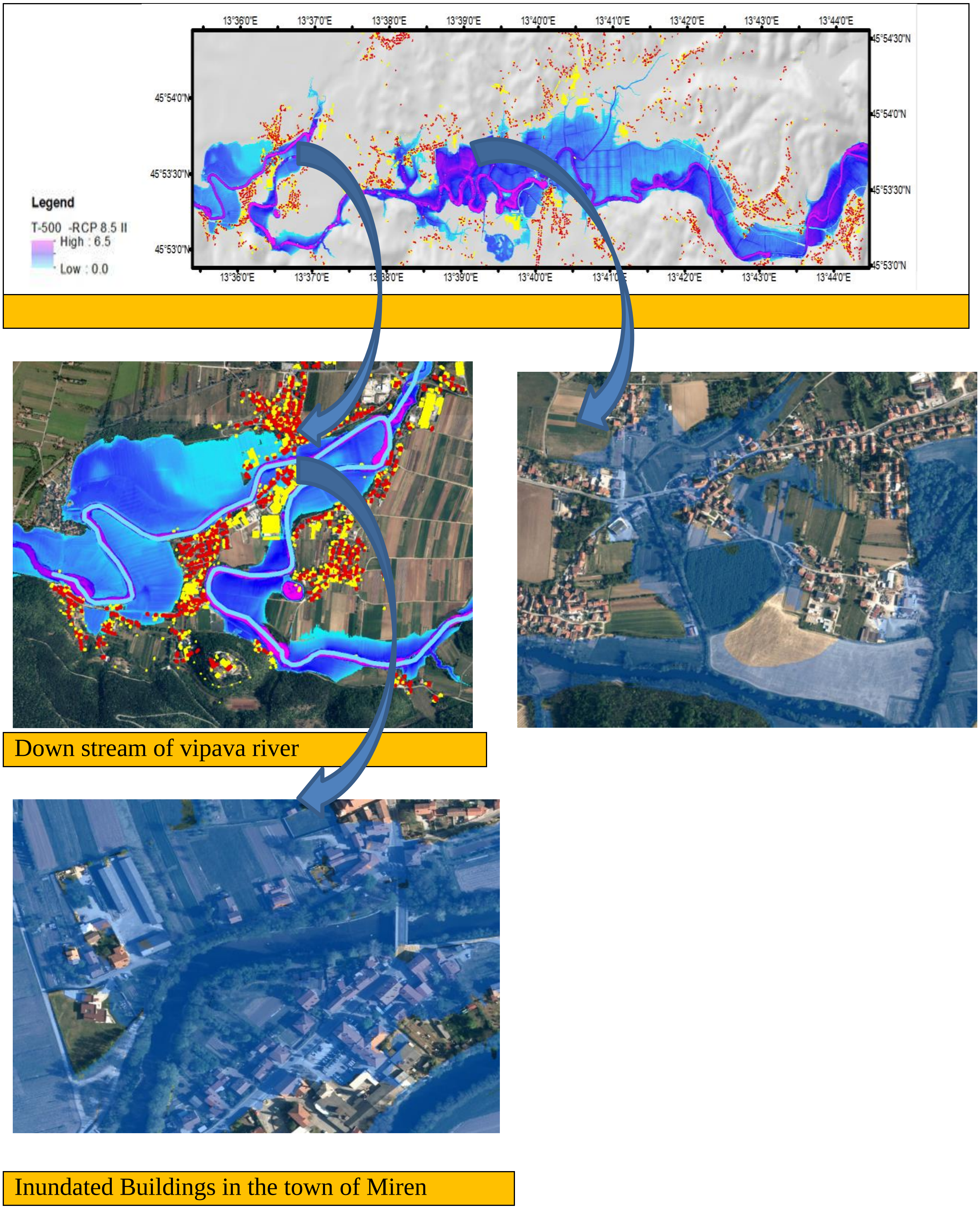
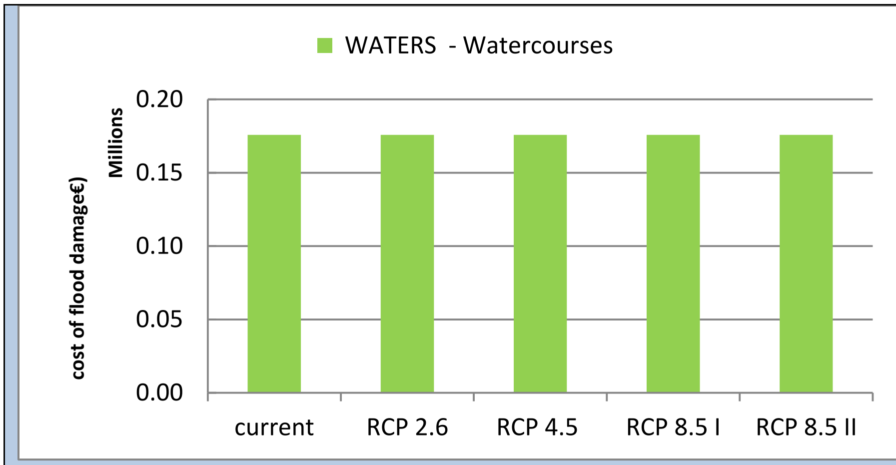
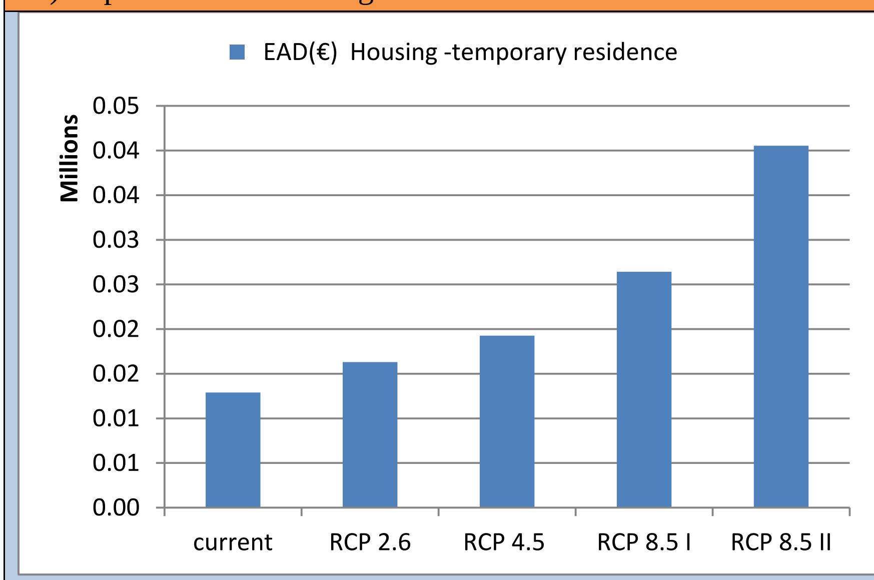



Figure 25: The residential and non-residential buildings in the flood risk area of Vipava

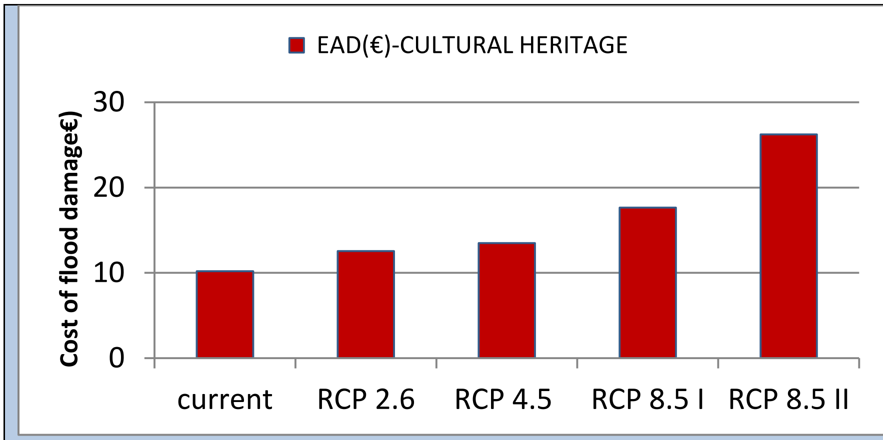
Moreover, the flood damage results of the other categories in the Vipava river catchment are displayed below. The cost of flood damage for each sector (environment, water courses, cultural heritage, and housing temporary residence) is shown for current and climate-driven flood scenarios. Except for the watercourses, the flood damage cost for all sectors increases significantly with the impact scenarios.



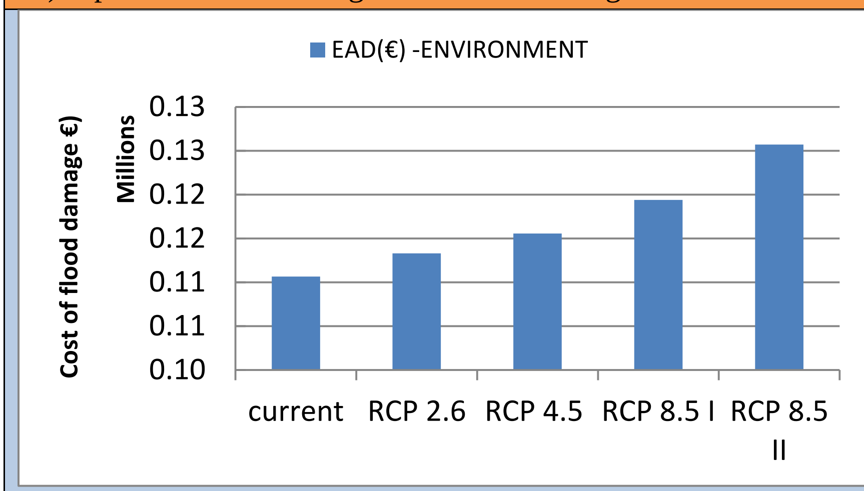

A ) Expected annual damage to watercourses sector for all scenarios




B )Expected annual damage to housing temporary residence for all scenarios




C )Expected annual damage to Cultural heritage sector for all scenarios




D )Expected annual damage to Environment sector for all scenarios

Figure 26: Expected Annual Damage for different sectors

### 5.3.4 Damage probability curve

A damage probability curve is projected from the total expected annual damage, which is determined based on the overall damage cost for each return period. The damage-probability curves in Figure 27 illustrate the relationship of the expected flood damage for the studied lower Vipava River valley with the respective exceedance probability. As illustrated by the graph, the curve shifted upward due to foreseen changes in the flow of the Vipava river at the end of the century due to foreseen climate change.

The estimated direct damage for the pessimistic emission scenario RCP 8.5 of probability 0.1 increases abruptly. With different relationships for high and low probability occurrences, this breaking point demonstrates that the damage probability curves roughly have a log-linear function. The steep slope of the log-linear trend for return periods of 50, 100, and 500 years suggests that damage losses from these occurrences increase rapidly, whereas the trend's gentle slope for return times of 5 to 10 years indicates that damage increases gradually as the river flow increases.

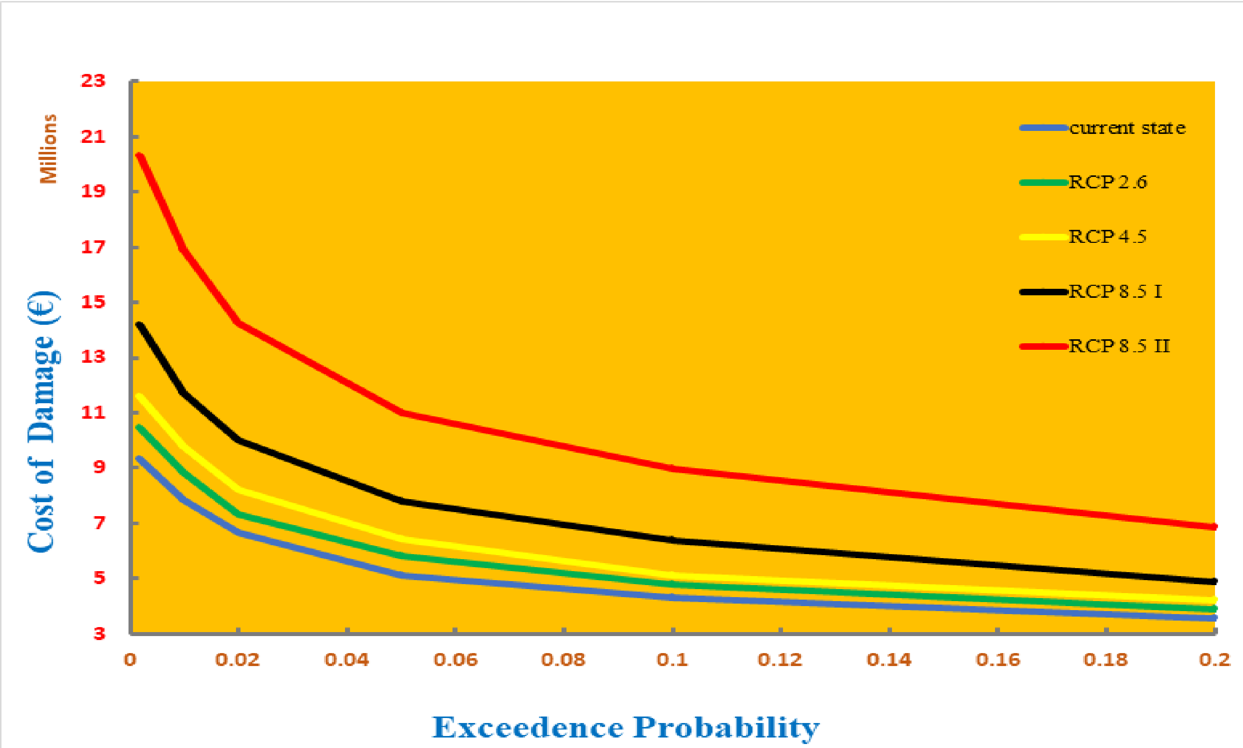



Figure 27 : Total Expected Damage in the studied section of the Vipava river valley

The share of expected annual damage of the sectoral entities in the study area is presented in the Figure 28 below. The building sector in the Vipava river catchment is the category affected mainly by flood damage, accounting for more than 50% of all flood damage inflicted in the study area. The percentage of flood damage caused by the building ranges from a 57% share of the flood damage in the current state to a 72% share of the total flood damage in the case of a pessimistic scenario of RCP 8.5 II. Agriculture, watercourses, and public infrastructure are the other categories with the highest flood damage among the sectoral entities. Watercourses also have significant flood damage costs in Vipava, which has a 19 % share of flood damage in all scenarios; which necessitates proper flood protection measures to be implemented in the Vipava river catchment to minimize the possible impact of flood damage, which could arise due to the overbank flow and damage to the watercourses. The business sector and cultural heritage share minor flood damage among the sectoral entities in the study area.

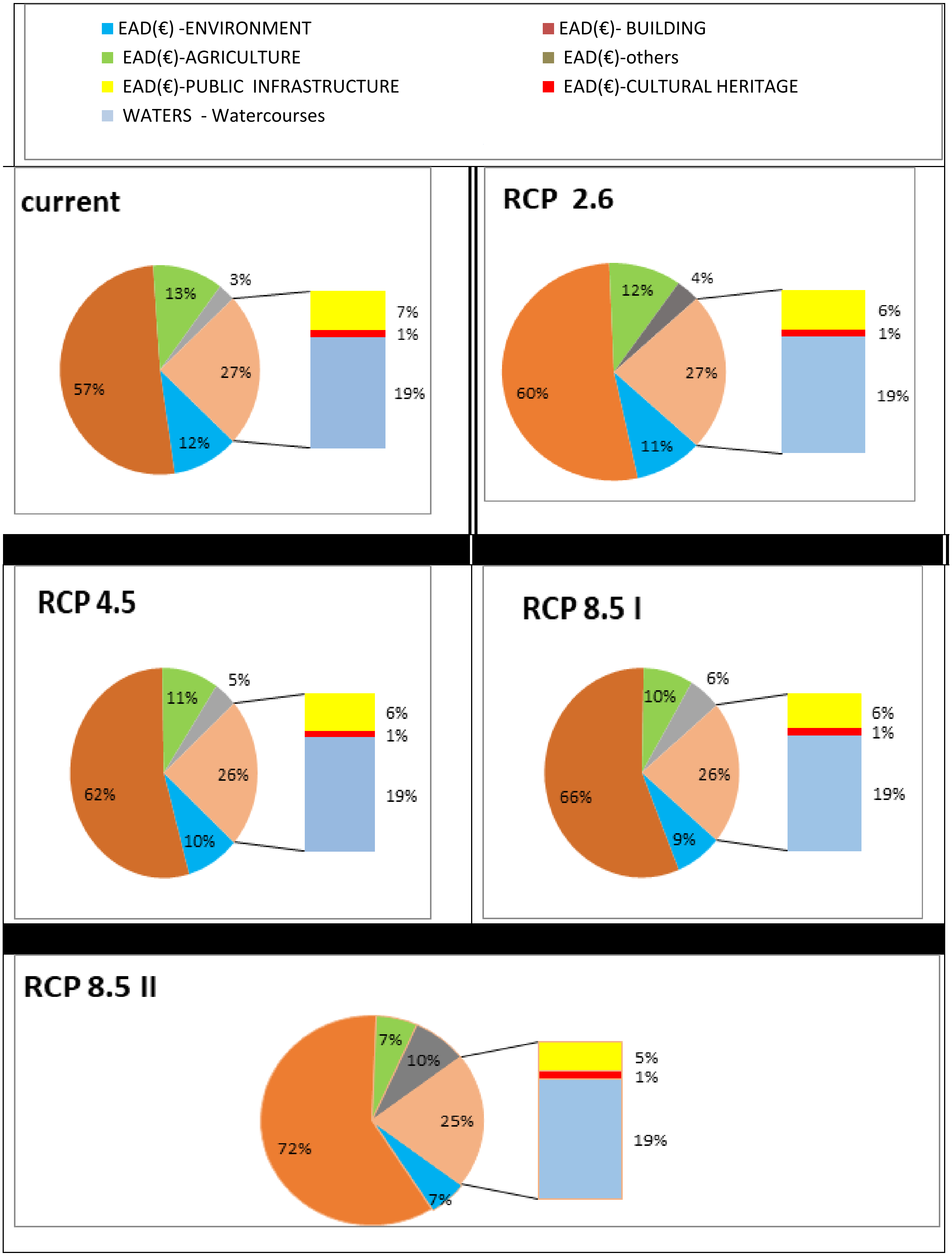



Figure 28: Shares of EAD by sectors for all scenarios

# 6. CONCLUSIONS AND RECOMMENDATIONS

The main research findings and a comprehensive overview of the work done to accomplish the research objectives of this thesis are summarized in this section. The chapter also discusses the study limitations and the methods and approaches used. Below are also included suggestions for the future development of this research as well as the applicability of the results.

## 6.1 Summary and Conclusions

Climate change may negatively affect populations and the environment by altering river flows, particularly in high or low flow cases (Kay et al., 2021). In southwest Slovenia's Vipava River watershed, there is a risk of flooding. Several catastrophic floods have happened in recent years due to extreme rainfall events in the region resulting from climate change (Magjar et al., 2021). Assessment of flood damage has been stressed in ongoing efforts to reduce flood risk because doing so enables policy-makers to obtain crucial information for long-term flood risk management (Merz et al., 2010). No systematic assessment of potential flood damage has been carried out for the Vipava river catchment. Accurate flood damage estimation is required to measure actual risk and analyze the cost-effectiveness of mitigation measures. As a result, the Vipava river flood damage potential is examined in this study while considering the impact of climate change.

The return period and the corresponding discharge values for the Vipava river catchment are used to generate the flood hydrographs with the Synthetic SCS method. The climate change impact on the Vipava river was analyzed by referencing Slovenia's ARSO climate projection studies. The changes in high discharges have been associated with particular RCP scenarios. The hydraulic modeling was conducted using Hec-RAS software to define the presence of flood hazards with different return periods. The simulation results from the hydraulic modeling used to assess the flood damage in the study area using the KRPAN model. KRPAN enables the calculation of flood damage estimation by sectors, and the method is applicable to the entire Republic of Slovenia's territory. Damages to buildings, the environment, public infrastructure, agriculture, and water courses were analyzed, and a damage probability curve for six return periods was generated and used to estimate the expected annual damage in the study area.

Thirty different flood scenarios were modeled in this study. The flood map shows that the extent of the flood varies as the return period increases, with the area around the Miren water station becoming significantly larger for higher return periods. The outcomes for the pessimistic emission scenario of RCP 8.5 II simulation for the six return periods show a 13–23% increase in the total flooded area for the current state. However, in the case of the optimistic emission scenario RCP 2.6, the flood extent varies from 2 %-5%. The 5-year return period shows a higher variation in the inundated area with respect to the climate-driven flood scenarios. This shows that the climate change impact on flood inundation will have a higher impact for the 5-year return period than the other return periods. According to the damage estimation analysis, the total expected annual damage for the Vipava river catchment in this study ranges from 0.97 million euros for the current situation to 1.97 million euros for the most pessimistic emission scenario. In this case, the cost of the damage is increased by a factor of 2.08 compared to the current situation. In addition, the flood damage analysis shows that the building sector in the lower Vipava valley is the most vulnerable category in terms of flood damage. Since there is high potential flood damage downstream of the Vipava river, as demonstrated in previous chapters, it is essential to consider flood protection measures in the future to prevent the inundation of the buildings and other flood damage categories.

As there is uncertainty in the impact analysis of climate change, a wide range of impact values was chosen for this study to consider all possible future scenarios. The peak discharge values were increased by 5%, 10%, 20%, and 40%, and six return periods were selected to analyze the impact of climate-induced change in flood characteristics on flood damage. This results in 30 flood simulations with corresponding flood damage assessments. This wide variety of evaluations could provide a comprehensive image of the flood damage potential in the Vipava river catchment.

Another uncertainty in this study is the hydraulic simulation result. Several steps were taken during the hydraulic model setup process to minimize this uncertainty to determine the proper hydraulic and numerical parameter settings. These steps included adjusting the mesh size, computation time step, weir width, and coefficient values to create a numerically and hydraulically stable model. the simulation outputs for several return periods were also compared with Slovenia's official flood hazard map in the study area, and the result was similar in the flood extent. As a result, even though there is uncertainty in the assumption of the climate change impact as well as in the simulation result, the consideration of two extremities in this study, the most minor impact scenario, as well as the high impact scenario with a wide range of flood simulation and damage assessment, could give a brief image of the possible climate-driven flood scenario impact in Vipava river catchment.

## 6.2 Recommendations

A recommendation of this study for future analysis is to assess the climate change effects on the Vipava river discharge using hydrological models that use GCM outputs to generate estimates of streamflow and runoff. Combining the hydrological model with a scaled-down GCM value analysis could provide a more practical result regarding the hydrological parameters of the Vipava River concerning climate change projections.

In order to project the consequences of climate change and assess those impacts, initially, it is essential to prepare a hydrological model for the Vipava river catchment. The future climate impact could be projected using atmosphere-ocean general circulation models (GCMs) output outs or a finer geographical scale of a statistical and dynamical downscaling technique of regional climate models (RCM). Moreover, since socio-economic growth substantially impacts flood damage assessment, it is necessary to incorporate projections for land use change to have a more accurate and practical evaluation of potential flood damage.

# 7 REFERENCES

Abd El Shafy, M., & Mostafa, A. (2021). Flash Flood Modeling Using HEC-RAS (2D) model on Wadi Reem in the western region, Kingdom of Saudi Arabia. *Journal of Egyptian Academic Society for Environmental Development. D, Environmental Studies*, *22*(1), 17-32.

Ahmad, H. F., Alam, A., Bhat, M. S., & Ahmad, S. (2016). One dimensional steady flow analysis using HECRAS–A case of River Jhelum, Jammu and Kashmir. *Eur. Sci. J*, *12*, 340-350.

Alfieri, L., Dottori, F., & Feyen, L. (2017). Task 7–River floods. *European Commission EUR*, *29422*.

Alzahrani, A. S. (2017). *Application of two-dimensional hydraulic modeling in riverine systems using HEC-RAS* (Doctoral dissertation, University of Dayton).

Arnell, N. W., Lowe, J. A., Bernie, D., Nicholls, R. J., Brown, S., Challinor, A. J., & Osborn, T. J. (2019). The global and regional impacts of climate change under representative concentration pathway forcings and shared socioeconomic pathway socioeconomic scenarios. *Environmental Research Letters*, *14*(8), 084046.

Arnell, N. W., & Lloyd-Hughes, B. (2014). The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic change*, *122*(1), 127-140.

Arseni, M., Rosu, A., Calmuc, M., Calmuc, V. A., Iticescu, C., & Georgescu, L. P. (2020). Development of flood risk and hazard maps for the lower course of the Siret River, Romania. *Sustainability*, *12*(16), 6588.

Askar, M. K. (2013). Rainfall-runoff model using the SCS-CN method and geographic information systems: a case study of Gomal River watershed. *WIT Transactions on Ecology and the Environment*, *178*, 159-170.

Bai, Y., Zhang, Z., & Zhao, W. (2019). Assessing the impact of climate change on flood events using HEC-HMS and CMIP5. *Water, Air, & Soil Pollution*, *230*(6), 1-13.

Bates, B., Kundzewicz, Z., & Wu, S. (2008). *Climate change and water*. Intergovernmental Panel on Climate Change Secretariat.

Betsholtz, A., & Nordlöf, B. (2017). Potentials and limitations of 1D, 2D and coupled 1D-2D flood modelling in HEC-RAS. *TVVR17/5003*.

Blöschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., ... & Viglione, A. (2015). Increasing river floods: fiction or reality?. *Wiley Interdisciplinary Reviews:*

Booij, M. J. (2005). Impact of climate change on river flooding assessed with different spatial model resolutions. *Journal of hydrology*, *303*(1-4), 176-198.

Brilly, M., Kavčič, K., Šraj, M., Rusjan, S., & Vidmar, A. (2014). Climate change impact on flood hazard. *Proceedings of the International Association of Hydrological Sciences*, *364*, 164-170.

Brunner, G. W., Piper, S. S., Jensen, M. R., & Chacon, B. (2015). Combined 1D and 2D hydraulic modeling within HEC-RAS. In *World Environmental and Water Resources Congress 2015* (pp. 1432-1443).

Cammerer, H., Thieken, A. H., & Lammel, J. (2013). Adaptability and transferability of flood loss functions in residential areas. *Natural Hazards and Earth System Sciences*, *13*(11), 3063-3081.

Change, I. C. (2014). Synthesis Report. Contribution of working groups I. *II and III to the fifth assessment report of the intergovernmental panel on climate change*, *151*(10.1017)

Cook, A. C. (2008). Comparison of one-dimensional HEC-RAS with two-dimensional FESWMS model in flood inundation mapping. *Graduate School, Purdue University, West Lafayette*..

Dasallas, L., Kim, Y., & An, H. (2019). Case study of HEC-RAS 1D–2D coupling simulation: 2002 Baeksan flood event in Korea. *Water*, *11*(10), 2048.

De Roo, A., Bisselink, B., Beck, H., Bernhard, J., Burek, P., Reynaud, A., ... & Dosio, A. (2016). Modelling water demand and availability scenarios for current and future land use and climate in the Sava River Basin. *Publications Office of the European Union, Luxembourg*.

Dobler, C., Bürger, G., & Stötter, J. (2012). Assessment of climate change impacts on flood hazard potential in the Alpine Lech watershed. *Journal of Hydrology*, *460*, 29-39.

Döll, P., & Schmied, H. M. (2012). How is the impact of climate change on river flow regimes related to the impact on mean annual runoff? A global-scale analysis. *Environmental Research Letters*, *7*(1), 014037.

Dottori, F., Martina, M. L. V., & Figueiredo, R. (2018). A methodology for flood susceptibility and vulnerability analysis in complex flood scenarios. *Journal of Flood Risk Management*, *11*, S632-S645.

Doulabian, S., Golian, S., Toosi, A. S., & Murphy, C. (2021). Evaluating the effects of climate change on precipitation and temperature for Iran using RCP scenarios. *Journal of Water and Climate Change*, *12*(1),

Englhardt, J., de Moel, H., Huyck, C. K., de Ruiter, M. C., Aerts, J. C., & Ward, P. J. (2019). Enhancement of large-scale flood risk assessments using building-material-based vulnerability curves for an object-based approach in urban and rural areas. *Natural Hazards and Earth System Sciences*, *19*(8), 1703-1722.

Farooq, M., Shafique, M., & Khattak, M. S. (2019). Flood hazard assessment and mapping of River Swat using HEC-RAS 2D model and high-resolution 12-m TanDEM-X DEM (WorldDEM). *Natural Hazards*, *97*(2), 477-492.

Fedorova, D., Kovář, P., Gregar, J., Jelínková, A., & Novotná, J. (2018). The use of Snyder synthetic hydrograph for simulation of overland flow in small ungauged and gauged catchments. *Soil and Water Research*, *13*(4), 185-192.

Fletcher, C. (2018). *Climate change: what the science tells us*. John Wiley & Sons.

Fuchs, S., Heiser, M., Schlögl, M., Zischg, A., Papathoma-Köhle, M., & Keiler, M. (2019). A model to predict flood loss in mountain areas. *Environmental modelling & software*, *117*, 176-180.

Gerl, T., Kreibich, H., Franco, G., Marechal, D., & Schröter, K. (2016). A Review of Flood Loss Models as Basis for Harmonization and Benchmarking. PLoS One, 11(7), e0159791.

He, Y., Manful, D., Warren, R., Forstenhäusler, N., Osborn, T. J., Price, J., ... & Yamazaki, D. (2022). Quantification of impacts between 1.5 and 4 C of global warming on flooding risks in six countries. *Climatic Change*, *170*(1), 1-21.

Huang, Y., Ma, Y., Liu, T., & Luo, M. (2020). Climate change impacts on extreme flows under IPCC RCP scenarios in the mountainous Kaidu watershed, Tarim River basin. *Sustainability*, *12*(5), 2090.

Huizinga, J., De Moel, H., & Szewczyk, W. (2017). *Global flood depth-damage functions: Methodology and the database with guidelines* (No. JRC105688). Joint Research Centre (Seville site).

Ionita, M., & Nagavciuc, V. (2021). Extreme floods in the eastern part of europe: large-scale drivers and associated impacts. *Water*, *13*(8), 1122.

Islahuddin, M., Sukrainingtyas, A. L., Kusuma, M. S. B., & Soewono, E. (2015, September). Mathematical modeling of synthetic unit hydrograph case study: Citarum watershed. In *AIP Conference Proceedings* (Vol. 1677, No. 1, p. 030021). AIP Publishing LLC.

Kaffas, K., & Hrissanthou, V. (2014). Application of a continuous rainfall-runoff model to the basin of Kosynthos river using the hydrologic software HEC-HMS. *Glob. NEST J*, *16*(1), 188-203.

Kapović Solomun, M., Ferreira, C. S., Zupanc, V., Ristić, R., Drobnjak, A., & Kalantari, Z. (2022). Flood legislation and land policy framework of EU and non-EU countries in Southern Europe. *Wiley Interdisciplinary Reviews: Water*, *9*(1), e1566.

Kay, A. L., Rudd, A. C., Fry, M., Nash, G., & Allen, S. (2021). Climate change impacts on peak river flows: Combining national-scale hydrological modelling and probabilistic projections. *Climate Risk Management*, *31*, 100263.

Khatun, A., Ganguli, P., Bisht, D. S., Chatterjee, C., & Sahoo, B. (2022). Understanding the impacts of predecessor rain events on flood hazard in a changing climate. *Hydrological Processes*, *36*(2), e14500.

Kim, N. W., Lee, J. Y., Park, D. H., & Kim, T. W. (2019). Evaluation of future flood risk according to RCP scenarios using a regional flood frequency analysis for ungauged watersheds. *Water*, *11*(5), 992.

Kirkpatrick, J. I. M., & Olbert, A. I. (2020). Modelling the effects of climate change on urban coastal-fluvial flooding. *Journal of Water and Climate Change*, *11*(S1), 270-288.

Koike, M. P. T., & Perera, D. Investigating the Impact of Climate Change on Flooding in the Sittaung River Basin, Myanmar.

Kryžanowski, A., Brilly, M., Rusjan, S., & Schnabl, S. (2014). Structural flood-protection measures referring to several European case studies. *Natural hazards and earth system sciences*, *14*(1), 135-142.

Kučić, L. (2019; February 16). *Floods in Slovenia: millions of euros worth of damage, for which we are mostly guilty*. European data journalism network. https://www.europeandatajournalism.eu/eng/News/Data-news/Floods-in-Slovenia-millions-of-euros-worth-of-damage-for-which-we-are-mostly-guilty

Magjar, M., Suhadolnik, P., Šantl, S., Vrhovec, Š., Klemencic, A. K., & Smolar, N. (2021). Vipava river basin adaptation plan.
.

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Review article" Assessment of economic flood damage". *Natural Hazards and Earth System Sciences*, *10*(8), 1697-1724.

Mushar, S. H. M., Ahmad, S. S. S., Kasmin, F., & Kasmuri, E. (2019). Flood Damage Assessment: A Preliminary Studies. *Environmental Research, Engineering and Management*, *75*(3), 55-70.

Nasa. (n.d.). *How does climate change affect precipitation?* Global precipitation measurement. **https://gpm.nasa.gov/resources/faq/how-does-climate-change-affect-precipitation**

Nohara, D., Kitoh, A., Hosaka, M., & Oki, T. (2006). Impact of climate change on river discharge projected by multimodel ensemble. *Journal of hydrometeorology*, *7*(5), 1076-1089.

Nouri, M., Morid, S., Karimi, N., & Gholami, H. (2021). Spatial and Temporal Variation of Temperature and Precipitation Trends of Aras Transboundary River Basin. *Iran-Water Resources Research*, *17*(3), 104-117.

Olesen, L., Löwe, R., & Arnbjerg-Nielsen, K. (2017). Flood damage assessment–Literature review and recommended procedure.

Ongdas, N., Akiyanova, F., Karakulov, Y., Muratbayeva, A., & Zinabdin, N. (2020). Application of HEC-RAS (2D) for flood hazard maps generation for Yesil (Ishim) river in Kazakhstan. *Water*, *12*(10), 2672.

Peng, L., & Li, Z. (2021). Ensemble Flood Risk Assessment in the Yangtze River Economic Belt under CMIP6 SSP-RCP Scenarios. *Sustainability*, *13*(21), 12097.

Pistrika, A., Tsakiris, G., & Nalbantis, I. (2014). Flood depth-damage functions for built environment. *Environmental Processes*, *1*(4), 553-572..

Poljanšek, K., Casajus Valles, A., Marin Ferrer, M., De Jager, A., Dottori, F., Galbusera, L., ... & Wood, M. (2019). Recommendations for national risk assessment for disaster risk management in EU. *Publications Office of the European Union, Luxembourg*.

Potential Contribution of Hazus-MH to Flood Risk Assessment in the Context of the European Flood Directive G Kaveckis, G Paulus, K Mickey - 2011 - researchgate.net

Quilbé, R., Rousseau, A. N., Moquet, J. S., Trinh, N. B., Dibike, Y., Gachon, P., & Chaumont, D. (2008). Assessing the effect of climate change on river flow using general circulation models and hydrological modelling–Application to the Chaudière River, Quebec, Canada. *Canadian Water Resources Journal*, *33*(1), 73-94.

Ragettli, S., Immerzeel, W. W., & Pellicciotti, F. (2016). Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proceedings of the National Academy of Sciences*, *113*(33), 9222-9227.

Ramachandran, A., Palanivelu, K., Mudgal, B. V., Jeganathan, A., Guganesh, S., Abinaya, B., & Elangovan, A. (2019). Climate change impact on fluvial flooding in the Indian sub-basin: A case study on the Adyar sub-basin. *PloS one*, *14*(5), e0216461.

Razi, M. A. M., Marimin, N. A., Ahmad, M. A., Adnan, M. S., & Rahmat, S. N. (2018). HEC-RAS hydraulic model for floodplain area in Sembrong River. *International Journal of Integrated Engineering*, *10*(2).

REPUBLIC SLOVENIJA MINISTRSTVO ZA OKOLJE IN PROSTER. (2018, Novemebr ). *ARSO: Ocena podnebnih sprememb v Sloveniji do konca 21. stoletja (1. sintezno poročilo).* **https://podatki.gov.si/dataset/arsopodnebne-spremembe-projekcije-visine-padavin-dnevni-podatki-scenarij-rcp2-6-locljivost-0-125/resource/729e1bcb-d639-487f-8e9e-fb4ab6bfaf61**

Rojas, R., Feyen, L., & Watkiss, P. (2013). Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change*, *23*(6), 1737-1751.

Sairam, N., Brill, F., Sieg, T., Farrag, M., Kellermann, P., Nguyen, V. D., ... & Kreibich, H. (2021). Process-based flood risk assessment for Germany. *Earth's Future*, *9*(10), e2021EF002259.

Salami, A. W., Bilewu, S. O., Ibitoye, B. A., & Ayanshola, M. A. (2017). Runoff hydrographs using Snyder and SCS synthetic unit hydrograph methods: A case study of selected rivers in south west Nigeria. *Journal of Ecological Engineering*, *18*(1).

Sauer, I. J., Reese, R., Otto, C., Geiger, T., Willner, S. N., Guillod, B. P., ... & Frieler, K. (2021). Climate signals in river flood damages emerge under sound regional disaggregation. *Nature communications*, *12*(1), 1-11.

Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., ... & Lawrence, M. (2006). HAZUS-MH flood loss estimation methodology. II. Damage and loss assessment. *Natural Hazards Review*, *7*(2), 72-81.

Schramm, P. J., Uejio, C. K., Hess, J. J., Marinucci, G. D., & Luber, G. (1915). Climate models and the use of climate projections: a brief overview for health departments.

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., ... & Zwiers, F. W. (2012). Changes in climate extremes and their impacts on the natural physical environment.

Sinnakaudan, S. K., Ab Ghani, A., Ahmad, M. S. S., & Zakaria, N. A. (2003). Flood risk mapping for Pari River incorporating sediment transport. *Environmental Modelling & Software*, *18*(2), 119-130.

Špitalar, M., Brilly, M., Kos, D., & Žiberna, A. (2019). Analysis of flood fatalities–Slovenian illustration. *Water*, *12*(1), 64.

Stoleriu, C. C., Urzica, A., & Mihu-Pintilie, A. (2020). Improving flood risk map accuracy using high-density LiDAR data and the HEC-RAS river analysis system: A case study from north-eastern Romania. *Journal of flood risk management*, *13*, e12572.

Sun, Q., Fang, J., Dang, X., Xu, K., Fang, Y., Li, X., & Liu, M. (2021). Multi-scenario urban flood risk assessment by integrating future land use change models and hydrodynamic models. *Natural Hazards and Earth System Sciences Discussions*, 1-22.

Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific reports*, *10*(1), 1-10.

Thieken, A. H., Olschewski, A., Kreibich, H., Kobsch, S., & Merz, B. (2008). Development and evaluation of FLEMOps–a new Flood Loss Estimation MOdel for the private sector. *WIT Transactions on Ecology and the Environment*, *118*, 315-324.

Tsakiris, G. J. N. H. (2014). Flood risk assessment: concepts, modelling, applications. *Natural Hazards and Earth System Sciences*, *14*(5), 1361-1369.

Ukumo, T. Y., Abebe, A., Lohani, T. K., & Edamo, M. L. (2022). Flood hazard mapping and analysis under climate change using hydro-dynamic model and RCPs emission scenario in Woybo River catchment of Ethiopia. *World Journal of Engineering*.

Vozinaki, A. E. K., Morianou, G. G., Alexakis, D. D., & Tsanis, I. K. (2017). Comparing 1D and combined 1D/2D hydraulic simulations using high-resolution topographic data: A case study of the Koiliaris basin, Greece. *Hydrological Sciences Journal*, *62*(4), 642-656.

Wang, S., McGrath, R., Semmler, T., Sweeney, C., & Nolan, P. (2006). The impact of the climate change on discharge of Suir River Catchment (Ireland) under different climate scenarios. *Natural Hazards and earth system sciences*, *6*(3), 387-395.

Wang, Z., Lin, L., Zhang, X., Zhang, H., Liu, L., & Xu, Y. (2017). Scenario dependence of future changes in climate extremes under 1.5 C and 2 C global warming. *Scientific reports*, *7*(1), 1-9.

Wobus, C., Gutmann, E., Jones, R., Rissing, M., Mizukami, N., Lorie, M., ... & Martinich, J. Climate Change Impacts on 100 year Flood Risk and Asset Damages within Mapped Floodplains of the Contiguous United States.

Xu, X., Wang, Y. C., Kalcic, M., Muenich, R. L., Yang, Y. E., & Scavia, D. (2019). Evaluating the impact of climate change on fluvial flood risk in a mixed-use watershed. *Environmental modelling & software*, *122*, 104031.

Yin, Z., Hu, Y., Jenkins, K., He, Y., Forstenhäusler, N., Warren, R., ... & Guan, D. (2021). Assessing the economic impacts of future fluvial flooding in six countries under climate change and socio-economic development. *Climatic Change*, *166*(3), 1-21.

Zainalfikry, M. K., Ab Ghani, A., Zakaria, N. A., & Chan, N. W. (2019, August). HEC-RAS One-Dimensional hydrodynamic modelling for recent major flood events in pahang river. In *AWAM International Conference on Civil Engineering* (pp. 1099-1115). Springer, Cham.

Zeleňáková, M., & Gaňová, L. (2018). Flood damage assessment. *WIT Transactions on The Built Environment*, *184*, 61-68.