Utrecht University

Master thesis – Sustainable Development

Anthrome exposure to extreme flood hazards in the future

HIGH WATER Floods along the Mississippi River in spring 2011 rivaled the Great Flood of 1927 in size. Human engineering of the river may be making such floods bigger. Carolyn Gramling, 2018.

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Abstract

Under the context of global warming, the frequency and magnitude of extreme flood events will increase in the future, threatening the terrestrial system effecting future anthromes. This master's thesis investigates the relationship between flood hazards and anthromes, unraveling the implications of varying climate scenarios and time frames. Leveraging hydrological modeling, this study investigates three major river basins—the Limpopo, Mississippi, and Mekong—across multiple climate scenarios (ssp126, ssp370, ssp585) and time slices (2030, 2060, 2090).

Moreover, the investigation incorporates the overlay of anthromes maps onto flood hazard datasets to determine the spatial relationships of anthropogenic influence on flood-prone regions. The findings reveal a consistent pattern across all three river basins. Flood magnitude and frequency tend to increase markedly under the SSP370 and SSP585 scenarios, posing substantial challenges to communities residing in these regions. The Mekong basin, with its vast population and significant agricultural activity, faces heightened vulnerability to flooding. On the other hand, the Mississippi basin exhibits noteworthy resilience, albeit with some variations under different scenarios. In the Limpopo basin, the discernible impact of human activities is primarily observed in rangelands and pastoral settlements. Where in this case the availability of knowledge and/or funding to protect against flood events is limited. Urban areas and settlements become focal centres of flood risk in the Mississippi basin, illustrating the strong relationship between population density patterns and flood hazard sensitivity. Indicating an increased need for flood hazard mitigation strategies, in order to protect urban areas. Likewise, the Mekong basin accentuates the vulnerability of cropland zones and urban centres to inundation. These results demonstrate the need of taking into account localized anthropogenic dynamics when estimating the inherent flood hazards.

In light of these results, it is evident that socioeconomic factors, including GDP and infrastructure development, play a pivotal role in a region's ability to mitigate and manage floods. Moreover, the study underscores the importance of tailored adaptation strategies for each river basin, considering their unique characteristics and vulnerabilities

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1. Introduction

Climate change due to anthropogenic greenhouse gas (GHG) emissions is expected to change the frequency and magnitude of precipitation (IPCC, 2014; Alfieri et al., 2015; Alfieri et al., 2017). As the climate warms, the water holding capacity of earth's atmosphere increases, expected to increase the intensity of precipitation events. These events are likely to have an impact on the frequency of river and coastal floods (Allen & Ingram, 2002; Min et al., 2011). Potential increase in flood hazards have been frequently cited impacts of future climate change (Arnell & Gosling, 2016; Bell et al., 2007; Dankers et al., 2014). Extreme floods can have a devastating impact on the land system, from damaging infrastructure and buildings to causing crop losses and threatening human lives. While various studies (Hirabayashi et al., 2013; Kundzewicz et al., 2014; Jongman et al., 2015; Alfieri et al., 2015) have explored and investigated extreme flood events under different future climate scenarios. there is still limited research on extreme floods in large-scale land patterns.

Recent research studies that utilize hydrological models to predict future flood occurrences often neglect essential factors that significantly influence the severity and extent of flood damages. These factors include critical aspects such as flood prevention measures (Neumann et al., 2015; Şen, 2018), flood control policies (Barraqué, 2017), and potential changes in land cover due to human activities or climate change (Verburg et al., 2019). In a global-scale study, Alfieri et al (2017) utilized downscaled projections from seven Global Climate Models (GCMs) as input to drive a hydrodynamic model. Their findings revealed that, except for Europe, all continents experienced a successive increase in the frequency of high floods correlated with rising levels of global warming (1.5°C, 2°C, 4°C). These findings are corroborated by Paltan et al. (2018), who utilized a simplified runoff aggregation model driven by outputs from four GCMs. In a study conducted by S. Huang et al. in 2018, three hydrological models were used to generate projections for four major river basins, namely the Rhine, Upper Mississippi, Upper Yellow, and Upper Niger. These projections were based on bias-adjusted outputs from four GCMs and were developed for different global warming scenarios of 1.5°C, 2°C, and 3°C. Here they found various projections for different basins, results included earlier flooding in the Rhine and Upper Mississippi, a considerable increase in flood frequency in the Rhine in the 1.5°C and 2°C scenarios and a decrease in flood frequency in the Upper Mississippi under all scenarios

Anthropogenic factors, such as deforestation, urbanization, and land use changes, have altered the land's ability to absorb and retain water, resulting in increased runoff and flooding events (Ellis et al., 2008). However, there is limited research on extreme flood events in large-scale land patterns. Anthropogenic activities will continue to be the dominant factor contributing to land use and cover change in the future. Therefore, the concept of Anthromes, first introduced by Ellis et al. (2010), which considers both land use/cover and vegetation type along with population density as classification criteria, may be more suitable for assessing the effects of future flood hazards. Looking at anthromes from the extreme flood hazard perspective may be more detailed to assess the vulnerability of a landscape to flooding than land use. Anthromes can help to identify areas that are more vulnerable to flooding due to human activities. Anthromes can be used to develop more effective strategies for managing flooding. Therefore, this study aims to investigate extreme floods in different future climate scenarios from the anthromes perspective, addressing this knowledge gap and contributing to the understanding of flood impacts on different types of land patterns with a focus around delta regions of earth.

1.1 Problem definition

The Earth's climate is projected to become warmer in all future scenarios, which is expected to lead to more frequent and intense extreme flood events. As discussed above, extreme floods can have significant negative impacts on the land system, including human health, infrastructure, and ecosystem functions. While extensive research has been conducted on flood hazards and their consequences, there is a noticeable gap in understanding the relationship between extreme flood events and Anthromes. Anthromes, which consider the influence of human activities on land use and cover, provide a novel framework for classifying and analyzing land patterns that is more suitable for analyzing flood hazards compared to the traditional concept of biomes and may provide new solutions or insights. However, no research has explored the specific interactions between Anthromes and extreme flood events.

Historically, the macroclimate has been recognized as the primary driver shaping large-scale regional biomes (Valdés et al., 2015; Klinges & Scheffers. 2020). Over the past 8,000 years, human activities, such as intensive agriculture and urbanization, have significantly altered landscape patterns. Looking forward, human actions will remain the dominant factor contributing to changes in land use and cover. Understanding the implications of these anthropogenic changes in the context of extreme flood events is crucial for effective flood risk management, sustainable land management, and the well-being of communities and populations whose livelihood depend on these river basins. The lack of extensive research on extreme flood events in relation to Anthromes poses a significant challenge to developing a comprehensive understanding of the impact of human-induced land use and cover changes on the occurrence, severity, and spatial distribution of these floods. This knowledge gap hinders our ability to accurately assess the potential risks and vulnerabilities associated with extreme floods in Anthropocene landscapes.

Given the significance of extreme flood events in the Mississippi, Limpopo, and Mekong River basins, it is imperative to address this research gap and investigate the connections between Anthromes and extreme flood events in these regions. By examining the complex interplay between land use, cover, and flood dynamics, we can gain valuable insights into the underlying drivers of extreme floods and develop targeted strategies for mitigating their impacts. This research will provide a more comprehensive understanding of the vulnerabilities and resilience of these river basins to extreme flood events, informing decision-making processes, disaster preparedness, and adaptation measures to ensure the long-term sustainability of these regions in the face of global warming and climate change.

1.2 Research objective

The current understanding of future flood hazards in relation to Anthromes is limited, highlighting the need for research in this area. This study aims to address this gap by examining the frequency and magnitude of future flood events, with an analysis on Anthromes and their implications for human well-being. The PCR GLOBWB model provides a framework for defining flood hazards. In this research, we will use the model to quantify the frequency and magnitude of flood events under different future scenarios in three distinct delta regions located across different parts of the world and make a first spatial analysis qualitative analysis of future flood hazards and its effect on future anthromes.

Overall, this research aims to advance knowledge on future flood hazards, from an anthrome perspective, and contribute to informed decision-making processes for sustainable development and disaster risk reduction in delta regions worldwide.

The main research question is:
How will anthromes be affected by extreme flood events modelled under different future climate and socio-economic scenarios?

The following sub-questions have been determined to support the main research question:

a. How will the frequency and magnitude of extreme flood events evolve over time under different climate scenarios?
b. How will the frequency of flood hazards affect population anthrome within each river basin?
c. How will the frequency of extreme flood events affect crop anthromes?

1.3 Study area

The Mississippi, Limpopo, and Mekong River basins are important to study for flood hazard analysis because they are all large, populous river systems that are vulnerable to flooding. The Mississippi, Limpopo and Mekong River basins were chosen due to their important to the populations that depend on them. These basins differ in GDP where Mekong basin covering countries Cambodia, Thailand, and Vietnam, collectively amounting to a GDP of $980 billion USD, the Mississippi basin, located in North America, with a GDP of $23 trillion USD and the Limpopo River basin covering countries Botswana, Mozambique, South Africa, and Zimbabwe, have a combined GDP of $445 billion USD (World Bank, 2022). They are all facing significant challenges, such as climate change, deforestation, and pollution. Climate change is expected to increase the frequency and intensity of floods in the Mekong River Basin, which could have a devastating impact on agriculture and food security (Schmeier, 2011; Pohkrel et al., 2018). Deforestation is a major problem in the Mississippi River Basin, which is causing soil erosion and water pollution (Niebling et al., 2014). Pollution is also a problem in the Limpopo River Basin, which is threatening the health of people and ecosystems (Shewmake, 2008; Botai et al., 2020)

The Mississippi River basin is the largest river basin in North America, and it is home to over 30 million people. The Mississippi river basin spans 3,264,800 km^2 (Reed et al., 2020). The basin is also home to a number of major cities, including Minneapolis, St. Louis, Memphis, and New Orleans. Flooding in the Mississippi River basin can have a devastating impact on these cities and the people who live there. The Mississippi River basin is prone to flooding because it is a large, low-lying basin with a relatively flat topography. The basin is also home to a number of levees and dams, which can sometimes fail during floods, causing even more damage.

Figure 1. Mississippi River basin map.

The Limpopo River basin is located in southern Africa, and it is home to over 20 million people. The Limpopo River basin cover an area of 406,500 km^2 (McCraken et al., 2019). The basin is also home to a number of important ecosystems, including the Kruger National Park. Flooding in the Limpopo River basin can damage these ecosystems and displace people from their homes. The Limpopo River basin is prone to flooding because it is located in a region with a high rainfall variability. The basin also experiences a number of other climate-related hazards, such as droughts and wildfires, which can increase the risk of flooding.

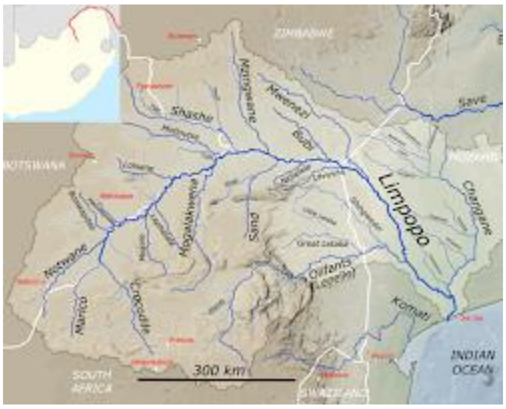


Figure 2. Limpopo river basin map

The Mekong River basin is located in Southeast Asia, and it is home to over 60 million people (Yoshida et al., 2020). The Mekong basin measures at an area of 781,600 km^2. The basin is also home to a number of important agricultural areas. Flooding in the Mekong River basin can damage crops and displace people from their homes. The Mekong River basin is prone to flooding because it is located in a region with a monsoonal climate. The basin also experiences a number of other climate-related hazards, such as droughts and tropical cyclones, which can increase the risk of flooding.

Figure 3. Mekong river basin map

In addition to being large and populous, the Mississippi, Limpopo, and Mekong River basins are also all vulnerable to climate change. Climate change is expected to cause more extreme weather events, including floods. This means that the risk of flooding in these basins is only going to increase in the future. For these reasons, it is important to study the Mississippi, Limpopo, and Mekong River basins for flood hazard analysis. This research can help us to better understand the risks of flooding in these basins and to develop better ways to mitigate these risks.

1.4 Scientific and societal relevance

In the context of global warming frequency and intensity of extreme flood events will increase in the future (Ochoa et al., 2020). Anthromes, a new land classification method, re-defines the biome by considering the interaction between humans and the ecosystem (Ellis & Ramankutty, 2008). Past studies have examined future flood hazards for and local region or specific areas around the world, but none have considered the Anthromes perspective. There are limited research quantifying flood hazards from the anthromes perspective. This type of research in needed, due to the current research with climate information and models that is useful for land use risk assessment and decision-making.

Besides the scientific relevance, this research can also provide can be important for decision-makers and policy makers. several Sustainable Development Goals (SDGs) are relevant due to their alignment with the societal impact of studying flood hazards, anthropogenic land use changes, and climate change. One key SDG is Goal 11: Sustainable Cities and Communities, as urban areas are particularly vulnerable to extreme floods and require effective flood risk management strategies. Additionally, Goal 13: Climate Action is crucial, as understanding the impact of climate change on flood hazards contributes to mitigation and adaptation efforts. Goal 15: Life on Land is significant, as floods can disrupt ecosystems and threaten biodiversity, necessitating sustainable land management practices. Furthermore, Goal 1: No Poverty and Goal 2: Zero Hunger are relevant, as floods can impact food security and livelihoods, particularly in agricultural areas. By investigating the interplay between floods, land use changes, and climate change, your research can contribute to informed decision-making, policy development, and the pursuit of these sustainable development objectives, ultimately enhancing societal resilience and well-being.

Major floods have profound scientific and societal implications, highlighting the urgent need for understanding and mitigating the impacts of extreme hydrological events. Recent floods in various regions of the world have underscored the importance of advancing flood risk assessment and management strategies to protect human lives and livelihoods and to safeguard critical infrastructure and ecosystems. The Italy floods of 2022 (Marche region, Central Italy), China floods of 2021 (Henan province, central China), and Germany floods of 2021 (Eifel-Ardennes mountains, western Germany) were all triggered by heavy rainfall, leading to substantial loss of life and extensive damage. These three flood events are just a small mention of the numerous flooding events that have occurred around the world in recent times. Each event presents unique challenges and offers valuable lessons that can enhance emergency response strategies and the development of effective flood risk reduction measures for the future. It is crucial to recognize that flooding events can occur on various scales, not limited to river basin scale alone. Floods can happen at very local levels, impacting communities and landscapes in unexpected ways. The local-scale impacts of floods further emphasize the need for comprehensive research and adaptive flood management approaches to address the diverse challenges posed by these events.

2. Theory

2.1 Global climate change

Around 12,800 years ago, the global climate maintained a relatively stable state, providing favorable conditions for human development (Berkman & Young, 2009). However, since the industrial revolution, human activities have rapidly transformed the terrestrial biosphere ecosystem and exerted a significant influence on Earth's climate (Rockström et al., 2009). While the focus of climate change research has often been on the rise in global temperatures, it is important to recognize the impact of extreme floods, which can have devastating consequences for human societies, ecosystems, and landscapes.

Since 1750, human activities have resulted in the emission of over 1.5 trillion tonnes of CO_2, contributing to the greenhouse effect and the warming of the planet (Günthardt-Goerg & Arend, 2013). Although there has been a recent slowdown in the rate of greenhouse gas emissions, the total cumulative emissions continue to rise steadily (IPCC, 2022). The global average temperature has already increased by approximately 1°C since the pre-industrial period, approaching the critical threshold of 2°C set in the Paris Agreement (Rockström et al., 2009; Anderson, 2012). This increase in temperature poses immense pressure on the land system and has implications for the frequency and intensity of extreme weather events.

While the relationship between rising temperatures and extreme weather events has been extensively studied (Choi & Kim, 2019; Dai et al., 2015), the impact of extreme floods requires careful examination. In populated regions, observational records reveal significant changes in extreme weather patterns over the past four decades. The frequency and intensity of extreme flood events have risen noticeably, accompanied by an increase in extreme precipitation events (Sadeghi et al., 2015; Matonse & Frei, 2013; Garg & Mishra, 2019). These changes have profound implications for societies, ecosystems, and infrastructure vulnerable to flooding. Extreme floods can result in widespread property damage, displacement of populations, loss of lives, and severe ecological disruptions.

2.2 Land system

The land system refers to the terrestrial aspect of the Earth system, encompassing various human activities and processes related to land use. This includes factors like socioeconomic aspects, technology, organizational structures, and the ecosystem services provided by land. It also takes into account the unintentional impacts and consequences of human activities on land (Verburg et al., 2013). The Earth's land is vital to humans, providing important resources such as food, fuel, fiber, and raw materials. Before the Holocene period, which started around 12000 years ago, early humans used fire as a tool for hunting without significantly altering the landscape (Klein Goldewijk et al., 2017). During this time, microclimate was considered the most important factor in shaping vegetation patterns and land cover (Mucina, 2019; Stevens et al., 2022). Interactions between humans and the natural environment had already begun, leading to changes in local environmental dynamics, ecosystems, and landscapes (Ellis et al., 2021).

Humans then transitioned from a more hunting lifestyle to domesticating animals and growing plants on more permanent agricultural lands, transforming natural landscapes into farmland (Klein Goldewijk et al., 2017). Since then, humans have been the main driver of land use change. By 4000 CE, recent reconstructions of land use showed that three-quarters of natural terrestrial ecosystems were already impacted by hunting and agricultural activities (Ellis et al., 2021).
By 1 CE, agricultural and pastoral land-use change had already begun in Europe, Asia, and other parts of the world. However, this transformation accelerated significantly after World War II as populations increased rapidly and the Industrial Revolution increased demand for food and improved food production. As a result, more than 80% of terrestrial ecosystems were altered by human activities, leading to a complete change in human lifestyles (Ellis et al., 2021; Sanderson et al., 2018).

Currently, most of the world's population is concentrated in urban areas, where the footprint of urban populations results in significant and irreversible changes to the land system. Human activities have exerted a significant impact on approximately 44% of the Earth's land area, resulting in permanent and irreversible impacts (Jacobson et al., 2019). The global population is projected to continue to increase, reaching an estimated 9.8 billion by 2050 and 11.8 billion by 2100 (United Nations., 2022). This escalating population growth will inevitably increase demand for food and put additional pressure on the conversion of semi-natural lands to cropland and pasture. Consequently, the exploitation of highly productive land by human activities is already underway, with an expected acceleration of land scarcity due to urbanization and increasing demand for food and resources (Popp et al., 2017)

2.3 Anthromes

Anthromes, also known as anthropogenic biomes, are ecosystems that have been significantly altered by human activities (Ellis et al., 2010). Humans have been altering their environment for thousands of years, resulting in the creation of new ecosystems that differ from their pre-human counterparts (Ellis et al., 2010). The concept of anthromes recognizes that humans are a major force shaping Earth's ecosystems and that these ecosystems can be understood as the result of the interplay between human societies and the natural world (Ellis et al., 2010).

Anthromes are often classified on the basis of their predominant land use, distinguishing between different types such as dense settlements, villages and farmlands, grasslands, forests, and wetlands. This classification system was first proposed by Ellis and Ramankutty (2008) and has since been refined and expanded by other researchers. The anthrome classification system divides land patterns into 20 Anthromes, including intensively used land, cultured land, and wildland (Ellis et al., 2010). Despite its widespread adoption among researchers, there has been limited research on the relationship between Anthromes and climate change. It is a useful framework for understanding the diversity of human impacts on ecosystems and for identifying patterns and trends in the formation and distribution of anthromes (Ellis et al., 2010; Ellis et al., 2021).

The most recent version of the Anthromes Database, covering the period from 12,000 BCE to 2015 CE, was completed using the History Database of the Global Environment (HYDE 3.2) and other data sources. A distribution rule (figure 12, see appendix) was utilized for classification and mapping of the anthropogenic transformation of terrestrial ecosystems (Ellis et al., 2021). An unpublished future anthrome database covering the period from 2015 to 2100 was also completed last year and is being used in this research (van der Wielen, 2021).Overall, understanding anthromes and the ways in which humans have altered the natural world is essential for developing effective conservation and management strategies. By recognizing the many ways in which humans interact with and shape their environment, we can work toward creating sustainable and resilient ecosystems that promote both human well-being and biodiversity conservation.

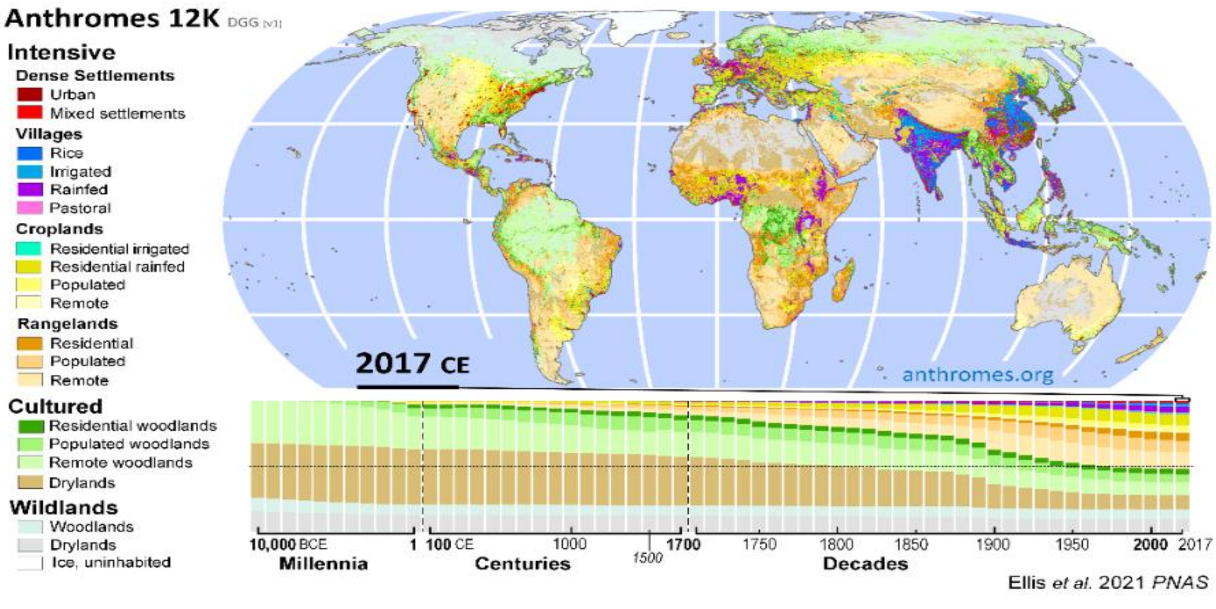


Figure 4. The anthrome classification (Ellis et al., 2010)

2.4 Extreme flood hazards

Floods, which involve the inundation of typically dry land, can be classified into various types based on spatial and temporal processes, such as pluvial floods, flash floods, river floods, groundwater floods, surge floods, and coastal floods (Nied et al., 2014; Aerts et al., 2018). Pluvial and urban floods often occur when extreme precipitation exceeds the capacity of natural or artificial drainage systems (May, 2008). Nevertheless, besides intense precipitation, other factors can also influence flood occurrence. These factors include antecedent soil moisture (Berghuijs et al., 2016; Woldemeskel and Sharma, 2016), stream morphology (Borga et al., 2014), river and catchment engineering (Pisaniello et al., 2012; Kim and Sanders, 2016), and land use/cover characteristics (Rogger et al., 2017; Brody et al., 2014).

Extreme floods are a major threat to human health, the environment and agriculture. Extreme floods pose a severe threat to human lives and livelihoods which can result in loss of life, displacement of populations, and extensive property damage (IPCC, 2012). Flood-related disasters can lead to significant economic losses, disrupting local economies and infrastructure (Khan et al., 2019; Silva & Kawasaki, 2020). The costs associated with flood recovery, rebuilding, and rehabilitation efforts can be substantial and have long-lasting effects on affected communities. Extreme floods can also have significant impacts on crop growth and production. While different crops exhibit varying responses to global climate change, the increasing frequency and intensity of extreme flood events associated with climate change can reduce crop productivity (Shi et al., 2020; Banerjee. 2010). Ensuring food security is a critical objective in meeting the nutritional needs of the growing global population (Kang et al., 2009). In agricultural areas, climate change-related extreme events can disrupt local agricultural activities and pose a threat to food system infrastructure, thereby jeopardizing global food security. When flood events occur, they can lead to waterlogging, soil erosion, and nutrient loss, all of which can adversely affect crop growth and yield (Muller et al., 2015; Tito, Vasconcelos & Feeley. 2018)

Improved water regulation and management practices have generally enhanced flood resilience (Formetta and Feyen, 2019). While these measures have partially mitigated the impact of increased extreme precipitation on flood probability in certain regions, they do not eliminate the risk of highly severe floods (Vicente-Serrano et al., 2017). Therefore, it is not always a straightforward relationship where an increase in precipitation extremes automatically leads to a proportional rise in regional river floods (Sharma et al., 2018). Nonetheless, extreme precipitation can emerge as a dominant factor contributing to river floods, and thus, there can be some correlation between extreme precipitation and flood occurrences (Ivancic and Shaw, 2015; Wasko and Sharma, 2017; Wasko and Nathan, 2019). Such relationships have been observed in various regions, including the western Mediterranean (Llasat et al., 2016), China (Q. Zhang et al., 2015a), and the USA (Peterson et al., 2013b; Berghuijs et al., 2016; Slater and Villarini, 2016).

2.5 Future climate scenarios

Given the uncertainty of the future, the scenario approach has become widely adopted and plays a crucial role in climate change research (Riahi et al., 2017). This approach for future climate projections provides plausible climate pathways as it takes into consideration factors like land use and cover, technology development, economic growth, and greenhouse gas (GHG) emissions (Vuuren et al.,2011). The climate change scenarios prove to be essential for climate change assessments by governments and policy makers (Ibid). More recently, the Representative Concentration Pathways (RCPs) were introduced, providing reasonable climate pathways for environmental modelling researchers to conduct longer term climate experiments (Moss et al., 2010; van Vuuren et al., 2011). More specifically, RCPs estimate future GHG emissions that result in radiative forcing relative to pre-industrial levels, allowing for a comprehensive understanding of potential impacts of climate change under different emission levels.

However, a gap was realized in the socioeconomic descriptions that could contribute to the Representative Concentration Pathways (RCPs). To address this, a novel design of plausible socioeconomic scenarios called Shared Socioeconomic Pathways (SSPs) was proposed by Van Vuuren et al. (2014), incorporating both quantitative and qualitative elements. There are 5 different storylines: Riahi et al (2017) describes them as: SSP1 represents a sustainable future with low challenges to mitigation and adaptation; SSP2 portrays a middle-of-the-road scenario with moderate challenges to mitigation and adaptation; SSP3 depicts a regional rivalry scenario with high challenges to mitigation and adaptation; SSP4 describes an inequality road scenario with low challenges to mitigation but high challenges to adaptation; and SSP5 reflects a high fossil fuel development scenario with high challenges to mitigation but low challenges to adaptation. These distinct SSP storylines are combined with the RCPs to develop comprehensive climate and socioeconomic future scenarios. The matrix method is used to generate various SSP-RCP scenarios, enabling the exploration of plausible futures and comparison of different future scenarios.

3. Methodology

In this chapter the research design is explained. The chapter is divided into research framework, data collection and management, scenario selection and the model parameters and preparation.

3.1 Research framework

The research design involves a comprehensive investigation into the dynamics of extreme flood events in the Mississippi, Limpopo, and Mekong River basins, focusing on the years from 2023 to 2100. The study employs a time-slice experiment, spanning three key time periods: 2030, 2060, and 2090, with each time slice encompassing a 15-year time slice. Through the analysis of these specific time slices, the aim is to understand the potential changes in flood occurrences and intensities within the context of future climate scenarios. The research is divided into two main parts. Firstly, an analysis is conducted to examine the changes in flood events over time under different climate scenarios. Secondly, a qualitative spatial analysis is performed to establish a relationship between flood volumes and their impact on specific Anthromes. This analysis primarily focuses on significant population and crop-related Anthromes within the study area. In order to simulate future flood hazards, PCRGLOB WB 2.0 (PCRaster Global Water Balance), hereafter 'PCR GLOBWB, a hydrology model serving as a crucial tool in simulating and assessing the impacts of climate change on hydrological processes. PCR-GLOBWB 2 is a global hydrology and water resources model created by Sutanudjaja et al (2018) at Utrecht University. It operates on a grid with a 5 arc-minute resolution (approximately 10 km at the equator) and covers most continents except Greenland and Antarctica. The model uses one-day time steps for hydrology and water use, with variable time stepping for hydrodynamic river routing. It simulates moisture storage and water exchange between soil, the atmosphere, and groundwater for each grid cell and time step. This includes processes like precipitation, evaporation from various surfaces, transpiration, and snow and glacier-related processes. The model also computes runoff, distinguishing between surface runoff, interflow, and groundwater recharge, and simulates the routing of water across the terrain and river networks using the kinematic wave approximation.

In the context of PCR GLOBWB, floods are calculated in the following manner. In PCR GLOBWB, riverine floods are defined based on the channel volume and storage within the hydrological model. Riverine floods refer to the overflow of water from a river channel onto adjacent floodplains or surrounding areas. This occurs when the volume of water in the channel exceeds its capacity, leading to the inundation of the surrounding land. The channel volume and storage are key variables used to estimate the potential for riverine floods within the model. By simulating the dynamics of channel flow and storage, PCR GLOBWB can assess the occurrence, magnitude, and spatial extent of riverine floods under various climatic and hydrological conditions.

The future climate variables are derived from Coupled Model Intercomparison Project phase 6 (CMIP6) (Eyring et al., 2016). Five bias-adjusted subsets GCMs of CMIP6 have been selected: (1) GFDL-ESM4, (2) IPSL-CM6A-LR, (3) MPI-ESM1-2-HR, (4) MRI-ESM2-0, and (5) UKESM1-0-LL (Lange, 2021). The selected five climate databases, three of which had relatively lower climate response and sensitivity: (1) GFDL-ESM4 (2) MPI-ESM1-2-HR (3) MRI-ESM2-0, and the other two databases have relatively higher climate response and sensitivity: (4) IPSL-CM6A-LR (5) UKESM1-0-LL. The benefit of using an ensemble of a subset of the CMIP6 project is to reduce projection uncertainty. The SSPs can be integrated with RCPs to create new future scenarios, and three future scenarios are selected to conduct this research that is SSP1-RCP26, SSP3-RCP70, and SSP5-RCP85 (hereafter 'ssp126', 'ssp370' and 'ssp585') (Riahi et al., 2017).

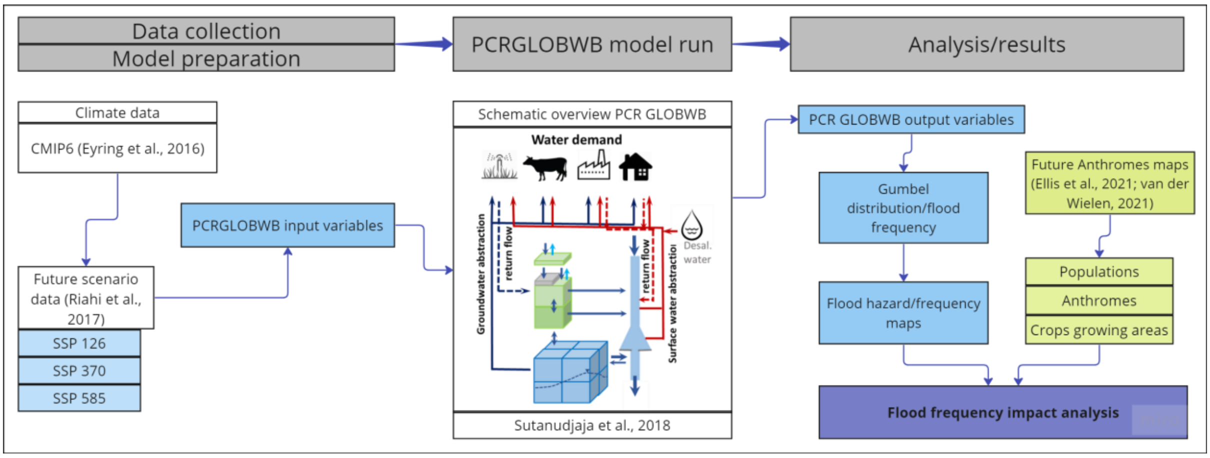


Figure 5. conceptual research framework: (1) data collection (2) model preparation (3) PCRGLOB WB model run (4) analysis and results (5) anthrome flood hazard analysis

3.2 Data management

Robust data management and safety practices were paramount throughout the thesis, particularly concerning data retrievability and storage, as extensive model runs were performed in Snellius, and the data needed to be securely preserved for analysis and future reference. Snellius is a High-Performance Computing cluster (a supercomputer) at Utrecht University, this facility is used by researchers and scientists to perform computationally intensive tasks, simulations, climate modelling, data analysis, and other complex calculations that require substantial computing power.

For data retrievability, all model outputs were carefully organized and labeled, ensuring that each dataset was easily identifiable and accessible. Additionally, comprehensive documentation was maintained, outlining the context, parameters, and methods used in each model run. The code and modelling process can be found back in GitHub (a cloud-based service for code/file storage), and the flood anthrome overlays can be found back on a Linux online server. Regarding data storage, Snellius's storage capabilities, as well as the personal Linux server, were utilized to store all the processed final data. Furthermore, regular data backups were implemented to ensure the redundancy and resilience of the datasets. Moreover, to ensure data safety, appropriate access controls and authentication mechanisms were implemented, restricting access to authorized users only, in relation to access of the PCR GLOBWB data in Snellius.

3.3 Data collection

The data required for this master thesis can be divided into two main parts. Firstly, the inputs for the PCR GLOBWB model encompass essential datasets, including climate forcing data and monthly maximum channel storage values of river basins. These critical inputs will enable the hydrological model to simulate and project future flood events accurately. Secondly, the future anthromes maps were sourced from prior research conducted by Van der Wielen (2021). This valuable dataset of future anthromes data has been further refined and updated by Lu Yin in his 2022 research work. The anthromes maps provide crucial information about the evolving human impact on land use and land cover, and they are instrumental in understanding the interactions between human activities and flood hazards.

All the climate datasets needed in this research are listed in Table 1 and 2. Among them, three climate variables are sourced from CMIP 6 (Eyring et al., 2016). Historical daily maximum precipitation (W5E5 v2.0) is also extracted from ISIMIP (Lange et al., 2021) covering a time period of 1979 to 2019 and used as a historical reference climate. Population density (Bryan Jones et al., 2015) and future anthrome (van der Wielen, 2021; Yin, 2022) are also acquired.

3.4 Climate forcing database input

The research focuses on quantifying extreme flood events under different future climate scenarios. Subset climate databases were selected from the CMIP6 project to analyse extreme flood events. The CMIP project, under the sponsorship of the Working Group on Coupled Modelling (WGCM), provides a framework to improve climate change knowledge (Eyring et al., 2016). The project began in 1995 and now involves more than 30 climate models, which have been used in numerous scientific studies to better understand past, present, and future global climate change (Eyring et al., 2016). However, the increasing number of different GCMs participating in CMIP6 has led to more uncertainty about future climate change. Some GCMs are "too hot," meaning they overestimate global warming (Hausfather et al., 2022). Therefore, it is essential to choose suitable GCMs. Two main indicators can be used as a standard to select GCMs with good performance: transient climate response (TCR) and equilibrium climate sensitivity (ECS). TCR is the total amount of warming in the year when atmospheric CO_2 concentration doubles after a fixed increase of 1% per year. The second similar metric, ECS, is defined as the final long-term temperature response to CO_2 concentrations that have doubled. These two indicators are similar but distinct, and models with higher TCR tend to have higher ECS (Hausfather et al., 2022). The IPCC working groups have reached a consensus that research should be encouraged to adopt climate models with better performance, as this will make research results more consistent and comparable with the AR6 report (Hausfather et al., 2022). In addition to TCR and ECS, the selection of databases is also based on daily data availability, historical behaviour, and structural independence (Lange, 2021).

However, the raw databases of GCMs are always low resolution due to the potential for expensive computational costs (Enayati et al., 2020). Therefore, statistical downscaling techniques are used by scholars to process and re-calibrate the raw data. The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) is a framework that consistently assesses the impacts of climate change on different sectors (Warszawski et al., 2014). ISIMIP selected five climate databases, three of which had relatively lower ECS and TCR: (1) GFDL-ESM4, (2) MPI-ESM1-2-HR, and (3) MRI-ESM2-0. The other two databases had relatively higher TCR and ECS: (4) IPSL-CM6A-LR and (5) UKESM1-0-LL. The benefit of using an ensemble of a subset of the CMIP6 project is to reduce projection uncertainty. The raw databases of the five GCMs (Table 1) have biases and different resolutions. Therefore, they were downscaled to 0.5° × 0.5° at daily time steps and bias-corrected by ISIMIP (Lange, 2021). ISIMIP used a new bias-corrected method and statistical downscaling strategy to reproduce better performance and fine resolution datasets (Lange, 2019). This research adopted the output of these five climate forcing models. To reduce the uncertainty of future projections, all analyses based on climate databases will be conducted separately instead of taking the mean values

Table 1. Description of Global Climate Models used in PCR GLOBWB

GCM	ECS(°C)	TCR(°C)
GFDL-ESM4	2.63	1.63
IPSL-CM6A-LR	5.18	2.35
MPI-ESM1-2-HR	3.34	1.64
MRI-ESM2-0	3.42	1.67
UKESM1-0-LL	5.49	2.77

3.5 Scenario selection

This research will focus on three future climate scenarios: SSP-RCP 1.26, SSP-RCP 3.70, and SSP-RCP 5.85 (hereafter, ssp126, ssp370 and ssp585 respectively (see introduction for SSP-RCP explanation). Due to the dataset availability and time limitation, this research, focused on three key future scenarios: ssp126, ssp370, and ssp585, which were used to quantify future flood events with a consideration of terrestrial system (anthrome), human health and four major crops. The detailed information about different parts in terms of various SSP-RCPs is illustrated in Table 2.

Table 2. key elements among selected scenarios related to climate and land use(cover) change. This table is retrieved and modified from (Popp et al., 2017)

SSP-RCP element	**ssp126**	**ssp370**	**ssp585**
General pathway	Sustainability	Regional Rivalry	Fossil-fuelled development
Climate forcing (O'Neill et al., 2016; van Vuuren et al., 2011)			
Radiative forcing	Sustainable forcing pathway (2.6 W/m^2)	Stabilization of forcing pathway (7.0 W/m^2)	Increasing radiative forcing pathway (8.5 W/m^2)
Population growth (Jones & O'Neill, 2016)			
High fertility	Low	High	Low
Other low fertility	Low	High	Low
Rich low fertility	Medium	Low	High
Total (2050/2100, billion)	8.5/7.0	10.0/12.8	8.6/7/4
Land-use change (Popp et al., 2017)			
Land use change regulation	Strong regulation	Limited regulation	Medium regulation
Land productivity growth	High improvements in crop production	Low improvement	High-intensive resource management, high improvement
Environmental influence of food consumption	Low meat-based diet, low food demand	Resource intensive consumption	High meat-based diet, intensive food consumption
Land-based mitigation policies	Good cooperation for climate change mitigation	Heavily delayed cooperation for climate change mitigation, limited participation	Delayed cooperation, full participation

Ssp126 illustrates the sustainable pathway of the earth's future scenarios with more respect to environmental protection. The goal of ssp126 is to limit the increasing temperature to 2°C at the end of this century. The whole world will change slowly towards the ideal path. The emission of greenhouse gas will be well limited, leading to a peak radiative forcing level of 3.0 W/m^2 and then will decrease to 2.6 W/m^2 at the end of this century. Land use is strongly regulated, and crop production is significantly improved due to the development of agricultural technology worldwide (Popp et al., 2017). The population will increase to 8.5 billion and then decrease to 7.0 billion in 2100, not putting too much pressure on the terrestrial system.

Ssp370 implies a rocky way. More conflicts will occur between regions, and countries focusing more on domestic development and growing nationalism will prevent globalization (Popp et al., 2017). The emission of GHGs will continue to increase until the radiative forcing level reaches 7.0 W/m^2. The population will grow rapidly to 12.8 billion at the end of this century. There will be limited land use limitations and no apparent improvement in agricultural technology because of low international cooperation.

Ssp585 describes a highway based on fossil fuel development. There will be increased confidence in the competitive market due to the successful industrialization and emerging economics, contributing to a more globalization world. The GHGs will be emitted unlimitedly, and the radiative forcing level will arrive at the highest level: 8.5 W/m^2. Like ssp126, ssp585 sees a rapid development, and of course, more investment will be implemented in education and health, causing a relatively slow population growth (Jones & O'Neill, 2016), which will increase to 8.6 billion in 2050 and decline to 7.4 billion in 2100. The regulation of land use will not be well limited, and highly intensive management of agricultural land and improved agricultural technology will develop.

3.6 Model preparation

The PCR GLOBWB model, which is utilized for assessing future flood hazards, was implemented in a Linux™ environment using Mobaxterm™. Mobaxterm is a toolbox for remote computing. The main script, along with input files, was modified to incorporate relevant data on future flood hazards, including information on rainfall patterns, land cover, channel storage and hydrological variables. The integration of hydrological variables, such as precipitation, evaporation, soil moisture, and land cover, with climate projections was performed using the PCR GLOBWB model. This allowed for the estimation of riverine channel storages and provided valuable insights into the spatial and temporal trends of future flood hazards. The model captured the complex interactions between climate, land use, and hydrological processes to comprehensively assess flood risks. Through the representation of river flow dynamics, the PCR GLOBWB model simulated the propagation of flood events and provided information on the duration, magnitude, and frequency of floods. This enabled the understanding of the patterns and characteristics of future flood hazards. Furthermore, the PCR GLOBWB model was employed to simulate flood events in different scenarios, considering various climate projections.

A total of 46 climate simulations were run (see table 3). Each simulation used one of five different general circulation models (GCMs) to generate a prediction of future climate change. The three climate scenarios that were used were based on different assumptions about how greenhouse gas emissions will change in the future (ssp126, ssp370 and ssp585). Each climate scenario included three time slices, representing the years 2030, 2060, and 2090.

Table 3. overview of the model runs including scenarios and time slices.

Total number of runs	45 + 1 historical simulation
Number of GCMs **+ W5e5 (historical climate reference)**	5
Number of climate scenarios	3
Time slices	3

3.7 Data Output

When the runs were completed, the various variables produced in the form of netCDF files were collected. netCDF files were creates of flood volumes per recurrence interval for each GCM and climate scenarios for the years 2030, 2060 and 2060. Table 4 shows an overview of the files generated. The files in table 4 were created for each of the 3 river basins.

In this study, the methodology involved analyzing the monthly maximum channel storage data as the initial step. The maximum channel storage variable served as a key input for assessing flood hazards and recurrence intervals. The recurrence interval, also known as the return period average time between flood events. The data was then fitted to a Gumbel distribution, a widely used statistical approach for modeling extreme events. This enabled us to quantify the probability of different flood magnitudes and determine their recurrence intervals. Once the model was run the model produced netCDF files with flood volumes per recurrence interval for 5 GCM's and 3 time slices. Subsequently, the results were bias corrected and downscaled to improve their accuracy and reliability. The downscaled data, presented in netCDF files, provided a comprehensive representation of flood hazards with associated recurrence intervals. Once the data was bias corrected and downscaled. The data was then merged using CDO (Climate Data Operators). CDO is collection of command line operators used to manipulate and analyze climate model data. CDO is used with a merge function to process all individual GCM flood data files into a single file for each recurrence interval. Leaving me with for each time slice (2030, 2060 and 2090), 27 files (9 recurrence intervals for each climate scenario).

In QGIS, I conducted a spatial analysis to explore the interactions between flood hazards and anthropogenic features within the studied river basins. This involved overlaying flood hazard maps with anthromes maps to identify areas of potential vulnerability. By visualizing the spatial distribution of flood-prone regions in relation to anthropogenic activities, the goal being to gain insights into the susceptibility of anthromes across different land uses.

Table 4. overview of all final output files after data processing for each of the river basins.

Time slice	**2030**			**2060**			**2090**		
Climate scenario	**ssp126**	**ssp370**	**ssp585**	**ssp126**	**ssp370**	**ssp585**	**ssp126**	**ssp370**	**ssp585**
Recurrence interval	2	2	2	2	2	2	2	2	2
	5	5	5	5	5	5	5	5	5
	10	10	10	10	10	10	10	10	10
	25	25	25	25	25	25	25	25	25
	50	50	50	50	50	50	50	50	50
	100	100	100	100	100	100	100	100	100
	250	250	250	250	250	250	250	250	250
	500	500	500	500	500	500	500	500	500
	1000	1000	1000	1000	1000	1000	1000	1000	1000

Additionally, the Anthromes maps were given with a map for every ten years. Therefore, the Anthromes maps were simply reused for the years 2030, 2060 and 2090 for each climate scenario (SSP126, SSP370 and SSP585). This resulted in 9 maps containing the data for the Anthromes classification as can be seen in table 5 below.

Table 5: overview of Anthromes maps output.

2030	**2060**	**2090**
ssp126	ssp126	ssp126
ssp370	ssp370	ssp370
ssp585	ssp585	ssp585

In order to complete the first part of the results section an overview of the coefficient of determination and p values will be given. In the context of my master thesis research, the coefficient of determination (R-squared) and p values serve as valuable statistical measures to assess the quality and significance of the relationships between variables. The coefficient of determination, often denoted as R-squared, quantifies the proportion of variability in one variable that can be explained by another variable. A higher R-squared value indicates a stronger linear relationship between the variables, suggesting that changes in one variable are more likely to be reflected in the changes of the other. R-squared values range from 0 to 1, with higher values indicating a better fit of the model to the data.

On the other hand, p values play a crucial role in hypothesis testing. A p value represents the probability of observing the obtained results if the null hypothesis is true. The null hypothesis states that there is no impact of flood hazards on Anthromes. A small p value (typically less than 0.05) suggests that the observed relationship between variables is unlikely to have occurred by chance alone, and therefore, the null hypothesis can be rejected. Conversely, a larger p value indicates that the observed results could reasonably occur under the assumption of the null hypothesis.

4. Results

The results chapter first reviews the frequency and magnitude of extreme floods for each river basin, to understand the differences between each climate scenario and river basin. Hereafter the analysis will focus on the relationship between flood hazards and the anthromes framework.

4.1 Flood magnitude and frequency

Looking at the flood volume graphs below, the flood magnitude analysis conducted for the three river basins (Limpopo, Mississippi, and Mekong) under different climate scenarios (SSP126, SSP370, and SSP585).

4.1.1 Limpopo River basin.

The flood frequency curve analysis conducted in the Limpopo river basin (figure 6) yielded valuable insights into the impact of different climate scenarios on flood magnitudes. Notably, the ssp370 and ssp585 scenarios exhibited substantially higher flood magnitudes compared to the ssp126 scenario. Where in 2030 the maximum flood volume for the 1000-year recurrence interval for spp126 is almost 2E+09 m^3 lower than the ssp370 and ssp585. These results were consistent with our initial expectations, as higher emission scenarios such as ssp370 and ssp585 were anticipated to trigger more frequent and extreme floods due to intensified climate forcing and amplified hydrological processes. The increased flood magnitudes observed in these scenarios underscored the potential risks posed by climate change and highlighted the urgency of developing effective flood mitigation strategies for the region. However, amidst the overall increasing trend in flood magnitudes, a noteworthy observation emerged when examining the flood response during the 2030 and 2060 time slices. Surprisingly, the ssp370 scenario demonstrated a relatively higher trend in flood magnitudes compared to ssp585 in the 2090 time slice. This finding suggested that while higher emission scenarios generally lead to more severe floods, other factors, such as local-scale variations or unique climate drivers, might have contributed to variations in flood patterns within the same river basin. This observation emphasized the complexity of climate interactions and the need to consider multiple influencing factors when assessing flood hazards and formulating adaptive strategies.

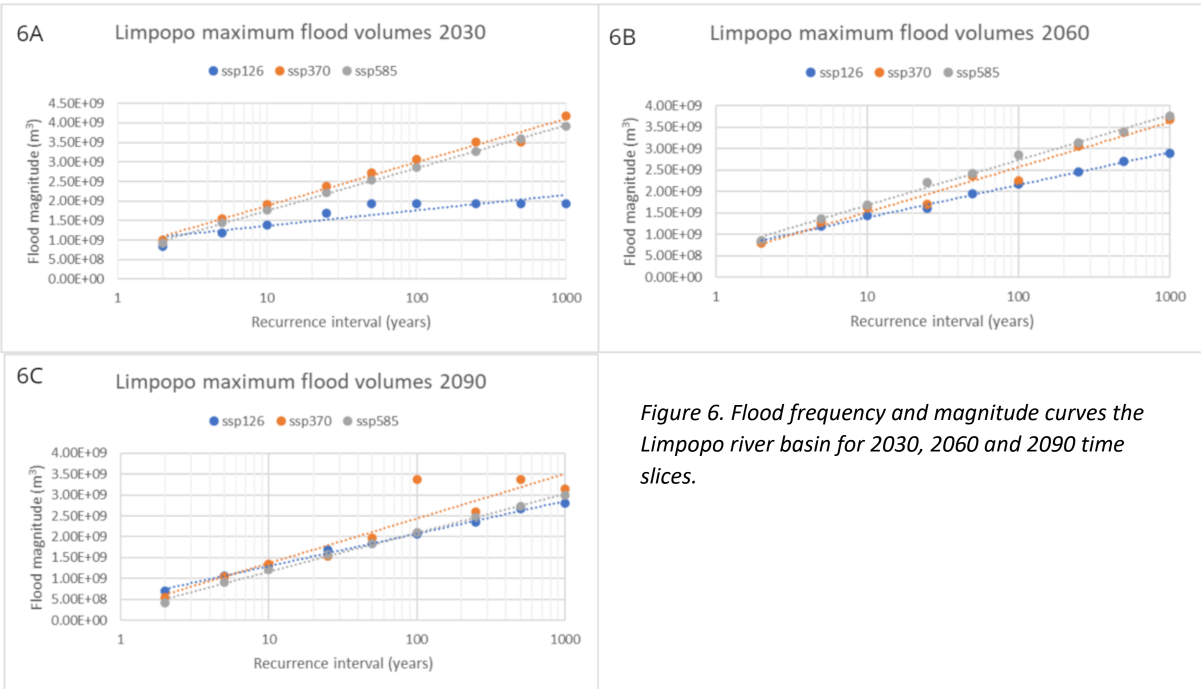


Figure 6. Flood frequency and magnitude curves the Limpopo river basin for 2030, 2060 and 2090 time slices.

4.1.2 Mississippi river basin

The flood frequency curve analysis conducted in the Mississippi river basin (figure 7) provided intriguing insights into the variations in flood magnitudes under different climate scenarios across multiple time slices. Notably, during the 2030 and 2060 time periods, the ssp585 scenario displayed relatively higher flood magnitudes compared to the other scenarios examined. These findings indicated that under certain conditions, the ssp585 scenario might lead to more intense and frequent flood events, potentially influenced by specific climate drivers and hydrological interactions during those time slices. Conversely, in the 2090 time slice, the flood magnitude curve associated with the ssp126 scenario exhibited the highest flood volumes. This observation suggested that as the future approaches, the ssp126 scenario could potentially result in more extreme floods within the Mississippi basin, which not what was expected. The contrasting flood magnitudes between the different scenarios highlighted the importance of considering various climate projections to assess the full spectrum of potential flood hazards in the region. Intriguingly, when investigating the maximum flood magnitudes of the ssp585 scenario across different time slices, a distinct pattern emerged. The 2090 time slice demonstrated a relatively lower maximum flood volume compared to both the 2030 and 2060 time slices. For instance, the 1000-year recurrence interval flood volume in the 2090 time slice amounted to 5.3E+09 m^3, whereas the corresponding 1000-year recurrence interval flood volumes for the 2030 and 2060 time slices were 8.8E+09 m^3 and 6.6E+09 m^3, respectively. These results indicated that the ssp585 scenario might exhibit fluctuations in flood magnitudes over time, further highlighting the complex nature of flood hazard dynamics under varying climate conditions.

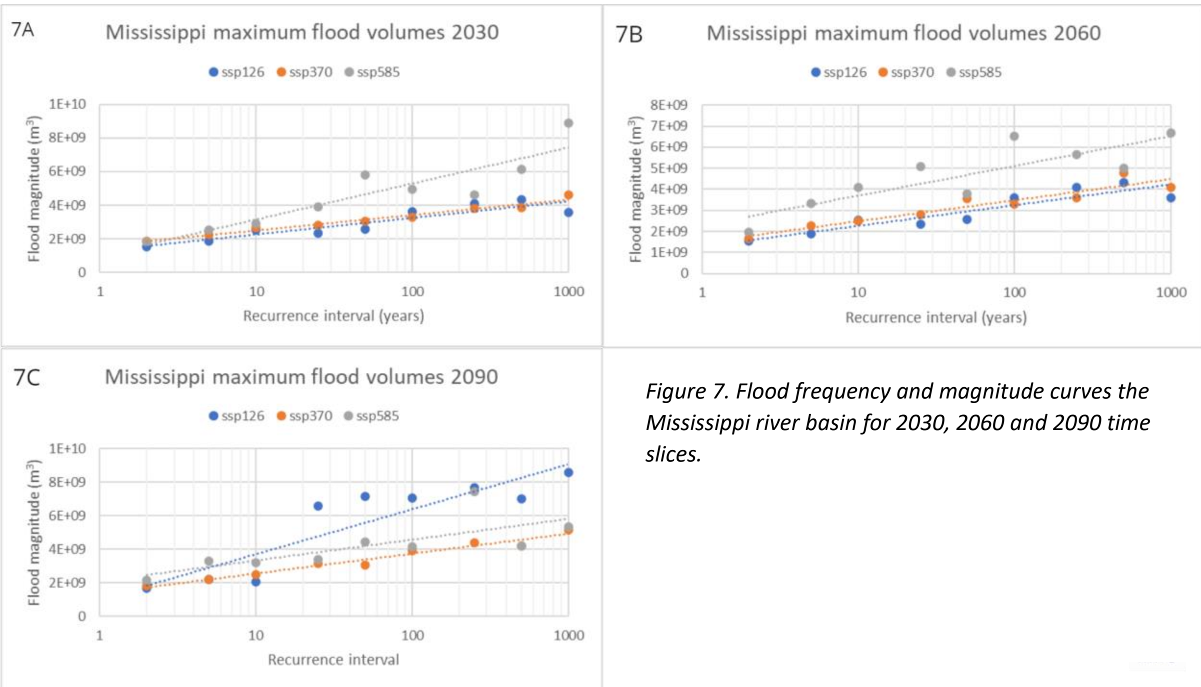


Figure 7. Flood frequency and magnitude curves the Mississippi river basin for 2030, 2060 and 2090 time slices.

4.1.3 Mekong River basin

In the context of the Mekong River basin (figure 8), the flood frequency curve analysis exhibited a consistent trend in values across the studied climate scenarios, which merits attention in understanding the flood hazard dynamics. Surprisingly, even the higher emission scenario of ssp585 demonstrated a remarkably similar flood hazard trend to the two relatively lower emission scenarios, ssp126 and ssp370. This observation suggests that flood magnitudes remained relatively stable, with minimal variance, across all three climate scenarios and time slices. Throughout all the time slices and scenarios studied, the flood magnitudes displayed striking similarity in their values. For instance, the 2-year flood recurrence interval consistently exhibited a magnitude of 1E+09 m^3, while the 1000-year flood recurrence interval flood magnitudes ranged from 1.5E+09 m^3 to 2E+09 m^3. These findings emphasize the relative consistency in flood hazard patterns over time and under different climate scenarios, highlighting the robustness of the hydrological response in the Mekong basin. Interestingly, a distinct pattern emerged among the climate scenarios, where ssp585 consistently portrayed the relatively lowest flood magnitudes, and ssp370 exhibited the relatively highest flood magnitude curve across all three time slices. This observation could be attributed to the varying levels of greenhouse gas emissions and climate forcings represented by these scenarios. The relatively higher flood magnitudes under ssp370 may be associated with its more aggressive greenhouse gas emission trajectory, suggesting a potentially higher flood risk in the future for this scenario.

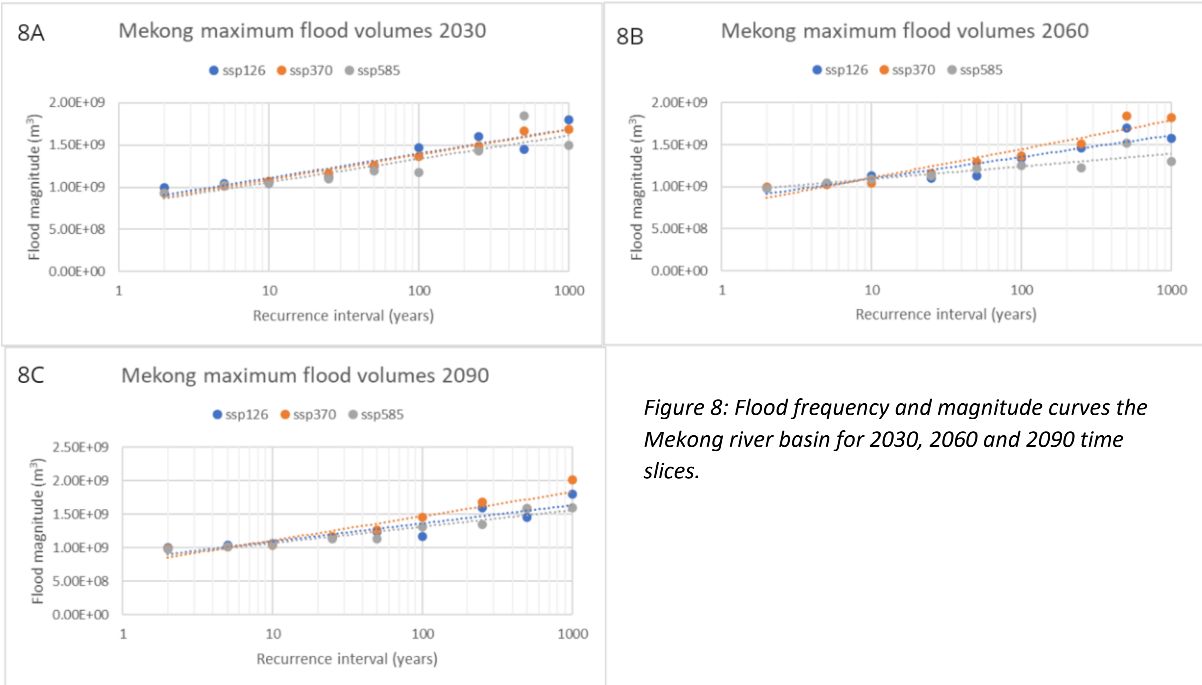


Figure 8: Flood frequency and magnitude curves the Mekong river basin for 2030, 2060 and 2090 time slices.

4.2 Anthrome

The next part of the results will look at the spatial relationships between flood hazard maps and anthrome maps. In order to see how anthromes will change till the year 2100, I have chosen to analyze the last time slice 2090.

4.2.1 Limpopo River basin

In the context of the Limpopo River basin, the overlay (figure 9) of anthromes maps with flood volumes across different recurrence intervals reveals intriguing patterns that provide valuable insights into the interaction between human land use and flood hazards. When analyzing the short recurrence intervals (2, 5, and 10 years), it becomes evident that the primary anthrome which are affected by flood events are rangelands, inhabited drylands and a scattering of pastoral and rainfed villages where the flood volumes range from 4E+09 to 6E+09 m^3. Remarkably, this relationship holds consistently across all three climate scenarios investigated in this study. These findings suggest that flood recurrence intervals of 2, 5, and 10 years exert a minimal influence on anthromes. This influence holds true regardless of the climatic conditions projected by the various scenarios. Delving deeper into the spatial analysis, a noteworthy trend emerges as the recurrence intervals increase. Specifically, as the recurrence interval extends from 25 to 1000 years, the impact on the same anthrome types (rangelands, pastoral and rainfed villages) becomes more pronounced, where the floods cover more extensive geographic areas. At the end of 2090, for all 3 scenarios it is evident from the overlay between flood volumes and anthrome maps that cropland anthromes are more affected that population anthromes. Especially when we move towards the more extreme recurrence intervals where the flood volumes have range from 4E+09 to 8E+09 m^3. This progressive effect is consistent across the climate scenarios, underscoring the importance of long-term recurrence intervals when assessing the broader influence of flood events on anthromes.

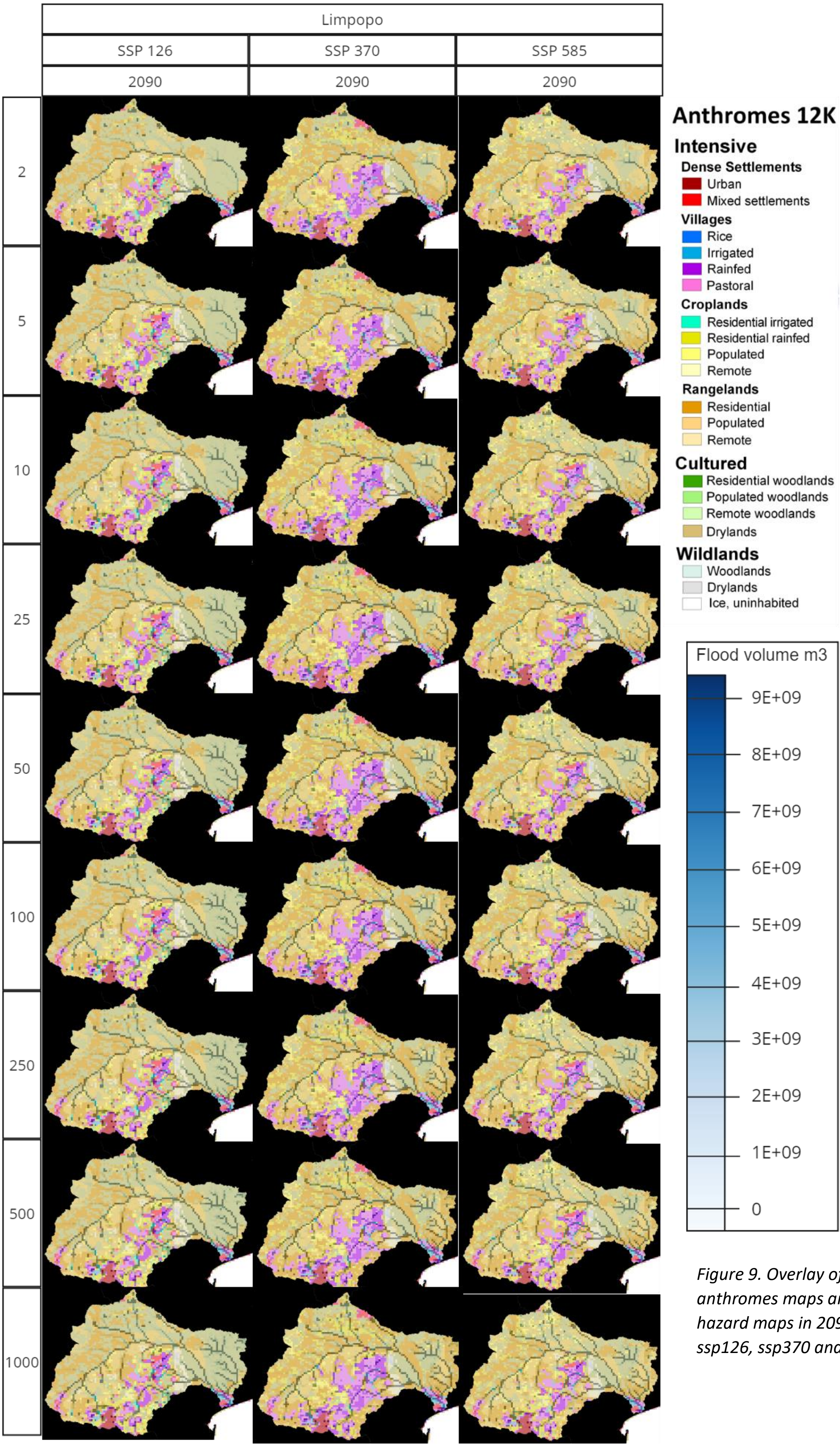


Figure 9. Overlay of anthromes maps and flood hazard maps in 2090 for ssp126, ssp370 and ssp585

4.2.2 Mississippi river basin

Examining the overlay (figure 10) of anthromes maps with flood hazard maps within the context of the Mississippi river basin offers insightful revelations regarding the intricate relationship between land use patterns and flood events across different climate scenarios. Notably, all three climate scenarios—ssp126, ssp370, and ssp585—exhibit a consistent trend where population anthromes bear the brunt of flood impacts. These findings indicate the vulnerability of densely populated areas to flooding, highlighting the need for strategic planning and resilient infrastructure in managing flood hazards. Intriguingly, a spatial pattern emerges in the eastern region of the river basin, which is characterized by a concentration of population anthromes. This region also coincides with the geographical area experiencing the highest frequency of flood occurrences. The presence of residential and populated croplands further exacerbates the vulnerability, as these areas are also profoundly affected by flood hazards with flood volumes ranging from 5E+09 to 7E+09 m^3. This spatial correlation emphasizes the intricate interplay between land use, population density, and flood vulnerability, particularly in regions where human activities are more concentrated. An insightful observation pertains to the distinct anthrome distribution patterns among the different climate scenarios. The ssp126 scenario reveals a prevalence of cultured anthromes, indicating human influence on the landscape. In contrast, ssp585 showcases dense settlements and residential irrigated croplands as prominent anthrome types. The ssp370 scenario exhibits fewer dense settlements compared to ssp126 and ssp585. These variations in anthrome distributions underscore the nuanced impacts of different climate scenarios on land use patterns and their interactions with flood hazards. Importantly, despite the varying anthrome distributions and flood scenarios, the Mississippi river basin does not exhibit pronounced flood hotspots. Instead, a more widespread and regular pattern of flooding is observed in the eastern portion of the basin, particularly within the population and cultured anthromes with flood volumes ranging from 6E+09 to 8E+09 m^3. This pattern implies that while specific areas may not stand out as flood concentration points, the overall flood hazard is distributed across various anthrome types, making it crucial to implement comprehensive flood management strategies that consider diverse land use characteristics.

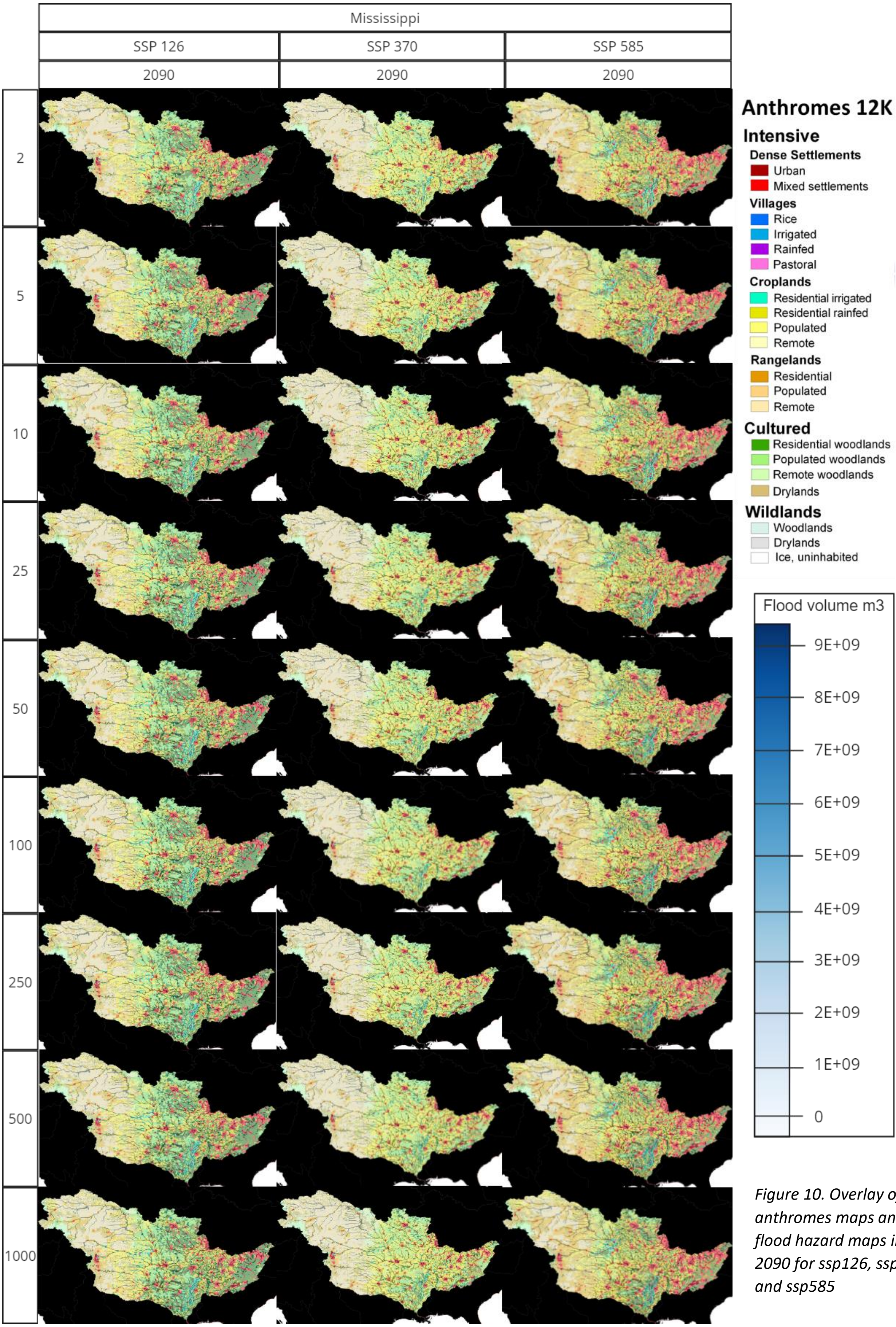
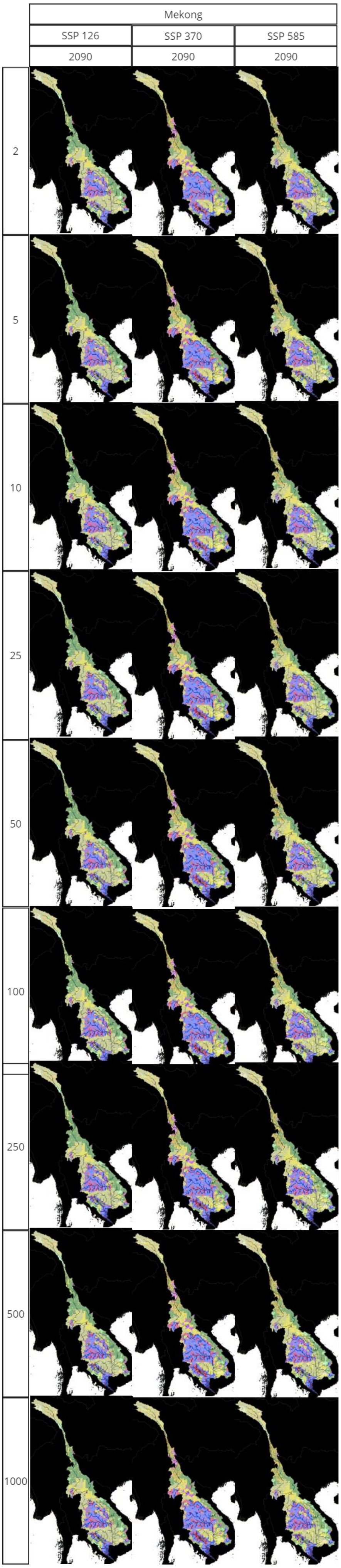


Figure 10. Overlay of anthromes maps and flood hazard maps in 2090 for ssp126, ssp370 and ssp585

4.2.3 Mekong River basin

The overlays (figure 11) between anthromes maps and flood hazard maps in the context of the Mekong River basin reveals insights into the intricate connections between land use patterns and flood susceptibility across three scenarios. Evidently, a significant portion of the basin is utilized for agricultural activities, primarily comprising rice villages and populated residential rainfed croplands. The juxtaposition of anthrome distribution and flood hazard overlays underscores the vulnerability of these cropland anthromes to flood impacts, particularly rice villages and residential croplands, which appear to be exposed to a substantial flood risk. The flood volumes in these anthromes range from 2E+09 to 5E+09 m^3. Furthermore, the overlays consistently illustrate that urban and dense settlements (population anthromes) are substantially susceptible to flood hazards. The convergence of these anthrome types with flood-prone areas signifies the inherent vulnerability of human settlements to flooding in the Mekong River basin, highlighting the need for robust urban planning and flood resilience strategies. This observation is particularly pronounced in the southern part of the river basin, where dense settlements consistently demonstrate heightened susceptibility to floods across all the recurrence intervals where the flood volumes range from 6E+09 to 8E+09 m^3. The overlays provide insights into the complex interactions between land use and flood dynamics within the Mekong River basin.



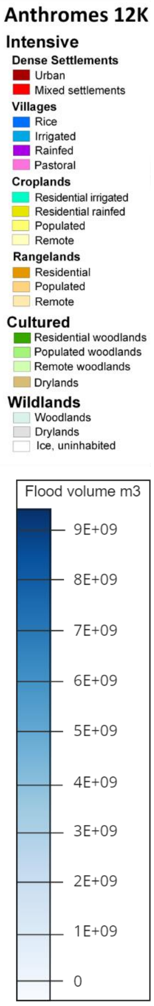


Figure 11. Overlay of anthromes maps and flood hazard maps in 2090 for ssp126, ssp370 and ssp585

4.3 Statistical significance

Both R-squared and p values contribute to the interpretation of the statistical significance of the findings. The R-squared values help evaluate the strength of the relationships between variables, while p values provide insight into whether the observed relationships are statistically significant. By considering both measures, I am able to draw meaningful conclusions about the significance and reliability of the observed patterns and correlations in the context of my research on flood hazards and their impact on anthromes. Both of these measures were produced as a byproduct of the PCR GLOBWB model, during the model runs. As can be seen in table 6 below, every coefficient of determination is either 0.93 or 0.94. This means that that there is a strong relationship between the variables.

The R-squared value of 0.94 between the climate scenarios and time slices reveals a strong connection between these two factors in our analysis. This value means that around 94% of the changes we see in the flood volumes can be explained by the variations in the ssp scenarios we're studying. In simpler terms, this high R-squared value suggests that the chosen climate scenario is a good predictor of how the flood volumes change. However, it's important to note that a high R-squared value doesn't mean one thing causes the other. Instead, it highlights a solid statistical connection between them. With an R-squared value of 0.94, the specific ssp scenario values we've picked in the model do a good job of explaining how flood volumes change in the future.

Table 6. Coefficient of determination for climate scenarios and hydrology of each time slice.

Coefficient of determination (R-squared)			
	2030	**2060**	**2090**
ssp126	0.94	0.94	0.94
ssp370	0.94	0.93	0.93
ssp585	0.94	0.93	0.94

Having p-values between 0.0099 and 0.0055 (both <0.05) generally indicate that the results obtained from the research were statistically significant. With p-values between 0.0099 and 0.0055, the results provide robust evidence against the null hypothesis, substantiating the notion of the presence of a meaningful relationship or effect within the data. The p-values results in table 7, shows that results obtained from PCR GLOBWB are statistically significant.

Table 7. p-values for ssp scenarios and hydrology of each time slice.

P values			
	2030	**2060**	**2090**
ssp126	0.0064	0.0099	0.0064
ssp370	0.0065	0.0092	0.0060
ssp585	0.0053	0.0097	0.0057

5. Conclusion

In conclusion, it has become clear that anthromes will be affected by floods events in the future. For the three river basins studied, Mekong, Mississippi and Limpopo River basin, it has also become clear that in the regional rivalry and fossil fueled development scenarios (ssp370 and ssp585 respectively) have a higher frequency and magnitude of floods compared to the sustainable pathways (ssp126).

The analysis of anthromes maps overlaid with flood hazard maps within the Mekong River basin provide insights into the pronounced susceptibility of agricultural and urban areas to flood hazards. The effects of future flood hazards on important anthromes in the Mekong River basin like rice villages, croplands and dense settlements show the importance of studying flood hazards. These findings underscore the pivotal role of adaptive strategies and policies in ensuring the resilience of the Mekong River basin against future flood events. Additionally, the spatial distribution of flood impacts underscores the need for tailored flood mitigation strategies that account for the geographic concentration of vulnerable areas. It is imperative for land use planning and disaster management policies to consider these findings, aiming to enhance flood resilience and minimize potential risks in the Mekong River basin.

The spatial analysis of anthromes in conjunction with flood hazards in the Mississippi river basin underscores the vulnerability of urban and mixed settlements to flood events. The alignment of flood impacts with population anthromes and the absence of concentrated flood hotspots underscore the complex interplay between land use, climate scenarios, and flood dynamics. These findings inform the formulation of targeted policies and adaptive measures to enhance flood resilience and mitigate potential impacts within the Mississippi river basin.

The spatial analysis of anthromes in conjunction with flood volumes in the Limpopo River basin illuminates the varying impacts of different flood events on anthrome types. The consistent influence of flood events on rangelands, pastoral and rainfed villages as well as inhabited drylands, underscores the important need for understanding of how future flood events might affect future anthromes. These findings contribute to the understanding of the interplay between flood hazards and land use patterns, informing future planning and mitigation efforts tailored to the distinctive characteristics of the Limpopo River basin.

6. Discussion.

To discuss the findings of this research paper, first the discussion of the results will be made followed by the assumptions and flaws of this research.

6.1 Extreme flood events and anthromes

In examining the flood hazard trends across the three river basins under different scenarios, several noteworthy patterns emerge. Firstly, it is apparent that the flood magnitude and frequency generally exhibit a lower level of risk in the ssp126 scenario compared to both ssp370 and ssp585. This observation underscores the importance of sustainability-focused approaches, suggesting that regions prone to flooding, regardless of the river basin, should prioritize comprehensive flood mitigation strategies.

As we look ahead to the year 2090, a significant trend emerges in the Mekong River Basin. A convergence in the frequency and magnitude of flood events across all three scenarios. This convergence strongly indicates that, irrespective of the chosen socioeconomic pathway, the Mekong basin is poised to encounter considerable flood hazards. This finding underscores the critical importance of implementing resilient adaptation strategies within this region. With rice villages, populated croplands, residential rainfed croplands, urban areas, and dense settlements prevalent in this basin, there is a pressing need for multifaceted flood management approaches. As 60 million people live and depend on the Mekong River basin, an extreme flood event may negatively affect crop growing areas as well as force vulnerable communities in flood prone areas such as rice villages, populated croplands, and urban settlements to migrate. The convergence of flood risk among the climate scenarios also emphasizes the significance of proactive regional and international cooperation. Climate change and varying socioeconomic conditions will likely necessitate adaptive strategies that transcend political boundaries, focusing on risk reduction and community resilience.

The Mississippi River Basin offers a distinctive perspective as we approach the year 2090. Surprisingly, the sustainability-driven ssp126 scenario stands out with the highest flood frequency and magnitude, surpassing ssp370 and ssp585. This anomaly may be linked to the inherent flood vulnerability of the Mississippi River Basin, compounded by the coexistence of extensive urban areas and fertile croplands. For a population of over 30 million people, it becomes imperative to meticulously assess the region's susceptibility to future flood events, emphasizing the significance of comprehensive flood risk management strategies, even within sustainability-oriented pathways. This calls for a nuanced approach that integrates resilient infrastructure, floodplain zoning, and heightened preparedness to safeguard the basin's communities against escalating flood hazards.

Similarly, by the conclusion of 2090, the Limpopo River Basin reveals a convergence in flood frequency and magnitude across the three distinct climate scenarios. Notably, within this basin, the ssp370 scenario, characterized by regional rivalry and competition, exhibits the highest flood magnitude. This convergence of flood risk in the Limpopo River Basin signifies that, regardless of the climate scenario, the region is projected to encounter substantial flood hazards. The prevalence of pastoral lands, rainfed villages, and inhabited drylands in this basin accentuates the importance of proactive flood management strategies. The elevated flood magnitude observed in the ssp370 scenario could be attributed to heightened regional tensions and competition, which might impact resource allocation and flood resilience. This finding underscores the need for collaborative, cross-border flood risk reduction efforts in the Limpopo River Basin.

Along with other studies that have looked at how flood events will change in the future according to different climate scenarios (Alfieri et al., 2015; (Alfieri et al., 2016; Bouwer et al., 2010; Arnel & Gosling, 2016), there is a clear agreement that as atmospheric carbon concentrations increase and more fossil fuels are burned for fuel, extreme flood events will increase in frequency and magnitude. Where countries with a higher GDP will be more able to mitigate and plan for extreme flood events than lower GDP nations (Ward et al., 2017; Winsemius et al., 2018). Therefore, looking at the results from this study, we can assume that the Mississippi river basin, located in North America, with a GDP of $23 trillion USD will be more able to mitigate and plan for floods and deal with the aftermath. Especially when compared to the Mekong River Basin, which encompasses flood-prone areas primarily situated in Cambodia, Thailand, and Vietnam, collectively amounting to a GDP of $980 billion USD, the Mississippi River Basin where America has a GDP of $23 trillion USD, demonstrates a superior capacity to prepare for, mitigate, and manage floods and their aftermath. Conversely, the Limpopo River Basin, situated in southern Africa, encompasses countries such as Botswana, Mozambique, South Africa, and Zimbabwe, with a combined GDP of $445 billion USD. In the event of severe flood events, the consequences within the Mekong and Limpopo River Basins may be significantly more severe due to the limited capacity of these communities to effectively respond and recover. It is crucial to acknowledge that flood resilience is influenced by factors extending beyond GDP statistics. Socioeconomic disparities, infrastructure development, governance, and resource accessibility collectively contribute to a region's ability to withstand flood impacts.

Now, delving deeper into anthrome literature, Yin (2022) is the first in investigating future anthrome classifications within the context of extreme weather events, focusing particularly on extreme heat events. Yin's study, examining extreme heat patterns, arrived at the conclusion that extreme heat remains relatively stable in the ssp126 scenario, but exhibits a gradual increase in both the ssp370 and ssp585 scenarios. Interestingly, this mirrors a similar trend observed in extreme flood hazards, albeit with some notable exceptions. For instance, by the end of 2090, the Mississippi River Basin under the ssp126 scenario experiences the highest frequency and magnitude of extreme flood events, deviating from the general trend.

6.2 Limitations.

This research encountered certain challenges during the data processing and analysis stages that warrant discussion. The execution of coding bias correction and downscaling for the flood data consumed a duration longer than initially anticipated. Consequently, the timeline for conducting comprehensive statistical analyses was constrained, leading to specific limitations in the depth of the analysis performed. As a result of these challenges, the intended investigation into the correlation between flood frequency and specific anthromes could not be executed as planned. Likewise, the precise calculation of flood frequency for individual anthromes faced limitations. Despite these constraints, the study retains valuable insights into the magnitude and maximum flood volumes observed across the designated research areas. While the data limitations prevented a granular examination of flood frequency distribution per anthrome, the ability to observe and analyse the flood magnitude and maximum flood volumes across different regions remains intact. This facet of the research sheds light on the broader patterns of flood hazards within the study area, offering valuable insights into the general trends and variability of flood magnitudes.

6.3 Assumptions

Firstly, a central aspect of this study involves the assumption concerning the accuracy of climate models utilized for projecting future climate scenarios. These models, while built upon established scientific principles, embody complex representations of intricate climate processes. The assumptions made encompass the models' ability to capture the interactions and feedback loops among various components of the Earth's climate system. It's important to acknowledge that inherent uncertainties within climate modelling can contribute to divergent outcomes. In light of this, the results and implications of this research should be considered within the broader context of climate model reliability and limitations. A fundamental assumption guiding the analysis is the notion of stationarity, implying that the patterns and relationships observed in historical data will persist into the future. However, it's imperative to acknowledge the potential challenges posed by changing climate dynamics and evolving land use practices. The assumption of stationary hydrological conditions might not fully encompass the multifaceted impacts of dynamic climate shifts and anthropogenic activities on hydrological processes. The foundation of this study rests on the assumption that the data used, spanning flood volume records, anthromes maps, and climate projections, accurately reflect real-world conditions. Recognizing the importance of data quality and integrity, it's vital to acknowledge the potential presence of data errors, uncertainties, and biases that can influence research outcomes.

6.4 Uncertainties

One notable source of uncertainty lies in the underestimation of extreme data values within the dataset. This can impact the comprehensiveness of the flood hazard analysis, as extreme events may be inadequately represented in the recorded data. Such limitations highlight the need for careful scrutiny and the application of appropriate methods to address potential underestimation effects. An important point of consideration pertains to the methodological handling of the monthly maximum values within the W5E5 dataset, which was used as a reference climate for the future. An error arose due to the placement of these values at mid-month (day 15 or 16), diverging from the PCR GLOBWB convention of placing them on the last day of the month. This deviation introduced a discrepancy that must be acknowledged when assessing flood hazard outcomes, underscoring the significance of meticulous data processing to ensure accuracy. The study recognizes the inherent uncertainties associated with the climate input data and model projections. The relatively limited sampling length, spanning 100 years, coupled with variations in climate models, introduces uncertainties in capturing the full spectrum of future climatic conditions. The PCR GLOBWB model itself is not exempt from inherent uncertainties. These uncertainties encompass aspects such as parameterizations of soils, vegetation, floodplain dimensions, and roughness. While such uncertainties are characteristic of hydrological models, their implications on flood hazard estimations are acknowledged. The proposal to construct a multi-model ensemble derived from different hydrological models capable of estimating flood hazards aims to address this uncertainty by pooling diverse model perspectives. The research acknowledges the sensitivity of the downscaling algorithm to variables such as elevation models and the selection of river and flood return periods. This sensitivity holds particular relevance when computing flood risk for events of lower return periods. In contrast, high return period events exhibit less sensitivity due to the relatively smaller bank-full volume compared to the total flood volume. The uncertainty surrounding the chosen bank-full volume extends to regions with stringent protection standards against infrequent flood events (e.g., 100-, 500-, or 1000-year floods). The study notes that simulated time series might be inadequately lengthy to robustly establish probability distributions for events of such rarity, further emphasizing the complexities of capturing a full spectrum of potential flood scenarios.

Additionally, the results would be more reliable and able for analysis if the anthromes framework were included as variables in the PCR GLOBWB model. This way, a more specific and detailed analysis can be given to see how floods in specific regions may affect anthromes, as flood events can be very local.

6.5 Outlook

With the evolving dynamics of flood events, there is a possibility that new types of Anthromes might emerge or existing classifications might need to be adapted to accommodate the shifting landscape. This could necessitate the development of a revised classification system that reflects the changing relationships between flood hazards and human activities. Moreover, the differential economic resources of various river basins could influence their resilience and adaptive capacities in the face of increasing flood hazards. River basins with greater economic resources might be better equipped to implement mitigation and adaptation strategies, potentially altering the distribution of specific Anthromes. Conversely, regions with fewer economic resources might experience challenges in managing flood-related impacts on Anthromes, leading to potential changes in land use patterns and population distribution. In the context of economic differences, the Mississippi river basin, spanning economically developed areas, generally possesses higher economic resources and infrastructure compared to the Limpopo and Mekong basins. This affords the Mississippi basin a relatively stronger ability to invest in advanced flood mitigation measures, such as improved levee systems and floodplain zoning, which can help reduce flood impacts on important Anthromes like urban areas and high-value croplands. The economic prowess of the Mississippi basin can thus influence its resilience against flood hazards and its capacity to adapt to changing conditions. In contrast, the Limpopo and Mekong River basins encompass regions with varying economic development levels and resource availability. These basins might experience challenges in terms of allocating sufficient funds and resources to implement comprehensive flood mitigation and adaptation strategies. Consequently, their Anthromes, including rural communities and subsistence farming areas, might face higher vulnerability to the changing flood hazards. The socio-economic disparities between these basins could influence the distribution of flood impacts and shape the potential for adaptive actions.

Furthermore, the changing flood hazards could influence the spatial distribution and characteristics of Anthromes. As flood patterns evolve, certain Anthromes might experience shifts in their vulnerability to flood events. Urban and densely populated areas, as well as economically important crop lands, could undergo modifications in response to changing flood risks. This might entail changes in land use practices, infrastructure development, and settlement planning to mitigate the adverse effects of floods on Anthromes.

Next, it is imperative for future researchers to undertake a meticulous and thorough frequency calculation, offering a more comprehensive understanding of flood magnitudes and their recurrence intervals. Incorporating a rigorous statistical approach to flood frequency analysis would provide a clearer depiction of the probabilities associated with varying flood events, thus enhancing the accuracy of predictions. Furthermore, integrating a cost estimation framework based on flood hazard levels could enrich the decision-making process. By quantifying the potential economic impacts of flood events, stakeholders and policymakers can better prioritize and allocate resources for flood mitigation and adaptation strategies. Incorporating this dimension into the existing model could yield more nuanced insights into the interplay between flood hazards and socioeconomic factors. Additionally, diversifying the selection of global climate models for input into PCR GLOBWB stands as a pertinent avenue for exploration. Incorporating a broader range of climate models could shed light on the sensitivities and uncertainties associated with different model outputs. This, in turn, would strengthen the robustness of the findings and contribute to a more comprehensive assessment of flood hazards under varying climatic scenarios.

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References

Aerts, J. C., Botzen, W. J., Clarke, K. C., Cutter, S. L., Hall, J. W., Merz, B., ... & Kunreuther, H. (2018). Integrating human behaviour dynamics into flood disaster risk assessment. *Nature Climate Change*, *8*(3), 193-199.

Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., ... & Feyen, L. (2017). Global projections of river flood risk in a warmer world. *Earth's Future*, *5*(2), 171-182.

Alfieri, L., Burek, P., Feyen, L., & Forzieri, G. (2015). Global warming increases the frequency of river floods in Europe. *Hydrology and Earth System Sciences*, *19*(5), 2247-2260.

Alfieri, L., Feyen, L., Dottori, F., & Bianchi, A. (2015). Ensemble flood risk assessment in Europe under high end climate scenarios. Global Environmental Change, 35, 199-212.

Allen, M. R., & Ingram, W. J. (2002). Constraints on future changes in climate and the hydrologic cycle. *Nature*, *419*(6903), 224-232.

Anderson, B. (2012). Intensification of seasonal extremes given a 2°C global warming target. Climatic Change.

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*, 387-401.

Banerjee, L. (2010). Effects of Flood on Agricultural Productivity in Bangladesh. Oxford Development Studies.

Bell, V. A., Kay, A. L., Jones, R. G., & Moore, R. J. (2007). Use of a grid-based hydrological model and regional climate model outputs to assess changing flood risk. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *27*(12), 1657-1671.

Berghuijs, W. R., Woods, R. A., Hutton, C. J., & Sivapalan, M. (2016). Dominant flood generating mechanisms across the United States. *Geophysical Research Letters*, *43*(9), 4382-4390.

Bouwer, L. M., Bubeck, P., & Aerts, J. C. (2010). Changes in future flood risk due to climate and development in a Dutch polder area. *Global Environmental Change*, *20*(3), 463-471.

Borga, M., Stoffel, M., Marchi, L., Marra, F., & Jakob, M. (2014). Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows. *Journal of Hydrology*, *518*, 194-205.

Botai, C. M., Botai, J. O., Zwane, N. N., Hayombe, P., Wamiti, E. K., Makgoale, T., ... & Tazvinga, H. (2020). Hydroclimatic extremes in the Limpopo River Basin, South Africa, under changing climate. *Water*, *12*(12), 3299.

Brody, S., Blessing, R., Sebastian, A., & Bedient, P. (2014). Examining the impact of land use/land cover characteristics on flood losses. *Journal of Environmental Planning and Management*, *57*(8), 1252-1265.

Choi, W., & kim, k. (2019). Summertime variability of the western North Pacific subtropical high and its synoptic influences on the East Asian weather. Scientific Reports.

Dai, J., Kesternich, M., Löschel, A., & Ziegler, A. (2015). Extreme weather experiences and climate change beliefs in China: : An econometric analysis. Ecological Economics.

Dankers, R., Arnell, N. W., Clark, D. B., Falloon, P. D., Fekete, B. M., Gosling, S. N., ... & Wisser, D. (2014). First look at changes in flood hazard in the Inter-Sectoral Impact Model Intercomparison Project ensemble. *Proceedings of the National Academy of Sciences*, *111*(9), 3257-3261.

Dinh, Q., Balica, S., Popescu, I., & Jonoski, A. (2012). Climate change impact on flood hazard, vulnerability and risk of the Long Xuyen Quadrangle in the Mekong Delta. *International journal of river basin management*, *10*(1), 103-120.

Earle, A., Goldin, J., Machiridza, R., Malzbender, D., Manzungu, E., & Mpho, T. (2006). *Indigenous and institutional profile: Limpopo river basin* (Vol. 112). Iwmi.

Ellis, E. C., & Ramankutty, N. (2008). Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment*, *6*(8), 439-447.

Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D., & Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. Global ecology and biogeography, 19(5), 589-606.

Ellis, E. C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Boivin, N., Díaz, S., ... & Watson, J. E. (2021). People have shaped most of terrestrial nature for at least 12,000 years. *Proceedings of the National Academy of Sciences*, *118*(17), e2023483118.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9(5), 1937-1958.

Formetta, G., & Feyen, L. (2019). Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*, *57*, 101920.

Garg, S., & Mishra, V. (2019). Role of Extreme Precipitation and Initial Hydrologic Conditions on Floods in Godavari River Basin, India. Water Resources Research. https://doi.org/10.1029/2019WR025863.

Günthardt-Goerg, M., & Arend, M. (2013). Woody plant performance in a changing climate.. Plant biology.

Hausfather, Z., Marvel, K., Schmidt, G. A., Nielsen-Gammon, J. W., & Zelinka, M. (2022). Climate simulations: Recognize the 'hot model'problem. *Nature*, *605*(7908), 26-29.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., ... & Kanae, S. (2013). Global flood risk under climate change. Nature Climate Change, 3(9), 816-821.

Intergovernmental Panel on Climate Change (IPCC). (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.

Ivancic, T. J., & Shaw, S. B. (2015). Examining why trends in very heavy precipitation should not be mistaken for trends in very high river discharge. *Climatic Change*, *133*, 681-693.

Jacobson, A. P., Riggio, J., M. Tait, A., & EM Baillie, J. (2019). Global areas of low human impact ('Low Impact Areas') and fragmentation of the natural world. *Scientific Reports*, *9*(1), 14179.

Jongman, B., Winsemius, H. C., Aerts, J. C. J. H., Coughlan de Perez, E., van Aalst, M. K., & Kron, W. (2015). Declining vulnerability to river floods and the global benefits of adaptation. Proceedings of the National Academy of Sciences, 112(18), E2271-E2280.

Khan, K., Zaman, K., Shoukry, A., Sharkawy, A., Gani, S., , S., Ahmad, J., Khan, A., & Hishan, S. (2019). Natural disasters and economic losses: controlling external migration, energy and environmental resources, water demand, and financial development for global prosperity. Environmental Science and Pollution Research.

Kim, B., & Sanders, B. F. (2016). Dam-break flood model uncertainty assessment: case study of extreme flooding with multiple dam failures in Gangneung, South Korea. *Journal of hydraulic engineering*, *142*(5), 05016002.

Klein Goldewijk, K., Beusen, A., Doelman, J., & Stehfest, E. (2017). Anthropogenic land use estimates for the Holocene–HYDE 3.2. *Earth System Science Data*, *9*(2), 927-953.
Klinges, D., & Scheffers, B. (2020). Microgeography, Not Just Latitude, Drives Climate Overlap on Mountains from Tropical to Polar Ecosystems. The American Naturalist.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., ... & Huang, C. (2014). Flood risk and climate change: global and regional perspectives. Hydrological Sciences Journal, 59(1), 1-28.

Llasat, M. C., Marcos, R., Turco, M., Gilabert, J., & Llasat-Botija, M. (2016). Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. *Journal of Hydrology*, *541*, 24-37.

Matonse, A., & Frei, A. (2013). A Seasonal Shift in the Frequency of Extreme Hydrological Events in Southern New York State. Journal of Climate.

May, W. (2008). Potential future changes in the characteristics of daily precipitation in Europe simulated by the HIRHAM regional climate model. *Climate Dynamics*, *30*(6), 581-603.

McCracken, M., & Wolf, A. T. (2019). Updating the Register of International River Basins of the world. *International Journal of Water Resources Development*, *35*(5), 732-782.

McElwee, P., Nghiem, T., Le, H., & Vu, H. (2017). Flood vulnerability among rural households in the Red River Delta of Vietnam: implications for future climate change risk and adaptation. *Natural Hazards*, *86*, 465-492.

Min, S. K., Zhang, X., Zwiers, F. W., & Hegerl, G. C. (2011). Human contribution to more-intense precipitation extremes. Nature, 470(7334), 378-381.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., Van Vuuren, D. P., ... & Wilbanks, T. J. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, *463*(7282), 747-756.

Mucina, L. (2019). Biome: evolution of a crucial ecological and biogeographical concept. *New Phytologist*, *222*(1), 97-114.

Müller, C., Elliott, J., Chryssanthacopoulos, J., Deryng, D., Folberth, C., Pugh, T., & Schmid, E. (2015). Implications of climate mitigation for future agricultural production. Environmental Research Letters.

Niebling, W., Baker, J., Kasuri, L., Katz, S., & Smet, K. (2014). Challenge and response in the Mississippi River Basin. *Water Policy*, *16*(S1), 87-116.

Nied, M., Pardowitz, T., Nissen, K., Ulbrich, U., Hundecha, Y., & Merz, B. (2014). On the relationship between hydro-meteorological patterns and flood types. *Journal of Hydrology*, *519*, 3249-3262.

Ochoa, C., Bolon, I., Durso, A., Castañeda, R., Alcoba, G., Martins, S., Chappuis, F., & Ray, N. (2020). Assessing the Increase of Snakebite Incidence in Relationship to Flooding Events. Journal of Environmental and Public Health. https://doi.org/10.1155/2020/6135149.

Paltan, H., Allen, M., Haustein, K., Fuldauer, L., & Dadson, S. (2018). Global implications of 1.5 C and 2 C warmer worlds on extreme river flows. *Environmental Research Letters*, *13*(9), 094003.
Pereira, J. M., Turkman, M. A., Turkman, K. F., & Oom, D. (2019). Anthromes displaying evidence of weekly cycles in active fire data cover 70% of the global land surface. *Scientific Reports*, *9*(1), 1-14.

Peterson, T. C., Heim Jr, R. R., Hirsch, R., Kaiser, D. P., Brooks, H., Diffenbaugh, N. S., ... & Wuebbles, D. (2013). Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: state of knowledge. *Bulletin of the American Meteorological Society*, *94*(6), 821-834.

Pisaniello, J. D., Tingey-Holyoak, J., & Burritt, R. L. (2012). Appropriate small dam management for minimizing catchment-wide safety threats: International benchmarked guidelines and demonstrative cases studies. *Water Resources Research*, *48*(1).

Reed, T., Mason, L. R., & Ekenga, C. C. (2020). Adapting to climate change in the upper Mississippi river basin: exploring stakeholder perspectives on river system management and flood risk reduction. *Environmental Health Insights*, *14*, 1178630220984153.

Pokhrel, Y., Burbano, M., Roush, J., Kang, H., Sridhar, V., & Hyndman, D. W. (2018). A review of the integrated effects of changing climate, land use, and dams on Mekong river hydrology. *Water*, *10*(3), 266.

Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... & Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global environmental change*, *42*, 153-168.

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., ... & Blöschl, G. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water resources research*, *53*(7), 5209-5219.

Sadeghi, M., Shearer, E., Mosaffa, H., Gorooh, V., Naeini, M., Hayatbini, N., Katiraie-Boroujerdy, P., Analui, B., Nguyen, P., & Sorooshian, S. (2021). Application of remote sensing precipitation data and the CONNECT algorithm to investigate spatiotemporal variations of heavy precipitation: Case study of major floods across Iran (Spring 2019). Journal of Hydrology.

Sanderson, J. S., Beutler, C., Brown, J. R., Burke, I., Chapman, T., Conant, R. T., ... & Sullivan, T. (2020). Cattle, conservation, and carbon in the western Great Plains. *Journal of Soil and Water Conservation*, *75*(1), 5A-12A.

Schmeier, S. (2011). Resilience to climate change-induced challenges in the Mekong river Basin: The Role of the MRC.

Shewmake, S. (2008). *Vulnerability and the impact of climate change in South Africa's Limpopo River Basin* (Vol. 804). Intl Food Policy Res Inst

Shi, W., Wang, M., & Liu, Y. (2020). Crop yield and production responses to climate disasters in China.. The Science of the total environment.

Shivaprasad Sharma, S. V., Roy, P. S., Chakravarthi, V., & Srinivasa Rao, G. (2018). Flood risk assessment using multi-criteria analysis: a case study from Kopili River Basin, Assam, India. *Geomatics, Natural Hazards and Risk*, *9*(1), 79-93.

Silva, M., & Kawasaki, A. (2020). A local-scale analysis to understand differences in socioeconomic factors affecting economic loss due to floods among different communities. International journal of disaster risk reduction.

Slater, L. J., & Villarini, G. (2016). Recent trends in US flood risk. *Geophysical Research Letters*, *43*(24), 12-428.

Stevens, N., Bond, W., Feurdean, A., & Lehmann, C. E. (2022). Grassy Ecosystems in the Anthropocene. *Annual Review of Environment and Resources*, *47*, 261-289.

Sutanudjaja, E. H., Van Beek, R., Wanders, N., Wada, Y., Bosmans, J. H., Drost, N., ... & Bierkens, M. F. (2018). PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model. *Geoscientific Model Development*, *11*(6), 2429-2453.

Tito, R., Vasconcelos, H., & Feeley, K. (2018). Global climate change increases risk of crop yield losses and food insecurity in the tropical Andes. Global Change Biology.
United Nations Department of Economic and Social Affairs, Population Division (2022). World Population Prospects 2022: Summary of Results. UN DESA/POP/2022/TR/NO. 3

Valdés, A., Lenoir, J., Gallet-Moron, E., Andrieu, E., Brunet, J., Chabrerie, O., Closset-Kopp, D., Cousins, S., Deconchat, M., Frenne, P., Smedt, P., Diekmann, M., Hansen, K., Hermy, M., Kolb, A., Liira, J., Lindgren, J., Naaf, T., Paal, T., Prokofieva, I., Scherer-Lorenzen, M., Wulf, M., Verheyen, K., & Decocq, G. (2015). The contribution of patch-scale conditions is greater than that of macroclimate in explaining local plant diversity in fragmented forests across Europe. Global Ecology and Biogeography.

van Beek, L. P. H., & Bierkens, M. F. P. (2008). The Global Hydrological Model PCR-GLOBWB: Conceptualization, Parameterization and Verification. Utrecht University Department of Physical Geography Tech. Rep., 53 pp.

van Vuuren, D. P., & Carter, T. R. (2014). Climate and socio-economic scenarios for climate change research and assessment: reconciling the new with the old. *Climatic change*, *122*, 415-429.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... & Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic change*, *109*, 5-31.

Verburg, P. H., Alexander, P., Evans, T., Magliocca, N. R., Malek, Z., Rounsevell, M. D., & van Vliet, J. (2019). Beyond land cover change: towards a new generation of land use models. *Current Opinion in Environmental Sustainability*, *38*, 77-85.

Verburg, P. H., Erb, K. H., Mertz, O., & Espindola, G. (2013). Land System Science: between global challenges and local realities. *Current opinion in environmental sustainability*, *5*(5), 433-437.
Vicente-Serrano, S. M., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., ... & González-Hidalgo, J. C. (2017). A high resolution dataset of drought indices for Spain. *Data*, *2*(3), 22.

Ward, P. J., Jongman, B., Aerts, J. C., Bates, P. D., Botzen, W. J., Diaz Loaiza, A., ... & Winsemius, H. C. (2017). A global framework for future costs and benefits of river-flood protection in urban areas. *Nature climate change*, *7*(9), 642-646.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., & Schewe, J. (2014). The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. *Proceedings of the National Academy of Sciences*, *111*(9), 3228-3232.
Wasko, C., & Nathan, R. (2019). Influence of changes in rainfall and soil moisture on trends in flooding. *Journal of Hydrology*, *575*, 432-441.

Wasko, C., & Sharma, A. (2017). Global assessment of flood and storm extremes with increased temperatures. *Scientific reports*, *7*(1), 7945.

Winsemius, H. C., Jongman, B., Veldkamp, T. I., Hallegatte, S., Bangalore, M., & Ward, P. J. (2016). Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. Environmental Research Letters, 11(9), 094023.

Woldemeskel, F., & Sharma, A. (2016). Should flood regimes change in a warming climate? The role of antecedent moisture conditions. *Geophysical Research Letters*, *43*(14), 7556-7563.

Yoshida, Y., Lee, H. S., Trung, B. H., Tran, H. D., Lall, M. K., Kakar, K., & Xuan, T. D. (2020). Impacts of mainstream hydropower dams on fisheries and agriculture in lower Mekong Basin. *Sustainability*, *12*(6), 2408.

Zhang, Q. Q., Ying, G. G., Pan, C. G., Liu, Y. S., & Zhao, J. L. (2015). Comprehensive evaluation of antibiotics emission and fate in the river basins of China: source analysis, multimedia modeling, and linkage to bacterial resistance. *Environmental science & technology*, *49*(11), 6772-6782.

Nyaupane, N., Thakur, B., Kalra, A., & Ahmad, S. (2018). Evaluating future flood scenarios using CMIP5 climate projections. Water, 10(12), 1866.

Appendices.

1: River basin geographical information

Basin	Basin area (km2)	Country	Basin country unit (BCU) area (km2)	Percentage total basin area
Limpopo	406,500	Botswana	81,400	20.0%
		Mozambique	79,500	19.6%
		South Africa	182,800	45.0%
		Zimbabwe	62,700	15.4%

Basin	Basin area (km2)	Country	Basin country unit (BCU) area (km2)	Percentage total basin area
Mississippi	3,264,800	Canada	52,300	1.6%
		United States of America	3,212,500	98.4%

Basin	Basin area (km2)	Country	Basin country unit (BCU) area (km2)	Percentage total basin area
Mekong/Lancang	781,600	China	164,700	21.1%
		Cambodia	154,100	19.7%
		Lao People's Democratic Republic	206,500	26.4%
		Myanmar	21,700	2.8%
		Thailand	188,100	24.1%

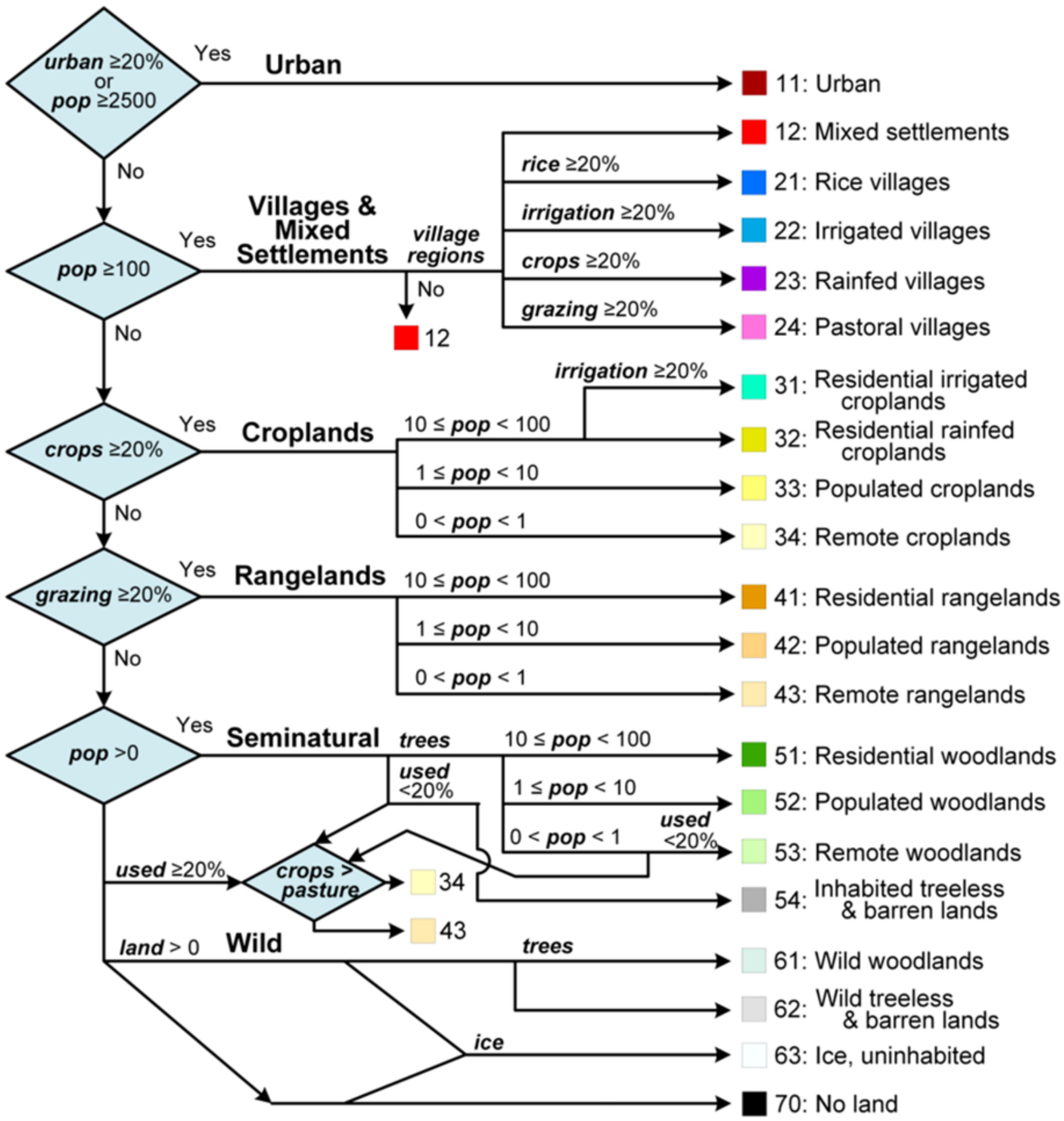

Figure 12: anthrome classification method, retirved from (van der Wielen, 2021)