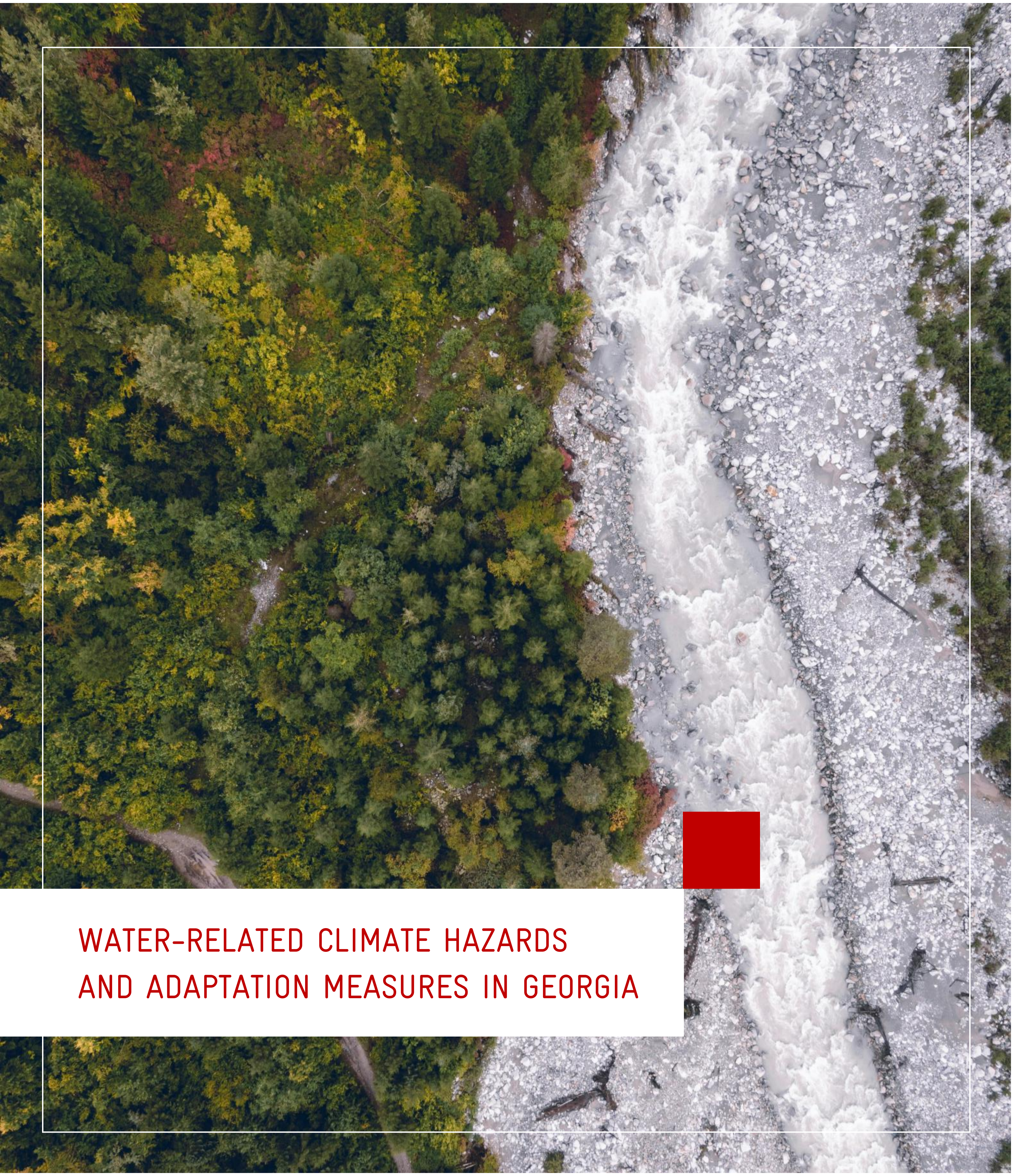

WATER-RELATED CLIMATE HAZARDS AND ADAPTATION MEASURES IN GEORGIA

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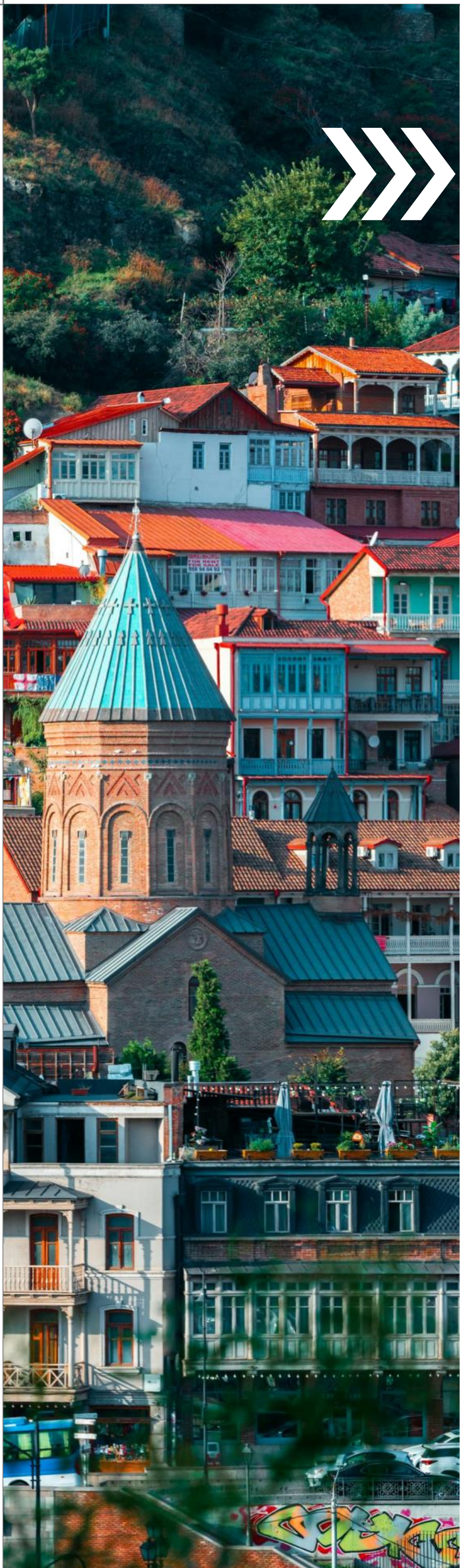
On behalf of
Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV)

Germany 2025



WATER-RELATED CLIMATE HAZARDS AND ADAPTATION MEASURES IN GEORGIA

▶ DATA AND LITERATURE ANALYSIS

EARTH YIELD ADVISORIES

Prepared by EarthYield Advisories GbR as part of the assignment "Development of climate change related water risk assessments for Georgia, Kazakhstan, and Mongolia"

Acknowledgement

This report was prepared as part of the assignment "Development of climate change related water risk assessments for Georgia, Kazakhstan, and Mongolia" delivered by EarthYield Advisories GbR Franziska Brundell and Sophia Lüttringhaus for GIZ. Additionally, we thank our cooperation partners for this assignment for their valuable inputs and guidance: Anastasia Lobanova and Christoph Gornott.

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*Source: Illustration by EarthYield Advisories GbR

Abbreviations

Abbreviation	Description
ADB	Asian Development Bank
BMUV	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
CBD	Convention on Biological Diversity
CCKP	Climate Change Knowledge Portal
CDS	Copernicus Data Climate Store
CMIP	Coupled Model Intercomparison Project
CRED	Policy Advice for Climate-Resilient Economic Development
DIAPOL-CE	Policy Dialogue and Knowledge Management on Climate Protection Strategies
EEA	European Environment Agency
ESM	Earth System Model
EU	European Union
GDP	Gross Domestic Product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IEA	International Energy Agency
IKI	International Climate Initiative
IMF	International Monetary Fund
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
MRI	Meteorological Research Institute
OECD	Organization for Economic Co-operation and Development
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathways
SPEI	Standardized Precipitation Evaporation Index
SSP	Shared Socioeconomic Pathways
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
WBG	World Bank Group
WMO	World Meteorological Organization

Purpose of the assignment

The Global Programme on Climate Resilient Economic Development (CRED) by GIZ tasked EarthYield Advisories with assessing water-related climate hazards, calculated based on the two most important variables for climate change analysis - precipitation and temperature -, in Georgia and identifying potential adaptation measures. The project was divided into several key tasks: identifying water-related climate hazards in Georgia, selecting the most pressing hazards, modelling the development of these hazards under different climate scenarios until 2100, identifying responsive adaptation measures, and evaluating the data findings. The primary aim of this project is to inform policymakers about potential risks and their likelihood, enabling informed decision-making regarding climate change policies in Georgia. The core objective of the assignment, carried out by EarthYield Advisories and presented in this report, is to integrate water-related risks into macroeconomic assessments in Georgia (e3.ge model) and policy advice, ensuring climate-resilient economic planning.

The structure of this report is designed to provide a comprehensive understanding of the water-related risks in Georgia and the necessary measures for adaptation. The report begins with an introductory section on the water-related risks facing Georgia, highlighting the impacts of climate change on hydrological systems, and emphasizing the importance of further knowledge regarding water-related risks. This is followed by a detailed "Background" section, which includes sub-sections on the geography and hydrology (2.1), climate and climate change (2.2) and economy (2.3) of the country. The third chapter describes the methodology of the data collection, manipulation and modelling to assess the water related risks. The fourth chapter presents results from the literature analysis and describes the water-related hazards specific to the country, providing more details for the hazards droughts (4.1), floods (4.2), heatwaves (4.3) and coastal hazards (4.4). The results of the data analysis and modelling are presented in the fifth chapter, economic damages are described in chapter 6 and adaptation measures in chapter 7. The report ends with a conclusion.

1. INTRODUCTION

Water is a fundamental resource for sustaining livelihoods and ecosystems. It further is the backbone of overall socio-economic stability and key economic sectors, including agriculture, industry, and energy production in Georgia. Climate change significantly impacts water resources both worldwide and specifically in Georgia, leading to various risks including a change of precipitation patterns, an increase in frequency and severity of extreme events such as droughts or floods, a degradation of water quality and a lack of freshwater availability (IPCC/Caretta et al., 2022).

In response to these growing challenges, EarthYield Advisories is supporting GIZ to assess water-related risks and adaptation measures to reduce these risks in Georgia and other partner countries. The assignment involves providing GIZ with data and information on water related risks, in particular droughts, and floods as well as the temperature-related risk heatwaves. These efforts are framed within the broader context of GIZ's Global Programme "Policy Advice for Climate-Resilient Economic Development" (CRED) and the project "Policy Dialogue and Knowledge Management on Climate Protection Strategies" (DIAPOL-CE), both implemented under the International Climate Initiative (IKI) on behalf of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

The Global Programme on Climate Resilient Economic Development (CRED) in Georgia is focused on enhancing the country's resilience to climate change through a variety of analyses regarding climate change impacts and possible adaptation measures. The project involves the development and implementation of the e3.ge macroeconomic model, which assesses the economy-wide impacts of climate change and adaptation measures. Through these efforts, CRED aims to foster resilient employment-intensive economic growth and reduce the vulnerability of Georgia's key economic sectors to climate change.

To address these challenges, our assignment includes the identification and modelling of the most critical water hazards and temperature hazards in Georgia. We project future scenarios under different climatic conditions. These projections serve as an input to the e3.ge model, enabling a detailed understanding of potential impacts. Further our compilation and analysis of possible adaptation measures can serve to enhance the resilience of multiple economic sectors with respect to water risks. The lessons learned from these processes will support the replication of water-risk assessments across other regions, building resilience and adapting to climate change's multifaceted impacts.

Georgia is experiencing significant climate change impacts, with average temperatures steadily increasing since the 1960s and projected to rise by 1.4°C to 4.9°C above the 1986-2005 baseline by the 2090s (WBG & ADB, 2021). The country's unique topography creates diverse climatic zones, making nationwide predictions challenging (Russo et al., 2013). Water-related risks in Georgia are multifaceted, encompassing both drought and flooding concerns (IMF, 2024). Despite generally abundant water resources, the country is becoming more vulnerable to drought conditions, with higher temperatures and faster evaporation rates leading to longer and more severe dry periods (WBG & ADB, 2021; USAID 2017)). Conversely, extreme precipitation events are becoming more frequent and intense, increasing the risk of flooding, particularly in urban areas (Donnelly et al., 2017). Climate change is also affecting water quality, with warmer temperatures and increased pollutant runoff potentially creating uninhabitable aquatic environments (WBG & ADB, 2021). Georgia's heavy reliance on hydropower, which accounts for over 80% of its electricity production, makes the energy sector particularly vulnerable to climate variability (IEA, 2020). Projected reductions in river flows, especially during summer months, may significantly impact hydropower potential and coincide with peak energy demand for cooling (Kordzakhia et al., 2019). These complex water-related risks underscore the need for comprehensive adaptation and management strategies to ensure Georgia's water and energy security in the face of climate change (UNDP, 2018).

2. BACKGROUND ON GEORGIA

2.1. Geography and hydrology

Georgia, situated at the crossroads of Eastern Europe and Western Asia, occupies a strategic position at the juncture of East and West. The country's diverse topography is characterized by the Greater Caucasus mountains in the north and the Lesser Caucasus in the south, with fertile lowlands nestled between these ranges (WBG & ADB, 2021). These lowlands, particularly in Kakheti, are renowned for their wine regions, contributing to the country's rich agricultural heritage. The western part of Georgia features a subtropical coastline along the Black Sea, adding to the nation's geographical diversity. This unique landscape creates a variety of microclimates and ecosystems, making Georgia a hotspot for biodiversity and contributing to its appeal as a tourist destination (CBD, 2022).

Georgia is abundantly endowed with water resources, such as rivers. These rivers are divided into two main drainage basins: the Black Sea basin in the west and the Caspian Sea basin in the east. The country's water resources are further augmented by numerous lakes and glaciers, particularly in the Greater Caucasus, which play a crucial role in the regional hydrological cycle (Elizbarashvili et al., 2017). Groundwater resources are also significant, with an estimated annual renewable volume of 18 km^3, though concerns about depletion are emerging due to climate change and increased extraction (WBG & ADB, 2021). Water use in Georgia is primarily distributed among agriculture, domestic supply, and hydropower generation, with the latter accounting for over 80% of the country's electricity production (IEA, 2020). This heavy reliance on hydropower underscores the critical importance of sustainable water management in the face of changing climatic conditions.

2.2. Climate and climate change

Georgia's climate is characterized by diverse climatic zones due to its varied topography and proximity to the Black Sea. The country can be broadly divided into several distinct climatic regions. Western Georgia, influenced by the Black Sea, experiences a humid subtropical climate with mild winters, hot summers, and heavy rainfall, supporting subtropical vegetation (WBG & ADB, 2021). Eastern Georgia, in contrast, has a more continental climate with hot summers and cold winters, influenced by a rain shadow effect, making it suitable for wine production, particularly in regions like Kakheti (Maghradze et al. 2016). The mountainous regions of the Caucasus feature cold winters and cool summers, with alpine vegetation and various microclimates. Additionally, some parts of eastern Georgia exhibit semi-arid to arid conditions, characterized by very dry and hot summers with sparse vegetation (WBG & ADB, 2021).

Climate change is significantly impacting Georgia, with the country's predominantly mountainous terrain playing a crucial role in shaping these effects. Projections indicate a rise in average temperatures of 1.5-2°C by the end of the century, with eastern Georgia expected to experience more pronounced warming (WBG & ADB, 2021). The frequency and duration of heatwaves is projected to increase, particularly under higher emissions scenarios (Ministry of Environmental Protection and Agriculture of Georgia, 2021). Georgia is also facing the rapid retreat of glaciers and reductions in mountain snowpack, which are likely to alter regional hydrology (WMO, 2024; WBG & ADB, 2021). Precipitation patterns are expected to change, with more intense rainfall in the west and drier conditions in the east (WBG & ADB, 2021).

Coastal areas are at risk from sea-level rise and increased erosion (WBG & ADB, 2021).

2.3. Economy

Georgia's economy has undergone significant transformation since gaining independence in 1991, with substantial reforms implemented since the early 2000s. These reforms have led to robust economic growth, averaging between 4-6% annually over the past two decades (WBG & ADB, 2021). The country has made great strides in creating a business-friendly environment, as evidenced by its consistently good ranking in the Global Competitiveness Report by the World Economic Forum. (World Economic Forum 2020).

The service sector dominates Georgia's economy, with tourism, financial services, and IT services playing crucial roles. Agriculture, particularly wine production, remains an important contributor to GDP and employment. Agriculture, forestry and fishing contributed 6% to the country's GDP in 2023 (World Bank 2025) and the employment in agriculture was approximately 40% of total employment, making agriculture particularly relevant in the labour sector (World Bank 2025a). Industry and manufacturing, including mining, hydropower, construction, and textiles, also form significant components of the economy (ADB, 2023). Georgia has made concerted efforts to attract foreign investment through measures such as low and flat tax rates, privatization, and deregulation (WBG & ADB, 2021).

Georgia's economic growth outlook remains positive, with GDP showing a rapid estimate of 9.5% in 2024 (Geostat 2025). However, addressing the challenges posed by climate change will be crucial for sustaining this growth and ensuring the resilience of key economic sectors in the long term (see chapter 5 on economic damages).

3. METHODOLOGY • Data collection, manipulation and analysis

The methodology followed a precise succession to ensure transparency and replicability of all necessary steps,

- Literature analysis and expert exchange to identify most important hazards and trends
- Identification of data requirements and model assumptions
- Data retrieval through trial and error
- Selection of the suitable data source
- Data download
- Identification of hazard classifications
- Preparation of data for each hazard
- Calculation of probability of occurrence for each classification

3.1. Literature analysis and expert exchange

As an initial step, this study analysed scientific and grey literature, i.e. peer-reviewed papers and reports issued by international organizations such as reports, white papers or conference papers as well as documents provided by GIZ to gain an insight into the scientific status quo and to isolate current trends and challenges as well as to identify the most pressing water-related hazards in relation to climate change in the relevant country. The analysis also aimed to analyse specific policy frameworks and guidelines relevant to each country. Lastly, the literature analysis provided an initial search of appropriate data and data frameworks to establish which climate models could be used and which scenarios could be appropriately depicted. This included data sets from Copernicus, the Aqueduct Water Risk Atlas by the World Resources Institute, the World Bank Climate Change Knowledge Portal The scientific literature was identified through systematic searches and grey literature was gathered from institutional repositories, government websites, and relevant international organizations. The initial focus was the identification of hazards and risks, searched with the keywords "climate change hazards Georgia", "hydrology Georgia", "water risks Georgia" and "climate change water hazards Georgia". Additionally, the most commonly used reports were analysed, including the sixth IPCC report, documents of the World Bank Climate Change Portal and the Climate Risk Country Profiles by the Asian Development Bank, Lastly, documents provided by GIZ, including internal reports, country-specific data, and project evaluations, served as a crucial source of context-specific information.

Correspondingly, expert talks from all country packages assisted in the identification of the most pressing water-related hazards that all countries have in common, the most vulnerable sectors in Georgia and the guidelines on possible adaptation measures. These talks were held in regular intervals with relevant stakeholders and economists, such as GWS and GIZ National Advisors for Georgia.

3.2. Data analysis

The literature analysis and the expert talks as well as the requirements by the economic model, namely the necessity for annual data, data for the SSP scenarios 1-2.6, 2-4.5 and 5-8.5 and for hazards with the most severe expected economic damages, led to the identification of the water-related hazards riverine floods and meteorological droughts as well as heatwaves. Other important water hazards such as general floods, hydrological droughts and general water depletion had to be abandoned due to a lack of available data. In the entire study data constraints were of importance, as the data situation is not fully established in Georgia. The preceding project focused on different hazards and the data used had to be preferably open-source and easily accessible to be considered.

The data and the hazard model had to fit the following criteria to be taken into consideration:

- Simulation of future values and interpretation of historical values for variables that are relevant to heatwaves, meteorological droughts and riverine floods.
- Differentiation of spatial grids with sufficient spatial resolution, i.e. grids that do not only show one value per country.
- Daily or monthly values that can be calculated into an annual probability of occurrence of three different hazard classifications.
- Establishment of three hazard classifications: low hazard, medium hazard, high hazard.
- Future projections from 2024-2080 or longer.
- Provision of annual projections.
- Possible recreation of data manipulation by future policymakers using open-source data and easily replicable workflows.
- Full projections for the following scenarios
  - Shared Socioeconomic Pathways (SSP) 1- Representative Concentration Pathway (RCP) 2.6 (Sustainability – Low Emissions, Paris Agreement),
  - SSP 2- RCP 4.5 (Middle of the Road – Intermediate Emissions), and
  - SSP 5- RCP 8.5 (Fossil-fueled Development – High Emissions).

3.2.1. Data sources

Data sources for Georgia include ISIMIP, Copernicus Climate Data Store, CMIP6, NASA EarthData, the World Bank Climate Change Portal and the Aqueduct Water Atlas by the World Resources Institute. They differ in how the data is presented (manipulated data vs raw data), resolution, temporal differentiation and RCD/SSP scenarios available. Constraints of the project included a specific timeframe, pre-selected SSP scenarios, the integration into the economic model and time available.

The initial workplan of this assignment aimed for the use of the Aqueduct data repository with pre-existing projections of drought and floods and its corresponding Water Atlas. Unfortunately, the data was only available in 30-year intervals, making it impossible to calculate accurate estimations of the probability of occurrence for each year in the economic model. Similarly, the Climate Change Knowledge Portal (CCKP), which also provides pre-manipulated data, had to be excluded as the variables were only available for the country as a whole and were already aggregated. Yet, both sources can be used as excellent reference points for verification and initial trends.

The study's objective was to fully work with unprocessed data from a widely used international climate model.

The selected model was the Meteorological Research Institute Earth System Model version 2 (MRI-ESM2-0), developed by Japan's Meteorological Research Institute (MRI) (Yukimoto et al., 2019). This model is part of the Coupled Model Intercomparison Project (CMIP6), a global initiative for climate projections under different future scenarios. MRI-ESM2-0 includes advanced simulations of atmospheric, oceanic, and land processes, making it particularly suitable for studying regional climate patterns in Central and Western Asia, including Kazakhstan, Mongolia, and Georgia.

This model was chosen for its ability to accurately represent mid-latitude weather patterns and capture variations in temperature and precipitation in continental and semi-arid climates. Such capabilities make it a valuable tool for assessing the potential impacts of climate change on agriculture, water resources, and ecosystems in these regions. Additionally, many other models had to be excluded due to limited data availability or missing scenario projections

MRI-ESM2-0 has a **spatial resolution of approximately 110 km × 110 km**. The historical baseline used for analysis is **1981–2010**. Although baselines from 1991–2020 are now more commonly used, this was not an option for MRI-ESM2-0, as its available data only extends to 2014. The **1981–2010 baseline** was chosen because it provides both climatic relevance and a sufficiently large dataset for analysis.

The data was retrieved from Copernicus Data Climate Store (CDS)[1]. The CDS provides free and open access to climate data, offers a comprehensive climate data collection, has a user-friendly interface and provides access to a variety of CMIP6 climate projections, which were published in 2021. Furthermore, the CDS is regularly updated and can be tailored for different applications. Lastly, the ability to apply spatial and temporal filters to data requests made the downloading process more efficient.

The original project scope required that the data had already been cleared for bias and manipulated for further research (such as with Aqueduct and CCKP) and that no programming skills are required. This, however, proved impossible if also taking spatial and temporal differences into account and allowing for the fact that the study aims to identify extreme events and the likelihood thereof. To fulfill a projection of this scope on an annual basis, both the use of international climate data and the ability to work with Python are necessary.

Therefore, the following steps were necessary to obtain the data sets for Georgia:

a. Identification of relevant data sets due to geography and time constraints of the project.
b. Evaluation of available climate data sources.
c. Exclusion of pre-processed data sources, such as the Aqueduct Water Atlas and the CCKP, due to limitations in temporal resolution and spatial aggregation.
d. Selection of a suitable international climate model for data processing
e. Justification of the selected model based on its spatial resolution and historical baseline, which provided a balance between data availability and climatic relevance
f. Retrieval of raw data from the CDS, which was selected for its open access, extensive climate projections, user-friendly interface, and ability to apply spatial and temporal filters to streamline data downloads.
g. Acknowledgement of necessary programming skills.

3.2.2. Variables

Based on the data requirements needed to identify and analyse the three water hazards heatwaves, droughts and riverine floods - and the restriction of available data for the respective countries, scenarios and time frame, the following variables in a 110km x 110km resolution for the whole landmass of all three countries were chosen:

[1] https://cds.climate.copernicus.eu/

- Daily precipitation
- Monthly precipitation
- Daily mean near-surface air temperature
- Daily maximum near-surface air temperature
- Monthly mean near-surface air temperature
- Daylight hours
- Monthly total runoff
- Monthly moisture in upper portion of soil column

3.2.3. Scenarios

The project favoured the more commonly used 6th generation SSP scenarios (SSP1-2.6, SSP2-RCP 4.5 and SSP5-RCP 8.5) for a seamless integration into the economic model. These SSP scenarios were chosen over earlier ones because they offer a more comprehensive framework that integrates socioeconomic conditions with climate projections. The 6th generation of climate scenarios, known as SSPs, combines socioeconomic development narratives with radiative forcing levels, providing a nuanced exploration of potential climate futures and their societal challenges. Unlike RCPs, which focus solely on greenhouse gas concentration trajectories, SSPs incorporate economic growth, population dynamics, technological advancements, and policy implementation. This integration allows SSPs to represent the interplay between socioeconomic factors and climate impacts, offering a broader context for understanding potential futures. SSPs work alongside RCPs, linking climate outcomes with realistic socioeconomic contexts, enabling researchers to explore a wider range of climate adaptation and mitigation strategies. This flexibility makes SSPs superior for studying climate risks and societal capacities to address these risks under varied development pathways, offering a holistic tool for policy-relevant climate research.

3.3. Data manipulation

The final required data from the CDS was downloaded on October 16, 2024, subsequently manipulated and the relevant indicators were modelled. The data can be accessed manually and does not require a specific program, i.e., an Application Programming Interface. It It is possible to choose any sub-setting of the data, for example temporal periods or geographical locations, manually.

Following the download of the data, the programming language Python (open-access) was used to run all calculations and visualizations. In order to perform different tasks with Python, a variety of so-called Individual packages and libraries are necessary and have to be installed accordingly and as needed, the most important examples include xarray, pandas, netCDF4 and matplotlib. Xarray was used, because it makes working with large, multi-dimensional datasets (like temperature and precipitation over time and space) much easier by using labelled dimensions. Pandas allows handling of missing values, data filtering and aggregation of data in time-series climate data. NetCDF4 is required to read data that is provided in a CDS4 file like most climate data. Matplotlib allows the user to visualizations out of climate data and was used to create graphs and maps.

All calculations and modelling presented here can be executed and replicated with the use of open-source software, but requires programming skills and knowledge of data science.

3.4. Calculation and modelling

3.4.1. Meteorological droughts

The Standardized Precipitation Evapotranspiration Index (SPEI) was selected as the primary parameter for the drought calculations in Georgia as it offers a comprehensive approach to assessing water balance, making it a highly effective tool for capturing drought conditions. Unlike indices that rely solely on precipitation, SPEI incorporates both precipitation and potential evapotranspiration, allowing it to account for the influence of temperature and other climatic variables on water availability. This sensitivity to multiple climate variables, especially temperature fluctuations, enhances the accuracy of drought assessment under changing climate conditions. Additionally, SPEI's multi-scalar nature is particularly valuable, as it allows for analysis over different timescales—from short-term monthly droughts to multi-year periods. This versatility makes SPEI an ideal choice for comparing drought severity across regions with differing climatic characteristics. In this study the 12-month scale was chosen, as it captures the balance between moisture input and atmospheric demand over a full annual cycle. This scale is well-suited for detecting prolonged periods of moisture deficit or surplus. Since it reflects cumulative water stress over a year, the 12-month SPEI can reveal trends and anomalies in annual hydrological balance, which are crucial for planning in water-sensitive regions and for managing long-term environmental and economic impacts of climate variability. For the calculation of the SPEI index and subsequently the probability of the occurrence of a drought, daily temperature, daily precipitation and sunlight hours were used. As a first step, potential evapotranspiration (PET) was calculated using the Thornthwaite equation, using that to calculate the water balance with the precipitation data on a monthly basis, daylight hours were required from the original data (Aschonitis et al. 2021), creating a SPEI index. The SPEI was subsequently calculated for each grid point on the map. To enhance the analysis of drought severity, we further classified each event by its SPEI score. Drought events were categorized into three hazard levels: low hazard for scores below -1, medium hazard for scores below –1.5 and high hazard for scores below –2. In order to identify the probability of occurrence for each hazard classification as well as the mean probability of occurrence for the historic baseline period, a gradient boosting regressor was run. The gradient boosting regressor method produces a continuous output that can directly be interpreted as the probability of occurrence. The project required the final presentation of the data to be in an Microsoft Excel format. As a last step, the data was thus saved as a NetCDF file and was then subset to the individual countries and exported to a CSV file.

The limitation of this approach to project droughts is the Thornthwaite equation because other equations are more precise as they use more data formats, but this data was not available to the project.

3.4.2. Riverine floods

For the projection of riverine floods in Georgia several variables had to be considered to fully portray the risk of riverine flooding in each country. Due to the meteorological complexity of floods, various hydrological factors such as soil porosity, vegetation, land use and steepness should be taken into consideration but are almost always impossible to do so on a large-scale basis. Further, due to the occurrence of flash floods and the necessity for real-time data, riverine floods are difficult to predict (Perrera et al 2020). Additionally, data shortages and restrictions only allowed for a specific selection of variables. The following variables were chosen and subsequently categorized into a composite risk score to project possible future riverine floods in each grid point:

- **Monthly Total Runoff**: Representing the volume of water that flows over land surfaces and into rivers after precipitation events, total runoff is an established key driver of riverine floods. Runoff levels can rise significantly due to heavy precipitation, snowfall, saturated soil conditions or persistent rainfall, which causes rivers or stream to exceed their capacity and can lead to overflow. Due to the varying nature of reasons for total runoff, this variable serves as a proxy for lacking data and is particularly useful for the assessment of riverine flooding as it integrates the effects of precipitation, land saturation, and watershed characteristics, all of which influence how quickly, and intensely riverine flooding may occur (IPCC, 2014).
- **5-Day-Precipitation-Events**: Daily precipitation is not an ideal proxy for floods, as duration, intensity and overall wetness are difficult to estimate when just looking at mean precipitation in any given location. 5-day-cumulative precipitation events on the other hand show an extreme event of prolonged precipitation more than average precipitation and affect the risk of riverine flooding accordingly. Statistically, riverine floods are more likely to occur after prolonged precipitation events (EEA, 2021)
- **Number of Days with Precipitation over the 95th Percentile**: A commonly used variable in flood prediction is the variable number of days with rainfall over 50mm. This variable is not suited for the particular project regions, as they are predominantly dry and in some regional cases arid or semi-arid. The isolation of the 95th percentile in the historical baseline therefore represents extreme rainfall more adequately. Flash floods and riverine floods often occur after extreme rainfall as the event overwhelms drainage systems, saturated soils and riverbeds (Cotterill et al, 2021; Tamm et al, 2023).
- **Daily Temperature**: Surface temperature is not directly linked to flooding, but commonly used as a proxy for snowmelt and evaporation. The variable is particularly useful in mountainous regions with increased snowmelt in specific seasons, during which rivers swell to more than their normal size. Additionally, in warm regions, high temperature can reduce soil moisture and increase frequency of heavy rainfall (UNEP 2020).
- **Soil Moisture**: Soil moisture directly affects how much rainfall infiltrates the soil versus how much becomes surface runoff that flows into rivers. High soil moisture levels indicate that the ground is near saturation, meaning it has limited capacity to absorb additional rainfall, which increases the volume of runoff entering river systems. When soil is already saturated from previous precipitation or snowmelt, even moderate rainfall can lead to rapid increases in river levels, raising the likelihood of flooding (Yu et al. 2023; Ran et al. 2022).

In the composite risk score, all variables were given equal weighting with the exception of temperature, which was given more importance (50%) between January and May due to flood risk caused by snowmelt in the mountains and no importance (0%) between June and December. Following that, the risk score was calculated for the baseline and future periods. The monthly risk score was then aggregated to an annual risk score.

To enhance the analysis of flood severity, we further classified each event by its percentile in the historic baseline period. Flood events were categorized into three hazard levels: low hazard for the 80th percentile, medium hazard for the 90th percentile and high hazard for the 98th percentile. In order to identify the probability of occurrence for each hazard classification as well as the mean probability of occurrence for the historic baseline period, a gradient boosting regressor was run. The gradient boosting regressor method produces a continuous output that can directly be interpreted as the probability of occurrence. The project required the final presentation of the data to be in a Microsoft Excel format. As a last step, the data was thus saved as a NetCDF file and was then subset to the individual countries and exported to a CSV file.

Limitations of this approach include that the inclusion of a hydrological model would be beneficial but was outside the scope of this project. Hydrological models often have the ability to include land use and terrain, understand individual river dynamics and can simulate rainfall-runoff relationships. Furthermore, risk scores are model estimates rather than facts. Additionally, floods are influenced by numerous factors including local geography, land use, river flow dynamics and more, which makes them non-linear, complex phenomena that should best be studied at a more local level.

3.4.3. Heatwaves

In this study, defining heatwaves required a tailored approach due to the variability of temperature norms across the three different countries as well as across the different regions within Georgia. A single temperature threshold is insufficient for capturing heatwave events universally, as what constitutes an extreme temperature in one region may be typical in another. To address this, we adopted the heatwave definition provided by the previous project partner University of the Balearic Islands (GIZ, 2021a), which aligns with previous research methodologies while allowing for regional climate variability. According to this definition, a heatwave occurs when daily maximum temperatures exceed the 99th percentile of historic baseline temperatures for that specific location and this elevated temperature persists for more than five consecutive days. This percentile-based approach provides a more regionally adaptable framework for identifying heatwaves by anchoring them in location-specific temperature extremes rather than a fixed absolute threshold.

Once heatwave periods were identified using this definition, we extracted these events from both historic baseline data and projected future climate data under various climate scenarios. To do this, the 99th percentile was calculated for each grid point of the data across the historical baseline period, followed by the calculation of exceedances under each SSP scenario. We then aggregated these heatwave occurrences on a monthly basis to quantify the frequency of heatwaves over time, capturing both the number of heatwaves per month and per year. This aggregation allowed us to track shifts in the seasonal and annual distribution of heatwave events, providing insights into potential changes in heatwave frequency and timing under different future climate conditions. To enhance the analysis of heatwave severity, we further classified each event by its duration. Heatwave events were categorized into three hazard levels: low hazard for events lasting for at least 5 days, medium hazard for events lasting at least 8 days, and high hazard for events persisting longer than 10 days. In order to identify the probability of occurrence for each hazard classification as well as the mean probability of occurrence for the historic baseline period, a gradient boosting regressor was run. The gradient boosting regressor method produces a continuous output that can directly be interpreted as the probability of occurrence. Compared to other methods such as a classifier it allows to capture the likelihood of an event in a given location and provides insights into areas which increasing or decreasing risk, making it suitable for identifying long-term climate trends.

The project required the final presentation of the data to be in an Microsoft Excel format. As a last step, the data was thus saved as a NetCDF file and was then subset to the individual countries and exported to a CSV file.

The limitations of this approach for heatwaves are that additional climate variables could be added, which influence heatwaves, such as humidity, soil moisture and wind speed if the data allows for it. Adding these features would help the model better capture the conditions leading to heatwaves, thereby enhancing prediction accuracy. Furthermore, combining this model with physical climate models could provide insights that are also physically interpretable in the future.

4. LITERATURE ANALYSIS • Findings

Georgia faces a complex array of water-related hazards due to its unique geographical position, diverse topography, and changing climate. The country's location at the juncture of Eastern Europe and Western Asia, coupled with its varied landscape ranging from the Greater and Lesser Caucasus mountains to the Black Sea coast, creates a mosaic of microclimates and hydrological conditions (WBG & ADB, 2021). This diversity, while contributing to Georgia's rich natural resources, also makes the country particularly vulnerable to a wide spectrum of water-related risks.

According to the most recent AQUEDUCT water stress data, Georgia currently faces low-medium water stress, with a baseline water stress index of 0.93 on a scale from 0 (low stress) to 5 (extremely high stress). However, projections indicate an aggravation of water stress in the future, with the index expected to rise to 1.18 by 2030, 1.20 by 2050, and 1.31 by 2080 (WRI, 2024). This gradual increase in water stress underscores the growing challenges the country faces in managing its water resources.

Climate change is exacerbating these vulnerabilities, with projections indicating significant alterations in temperature and precipitation patterns across the country (WBG & ADB, 2021). The primary water-related hazards facing Georgia include more frequent and intense droughts (particularly in Eastern Georgia), floods, landslides, glacial melts, reduced snowpack, and coastal erosion. These hazards are often accompanied by an increase in the number of hot days, a decrease in frost days, and more intense flash floods (WBG & ADB, 2021).

The frequency and intensity of extreme weather events are expected to increase, with some regions experiencing more severe droughts while others face heightened flood risks (Elizbarashvili et al., 2017). For instance, the 2021 Tbilisi flood serves as a stark example of the potential devastation caused by extreme weather events. Similarly, mountain flooding in regions like Svaneti and Adjara may lead to dangerous landslides.

These hazards pose immediate threats to human safety and infrastructure and have long-term implications for key economic sectors.

Water quality degradation is another significant concern, with pollution and algae blooms affecting water bodies such as the Tbilisi Reservoir, the Black Sea coast, and Lake Paravani. Changes in rainfall patterns could also impact sensitive ecosystems, including the wetlands in the Kolkheti Lowlands, which are vulnerable to altered hydrology and increased salinity.

The risks associated with these hazards are multifaceted, including impacts on infrastructure, disruption of hydropower and energy supply, water scarcity affecting drinking water supplies, agricultural land loss, river ecosystem degradation, and potential glacial lake outburst floods. Additional risks include the spread of disease-carrying insects, forest ecosystem stress, fish population decline, and increased insurance costs.

Understanding and addressing these water-related hazards is crucial for Georgia's sustainable development and climate resilience. The interplay between the country's unique topography, diverse climate zones, and changing hydrological conditions necessitates a comprehensive and nuanced approach to risk assessment and management. As we describe specific hazards and their impacts in the following sections, it becomes clear that Georgia's water-related challenges are multifaceted, requiring integrated strategies that consider both the physical environment and socio-economic factors. The first two hazards described below (droughts and floods) were chosen as they are relevant for all country packages analysed during our assignment (Georgia, Mongolia and Kazakhstan). The last two describe hazards specific for Georgia (coastal hazards and impacts on key sectors).

4.1. Droughts

Historically, Georgia has experienced varying levels of drought, significantly impacting its economy and environment. The country currently faces an annual median probability of severe meteorological drought of around 4%, as defined by the Standardized Precipitation Evaporation Index (SPEI) of less than −2 (WBG & ADB, 2021). The eastern regions, particularly arid and semi-arid areas, have been more susceptible to drought conditions. Past droughts have led to substantial economic repercussions, especially in agriculture, where damaged crops and vineyards have been reported. Additionally, irrigation canals have suffered damage, further straining water resources. The energy sector has also been affected, with hydropower plants experiencing reduced capacity during drought periods (WBG & ADB, 2021).

Projections for future drought conditions in Georgia are concerning. Research indicates that the duration and magnitude of droughts are expected to increase significantly by the end of the century (Naumann et al., 2018). Specifically, eastern Georgia is projected to experience a decrease in summer precipitation and reduced water availability in river basins such as the Kura River. This trend is likely to exacerbate desertification in these regions (WBG & ADB, 2021). By 2100, river flows in glacier-fed basins like Khrami-Debed and Alazani are projected to decrease by 30-55%, posing a significant threat to water supplies critical for both agriculture and energy production (WBG & ADB, 2021).

4.2. Floods and heavy precipitation events

Floods and heavy precipitation events have been significant hazards in Georgia's recent history. The country is highly exposed to hydrometeorological hazards, with floods, flash-flooding, and mudflows occurring regularly, particularly in mountainous regions and along major rivers (WBG & ADB, 2021). Between 1995 and 2012, Georgia recorded many flooding and flash flooding events, resulting in 38 fatalities (WBG & ADB, 2021). The frequency of these events has increased in recent years, with the average number of floods per year rising from 3-5 before 1995 to between 2-20 since then (WBG & ADB, 2021). Notable flood events have occurred in 1995, 1997, 2004, 2005, 2011, 2012, and 2013. A particularly severe flood in Tbilisi in 2015 caused 19 fatalities and resulted in combined physical damage and financial losses of $29 million (USAID, 2017). The rivers most at risk of flooding are those in Imereti, Samegrelo, Guria, and Mtskheta-Mtianeti, as well as the rivers of the Mtkvari basin, including Alazani (WBG & ADB, 2021).

Projections indicate that climate change is likely to exacerbate flood risks in Georgia. While there is considerable uncertainty surrounding local long-term future precipitation trends, some global patterns are evident. The intensity of sub-daily extreme rainfall events appears to be increasing with temperature, a finding supported by evidence from different regions of Asia and some observations within Georgia (WBG & ADB, 2021). Projections suggest that western and northern areas of the country, especially regions along the Black Sea, are likely to experience a slight increase in days with rainfall greater than 20 mm (WBG & ADB, 2021). The rapid retreat of glaciers is expected to shift the regional hydrological regime, potentially increasing the risk of flooding, particularly in regions like Svaneti, Kazbegi, and Racha (WBG & ADB, 2021). Climate change and socio-economic development are both expected to increase the population affected by riverine flooding and the associated economic damages. Currently, an estimated 15,000 people are affected annually by riverine flooding in Georgia, with expected annual damages of $73 million. These figures are projected to rise in the future (WBG & ADB, 2021). Additionally, increased flooding is likely to impact sediment loads in rivers, affecting dam management and potentially exacerbating flood risks. Urban areas such as Tbilisi, Kutaisi, and Batumi are expected to face higher flood risks due to the combination of increased heavy rainfall events and urbanization pressures (WBG & ADB, 2021).

4.3. Heatwaves

Georgia has experienced an increase in the frequency and intensity of heatwaves over the past few decades, with significant impacts on human health, agriculture, and energy consumption. Between 1961 and 2010, there was a notable rise in the number, duration, and severity of heatwave events across the country, particularly in the southwestern and southeastern regions (Keggenhoff et al., 2015). These heatwaves have led to increased mortality rates, especially among vulnerable populations such as the elderly and those with pre-existing health conditions (Ministry of Environmental Protection and Agriculture of Georgia, 2021). The capital city, Tbilisi, has been particularly affected due to the urban heat island effect, exacerbating the impacts of heatwaves on its residents (WBG & ADB, 2021). Additionally, heatwaves have contributed to reduced agricultural productivity and increased energy demand for cooling, straining the country's resources and economy (WBG & ADB, 2021).

Climate projections indicate that Georgia will face more frequent, intense, and prolonged heatwaves in the future due to climate change. By the end of the 21st century, under high emission scenarios, the average temperature in Georgia is expected to increase by up to 4.9°C above the 1986-2005 baseline (WBG & ADB, 2021). This warming trend is likely to result in a significant increase in the frequency of heatwaves, particularly under higher emissions pathways (Ministry of Environmental Protection and Agriculture of Georgia, 2021). These changes pose substantial risks to human health, biodiversity, and economic sectors such as agriculture and energy, necessitating the development and implementation of comprehensive adaptation strategies.

4.4. Coastal hazards

Georgia's coastal regions have been experiencing significant impacts from sea-level rise and storm surges in recent decades. The Black Sea coast of Georgia has seen a sea level rise of 0.7 m between 1956 and 2007, accompanied by a more than 50% increase in the frequency of storms over the same period (WBG & ADB, 2021). This rise in sea level and storm frequency has led to increased coastal erosion and loss of coastline, posing a significant threat to coastal communities and infrastructure. The port cities of Batumi and Poti have been particularly affected, with Poti experiencing flooding caused by sea storms in recent years (WBG & ADB, 2021). These changes are largely attributed to pressure anomalies in atmospheric circulations, notably the North Atlantic Oscillation (WBG & ADB, 2021). The impacts extend beyond physical damage to infrastructure; there have been reports of mass destruction of molluscs and other coastal species due to increased sea surface temperatures, significantly affecting diving attractions and tourist satisfaction in the Adjara coastal zone (WBG & ADB, 2021).

Projections for coastal hazards in Georgia paint a concerning picture for the future. Research by the UK Met Office (2014) suggests that without adaptation measures, between 29,000 and 33,000 people per year could experience flooding due to sea-level rise in Georgia by 2070-2100, under both low (RCP2.6) and high (RCP8.5) emissions scenarios (WBG & ADB, 2021). However, with proper adaptation strategies, it is estimated that almost none of these people would be exposed to flooding (WBG & ADB, 2021). The frequency of severe storms along the coastal zones is expected to increase, likely leading to further beach erosion and flooding of banks along the seashore (WBG & ADB, 2021). Additionally, there is an increased risk of flash floods and mudflows in the coastal zone, particularly during summer, which poses a significant threat to tourism sites located in mountain zones or along riverbanks (WBG & ADB, 2021; WBG, 2024).

5. DATA ANALYSIS • Findings

5.1. Meteorological droughts

The mean probability for the historical baseline for the probability of occurrence of low-hazard drought events in Georgia was at 16% per annum and at 4% and 2% for medium-hazard drought events and high-hazard drought events respectively. At the beginning of the projected period in 2024 the probability of occurrence was at approximately 15% for low hazard events (2% and <1%).

Under the SSP 1-2.6 scenario, the likelihood for droughts remains relatively stable with slight variations across the century, finishing at similar levels as at the beginning of the projected period at 15%, 3% and 2%. As the development of droughts in this scenario shows almost no change, the variation towards the end of the century could fall within the margin of error and be smaller than anticipated.

Under the SSP 2-4.5 scenario, the projections for drought in Georgia show similar results, with a slight increase of probability of all drought events occurring throughout the century. The probability of occurrence for low-hazard events finishes at around 20%, for medium-hazard events at around 6% and at around 2% for high-hazard events.

Under the SSP 5-8.5 scenario, the increase in drought events is much more dramatic for all hazard classifications, increasing to around 37% for low-hazard events and to 13% and 11% respectively. Although Georgia is not as prone to droughts as its neighbouring countries, this scenario will deteriorate water availability significantly.

Figure 1: Probability of occurrence of meteorological droughts for low hazard events

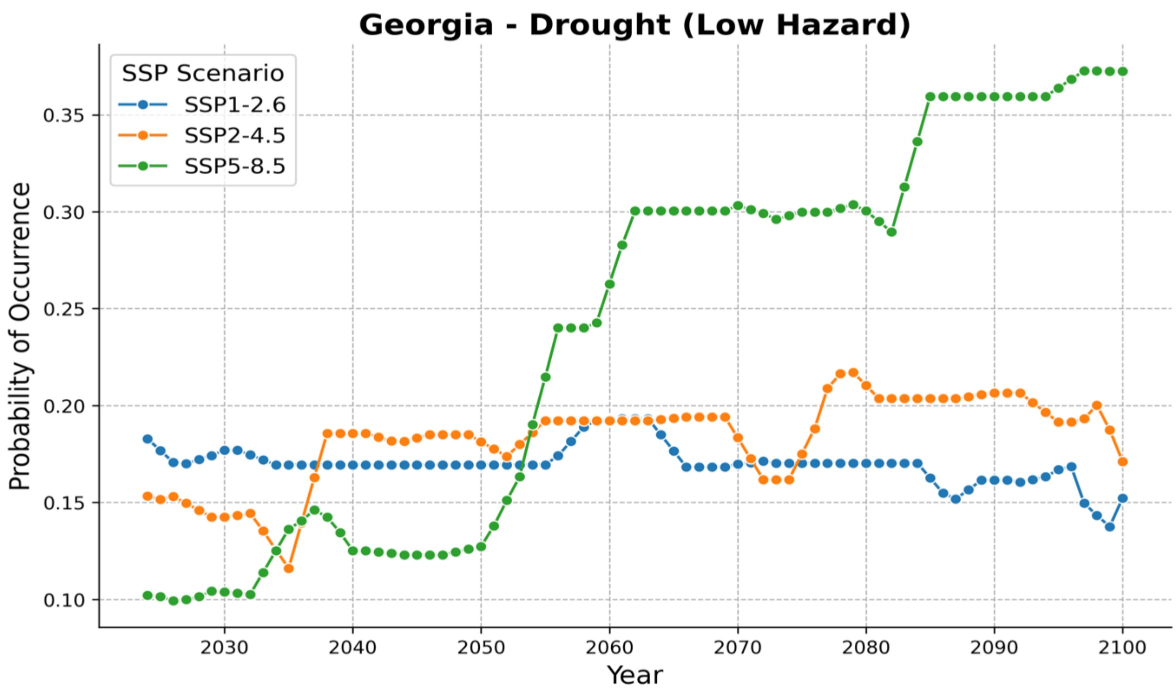


Figure 2: Probability of occurrence of meteorological droughts for medium hazard events

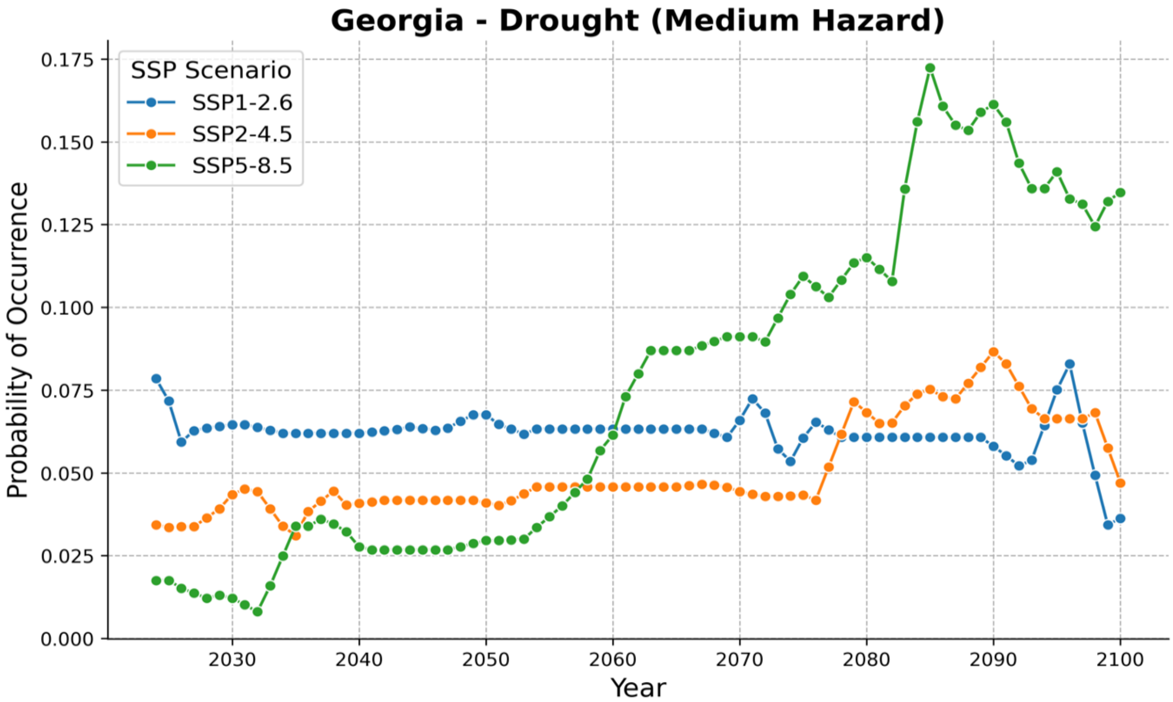
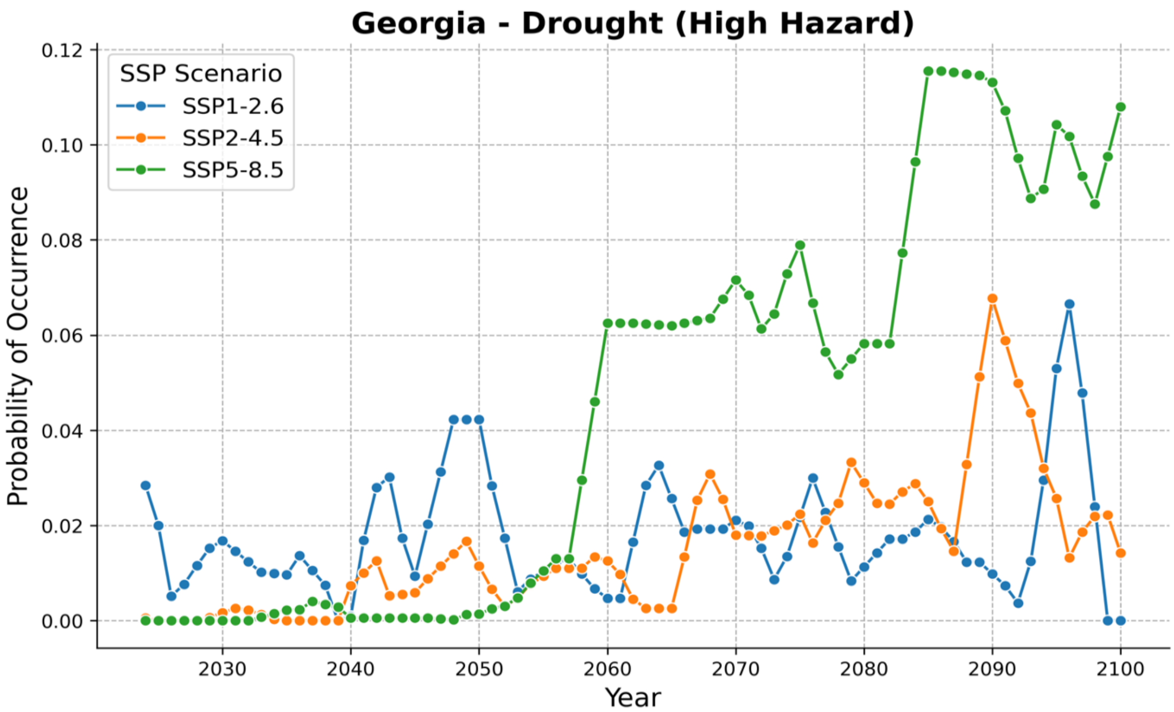


Figure 3: Probability of occurrence of meteorological droughts for high hazard events



5.2. Riverine floods

The mean probability of occurrence during the baseline period for low-hazard floods is 21% in Georgia and 12% for medium-hazard floods and approximately 3% for high-hazard floods. These numbers change to around 20%-25%% by 2024 and to 8% and less than 1%by 2024, with variations depending on the scenario.

Under the SSP 1-2.6 scenario, the risk for floods in Georgia in all three hazard classifications will remain relatively stable with annual variations and end with a probability of occurrence of around 35%, 15% and less than 1% at the end of the century, displaying a similar likelihood as at the beginning of the projected period, which could imply that policies under this scenario work.

Under the SSP 2-4.5 scenario, the development is also comparably stable and doesn't increase dramatically, albeit at a higher level, finishing the century at around 40% likelihood for low-hazard events, at around 17% for medium-hazard events and at around 3% for high-hazard events. When comparing this to floods in the past, this would imply that floods that used to occur every four years (low-hazard) would occur every 2.5 years by 2100.

Under the SSP 5-8.5 scenario, the risk starts similarly as in the other two scenarios and remains stable for a while but increases significantly as the century progresses. In the last phase of the projected timeframe, the probability of occurrence of low-hazard events is projected to be between 55% and 65% and medium-hazard events to be at around 31% and of high-hazard events to be at around 6%. Although high-hazard floods remain a rare phenomenon Georgia, medium-hazard flood events are expected to become much more likely, occurring every 3 years instead of every 10 years.

Figure 4: Probability of occurrence of riverine floods for low hazard events

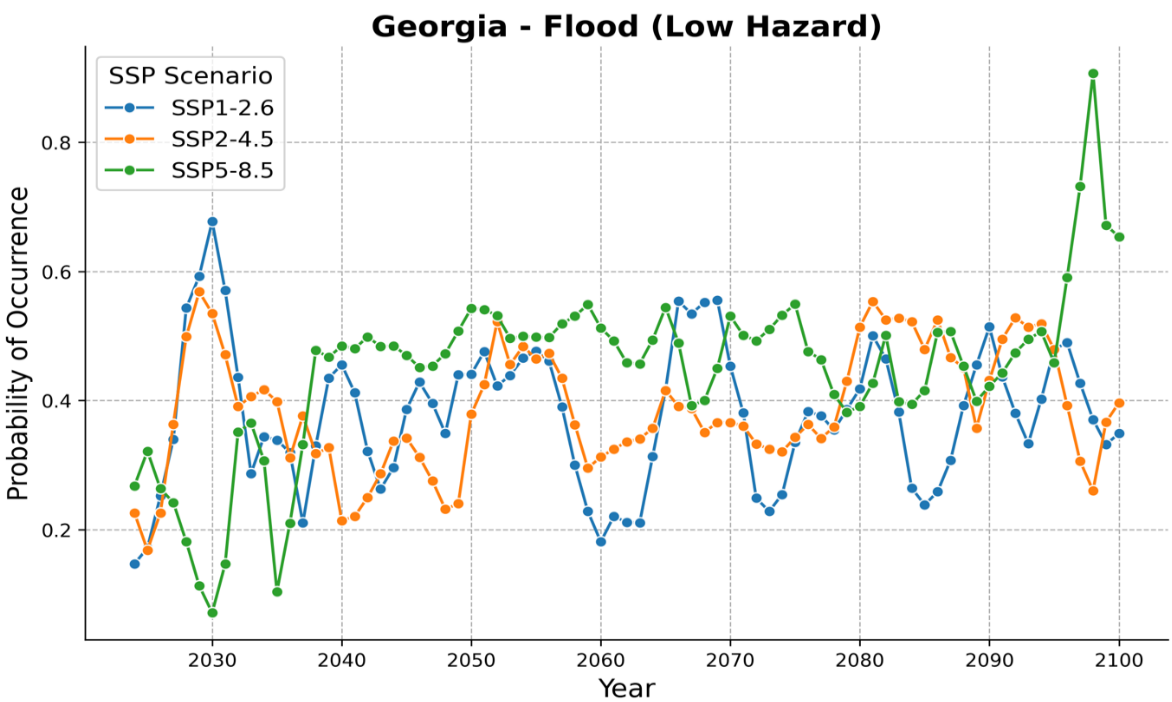


Figure 5: Probability of occurrence of riverine floods for medium hazard events

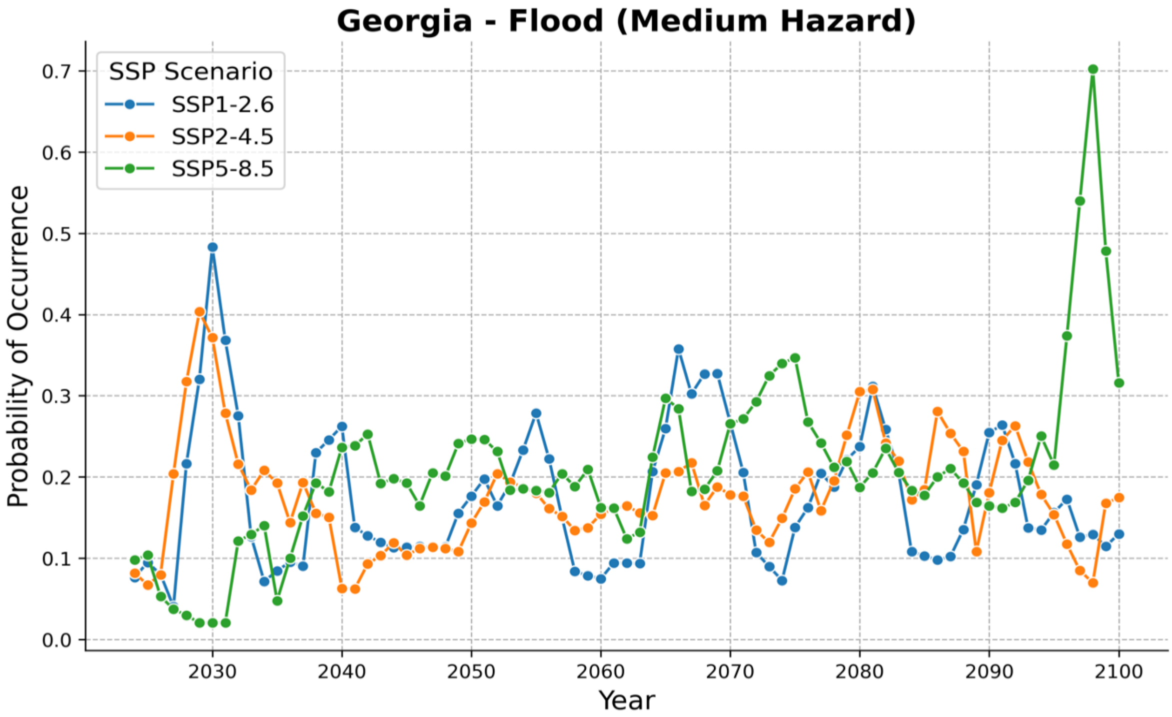
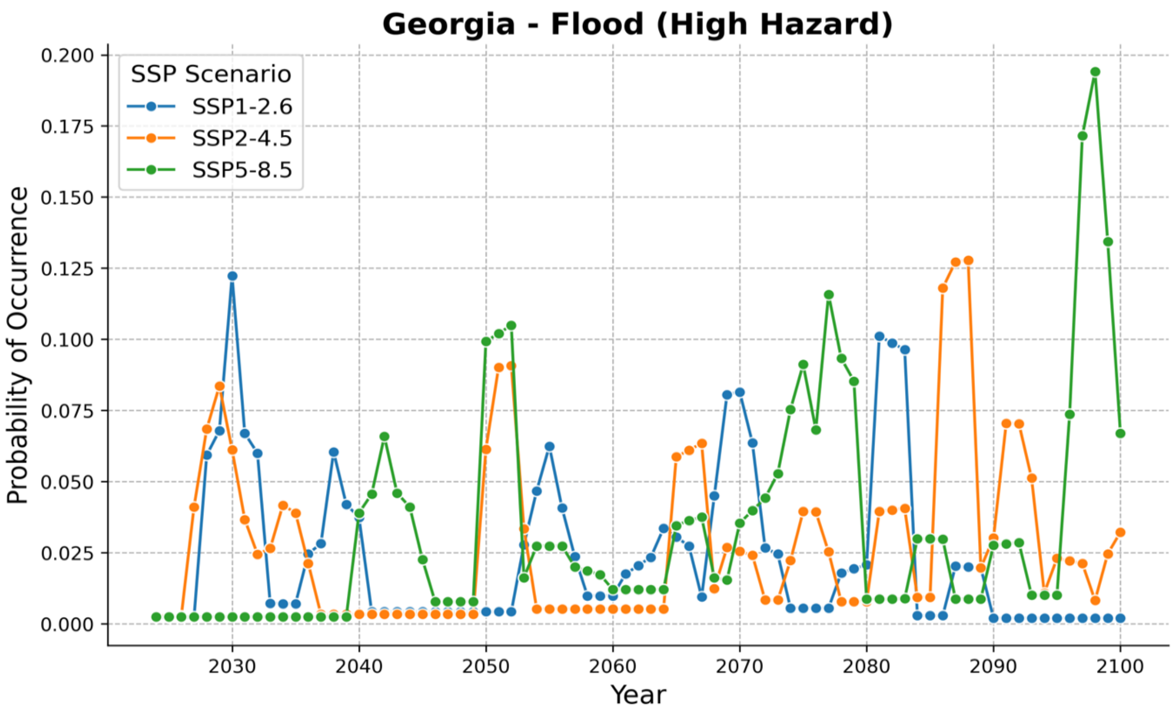


Figure 6: Probability of occurrence of riverine floods for low hazard events



5.3. Heatwaves

The threshold heatwave temperature for Georgia was defined individually for each grid point. The historical baseline showed a mean probability of occurrence of 13% for heatwaves above this threshold lasting longer than five days (low hazard), and around 4% and around 1% for heatwaves for longer than 7 days and 10 days respectively (medium and high hazard).

Under the SSP 1-2.6 scenario, the probability of occurrence for low hazard starts at 32% (11 % and 3% respectively) in 2024, showing a high increase in likelihood in comparison with the baseline period already and thus a high perceptibility for heatwaves in the country. The probability of occurrence of low hazard events under this scenario reaches a maximum mid-century and subsequently drops again to around 50%, while medium-hazard and high-hazard events are more stable and finish the projection at 16% and 5% respectively.

Under the SSP 2-4.5 scenario, the probability of heatwaves increases for all hazard classifications steadily over the century but starts decreasing again at the end of the century, finishing at 60% probability of occurrence for low-hazard events and at 28% and 13% for medium- and high-hazard events.

Under the SSP5-8.5 scenario, heatwaves in all hazard classifications increase dramatically throughout the century and become almost certain by the end of the projected period. Low-hazard events and medium-hazard events are projected to be at almost 100% likelihood of occurring and high-hazard events finish the projected period with a likelihood of occurring of 96%, which shows that this SSP scenario will certainly lead to regular and very intense heatwaves. Table 1 – Table 3 show all relevant SSP scenarios in the projected period for low-hazard events, medium-hazard events and high-hazard events.

Figure 7: Probability of occurrence of heatwaves for low hazard events

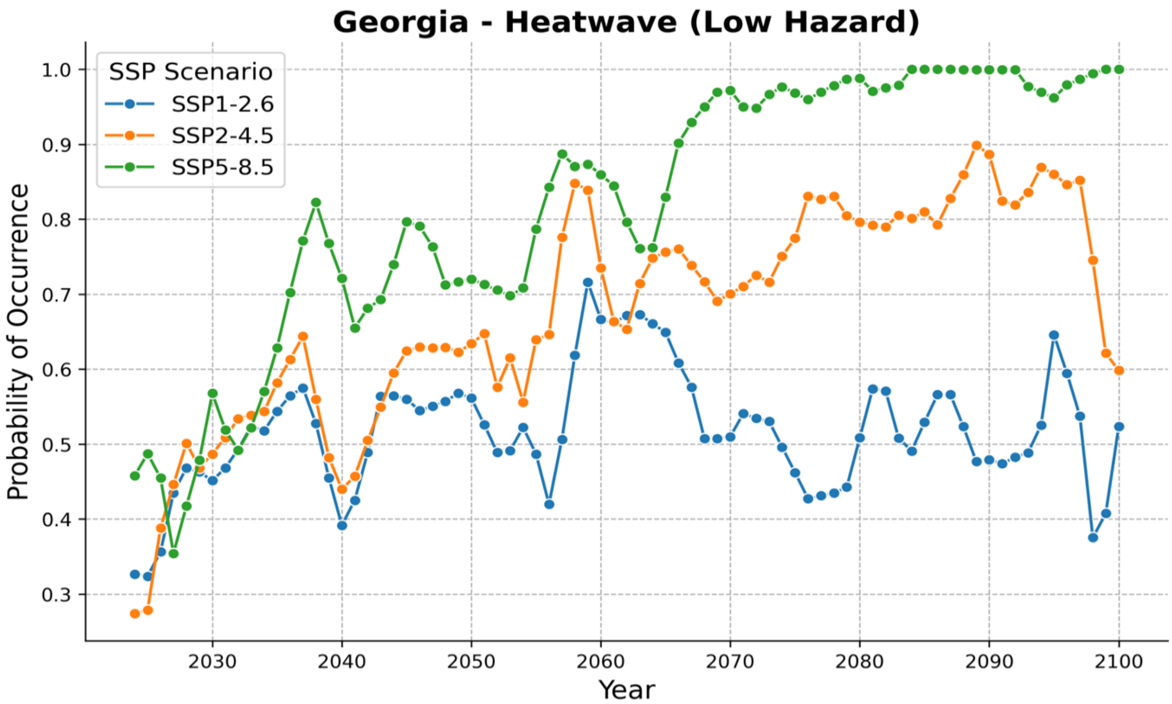


Figure 8: Probability of occurrence of heatwaves for medium hazard events

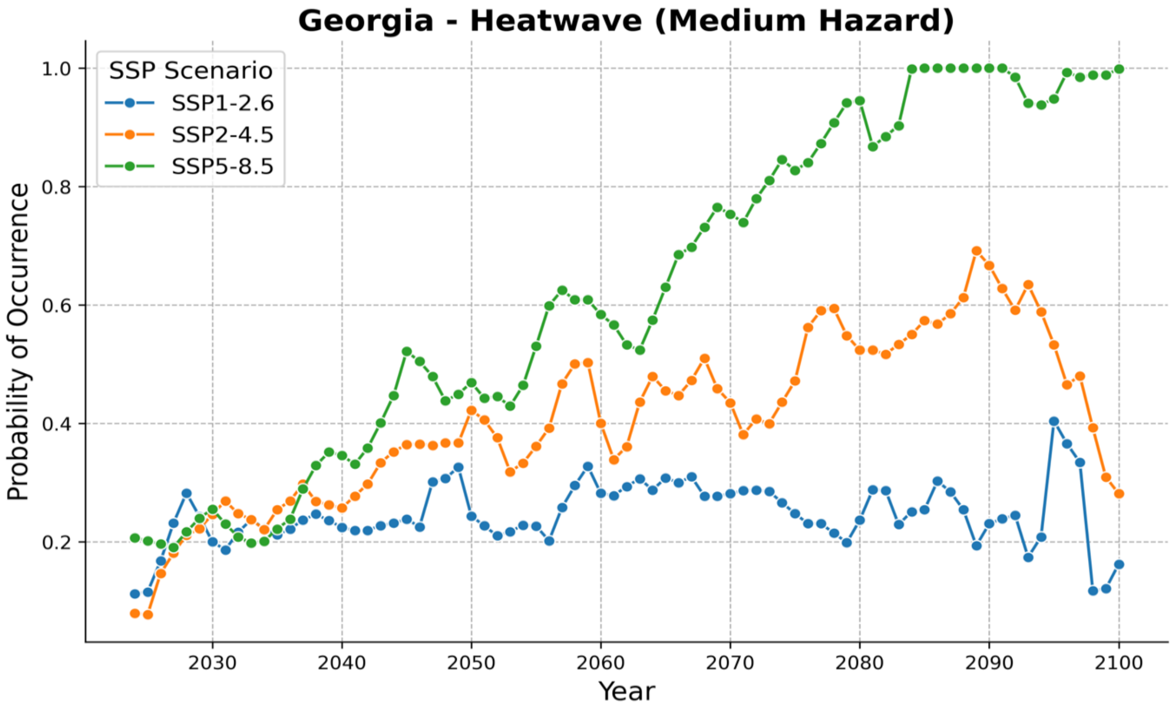
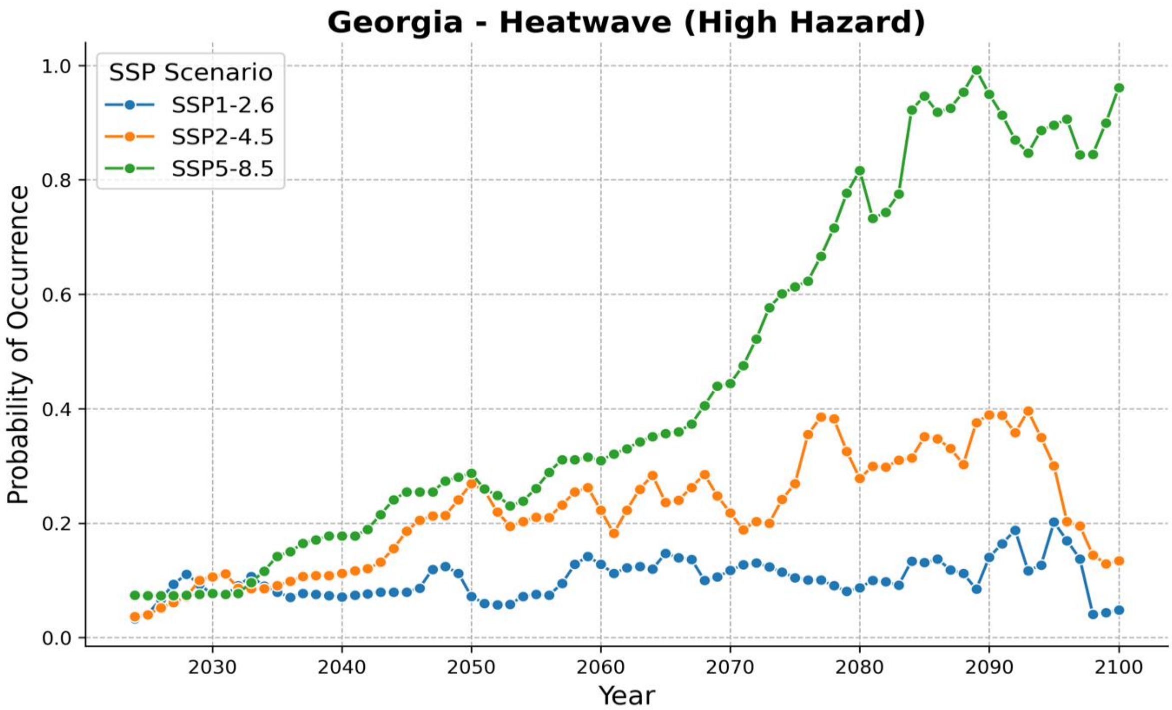


Figure 9: Probability of occurrence of heatwaves for high hazard events



5.4. Evaluation

The projection for water hazards under climate change for Georgia indicate increasing probabilities of heatwaves, droughts, and riverine floods, particularly under high-emission scenarios. These escalating risks underscore the need for effective climate policies and adaptive measures to manage and mitigate potentially severe socio-environmental impacts.

Heatwave frequency and intensity in Georgia are projected to rise significantly under all scenarios. By mid-century under SSP 1-2.6, low-hazard heatwaves will likely reach a 50% probability, stabilizing as global mitigation efforts limit emissions. In SSP 2-4.5, low-hazard heatwave events could peak at a 60% annual likelihood, with medium- and high-hazard probabilities also rising. However, the SSP 5-8.5 scenario predicts near-certainty for both low and medium-hazard events, and up to 96% likelihood for high-hazard events by 2100.

The implications are considerable for public health, agriculture, and energy demand in Georgia. Extended and intense heatwaves could increase heat-related illnesses and mortality, stress water resources for agriculture, and heighten the risk of wildfires, particularly in rural areas. This scenario would necessitate extensive adaptation in cooling infrastructure and public health responses, leading the country to a constant state of responsiveness and emergency and making normal policymaking increasingly difficult.

Drought projections show relative stability under SSP 1-2.6, with only minimal increases across the century, suggesting that aggressive climate action could mitigate drought risks. However, in SSP 5-8.5, Georgia would experience notable increases in drought probability, with low-hazard events reaching a 37% likelihood and high-hazard droughts projected to rise to 11%. Although Georgia has historically been less susceptible to drought than neighboring regions, prolonged dry periods under high-emission scenarios could threaten water availability, agricultural productivity, and food security. This would challenge Georgia's agricultural sector, necessitating improved irrigation practices, water conservation strategies, and shifts toward drought-resilient crop varieties to maintain stability in food production and rural livelihoods.

Flood risks in Georgia vary by scenario, but all projections indicate an elevated frequency compared to historical baselines. In SSP 1-2.6, probabilities for low- and medium-hazard floods stabilize around current levels, suggesting that effective climate policy can prevent a significant rise in flood frequency.

In contrast, SSP 2-4.5 and SSP 5-8.5 scenarios imply a pronounced increase, with low-hazard events potentially occurring every 2.5 years by century's end and medium-hazard floods rising from historically once every decade to every three years. Under SSP 5-8.5, flood probability reaches between 55% and 65% for low-hazard floods and 35% for medium-hazard floods by 2100. These increased flood risks carry severe implications for infrastructure resilience, public safety, and economic stability in Georgia, especially in densely populated and flood-prone regions. Regular flooding could damage critical infrastructure, disrupt transport and energy supplies, and lead to economic losses, necessitating investment in resilient infrastructure and flood management systems.

These climate projections underscore the necessity for both strong global mitigation and adaptive action within Georgia. SSP 1-2.6 projections reveal that emission reductions can stabilize or even reduce some hazards over time. However, the high-emission SSP 5-8.5 scenario suggests an unavoidable rise in severe hazards, requiring Georgia to adopt comprehensive adaptation strategies to minimize socio-economic impacts.

Priorities should include enhancing public health capacity to manage heatwaves, developing water management infrastructure to address drought, and investing in flood-resilient infrastructure. Furthermore, rural communities and agricultural sectors will need support to adapt to changing water availability, which could involve transitioning to drought-resilient crops and adopting water conservation practices.

In summary, Georgia's climate outlook highlights the critical need for a multi-faceted approach: sustained global mitigation to avoid high-emission scenarios and localized adaptation measures to bolster resilience against intensifying water-related hazards.

6. ECONOMIC DAMAGES

Georgia's economy faces significant challenges due to water-related climate impacts (IMF, 2024), with various sectors experiencing diverse effects. The country's heavy reliance on hydropower for electricity generation (over 80%) makes it particularly vulnerable to changes in water availability and river flow patterns (IEA, 2020). While glacial melt is currently increasing river discharge, benefiting hydropower generation, long-term projections indicate a potential 30-50% decrease in the future (Aryal, 2023), which could lead to energy shortages, particularly during summer months (WBG & ADB, 2021). Hence, hydropower output could be reduced by up to 20% by 2100 (WBG & ADB, 2021).

Agriculture, a key sector of Georgia's economy, faces multiple challenges including water scarcity, changing precipitation patterns, and potential impacts on crop yields. The eastern regions, like Kakheti, which heavily depend on irrigation, are highly vulnerable to droughts and water shortages, potentially impacting crop yields and food security (WBG & ADB, 2021). The 2000 and 2014 droughts caused significant damage to crops, with economic losses estimated at $200 million and $300 million respectively (USAID, 2017). The wine industry, crucial to Georgia's economy and heritage, may face challenges due to changing climatic conditions in traditional grape-growing regions (USAID, 2017).

Research has shown that mudflows and landslides have the greatest economic impact in Georgia, followed by floods and droughts, with severe damages recorded between 1995-2020 (WBG & ADB, 2021). A particularly severe flood in Tbilisi in 2015 caused 19 fatalities and resulted in combined physical damage and financial losses of $29 million (USAID, 2017). Floods have had significant economic impacts across various sectors, damaging crops, agricultural lands, roads, buildings, and energy infrastructure (WBG & ADB, 2021).

Climate change and socio-economic development are expected to increase the population affected by riverine flooding and the associated economic damages. Currently, an estimated 15,000 people are affected annually by riverine flooding in Georgia, with expected annual damages of $73 million (WBG & ADB, 2021). These figures are projected to rise in the future (WBG & ADB, 2021). Notably, extreme flood and drought events (1-in-100-year events) have a disproportionately greater impact compared to increases in average likelihood, emphasizing the importance of analysing and preparing for such extreme events (WBG & ADB, 2021).

The tourism sector, vital to Georgia's economy, may also be affected by climate change (WBG, 2024). Mountain tourism could suffer from reduced snowfall and glacial retreat in popular regions like Svaneti and Kazbegi, while coastal tourism may be impacted by rising sea levels and increased coastal erosion (WBG & ADB, 2021).

These impacts underscore the need for comprehensive adaptation strategies across all sectors to ensure Georgia's resilience to climate change impacts and to mitigate potential economic losses.

7. ADAPTATION MEASURES

The following chapter will provide two in-depth suggestions for adaptation measures based on the findings of the data of this report. These suggestions should be regarded as additional findings to existing or planned adaptation measures and do not represent a full analysis of the status quo. Both measures are preliminary approaches and should be further investigated with the help of economic modelling and cost-benefit analyses. The measures identified were chosen based on a number of reasons:

- Relevance to identified hazards: The measures directly address the primary climate hazards identified in the data analysis. They therefore respond to ongoing challenges, helping to mitigate the immediate impacts on the agriculture and hydropower sectors.
- Alignment with sectoral and regional needs: The measures kept small-scale and medium-scale farmers in mind as well as regional acuteness for the identified hazards.
- Feasibility: Measures were selected based on their feasibility of implementation and on success in similar sectors.
- Co-Benefits: Suggestions aim to provide multiple benefits beyond addressing the primary climate hazard.
- Integration with existing efforts: Measures were chosen for their complementarity with ongoing projects and efforts.

Following that, this chapter provides a list of additional adaptation suggestions that could be explored in the future.

7.1. Solar powered drip irrigation

Sector: Agriculture, small-scale farmers

Hazard: Droughts

Region: Eastern Georgia (prolonged droughts): Kakheti region, Kvemo Kartli region

Background: Overall, Georgia has sufficient surface water and groundwater supply, but is prone to seasonal fluctuations, in particular in Eastern Georgia (World Bank, 2024). However, the lack of sufficient water storage reservoirs and an increasing lack of snowmelt reservoirs due to progressing climate change can lead to shortages in the future (World Science 2018). The „Irrigation Strategy for Georgia 2017-2025"developed by the Ministry for Agriculture named the necessity for an expansion of irrigable land to 200,000 hectares by land as well as the strategy to increase crop production and introduce modernization to Georgian agriculture. The Ministry expects the country to remain an agriculturally focused society in which many members of rural communities work in the field. Conditions for rural communities must be improved in order to a) raise overall agricultural production, also amongst small-scale farmers and b) combat rural poverty (Ministry of Agriculture of Georgia, 2017).

Current Efforts: The government has focused investments of around $361 Million on irrigation rehabilitation projects, 100 individual farm projects and modernization schemes of drip irrigation (Ministry of Agriculture of Georgia, 2017). The Agricultural Strategy further prioritizes drainage and irrigation as pivotal for future Georgian agricultural production, in particular with a focus on high-quality, high-yield crops and crops produced for exports (Ministry of Agriculture of Georgia, 2017).

Suggestion: Introduction of solar-powered drip irrigation schemes for small-scale and medium-scale farmers.

Suggested Measures:

- Funding of initial costs for solar panels to overcome hesitation to invest in new technology through grants or loans by the government.
- Focus on farms with either high-quality crops or drip irrigation already in place as seen on Georgian vineyards and orchards.
- Additional measure to rehabilitation for farms not directly linked to previously irrigated land in Soviet times.
- Capacity building for installation and maintenance of solar panels
- Research on further grants for batteries for community-use of solar panels to provide electricity for drip irrigation system and additional needs in the rural community.

Expected Benefits:

- Precise water delivery and reduction of water use.
- Immediate adaptation response to droughts to maintain crop productivity.
- Energy independence through off-grid solutions with secondary benefits for rural communities.
- Expansion of growing season, in particular when the reservoirs of snow melts become less available with advancing climate change.
- Customisable for small-scale farmers and low maintenance.

7.2. Real-time flood monitoring and early warning systems

Sector: Energy, Hydropower

Hazard: Flood

Region: Western Georgia

Background: Hydrological, meteorological and flood observations deteriorated greatly after the collapse of the Soviet Union and funding as well as official backing remains challenging. The existing observation network is comprised of meteorological, agrometeorological, hydrological and snow monitoring stations but lacks upper-air monitoring stations, which would improve forecasts (WMO, 2015). Additionally, Georgia's current flood monitoring capabilities are not comparable to advanced standards, relying primarily on basic flood warnings and water-level gauges instead of radar-based systems and satellite remote sensing (Song 2024).

Current Efforts: The government has invested in several steps after the Tblisi flood in 2015 to be better prepared for floods, such as a network of hydrological monitoring stations along major rivers, the Flood Prevention and Early Warning System for the Rioni River Basin, which is funded by the UNDP and the Green Climate Fund and aims to move away from a reactive approach to flood warning toward a proactive warning system for all climate hazards (UNDP 2024), and collaborations with international partners like the EU, focusing on improving disaster preparedness.

Suggestion: Introduction of real-time flood monitoring and early warning systems to accelerate the proactive response to floods.

Suggested Measures:

- Expansion of the use of real-time sensor networks along critical rivers and installation of automated water-level sensors.

- Leveraging the Sentinel-1 satellite radar to track flood conditions, in particular in the Rioni basin.
- Development of a centralized early warning systems that integrates weather, hydrological, and remote sensing data.

Expected Benefits

- Leverage of response time: Communities would gain additional time to prepare, or in the worst case, evacuate their respective areas, particularly for regions with rapid-onset floods.
- Better resource allocation in emergencies.
- Increased agricultural protection: Farmers would receive accurate predictions to protect cattle and crops.
- Real-time flood monitoring provides accurate, up-to-date on river flows allowing operators of hydropower stations to optimize turbine usage.

7.3. Additional suggested adaptation measures

► Soil moisture management and conservation agriculture: Although the majority of the Georgian GDP comes from other sources, agriculture nevertheless plays an important role in Georgia society with a large number of people being employed in the sector. The introduction of conservation agriculture including mulching and ground cover, conservation tillage and contour farming could help improve soils, which makes floods less likely and helps combat desertification in affected areas. It would also help Georgia become more resilient to erratic precipitation patterns (Bernucci et al, 2022).

► The development of early warning systems with climate data specifically for famers. Georgia is currently investing money in early-flood detection, but could widen this to agricultural purposes for all hazards. Options include mobile-based alarm systems for farmers, hydrological modelling for hydropower plants and climate monitoring networks.

► Introduction of drought-resistant crop varieties

8. CONCLUSION

Georgia's unique geographical position and diverse topography makes it particularly vulnerable to the impacts of climate change. As extreme weather events like heatwaves, droughts, and floods intensify, Georgia's environmental, economic, and social landscapes face growing risks that necessitate effective adaptation measures. This project by GIZ aims to identify cost-effective strategies to address these hazards, focusing on the analysis of hazard patterns and calculating the probability of their occurrence up to 2100 using climate models and data.

Rising temperatures and shifting rainfall patterns are reshaping Georgia's climate. Projections indicate that Georgia could experience a 1.5-2°C temperature increase by the end of the century, with warming especially pronounced in eastern regions. This warming trend, coupled with irregular precipitation, exacerbates the potential for both drought and flooding, challenging Georgia's water resources and agricultural productivity. The mountainous terrain and river basins further compound these risks, with extreme precipitation events leading to flash floods, mudslides, and riverine floods that pose significant threats to both rural and urban communities.

Based on these trends, the project identified droughts, riverine floods and heatwaves as imminent threats to Georgia. Following, data was retrieved from the global climate model like MRI-ESM2-0, downloaded from Copernicus. We included specific criteria for spatial resolution, temporal coverage and annual projections. The selected climate model, MRI-ESM2-0, was chosen for its ability to accurately represent regional climates and its high spatial resolution. Data manipulation was carried out using Python. The study's approach ensures replicable, open-source methodologies while addressing data constraints and providing valuable projections for water hazards under different climate scenarios (SSP 1-2.6, 2-4.5, and 5-8.5).

The integration of the data into an economic model required the calculation of an annual probability of occurrence. In climate modelling, annual predictions are not common and should be treated as a trend, not as absolute numbers.

Furthermore, due to time constraints, spatial resolution and hydrological aspects were lacking. For further research we suggest the inclusion of a higher spatial resolution and the integration of a hydrological model into the calculation of riverine flooding.

Heatwaves are becoming increasingly likely across all climate scenarios. By mid-century, even under moderate emission reductions (SSP 1-2.6), low-hazard heatwaves could have a 50% annual probability, stabilizing only with sustained global mitigation efforts. In a high-emission scenario (SSP 5-8.5), however, high-hazard heatwave events could reach a 96% likelihood by century's end, bringing severe consequences for public health, agriculture, and energy demands. Such frequent and intense heatwaves could lead to widespread heat-related illnesses and mortality, strain Georgia's water supplies for both agricultural and domestic use, and increase wildfire risks, especially in rural areas. Preparing for this requires considerable investment in health infrastructure and urban cooling systems, as well as readiness for extended emergency response periods to safeguard vulnerable communities.

Droughts present a similarly troubling outlook, particularly under high-emission pathways. While projections show relative stability under SSP 1-2.6, a higher-emission trajectory like SSP 5-8.5 would significantly increase the likelihood of both low- and high-intensity drought events. Although historically less drought-prone than neighbouring regions, Georgia could face increasingly prolonged dry periods that reduce water availability and stress agricultural productivity. Eastern regions, reliant on the Kura River and surrounding basins, are particularly at risk of reduced water flow, posing threats to both rural livelihoods and food security. To address these challenges, Georgia will need to expand irrigation efficiency through measures like solar-powered drip irrigation, promote water conservation, and consider shifts to drought-resistant crop varieties.

Flood risks in Georgia, already significant due to the country's mountainous topography, are expected to worsen under climate change. The country is highly susceptible to hydrometeorological hazards, with frequent floods and mudflows, especially along major rivers and in mountainous areas. In scenarios with minimal mitigation, flood probabilities remain close to current levels, but with increasing emissions, both low- and medium-hazard floods could occur more frequently. Under SSP 5-8.5, the probability for low-hazard flood events could reach up to 55% annually by century's end. This trend has serious implications for infrastructure resilience, especially in flood-prone regions and densely populated areas. Floods disrupt transport, damage energy infrastructure, and impact public safety, making investment in resilient infrastructure, real-time flood monitoring systems, and community preparedness essential.

Given these projections, Georgia's path forward requires both global and local climate action. Emission reductions aligned with SSP 1-2.6 offer the possibility of stabilizing or reducing some climate risks by 2100. However, in the absence of substantial global mitigation, Georgia will face a growing likelihood of extreme hazards, underscoring the need for comprehensive adaptation strategies. Priority adaptation measures should include bolstering public health systems to manage heatwaves, developing sustainable water management and drought resilience initiatives, and strengthening flood-prevention infrastructure to protect at-risk areas.

In rural and agricultural sectors, transitioning to resilient crops and implementing solar-powered irrigation solutions could mitigate some of the impacts of changing water availability, helping to sustain agricultural productivity and rural livelihoods. In urban centres and vulnerable communities, real-time flood monitoring systems and proactive infrastructure reinforcement could reduce the devastating effects of frequent floods.

In conclusion, climate projections indicate that Georgia faces a future of intensified hazards without aggressive mitigation efforts, necessitating a two-fold approach: robust international action to limit emissions and a national commitment to adaptive strategies that enhance resilience against the unavoidable impacts of climate change.

9. LITERATURE

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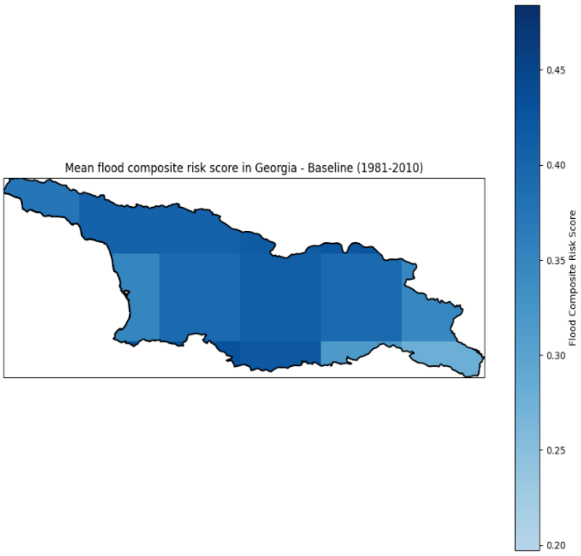
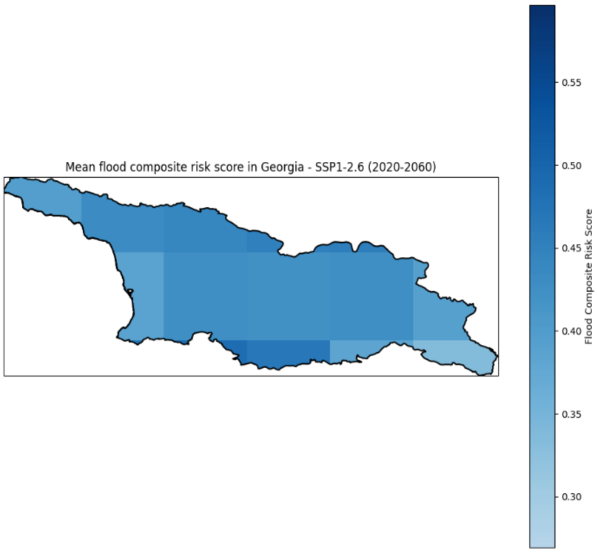
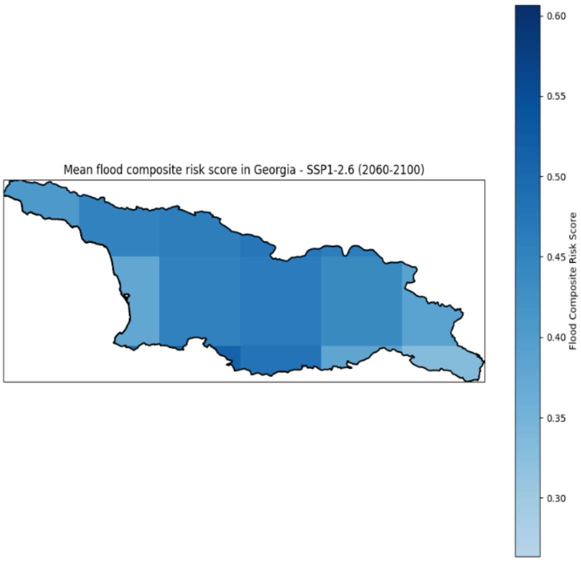
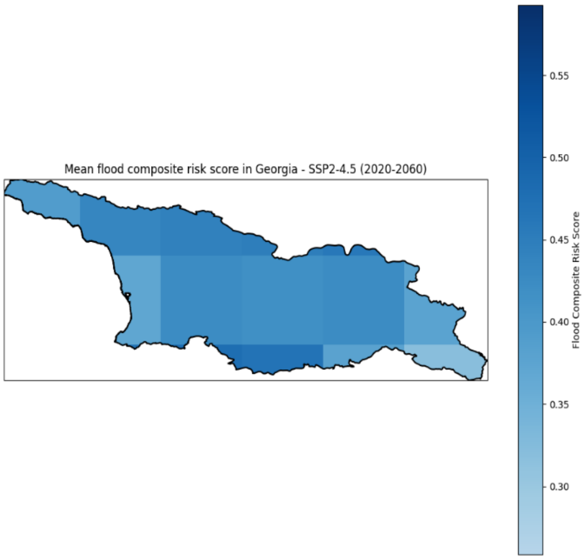
10. ANNEX • Figures for selected water-related hazards

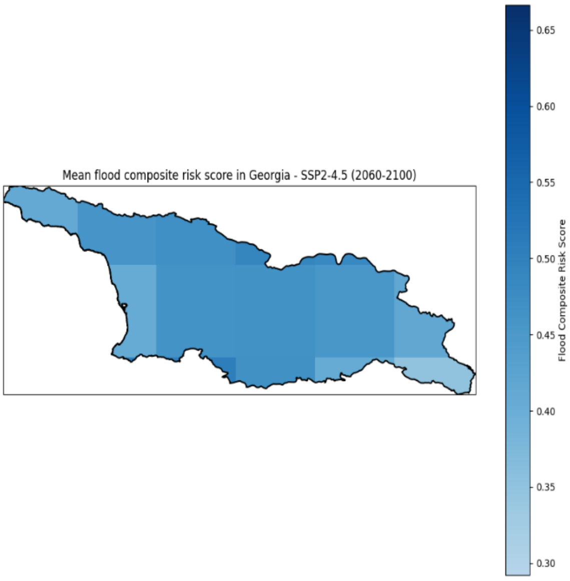
10.1. Mean flood composite risk score

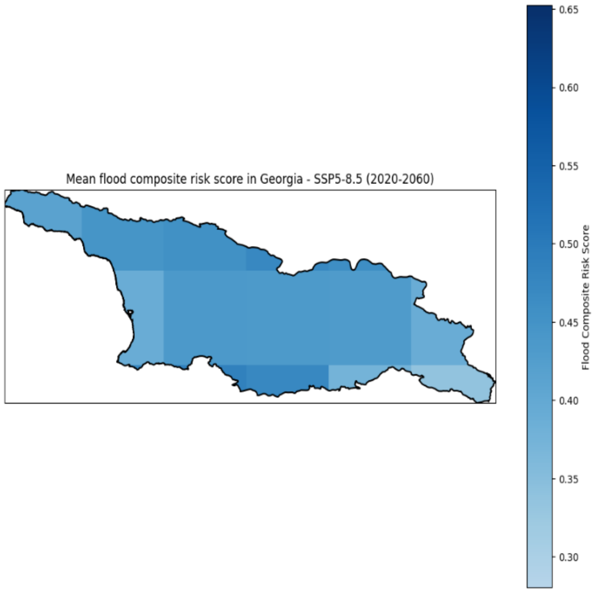


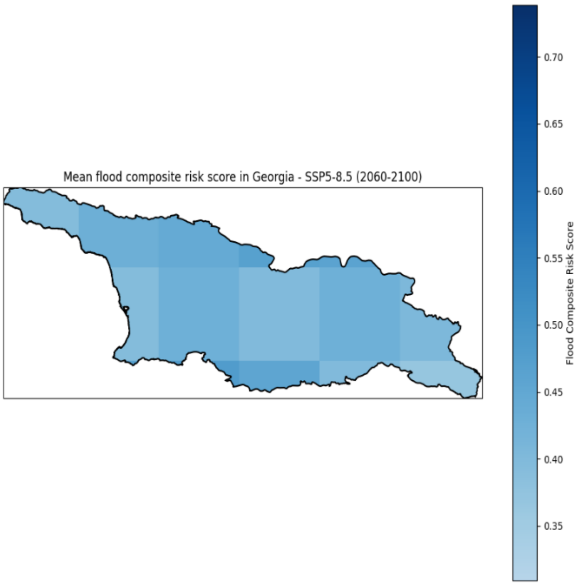




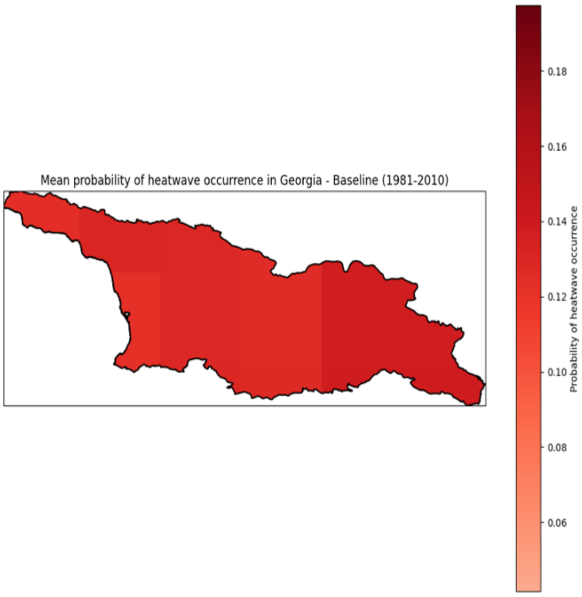


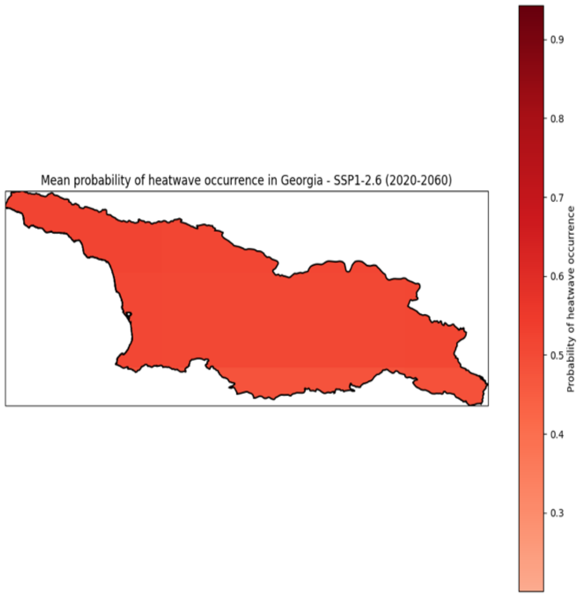

Mean flood composite risk score in Georgia - SSP2-4.5 (2060-2100)
Flood Composite Risk Score
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30

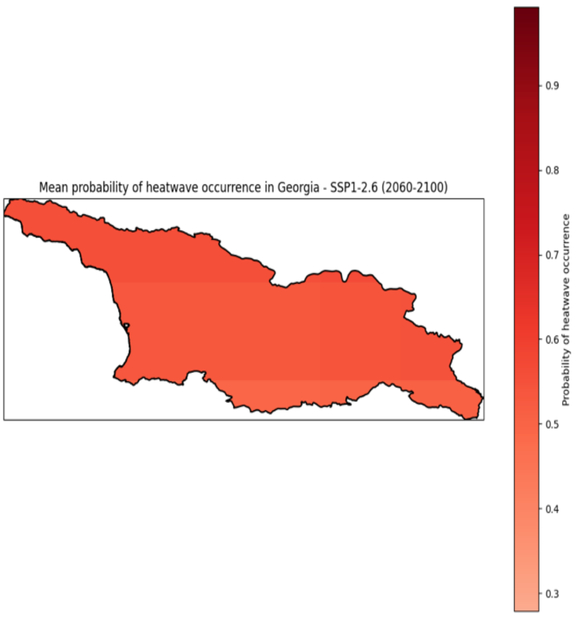

Mean flood composite risk score in Georgia - SSP5-8.5 (2020-2060)
Flood Composite Risk Score
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30

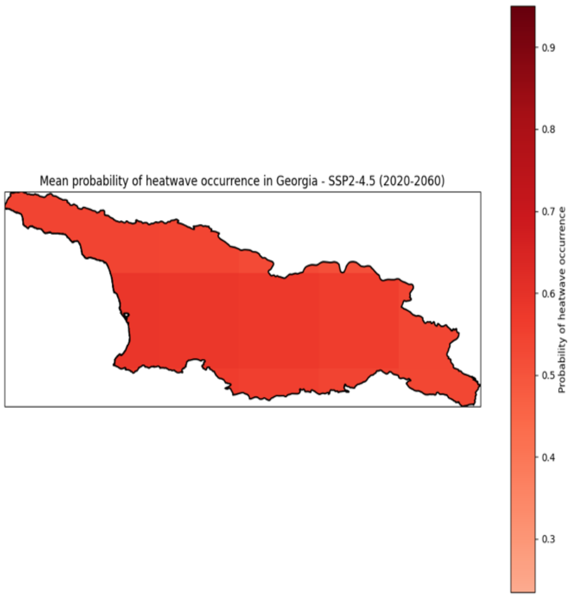

Mean flood composite risk score in Georgia - SSP5-8.5 (2060-2100)
Flood Composite Risk Score
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35

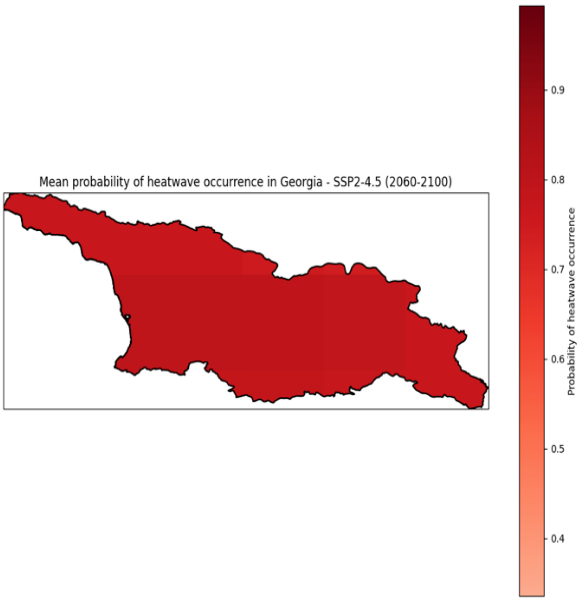
10.2. Heatwave probability

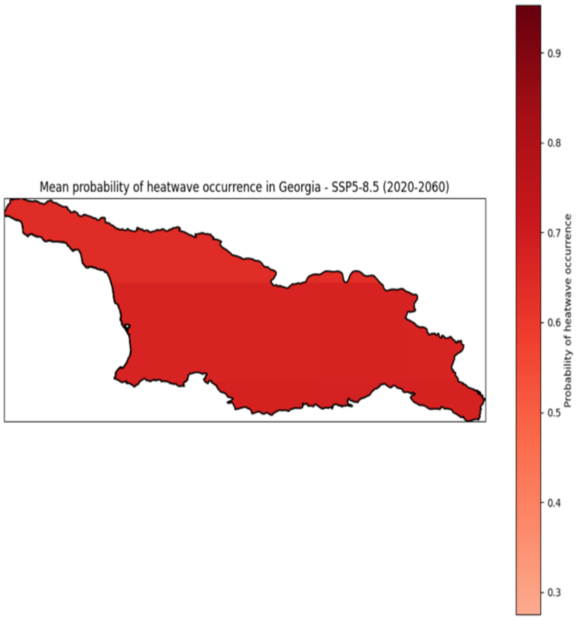


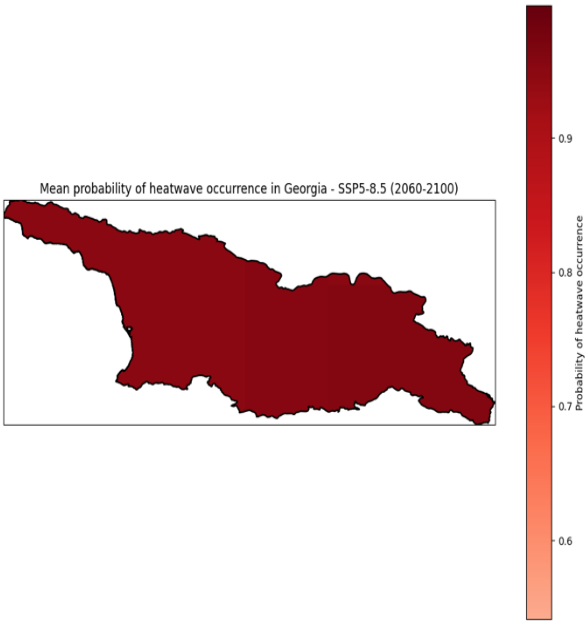




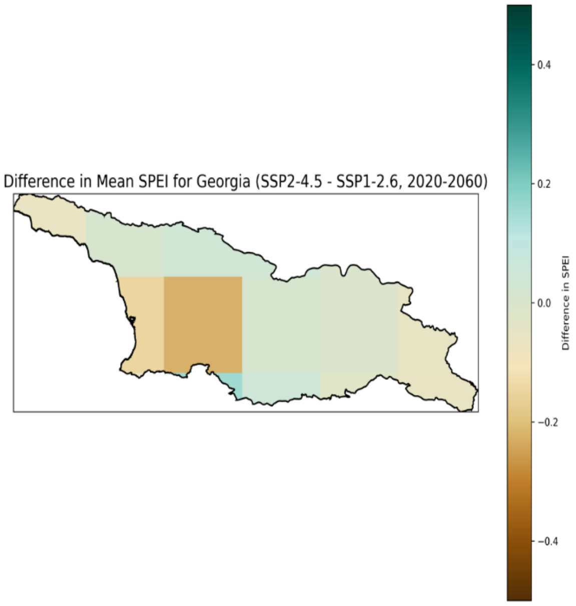


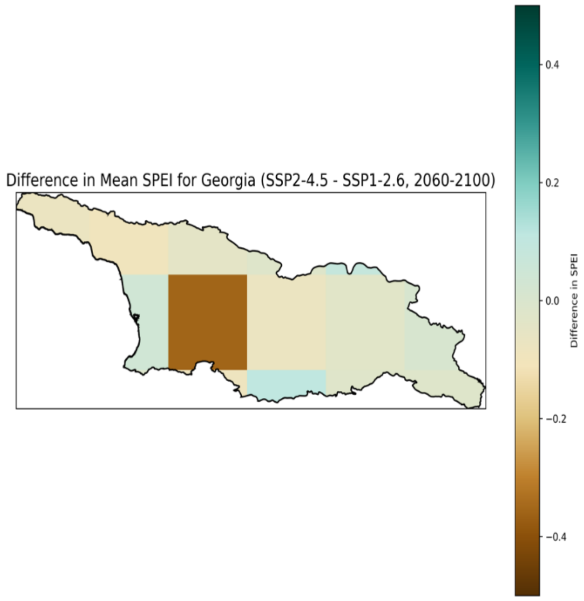

Mean probability of heatwave occurrence in Georgia - SSP2-4.5 (2060-2100)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6
0.5
0.4

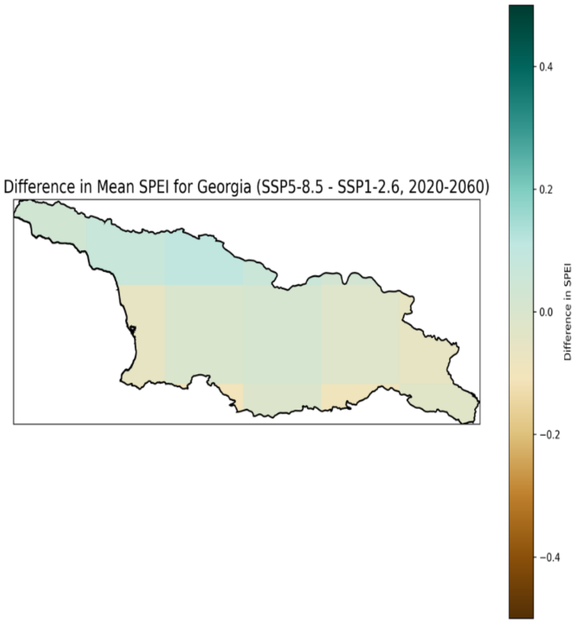

Mean probability of heatwave occurrence in Georgia - SSP5-8.5 (2020-2060)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6
0.5
0.4
0.3

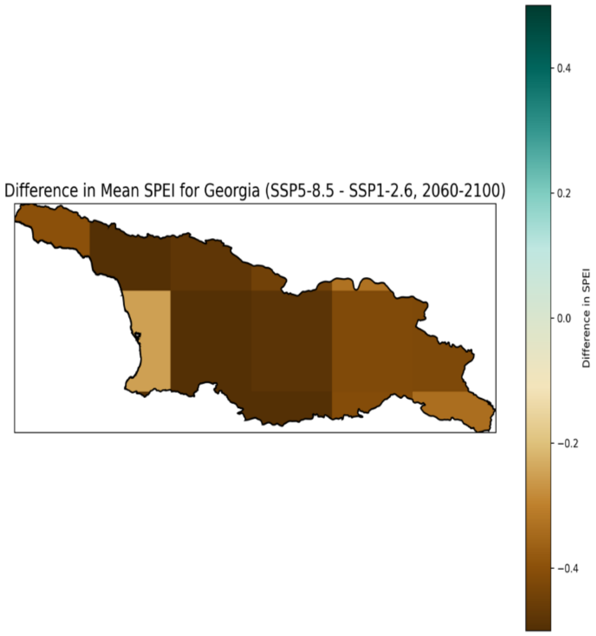

Mean probability of heatwave occurrence in Georgia - SSP5-8.5 (2060-2100)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6

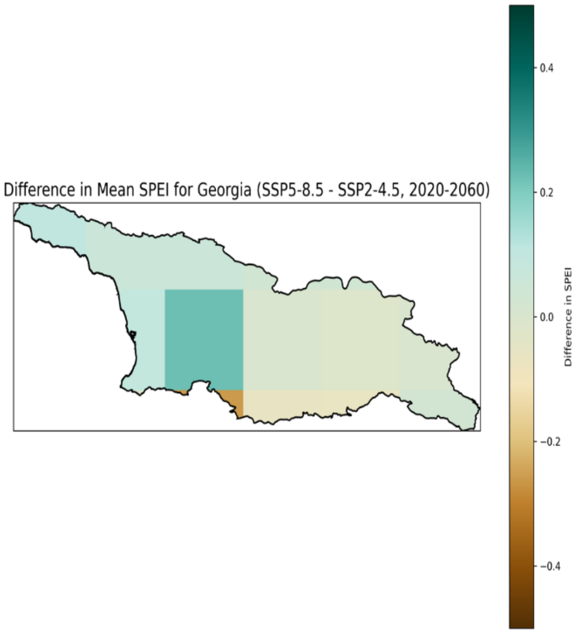
10.3. Differences in mean SPEI

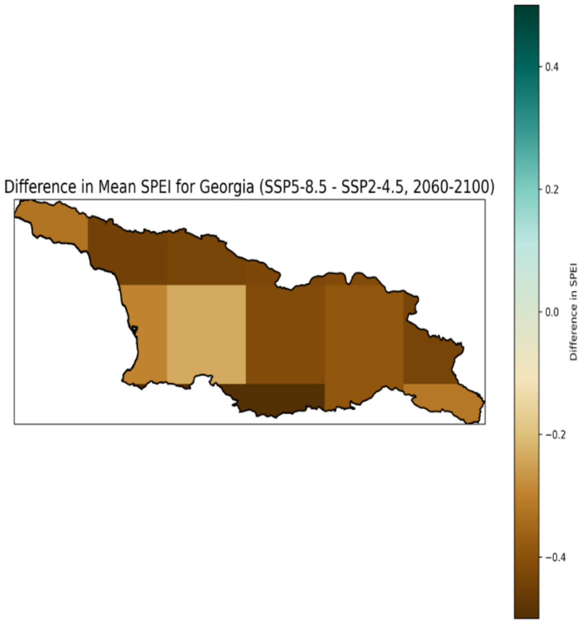









Difference in Mean SPEI for Georgia (SSP5-8.5 - SSP2-4.5, 2020-2060)
0.4
0.2
0.0
−0.2
−0.4
Difference in SPEI


Difference in Mean SPEI for Georgia (SSP5-8.5 - SSP2-4.5, 2060-2100)
0.4
0.2
0.0
−0.2
−0.4
Difference in SPEI