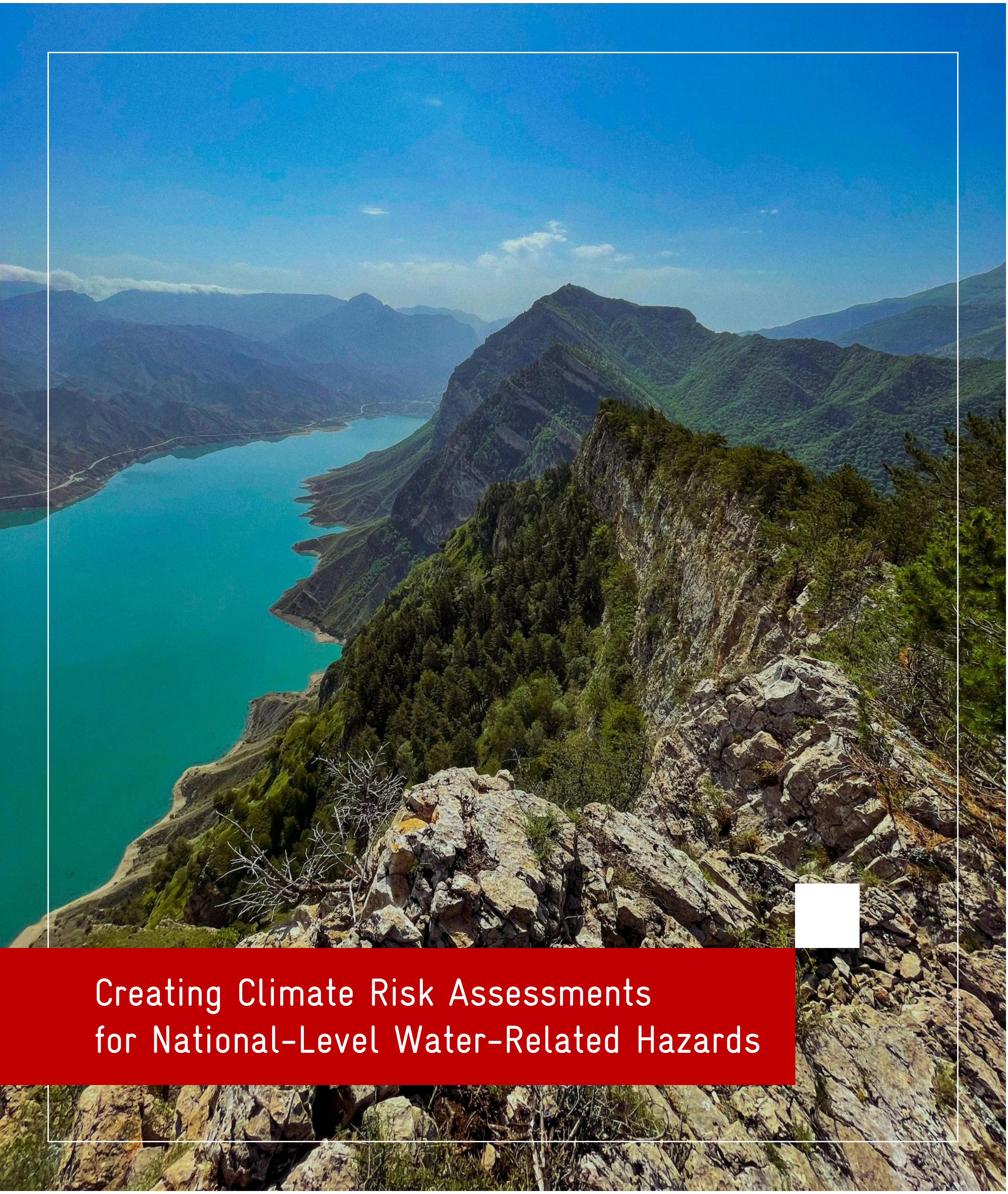

Creating Climate Risk Assessments for National-Level Water-Related Hazards

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

Germany 2025

CREATING CLIMATE RISK ASSESSMENTS FOR NATIONAL-LEVEL WATER-RELATED HAZARDS

June 2025

Prepared by EarthYield Advisories GbR as part of the assignment

"Development of climate change related water risk assessments for Georgia, Kazakhstan, and Mongolia"

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1 INTRODUCTION

The objective of the assignment was the retrieval and manipulation of water-related hazard data and the modelling of future water hazards under different climate change scenarios.

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

Retrieving and manipulating water-related data is essential to understand and mitigate these hazards and risks. By analysing this data, we can answer critical questions such as:

› What are the current and projected water-related hazards in a specific region?
› How do these hazards impact different sectors and communities?
› What adaptation measures can be implemented to reduce these risks?

Various stakeholders, including policymakers, researchers, and environmental organizations, can use this guide to make informed decisions and develop strategies for climate-resilient economic planning. The data can be obtained from multiple sources, including scientific literature, climate models, and publicly available data portals.

1.1 Background of this text

The Global Programme on Policy Advice for Climate Resilient Economic Development (CRED) by GIZ tasked the scientific consultancy EarthYield Advisories with assessing water-related climate hazards and identifying potential adaptation measures in Georgia, Kazakhstan, and Mongolia. The primary aim is to inform policymakers about potential risks and their likelihood, enabling informed decision-making regarding climate change policies. Further, the modelled water-related risks will be included into macroeconomic assessments (e3.ge model) and policy advice, ensuring climate-resilient economic planning.

The assignment of EarthYield Advisories was divided into several key tasks:

(1) The identification of water-related climate hazards through literature analysis and expert interviews
(2) Selection of the most pressing hazards, which are similarly severe in all three countries,
(3) Modelling the development of these hazards under different climate scenarios until 2100
(4) Identifying responsive adaptation measures

The first three tasks will be described in this guide. It serves as a good practice summary report to provide guidance on how to select, find and manipulate data on water-related hazards. And further describes how modelling can be done to project water-related hazards in the future.

The assignment produced several other publications which describe the specific water-related climate hazards in each country (Georgia, Kazakhstan and Mongolia):

- **Country Concept Notes:** Comprehensive assessment of water-related climate hazards detailing the methodology for data collection and analysis, identifying key hazards such as droughts, floods, and heatwaves, and proposing adaptation measures to mitigate these risks

  - Download for Georgia
  - Download for Kazakhstan
  - Download for Mongolia

- **Hazard profile:** Summary of main modelling findings described in Country Concept Notes

  - Download for Georgia
  - Download for Kazakhstan
  - Download for Mongolia

- **Technical brief:** Summary of methodology for assessing Dzuds in Mongolia.

  - Download for Mongolia

1.2 Structure of this text

This document is structured to provide a comprehensive overview of water-related hazard data manipulation and modelling. Chapter 2 focuses on how to select the research and assessment strategy to have a good basis for starting with the assessment of climate change-related water risks. Chapter 3 describes the data selection, retrieval, cleaning, and manipulation. Chapter 4 describes the methodology for calculating and modelling the selected hazards for all three country packages (droughts, floods and heatwaves) as well as Dzuds, specific to Mongolia. Finally, Chapter 5 discusses the lessons learned and concludes this document.

2 SELECTING THE RESEARCH AND ASSESSMENT STRATEGY

Before commencing the data collection process, it is crucial to first clarify the objectives of the envisioned assessment.

Therefore, it is highly recommended to think about the following questions and answer them in detail.

2.1 Defining the research objectives

Clarify what you want to know:

- What (water-related) risks and hazards are of interest (e.g., precipitation, temperature, drought, floods)?
- What region is of interest?
- Does the selected region have a special aspect such as topography or aridity?
- What spatial resolution (e.g., grids of 50km x 50km) do I want to look at?
- What time span is of interest (e.g., developments of the last century; trends or intervals and projections for 2030, 2050 and 2080)?
- Why do you want to know more about water-related climate risks? How can this knowledge be utilized (e.g., more knowledge about future risks to integrate them into policy making or inform inhabitants)?
- What outputs are needed (e.g., maps, graphs, text)?

Once you answered the above questions, combine them to one holistic research question:

- What research questions should be answered (e.g., How did precipitation change in region X over the last century and how will it change in the future according to different climate scenarios?)?

Please note, that the here outlined steps might lead to an iterative process, i.e. you might stop at one step and go back to the first steps to readjust your research questions or design. This might happen due to data scarcity or insufficient data quality, findings from the literature or other reasons. It is highly recommended to start over and acknowledge any shortcomings regarding the data and their possibility to answer your research questions as soon as possible in the process.

2.2 Check the status of science and projections

When you have formulated your precise research question, proceed to gather information what the status of science and projections is. This will give you an overview of what assessments have already been executed, and it will also show what you need to do to answer your specific research question. For instance, you might find out that research was done for one region of interest, but not for the other, or you might find out that projections have been done for the regions, yet the spatial resolution is not high enough for your purposes.

Generally, it is good to first put in your research questions to google, google scholar and AI tools such as perplexity, as this will give a broad overview of the most relevant literature. After selecting the most fitting literature, proceed to scan these to check what answers they provide for your specific questions. For the topic considered here (water-related climate risks) it is highly advisable to separately consult the current IPCC report, the current State of Global Water Resources report by WMO and the sources of the Climate Change Knowledge Portal by the World Bank as these condense the current scientific wisdom and are therefore highly reliable sources. Yet, depending on the specific research question, they might provide more general projections than desired.

Another important step is, if time and conditions allow, talking to experts in the field. Are there local researchers working on the issues? Talking to them might also create new networks and research teams to advance knowledge and exchange.

2.3 Selecting the modelling methodology

It is important to choose the appropriate research methods and tools based on your experiences and expertise and those of possible team members. If specific knowledge is available, ideally knowledge of the programming language python, leverage on these and use these tools (e.g., R).

3 DATA SELECTION, RETRIEVAL, CLEANING AND MANIPULATION

The data collection process involves identifying the necessary data sets, selecting appropriate data sources, and ensuring that the data meets the requirements of the assessment. This section will explain the data needs, possible data sets, and the criteria for selecting suitable data sources.

We will compile a list of data sources used in this assessment, detailing the source, availability (open access or restricted), available variables, scenarios, grid/spatial resolution, and how these data sources can be updated in the future, such as through CMIP cycles.

Additionally, we will compile a list of other potential data sources that were considered but not used for this assignment. For each source, we will provide a comment on the context in which it could be used and the reasons for its exclusion from our assessment.

This section covers the succession of steps we recommend for implementation:

- Literature analysis and expert exchange to establish an overview of the situation in each country.
- Establishment of data criteria to fulfil the model's needs.
- Identification of possible data sources within the data constraints
- Identification of variables needed and available.
- Identification of SSP scenarios.

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 analyze 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 the Institute of Economic Structures Research (GWS) and project experts of the different country packages.

3.2 Data criteria

The literature analysis and the expert talks as well as the requirements by the economic model, led to several criteria for the data to be compiled. Constraints of the project included a specific timeframe to look at, pre-selected climate change scenarios, the integration into the economic model, and time available. Please note that the following criteria are very specific to the described assignment and hence provide an example of what criteria might be necessary. Furthermore, note that climate projections usually do not display yearly values; rather, averages or trends are given for several decades to show how the climate will most likely have changed in 2030, 2050, 2080, and 2100. Despite its accelerating speed, climate change is a long-term process, and hence longer time intervals avoid large inter-annual fluctuations that blur the overall picture. Thus the data had to fit the following criteria:

› Hazard data for riverine floods, meteorological droughts, and heatwaves identified as the most severe expected economic damages across the three country packages.
› Establishment of hazard classifications (low, medium, high) to indicate varying degrees of severity.
› Annual data for each hazard classification required for economic model calculations to determine the probability of occurrence, this requirement made daily or monthly values necessary to calculate the annual probability of hazard classifications.
› Full projections needed for the following scenarios, which are a specific combination of Shared Socioeconomic Pathways (SSP) scenarios, representing changes in economic growth, population dynamics, technological advancements and policy implementation and the Representative Concentration Pathways (RCP) which represent different greenhouse gas emission scenarios:
  - SSP 1-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).
› Preference for open-source data to facilitate replication and reduce costs.
› Bias-corrected and downscaled data preferred due to assignment's time constraints.
› Simulation of future values (2024-2080 or longer) and interpretation of historical values relevant to heatwaves, meteorological droughts, and riverine floods.
› Differentiation of spatial grids with sufficient resolution to avoid single value per country representations, i.e., having a spatial resolution which allows to look at different sub-regions or topographies in the selected study regions.

Regarding the first criteria, i.e., the selection of hazard variables, other important water hazards, which were also of interest, such as general floods, hydrological droughts and general water depletion had to be abandoned. This omission happened for a variety of reasons: General floods require vast amounts of data, a solid hydrological model and are only applicable to small regions or specific bodies of water. If you are interested in floods for a specific river basin or the capital of a country, the calculations should be carried out for this region only. Furthermore, hydrological droughts are more complex than meteorological droughts, which are mostly dependent on precipitation and temperature. The latter, precipitation and temperature, are the standard variables when looking at climate changes and hence widely available. Hydrological droughts also require data on groundwater availability, water use, soil moisture and evaporation rates. Additionally, hydrological droughts manifest over longer time periods and thus show a lagged response. Similarly, water depletion requires a vast amount of data including uncertain data of human interaction. Additionally, to fully understand the impacts of extreme events on the economy and population, it is essential to combine infrastructure data and other influencing factors, such as topography, with the hazard projections. This combination will provide a solid risk assessment, as it makes a significant difference whether a flood occurs on levelled land without housing or in a steep valley with settlements.

3.3 Data sources

In the following section we provide an overview of the data sources we considered for the described assignment. They differ in how the data is presented (manipulated data vs raw data), access options, resolution, temporal differentiation and climate change scenarios available.

Currently, the main sources for scientific climate risk modelling are the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Lange & Büchner 2021; Lange, 2019). This data is downscaled and bias-corrected by e.g., the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 3b and Coordinated Regional Climate Downscaling Experiment (CORDEX). Other open-access sources include the Copernicus Data Climate Store (CDS) and other sources detailed below. Please note that all data bases are subject to changes or updates. This means that there might be a more current version, new variables, time frames, scenarios or other criteria then the ones explained below, when you start your calculations. Therefore, we refrained from detailing all variables below and provided comprehensive overviews instead which show the unique advantages of each source.

CMIP6 is a collection of about 100 advanced climate models from 49 research groups worldwide, providing a comprehensive set of simulations to project future climate scenarios and assess potential risks. It is the sixth phase of this model collection (CMIP, 2025). This ensemble is valuable for climate risk modelling as it allows researchers to compare results across different models, explore a wide range of possible outcomes, and better understand uncertainties in climate projections, ultimately informing policy decisions and impact assessments. This model collection is also features in the IPCC assessment reports of its sixth cycle (IPCC, 2023). For regional climate projections, CMIP6 provides multi-model ensembles that improve accuracy by incorporating different SSPs and climate variables. If using this data, it is recommended to read their guidance for data users.

ISIMIP3b is the latest phase of a project that uses multiple CMIP6 climate and impact models to assess climate-related risks across various sectors and spatial scales under different global warming and socioeconomic scenarios (ISIMIP, 2025). The appendix “3b” stands for the second part of the third simulation round. This comprehensive approach is valuable for climate risk modelling as it provides consistent projections of climate change impacts, helping to inform adaptation strategies and policy decisions by considering a wide range of potential future outcomes. This data is particularly valuable to model the data behind climate risk profiles. It requires less data manipulation and modelling then using the rawer CMIP6 data, as it is already downscaled and bias-corrected by modelling experts. This is why using ISIMIP3b also saves modelling and download time and computational power. ISIMIP provides an ensemble of different models, which contain 10 CMIP6 Global Circulation Models (GCMs), which cover a wide range of uncertainty. The ISIMIP repository is a service by the Potsdam Institute for Climate Impact Research (PIK).

The Coordinated Regional Climate Downscaling Experiment (CORDEX) is a framework that provides high-resolution regional climate model data for various domains worldwide, offering detailed climate information at scales ranging from 10km to 50km (CORDEX, 2025). This regional focus allows CORDEX data to capture local climate features and extremes more accurately than global models, making it particularly valuable for climate risk modelling in specific regions, such as individual country packages, and for informing local adaptation strategies. It captures local climate features more accurately due to its high resolution. Yet, it is less suitable if portraying several regions at a time, such as done in the here described assignment. To facilitate modelling and interpretation of the results, we recommend using ISIMIP or Copernicus data. Currently, the downscaled CMIP5 models are available, and the data access for CMIP6 models is under construction (as of March 2025).

The **Copernicus Climate Data Store (CDS)** provides access to a comprehensive collection of climate data, including global and regional climate projections from CMIP5, CMIP6, and CORDEX (Copernicus Climate Change Service, 2025). This platform offers quality-controlled datasets that allow users to quantify uncertainties in projected outcomes due to different emission scenarios, model formulations, and natural climate variability. The CDS is particularly valuable for climate risk modelling as it provides:

- Access to historical simulations and future projections
- Data covering various climate variables and indicators
- Tools for data analysis and visualization
- Regular updates with new datasets and functionality

The CDS is an excellent resource for researchers, policymakers, and practitioners conducting climate risk assessments and developing adaptation strategies. For the described assignment, we used CDS for the climate projections. We downloaded for example the model Meteorological Research Institute (MRI) Earth System Model (ESM) version 2 (MRI-ESM2) (Yukimoto et al. 2019). for Mongolia. It is a state-of-the-art Earth System Model which is valuable for regional climate projections because it

- Simulates interactions between the atmosphere, oceans, land, and cryosphere,
- Provides high-resolution climate projections for specific regions,
- Includes various climate variables and scenarios,
- Can be used to assess potential climate impacts on different sectors.

NASA EarthData is a leading source of free, scientific-grade satellite data for climate, land, ocean, and atmospheric research (NASA, 2025). It provides access to a vast collection of Earth observation datasets from NASA's fleet of Earth-observing satellites. Key features that make NASA EarthData valuable for climate hazard and risk assessments include:

- Global coverage with decades of historical data,
- High temporal and spatial resolution datasets,
- Access to multiple data categories (e.g., climate, land, oceans, atmosphere),
- Frequent updates and long-term satellite records.

NASA EarthData is particularly useful for tracking environmental changes over time, monitoring remote areas, and analysing long-term climate trends.

The **World Bank's Climate Change Knowledge Portal (CCKP)** is a web-based platform that provides comprehensive global, regional, and country-level information, data, and tools related to climate change and development (World Bank, 2021). The CCKP is valuable for climate risk modelling because it offers:

- Environmental, disaster risk, and socio-economic datasets,
- Synthesis products like Climate Adaptation Country Profiles,
- Spatially referenced data visualized on a Google Maps interface,
- Access to climate-related vulnerabilities, risks, and actions for specific locations.

The CCKP is particularly useful for development practitioners integrating climate resilience into planning and operations. To download data, it is necessary to register for free.

The **Aqueduct Water Risk Atlas**, developed by the World Resources Institute, is a global water risk mapping tool that helps users understand water-related risks and opportunities worldwide (World Resources Institute, 2025). Key features that make it valuable for climate risk modelling include:

- High-resolution, customizable global maps of water risk,
- Twelve global indicators grouped into a Water Risk Framework,
- Indicators covering water stress, variability, quality, and social conflict,
- Composite index based on the latest geo-statistical modelling techniques.

The Aqueduct Water Risk Atlas is particularly useful for companies, investors, governments, and communities assessing water-related risks in their operations or investments.

In the following we will describe the choice of data source for the example assignment to describe in more detail what aspects need to be considered.

The initial workplan of the described assignment (see introduction) 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. This was necessary as the economic model in which the water risk data was to be transferred, requires annual data. Yet, for most climate projections 30-year intervals seem very fit, as they provide a good and clear overview of how the climate will change.

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 countries as a whole and were already aggregated. Yet, both sources were be used as excellent reference points for verification and initial trends.

The assignment'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 (see above). 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 in particular concerning the spatial grid and variables 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) (Copernicus Climate Change Service (2025). 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 requirements into account and allowing for the fact that the study aims to identify extreme events and the likelihood thereof. In order to fulfil 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.

Data selection and retrieval process for the example assignment:

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

- Identification of relevant data sets based on the criteria (see previous section Data sources) and time constraints of the project,
- Evaluation of available climate data sources,
- Exclusion of pre-processed data sources, such as the Aqueduct Water Atlas and the CCKP, due to limitations in temporal resolution and spatial aggregation,
- Selection of a suitable international climate model for data processing,
- Justification of the selected model based on its spatial resolution and historical baseline, which provided a balance between data availability and climatic relevance,
- 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,
- Acknowledgement of necessary programming skills.

3.4 Variables

Depending on what hazards are to be projected, different variables are needed to calculate and project these. Please refer to chapter 4 for a more detailed description of how the hazards are calculated.

Based on the data criteria needed to identify and analyse the three water hazards of the example assignment, (heatwaves, droughts and riverine floods (see previous section *Data sources*) - 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:

- 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.

Additionally, we selected more variables for Dzuds in Mongolia. As this was only the case for one country, we will specify this case further below.

3.5 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.

3.6 Data retrieval and manipulation

To use the chosen climate data for hazard assessments, proceed to download it and consider that this process might take several days depending on the amount of data downloaded and computational capacity.

In the following, we describe how we proceeded in the example assignment. The final required data from the CDS was downloaded on October 16, 2024, and November 19, 2024 (for Dzuds), subsequently manipulated and the relevant hazard indicators were modelled processes are described below in this section and also in chapter 4 for each hazard. The data can be accessed manually and does not require a specific program, i.e., an Application Programming Interface. 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.

4 HAZARD MODELLING • Methodology for the climate risk assessments

4.1 Meteorological droughts

The Standardized Precipitation Evapotranspiration Index (SPEI) was selected as the primary parameter for the drought calculations 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 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.

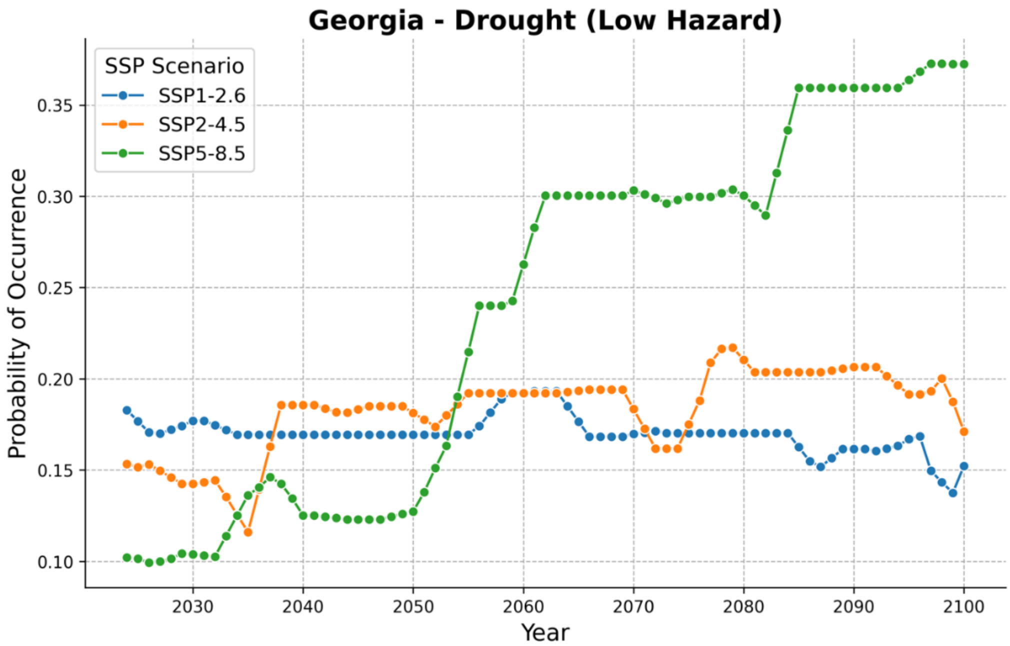

Figure 1: Probability of occurrence of meteorological droughts for low hazard events

Source: Illustration by EarthYield Advisories GbR"

Above in Figure 1 we provide an example of the assessment for Georgia regarding droughts. As can be seen in the graph, the final output is annual predictions of probability for each hazard classification. The individual years show high volatility and, in some instances, results that seem counter intuitive. The reason for that is that climate predictions are usually depicted in thirty-year intervals to show significant changes. However, when adding a trendline to the data, the results become much clearer and show expected changes.

4.2 Riverine floods

For the projection of riverine floods 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.

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 each country. 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 99^{th} 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 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.

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.

4.4 Dzuds (specific for Mongolia)

The hazard Dzud was projected specifically for the country package Mongolia, whilst the above-described hazards were calculated for all country packages. Dzuds are severe winter weather events in Mongolia characterized by extreme cold, heavy snowfall, and strong winds. These harsh conditions can lead to significant livestock mortality, as animals struggle to find food and shelter. Dzuds are a major concern for herders and the rural economy, as they can cause widespread loss of livestock and impact livelihoods. Therefore, there were included in the analysis for Mongolia to provide a comprehensive picture.

For the projection of possible Dzuds in Mongolia, several variables had to be considered to fully portray the risk of the most common types of Dzud to occur. Due to the complexity of Dzuds, various factors such as livestock characteristics, land use and vegetation, social and economic factors such as herding practices, access to veterinary care and economic resilience should be taken into consideration, as Dzuds are not only related to climate, but it's almost impossible to do so on a large-scale basis. 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 Dzuds in each grid point:

- **Number of windstorm days per winter:** The underlying variable used for this calculation is daily near surface wind speed, calculating the number of windstorm days by setting a threshold for windspeed (10m/s) to give an indication of how frequently severe wind events occur during the winter. Windstorms can cause the formation of snow drifts that can hinder livestock mobility and make grazing areas inaccessible (Sayed 2010; Fernández-Giménez 2012).
- **Extreme cold days:** The underlying variable was daily near-surface minimum air temperature. The number of extreme days was subsequently calculated by setting a threshold of –30 degrees Celsius. This threshold was chosen as cold becomes life-threatening below this point for livestock. It is a common threshold for extreme cold both globally and in Mongolian Dzuds (WHO 2024; GIZ 2023).
- **Monthly snow depth:** Snow depth is a commonly used variable when looking at Dzuds. A deep snow cover restricts access to forage, creates mobility restrictions, increases energy expenditure and carries an increased mortality risk (Nandintsetseg et al. 2018).
- **Average summer SPEI:** The Standardized Precipitation Evapotranspiration Index (SPEI) was selected as the primary parameter for the drought calculations of this project 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. Droughts are one of the main drivers of Dzuds in Mongolia because of reduced pasture growth, weakened livestock conditions, decreased fodder production and pasture degradation. When the summer preceding the Dzud winter is a drought summer, the Dzud is expected to get considerably worse (Haraguchi et al. 2022).
- **Wind chill:** The underlying variable for this wind chill calculation is daily near surface average temperature and the near-surface wind speed. Wind chill was picked it represents the perceived decrease in air

temperature due to the effects of wind and high wind speeds combined with cold temperatures significantly increase livestock stress and energy expenditure. The calculation of the wind chill index only becomes relevant when temperature is below 10 degrees and wind speed is above 4.8 kilometres per hour. Subsequently the mean wind chill for the winter season was calculated (Fernández-Giménez 2012)

- **Number of freeze-thaw cycles per winter:** The underlying variables for this calculation are minimum near-surface air temperature and the maximum near-surface air temperature as well as daily precipitation. The number of days were counted per winter that had a maximum temperature above zero and a minimum temperature below zero. The number of cycles was only calculated when winter precipitation was present on any given day, as the process of freezing and thawing only becomes relevant with precipitation. This calculation is the main indicator for iron Dzud, which is one of the defined Dzud types (UNDRR 2024).
- **The longest cold spell per winter:** The underlying variables used was near-surface minimum air temperature. The longest number of consecutive days below –30 degrees Celsius was calculated per winter to also consider the persistence of cold conditions, as long periods of consecutive extreme cold limits the ability of livestock to recover. It helps to distinguish between winters with short but severe cold events and winters with prolonged periods of extreme cold (Wignaraja 2024; IFRC 2022).
- **Total winter precipitation:** The underlying variable was daily precipitation between November and March. Heavy snowfall can contribute to the Dzud risk by creating thick snow cover that restricts grazing. Adding winter precipitation allows for a better understanding of how snow depth is formed and works well with mean snow depth to understand both the depth and the rate of snow accumulation (FAO 2018).

In the composite risk score four primary factors were considered: precipitation, drought, wind and temperature. These four factors were subsequently turned into different risk variables to create a risk score. The reasoning behind this was to give each factor approximately similar weights after comparing them to historical events. The risk score variables were thus given the following weights:

- Total winter precipitation: 15% (0.15)
- Longest cold spell per winter: 5% (0.05)
- Number of freeze/thaw cycles: 5% (0.05)
- Wind chill: 5% (0.05)
- Average summer SPEI: 30% (0.30)
- Monthly snow depth: 10% (0.10)
- Extreme cold days: 15% (0.15)
- Number of windstorm days: 15% (0.15)

Categorization of risk score variable to factor:

Temperature: Extreme cold days, wind chill, longest cold spell, freeze/thaw cycles (30%)

Wind: Windstorm days, wind chill (20%)

Precipitation: Snow depth, total precipitation (25%)

Drought: SPEI (30%)

The reasoning behind drought and temperature having a slightly higher weighting is that these are commonly referred to as the two main drivers of Dzud.

Following that, the risk score was calculated for the baseline and future periods to create an annual risk score. It is important to note that years represent winter seasons and the summer preceding it in this calculation. The data is therefore structured as the following: The year 2024 represents the winter season 2023/2024 (starting in November 2023 and ending in March 2024).

To enhance the analysis of Dzuds, we further classified each event by its percentile in the historic baseline period. Dzuds 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.

5 LESSONS LEARNED AND CONCLUSION

The following bullet points summarise our lessons learned from the assignment. They can be useful for similar endeavours.

- When mapping different regions, it is best to use one data base and the same models for all regions to maximize comparability and avoid confusions which might arise if different data sources or models were used.
- Kazakhstan and Mongolia fit well in the same model as they inhibit similar levels of aridity and weather patterns. Georgia however proved more difficult to integrate as the country requires a better grid solution and has unique characteristics in topography.
- Have knowledgeable experts in your team who can advise you in data compilation, cleaning and modelling. It is possible to start from scratch, learning python or R, yet it takes more time. This could be done if the skills will be needed in the future.
- Have statistical experts in your team.
- Plan enough time for data download. If time constraints are an issue, the best solution is to increase the grid, e.g. from 50x50km to 100x100km, as results will still show a trend but downloading and calculations take less time.
- The here outlined approach will most likely be an iterative process, i.e. you might stop at one step and go back to the first steps to readjust your research questions or design. This might happen due to data scarcity or insufficient data quality, findings from the literature or other reasons. It is highly recommended to start over and acknowledge any shortcomings regarding the data and their possibility to answer your research questions as soon as possible in the process.
- Take enough time to visualize and describe the results for your target audience, different formats and languages might be necessary.
- If possible, do not incorporate annual probabilities of occurrence. While this a useful tool for economic data, it is not common to predict annual values in climate science. It would be advisable to take 30-year intervals or trends.
- If the model requires annual values, it is helpful to add a trendline for the data in a graph to be able to show changing patterns over time.

For further research it would be advisable to integrate a hydrological model into the modelling of riverine flooding, as it captures the entire hydrological cycle and predicts flood magnitude. Conducting assessments of climate change-related water hazards around the globe and in specific regions of interest is highly important and interesting. Such assessments are crucial for evidence-based policy making and priority setting regarding policy execution, budget spending, and infrastructure projects, as climate change will continue to alter our environment. Further, water is a vital and complex resource. While the effort is undoubtedly worthwhile, several statistical, computational, and strategic considerations must be addressed before starting. Also, enough capacity should be available. The here described example assignment was very ambitious and had to be carried out in a comparably short time. While it is absolutely possible to select, retrieve, manipulate, and evaluate data within the given time constraints, a few data compromises had to be made. For further research, we would therefore recommend allowing more time in the initial data retrieval phase to integrate more variables and decrease the spatial grid, which would improve the data in the model. Additionally, a hydrological model would be helpful to better capture floods. Similarly, the calculations for Dzuds are a first suggestion for quantifying the event occurrence.

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