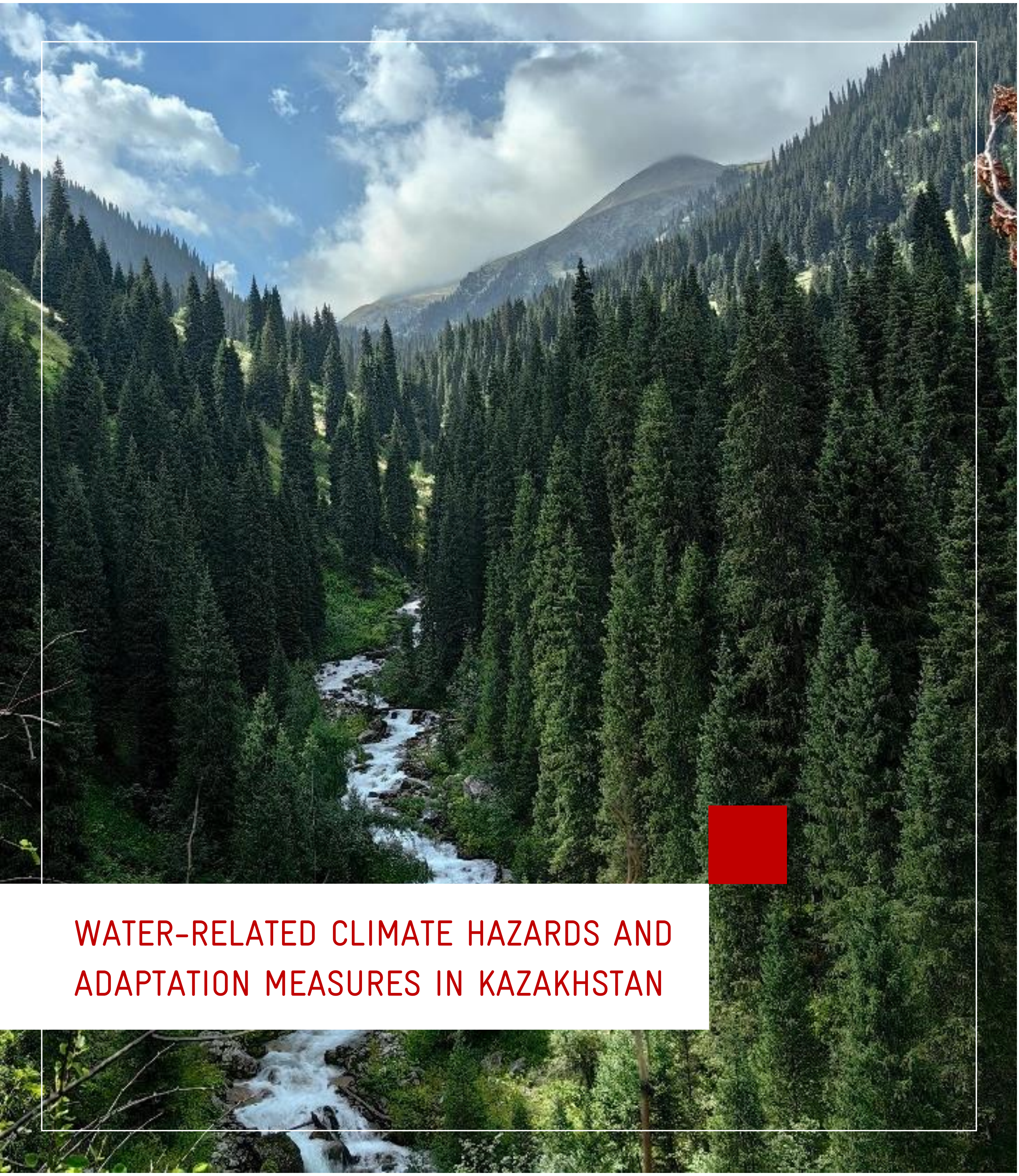

WATER-RELATED CLIMATE HAZARDS AND ADAPTATION MEASURES IN KAZAKHSTAN

Published by:

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Supported by:

Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection

IKI INTERNATIONAL CLIMATE INITIATIVE

based on a decision of the German Bundestag

As a federally owned enterprise, GIZ supports the German Government in achieving its objectives in the field of international cooperation for sustainable development.

Published by
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn, Germany

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This report was elaborated by the experts of the international consultancy EarthYield Advisories GbR within the global programme "Policy Advice for Climate Resilient Economic Development", implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on behalf of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

The contents of this report are the sole responsibility of the authors and can in no way reflect the official opinion of the GIZ project.

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 KAZAKHSTAN

▶ DATA AND LITERATURE ANALYSIS

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.

The authors would like to thank the colleagues from the GIZ Steering Unit Sebastian Homm, Naima Abdulle and Samuel Bryson for the continuous exchange and their contributions. We would further like to thank the GIZ colleague Dana Yermolyonok for the specific information and contributions for Kazakhstan.

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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
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
ESM	Earth System Model
FAO	Food and Agriculture Organization (FAO)
GDP	Gross Domestic Product
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IKI	International Climate Initiative
IOM	International Organization for Migration
IPCC	Intergovernmental Panel on Climate Change
MRI	Meteorological Research Institute
NDCs	Nationally Determined Contributions
PET	Potential Evapotranspiration
RCP	Representative Concentration Pathway
SPEI	Standardized Precipitation Evapotranspiration Index
SSP	Shared Socioeconomic Pathways
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
WMO	World Meteorological Organization
WRI	World Resources Institute

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 Kazakhstan and identifying potential adaptation measures. The project was divided into several key tasks: identifying water-related climate hazards in Kazakhstan, 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 Kazakhstan. 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 Kazakhstan (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 Kazakhstan and the necessary measures for adaptation. The report begins with an introductory section on the water-related risks facing Kazakhstan, 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 Kazakhstan. Climate change significantly impacts water resources both worldwide and in Kazakhstan, 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 (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 Mongolia 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 CRED project in Kazakhstan focuses on supporting decision makers in adaptation planning and capacity building for this purpose. Therefore, cost-benefit analyses and other analytical tools are used, and international best practices are implemented. One goal of the project's efforts is to integrate climate adaptation into the country's economic development plans. By developing the e3.kz model, the project assesses the macroeconomic impacts of climate change and various adaptation measures. This model aids policymakers in understanding the broader economic implications and identifying effective strategies. Through these efforts, CRED aims to foster resilient employment-intensive economic growth and reduce the vulnerability of Kazakhstan'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 Kazakhstan. 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.

Kazakhstan, a vast Central Asian country, is experiencing significant impacts from climate change that are reshaping its environmental and socioeconomic landscape. Over the past six decades, the average annual temperature in Kazakhstan has been rising by 0.3°C per decade, with more pronounced warming during spring and autumn (Ministry of Energy of the Republic of Kazakhstan, 2023). Projections indicate a further increase in mean annual temperatures (World Bank Group & ADB, 2021). These temperature changes are accompanied by shifts in precipitation patterns (Salnikov et al., 2015). The changing climate is exacerbating water-related risks in Kazakhstan, a country already grappling with water scarcity and uneven distribution of water resources. Furthermore, Kazakhstan highly depends on transboundary water sources. Following figures from FAO (2013), only 56% of the country's total annual water discharge originates from its own sources, the rest comes from neighboring countries. Climate models project a substantial reduction in runoff to streams and rivers due to higher evaporation rates and precipitation reductions (Reyer et al., 2017). This is particularly concerning for Kazakhstan's major rivers, which have already experienced significant shoaling in recent years (Zhupankhan et al., 2018).

The country's water security is further compromised by the melting of glaciers in the Tien Shan and Pamir Mountains (Sorg et al., 2012). The reduction of overall water availability Is likely to overwhelm the water management infrastructure. Additionally, the risk of flooding has increased due to projected extremes in daily rainfall, especially in mountainous regions (World Bank Group& ADB, 2021).

The economic implications of these climate-induced water risks are profound. The agricultural sector, which heavily relies on irrigation, is particularly vulnerable. Crop water requirements are projected to increase (USAID, 2017). This, coupled with the fact that irrigation water productivity in Kazakhstan is six to eight times lower than in other countries (FAO, 2013). Hence, these climate change impacts will tremendously impact food security as agricultural productivity declines and food supply, and prices can be more volatile. In recent years cereal production was below average due to droughts and excessive rainfall (FAO, 2024). Furthermore, the recurring floods lead to a displacement of rural and urban communities, increase poverty and ultimately livelihoods are lost. For example, the unprecedented flooding event in 2024 that affected over 6,000 houses and led to the evacuation of 117,000 residents, demonstrate the substantial economic and social costs associated with climate-related disasters (UNDRR, 2024a).

2. BACKGROUND ON KAZAKHSTAN

2.1 Geography and hydrology

Kazakhstan, the world's largest landlocked country, is situated in Central Asia, straddling both Asia and Europe (World Bank Group & ADB, 2021). Its vast territory encompasses diverse topographical features, including extensive steppes, expansive deserts like the Kyzylkum and Betpak-Dala, and prominent mountain ranges such as the Tian Shan and Altai (USAID, 2017). The country's western border is defined by the Caspian Sea, the largest inland body of water globally (Zhupankhan et al., 2018). Kazakhstan's geography is also marked by the tragic transformation of the Aral Sea, once the world's fourth-largest lake, which has shrunk dramatically due to Soviet-era irrigation projects, resulting in widespread environmental and economic repercussions (Micklin, 2007).

Kazakhstan's hydrology is characterized by a complex network of surface and groundwater resources. Furthermore, Kazakhstan is highly depended on transboundary water resources. Most of the surface water is comprised in lakes and rivers.

The country boasts approximately 39,000 rivers, with the Ili, Irtysh, Syr Darya, and Ural being the most significant (FAO, 2013). Lakes play a crucial role in Kazakhstan's water system, with Lake Balkhash being the most important for surface water resources (Propastin, 2012). While groundwater is not scarce, it is unevenly distributed, with reserves primarily located in the north and east, leaving southern and western regions facing water scarcity (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2023). The Syr Darya basin serves as a vital water storage area for these drier regions (Dukhovny & de Schutter, 2011). Lake Balkhash, a freshwater and brackish water body, is a critical source for agriculture and industry, though it faces increasing environmental threats, particularly rising salinity (Yapiyev et al., 2017). The Aral Sea, once one of the world's largest lakes, has been drastically reduced due to over-irrigation, leading to an environmental disaster that has prompted restoration efforts (Micklin, 2016). In terms of water consumption, agriculture dominates, using up to 70% of freshwater resources, followed by industrial and domestic use (FAO, 2024).

2.2 Climate and climate change

Kazakhstan's climate is predominantly continental, characterized by extreme temperature variations and dry conditions, with strong seasonal contrasts between long, harsh winters and short, hot summers (World Bank Group & ADB, 2021).

Temperature extremes are common, with cold winters featuring frequent snowfall and hot summers, though regional variations exist (FAO, 2024). Precipitation is generally low, with the country being predominantly arid to semi-arid; the northern areas receive moderate rainfall of about 315mm/year), while the central parts receive considerably less (around 150mm/year) (Zhupankhan et al., 2018). Steppes and deserts are prone to strong winds, particularly in winte (Zhupankhan et al., 2018). Kazakhstan is highly vulnerable to drought and desertification, as evidenced by the environmental disaster of the Aral Sea (Micklin, 2007).

Kazakhstan's climate can be divided into several distinct regions: Northern Kazakhstan (harsh continental), Central Kazakhstan (extreme continental), Southern Kazakhstan (arid to semi-arid), Eastern Mountainous Areas (cool and wet), and the Western Caspian Region (moderate continental) (Salnikov et al., 2015).

Kazakhstan has already experienced significant climate change impacts across various sectors. The country has seen an average temperature increase of 0.9°C between 1991-2020 compared to 1961-1990 (UNDP, 2023a). In 2020, Kazakhstan experienced a record high temperature of 1.92°C above the climate standard, surpassing the previous record of 1.89°C set in 2013 (UNDP, 2023b). These temperature increases have led to more frequent and intense heatwaves across the country, particularly in the south, southwest, and west of the country (UNDP, 2023a).

The changing climate has also altered precipitation patterns, affecting water resources and agricultural productivity. Glaciers in the Tien Shan and Pamir Mountains, crucial water sources for major rivers like the Amu Darya and Syr Darya, have been melting at an accelerated rate (WMO, 2024). These changes have contributed to an increase in natural disasters such as droughts, floods, mudflows, and landslides, resulting in land degradation, infrastructure damage, and loss of life (Isayev, 2024).

Projections indicate that climate change impacts on Kazakhstan will intensify in the coming decades. The country is expected to experience further increases in temperature and aridity, along with disruptions to precipitation patterns (IOM, 2023). Climate models further project a substantial reduction in runoff to streams and rivers due to higher evaporation rates and precipitation reductions (Reyer et al., 2017). By 2100, the entire territory of Kazakhstan is expected to experience a temperature rise of up to 7°C (World Bank Group & ADB, 2021).

This warming trend will likely exacerbate existing problems, particularly floods and droughts. Eastern and northern Kazakhstan is projected to face increased precipitation, while arid regions like Mangistau may experience more severe droughts (Khaibullina, 2024). The long-term availability of water is expected to decrease due to continued glacier retreat and reduced snowpack in mountainous areas. These changes will have far-reaching consequences for agriculture, ecosystems, energy production, and human health (UNDP Kazakhstan, 2022). Increased evaporation rates are likely to further strain water resources, leading to decreased soil moisture and reduced water availability for agricultural activities and ecosystems. The number of internal climate migrants in Kazakhstan is projected to increase, with estimates suggesting that between 3.1 to 4.6 percent of the population may need to migrate internally due to climate change by 2050 (World Bank Group & ADB, 2021; IOM, 2023).

2.3 Economy

Kazakhstan's economy has experienced significant growth since gaining independence from the Soviet Union in 1991, transitioning to a market-oriented system.

The country's GDP grew from $18.2 billion in 2000 to $133 billion in 2008, with an average annual growth of 10% during this period (Kanashayev, 2017). Rich in natural resources, Kazakhstan is the world's largest producer of uranium and a significant producer of oil, gas, and various minerals (World Bank Group, 2024). Apart from the mining industry, the manufacturing industry is important. Agriculture only accounts for a small part of the Gross Domestic Product.

Despite this growth, the economy faces challenges such as overdependence on exports to Europe, Russia and China, and the need for diversification. The agricultural and energy sectors, both crucial to Kazakhstan's economy, are increasingly affected by water risks and climate change. Agriculture, particularly in the Kazakh Steppe region, is vulnerable to droughts and heatwaves, which threaten crop yields and food security. Spring wheat yields, for instance, are projected to decline by as much as 50% by the 2050s due to higher temperatures and reduced soil moisture (World Bank, 2021). The energy sector, dominated by oil and gas, may face challenges due to changing environmental conditions, international policies and geopolitics. While hydropower is only regionally significant, reduced river flows could impact its productivity. Additionally, the oil and gas infrastructure may experience declining productivity amid rising demand, further complicating the country's economic landscape (World Bank, 2021).

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 Kazakhstan", "hydrology Kazakhstan", "water risks Kazakhstan" and "climate change water hazards Kazakhstan". 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, AdditionallyLastly, 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 Kazakhstan and the guidelines on possible adaptation measures. These talks were held in regular intervals with relevant stakeholders and economists, such as GWS, for Kazakhstan.

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 for Kazakhstan, 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 Kazakhstan 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 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 ere 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) . 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. In order 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 Kazakhstan:

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:

- 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 favored 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 modeled. 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 and cartopy. Xarray was used, because it makes working with large, multi-dimensional datasets (like temperature and precipitation over time and space) much easier by using labeled 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 create 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 Kazakhstan 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 Kazakhstan 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 Kazakhstan. 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 is 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

Kazakhstan faces significant water-related hazards exacerbated by climate change, uneven distribution of water resources, and transboundary water dependencies.

Kazakhstan is experiencing medium-high to high water stress, with projections indicating worsening conditions. The AQUEDUCT water stress index for Kazakhstan is expected to increase from 2.51 (baseline) to 3.11 by 2080 (WRI, 2024). The country may face water shortfalls amounting to 50% of its needs by 2040, potentially leading to a 6% decrease in GDP (UNDP, 2023c).

Water resources are unevenly distributed across Kazakhstan. Only 56% of the country's total annual water discharge originates from its own sources, with the rest coming from neighboring countries (FAO, 2013). This transboundary dependency is significant, with major rivers like Irtysh, Ili, Syrdarya, Ural, Shu, and Talas originating in neighboring countries (FAO, 2022).

The average annual temperature in Kazakhstan has been increasing in the past and will continue to do so (World Bank Group & ADB, 2021). This warming trend, coupled with shifts in precipitation patterns, is leading to reduced availability of river water (Salnikov et al., 2015; UNDP Kazakhstan, 2023). Climate models project a substantial reduction in runoff to streams and rivers due to higher evaporation rates and precipitation reductions (Reyer et al., 2017). Major rivers in Kazakhstan, including the Ural, Tobol, Ili, Irtysh, and Yesil, have experienced significant shoaling in recent years (Zhupankhan et al., 2018; UNDP Kazakhstan, 2023). The Ural River water level has dropped three times over the last 15 years (Khaibullina, 2024). The country's water security is further compromised by the melting of glaciers in the Tien Shan and Pamir Mountains, crucial sources for rivers like the Amu Darya and Syr Darya (Sorg et al., 2012; WMO, 2024).

Water stress varies across regions. The Aral-Syrdarya and Shu-Talas basins face excessive load, with 57% of freshwater stock being withdrawn. The Nura-Sarysu basin experiences even higher stress, reaching 88% (Institute of Geography and Water Security, 2022).

In the following this report will provide more detail on four specific water risks: droughts, floods, possible collapse of the Great Lakes and desertification. The first two (droughts and floods) threaten all three country packages analysed (Georgia, Mongolia and Kazakhstan), while the last two are particularly a problem for Kazakhstan.

4.1 Droughts

Drought has become an increasingly pressing issue in Kazakhstan, particularly in the southern, western, and central regions of the country. Over the past 20-30 years, the situation has deteriorated significantly due to climate change, low precipitation, over-reliance on irrigation, and glacial melt (World Bank, 2021).

This environmental challenge poses a severe threat to agriculture, livestock, water security, and overall economic stability. Several regions in Kazakhstan are particularly prone to drought conditions. The Akmola, Kostanay, and North Kazakhstan regions frequently experience drought events (FAO, 2022). Additionally, Atyrau, West Kazakhstan, and Mangistau are poorly supplied with water resources, exacerbating their vulnerability to drought (FAO, 2022). The southern and western regions of Kazakhstan experienced strong heatwaves from 2018 to 2021, leading to low water levels and soil drying up to 50 cm deep (Reliefweb, 2021). In 2021, a severe heatwave led to record temperatures of 46.5°C in the Southern and Western regions (Kyzylorda, Mangystau, and Turkestan), resulting in rapid runoff of rivers and reservoirs, and soil drying up to a depth of 50 cm, causing a lack of vegetation and natural feed on pastures (Reliefweb, 2021).

The frequency and intensity of droughts in Kazakhstan are expected to increase. Water scarcity in the country is classified as "high," with droughts projected to occur on average every 5 years (Think Hazard, 2020). This situation is likely to worsen, as crop water requirements are projected to increase (USAID, 2017). Currently, the annual mean probability of a meteorological drought in Kazakhstan does not exceed 5% (Sadrtdinova et al., 2024). However, even under the most optimistic scenario (RCP2.6), the probability of severe drought is expected to increase up to 40% by the end of the century, with the western and southern regions (Mangystau and Kyzylorda) facing the highest risk, with a probability of over 80% (Sadrtdinova et al., 2024). International projections show a concerning picture for Kazakhstan's future climate conditions. By 2050, temperatures are expected to rise by 2.6°C to 4.4°C, accompanied by a decline in precipitation. Summer rainfall could decrease by as much as 15-30% in some areas (World Bank, 2021).

These changes are likely to intensify drought conditions and their associated impacts. Kazakhstan is forecast to be affected by all types of droughts: meteorological, hydrological, and agricultural (Sadrtdinova et al., 2024). The impact of drought is already evident in some regions. West Kazakhstan has been experiencing severe drought conditions for the last three years, with the summer of 2021 being the severest in history (Sadrtdinova et al., 2024). The Mangistau region is already experiencing drought conditions and drastic loss of livestock (Sadrtdinova et al., 2024). Furthermore, five out of eight water economic basins in Kazakhstan are experiencing the highest levels of water stress, with the Shu-Talas and Nura-Sarysu basins registering indices of 0.98 and 1, indicating full utilization of river runoff (Sadrtdinova et al., 2024).

4.2 Floods

Kazakhstan faces significant flood risks, particularly during spring thaw in northern and eastern regions along major rivers such as the Irtysh, Syr Darya, and Ishim (World Bank Group & ADB, 2021). These risks are exacerbated by snowmelt, ice jams, intense rainfall, poor infrastructure, and earlier snowmelt due to climate change. The country's vulnerability to flooding is further increased by projected extremes in daily rainfall, especially in mountainous regions (World Bank Group & ADB, 2021). Recent events highlight the severity of this issue. In spring 2024, Kazakhstan experienced unprecedented flooding, described as the worst disaster in over 80 years (UNDRR, 2024a). This event affected nearly a third of the country, leading to the evacuation of over 120,000 people and inundating vast areas, including the city of Atyrau (UNDRR, 2024a).

Climate change projections indicate an increased likelihood of flooding from snowmelt in mountain regions until 2050, a higher frequency of ice jams, and an increase in heavy precipitation events by 20-30% (World Bank Group & ADB, 2021). Additionally, the potential rise in the Caspian Sea level poses further flood risks to coastal areas. Flooding impacts are far reaching (see chapter 7 on the economic damages).

Despite these challenges, Kazakhstan's flood management infrastructure remains inadequate. The government had plans to build 39 new reservoirs in nine regions for flood control and water storage, but the plan remained at the feasibility study stage (Khaibullina, 2024). This lack of progress in infrastructure development leaves many regions vulnerable to both flooding and water shortages, often within the same year

(Khaibullina, 2024). In response to these challenges, Kazakhstan is seeking international cooperation to enhance its flood risk management capabilities.

The recurring nature of flood events in Kazakhstan, coupled with their increasing severity due to climate change, underscores the urgent need for comprehensive flood risk assessment and the implementation of protective measures. As the country continues to grapple with this complex issue, balancing flood control with water resource management will be crucial for its environmental and economic stability.

4.3 Heatwaves

On par with global developments over the past few decades and global projections for the current century, heatwaves and extremely hot days have become an increasing concern for Kazakhstan, with climate change making them both more frequent and more intense in their occurrence. Kazakhstan has been experiencing a steady increase in average temperatures over the past century. The average annual mean temperature rose from 5.68°C in 1901 to 8.32°C in 2020. This warming trend is more pronounced than the global average, with projections suggesting potential warming of up to 5.3°C by the 2090s under high emission scenarios (Oladejo et al. 2023). In recent years, Kazakhstan has experienced an increasing number of record temperatures, a change in seasonal variations and a notable increase of days with high temperatures (ADB 2021).

There have been numerous repercussions following the increase in heatwaves and hot days including but not limited to a rapid runoff of rivers, soil degradation, destruction of agricultural crops, death of livestock, reduced labor productivity, a strain on energy infrastructure and an ever-increasing reduction of vegetation, making the soil more perceptible to desertification (IFRC 2021).

Future projections look equally alarming; air temperatures are expected to conitinue rising faster than the global average, heatwaves are projected to increase in frequency, intensity and duration, whcih is further supported by the data analysis of this report, and summer temperatures are expected to increase more than annual temperatures, making heatwaves more unbearable for both cattle and vulnerable groups in the population (ADB 2021).

4.4 Freshwater scarcity and stress

Kazakhstan faces significant challenges in managing its freshwater resources, with current stress levels and projected scarcity posing serious threats to the country's development and security. This section examines the current state of water resources, future projections, and the historical context of water-related disasters in the region.

Kazakhstan's overall water stress is at a moderate stress level (WRI, 2024; Karatayev et al., 2017). Eventhough, not yet a high stress level is reached, the stress level is approaching the threshold that the UN and other organizations often use to indicate the onset of water stress concerns (FAO, 2022). Furthermore, this national average masks significant regional disparities. The Aral-Syrdarya and Shu-Talas basins face excessive pressure, with 57% of freshwater stock being withdrawn, while the Nura-Sarysu basin experiences an alarming 88% water stress (Zhupankhan et al., 2018), i.e. 88% of the available renewable water resources are withdrawn. Several factors contribute to this water scarcity, including climate change, inefficient water management, and outdated infrastructure. Agriculture accounts for 60-65% of total water withdrawal, with losses during water transportation exceeding 50% due to poor irrigation infrastructure (FAO, 2022). The rapid urbanization in Kazakhstan, with an urbanization level of 57.4% as of 2020, is also increasing demand for water resources (World Bank Group, 2022).

Future projections show challenges regarding water security. For example a shortage in water supply will affect all sectors of the economy, primarily agriculture, industry, and municipal services. Climate change is expected to exacerbate water scarcity, with projections indicating a decrease in annual river runoff (Salnikov et al., 2015). For example, Lake Balkhash, which depends on the glacier-fed transboundary Ili River for 80% of its capacity, is highly vulnerable to runoff and climate change (UNDP Kazakhstan, 2023). The flow of the Ili River from northwest China has been steadily declining since the 1970s (UNDP Kazakhstan, 2023). Additionally, by 2050, Kazakhstan's population is projected to increase to 24-25 million people, which will further strain available water resources (United Nations, 2019).

Water resources in Kazakhstan are increasingly polluted from various sources, significantly diminishing the availability of adequate water for agricultural and other purposes. Industrial waste, agricultural runoff, and mining contaminants contribute to the degradation of water quality across the country (ADB, 2018). Industrial activities in Kazakhstan have been known to impact water resources, potentially exacerbating water scarcity issues (Karatayev et al., 2017). Lake Balkhash, in particular, has been the subject of environmental assessments due to concerns about its water levels and quality (Propastin, 2012). Additionally, the National Action Program to Combat Desertification highlights that pollution from industrial enterprises and agricultural practices is widespread, leading to secondary salinization and reduced access to clean drinking water (Kazakhstan Ministry of Ecology, 2019). These factors collectively threaten the sustainability of water resources essential for both agriculture and human health.

The historical context of water-related disasters in the region is exemplified by the Aral Sea catastrophe. Once the world's fourth-largest inland water body, the Aral Sea has shrunk by 90% since the 1960s due to excessive water diversion for irrigation projects (Micklin, 2007). This environmental disaster has had far-reaching consequences, including the exposure of toxic chemicals and salts from the dried seabed, leading to environmental degradation and health hazards for local populations (Whish-Wilson, 2002). The shrinking of the Aral Sea has also affected regional climate patterns, exacerbating water scarcity issues and impacting agriculture and biodiversity in the surrounding areas (Micklin, 2016). This historical example serves as a stark reminder of the potential consequences of mismanaging water resources and underscores the urgency of addressing current water scarcity challenges in Kazakhstan, in national, regional and also global fora, as many water resources are transboundary and impacted by climate change.

4.5 Desertification

Desertification in Kazakhstan affects many million hectares of degraded rangelands (Kazakhstan Ministry of Ecology, 2019). The causes of land degradation and desertification in Kazakhstan are both natural and anthropogenic, including water overuse for irrigation, unsustainable agricultural practices like overgrazing in the Kazakh Steppe, and over-extraction of water resources (Karatayev et al., 2017).

Climate change-induced droughts and rising temperatures have led to higher evaporation rates and reduced soil moisture (World Bank, 2021). The regions most affected include Southern Kazakhstan (Kyzylkum Desert, Aral Sea, Betpak-Dala Desert), Western Kazakhstan (Caspian Sea region, Mangystau region, Atyrau region), the Kazakh Steppe, and Central Kazakhstan. Soil salinization has become a significant issue, particularly in irrigated areas and abandoned farmlands (Khamzina et al., 2015).

Projections indicate that desertification in Kazakhstan is likely to worsen due to climate change. Temperature increases, changes in precipitation patterns, and the northward shift of arid zones are expected to intensify the risk of land degradation and erosion, resulting in lower agricultural productivity (IPCC, 2019). Climate models predict further increases in air temperature, expansion of drought zones in the north and center, and more extreme weather events such as heat waves, droughts, floods, landslides, and mudflows (Kazakhstan Ministry of Ecology, 2020). These changes are likely to exacerbate existing desertification trends, potentially leading to more significant losses of arable land, increased poverty in rural communities, rising food prices, and conflicts over water scarcity. The loss of biodiversity, increased soil erosion, more frequent dust storms, and a rise in respiratory and waterborne diseases are also anticipated consequences (Akhmetov et al., 2021).

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 Kazakhstan was 32% per annum and 15% and 3% 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 37% for low hazard events (22% and 6%), which shows that Kazakhstan is already under immense drought pressure.

Under the SSP 1-2.6 scenario, the likelihood for all droughts is projected to remain relatively stable with slight variations and an overall tendency to decrease at the end of the century, finishing the projected period at around 35%, 16% and 5% probability of occurrence.

The SSP scenario 2-4.5 shows very similar projections with stable drought hazard levels. The only difference is the end of the century, where the probability of occurrence finishes slightly higher than the SSP 1-2.6 scenario, at around 37% for low-hazard events, at 22% for medium-hazard events and at 7% for high-hazard events.

Under the SSP 5-8.5 scenario, this trend changes and the probability of occurrence is projected to increase for all three hazard classifications. The likelihood of a low-hazard drought taking place is almost 50%, 31% for a medium-hazard drought and 15% for a high-hazard drought, which shows that this SSP scenario will lead to more damage than the other scenarios. Please refer to the below figures for more details.

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

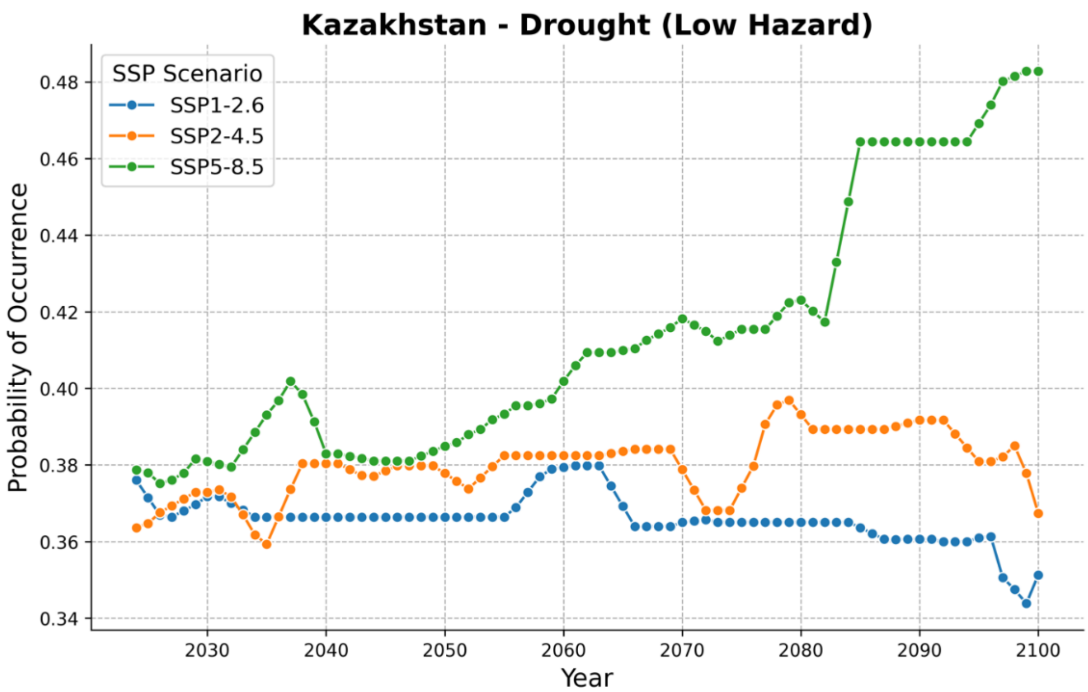


Figure 2: Probability of occurrence of meteorological droughts for medium hazard events

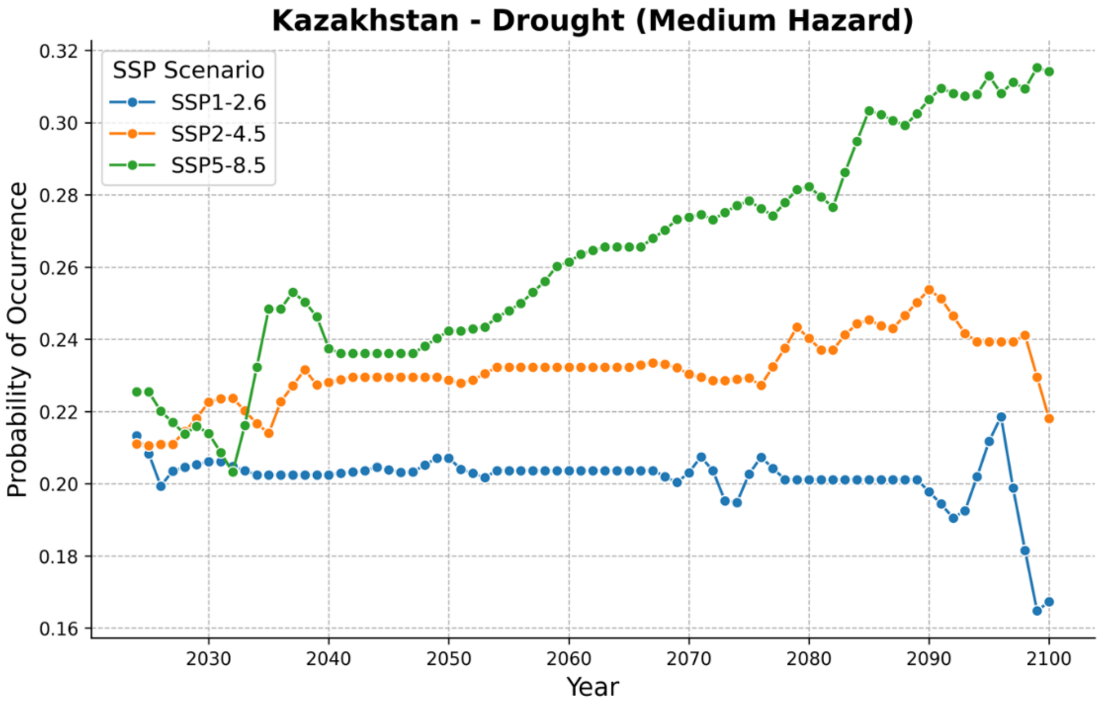
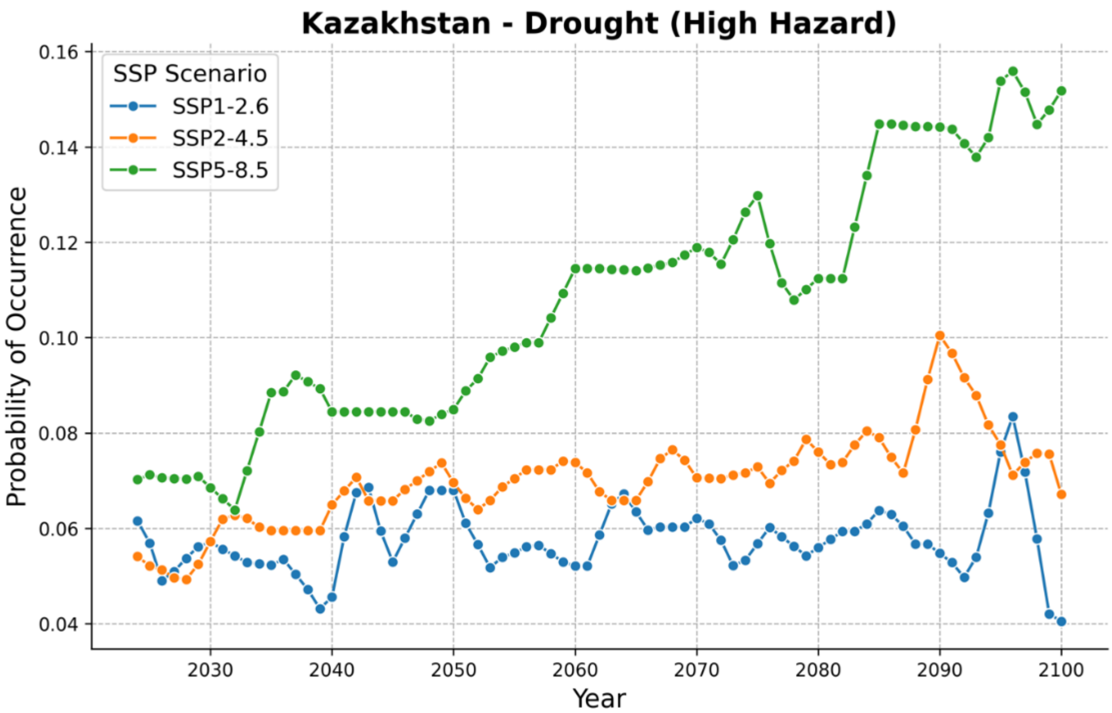


Figure 3: Probability of occurrence of meteorological droughts for high hazard events



5.2 Riverine floods

The mean probability of occurrence during the baseline period for low-hazard floods was 20% in Kazakhstan and 10% for medium-hazard floods and around 2% for high-hazard floods, corresponding to 5-year flood risks, 10-year flood risks and 100-year flood risk in the baseline period. These numbers change to around 35% by 2024 and to 18% and 2%-3% by 2024, with model variations depending on the scenario. Under the SSP 1-2.6 scenario, Kazakhstan sees an initial increase in the probability of occurrence of all hazard classifications but an overall decrease by the end of the century, finishing the projected period at around 25%, 11% and 1% respectively and bringing the risk for floods down throughout the country.

Under the SSP 2-4.5 scenario, the likelihood of floods will increase until the end of century, where a slight drop can be expected. Under these circumstances, the probability of occurrence is at around 47% for low-hazard events, at 30% for medium-hazard events and at 8% for medium-hazard events, making floods overall more likely.

Under the SSP 5-8.5 scenario, the projected results are more dramatic, in particular for low-hazard and medium-hazard events. Both are projected to increase significantly throughout the century and picking up speed in the second half of the century, finishing the projected period at around 85% likelihood for low-hazard floods, at almost 65% likelihood for medium-hazard events and at around 6% for high-hazard events. Please refer to the below figures for more details.

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

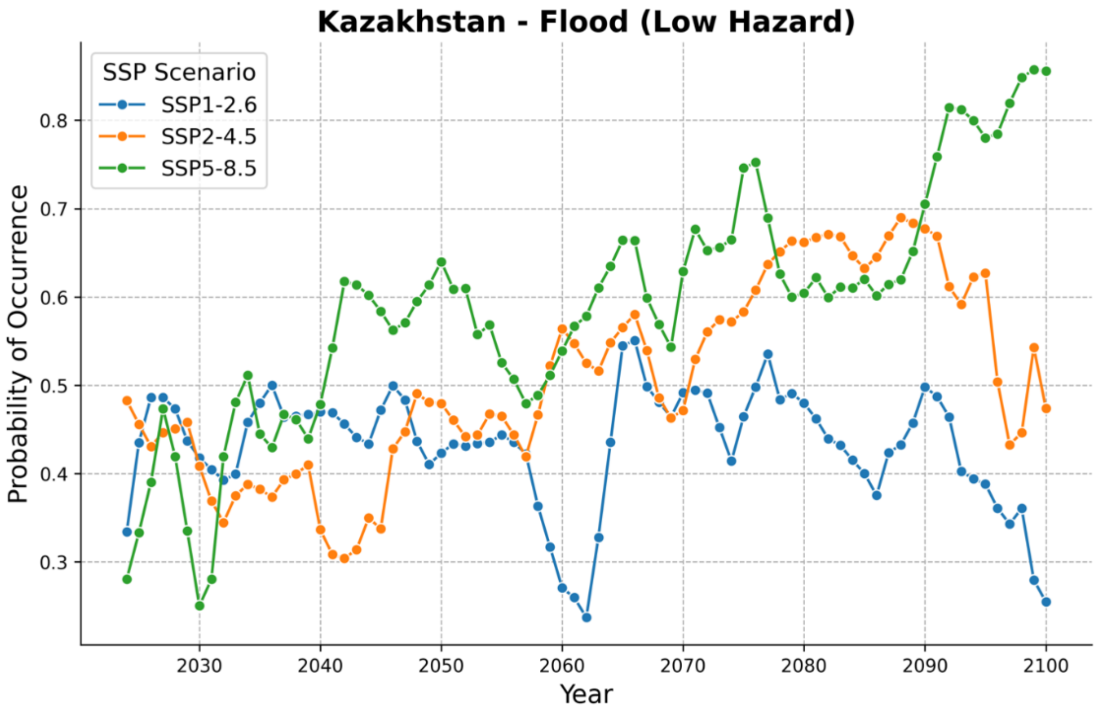


Figure 5: Probability of occurrence of riverine floods for medium hazard events

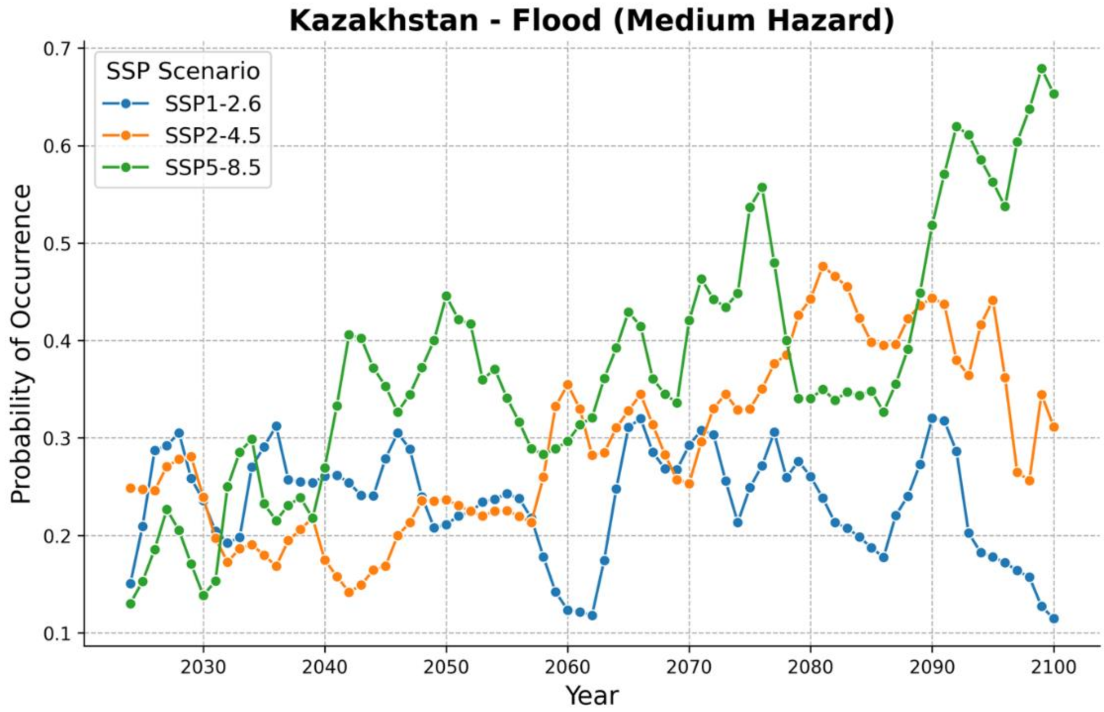
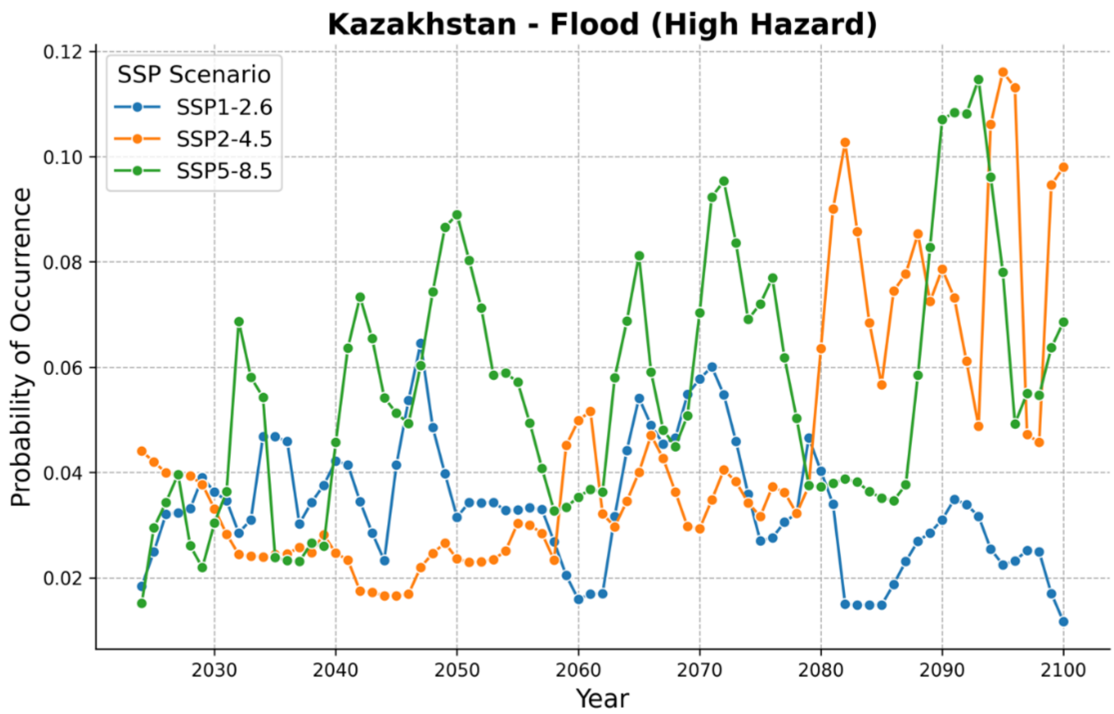


Figure 6: Probability of occurrence of riverine floods for high hazard events



5.3 Heatwaves

The threshold heatwave temperature for Kazakhstan was defined individually for each grid point. The historical baseline showed a mean probability of occurrence of 11% for heatwaves above this threshold lasting longer than five days (low hazard), and 2% and less than 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 events rises significantly at first, but decreases again towards the end of the century, finishing at approximately 30% likelihood at the end of the projected period. A similar scenario is projected for medium-hazard events and high-hazard events, albeit at a much lower level of likelihood, finishing at around 10% and 4% respectively. Both the average temperature and maximum temperature have already been increasing more than the global average in Kazakhstan, which makes it less surprising that even the best-case scenario will result in a higher likelihood for heatwaves.

Under the SSP 2-4.5 scenario, the probability of occurrence for all three hazard levels is projected to increase significantly and steadily until the end of the century. Low-hazard events and medium-hazard events are then expected to slightly decrease at the end of the century, finishing at around 50%, 25% and 6% respectively.

Correspondingly, under the SSP 5-8.5 scenario, the likelihood of all three hazard classifications is projected to increase dramatically throughout the entire projection period. The probability of occurrence for medium-hazard and high-hazard events see a slight decrease at the end of the century, which could be within the margin of error or showing the peak for this scenario. Low-hazard heatwaves have a probability to occur of more than 80% at the end of the century, while medium-hazard heatwaves are above 60% and high-hazard heatwaves at around 40%, all showing an extreme increase compared to the historic baseline period. Please refer to the below figures for more details.

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

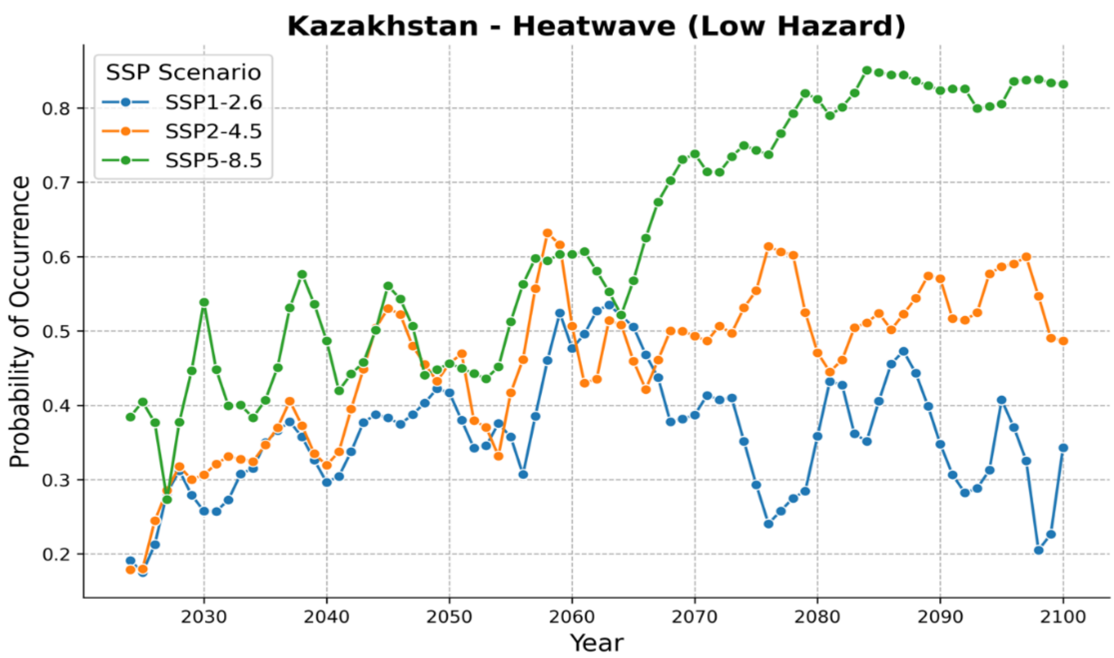


Figure 8: Probability of occurrence of heatwaves for medium hazard events

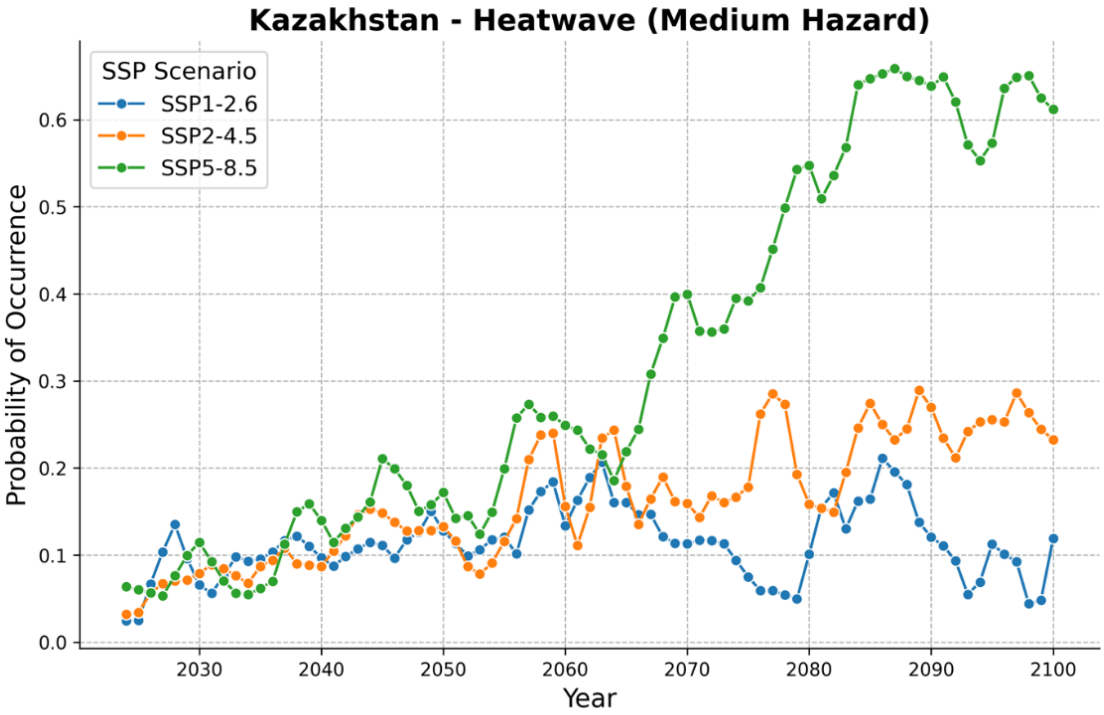
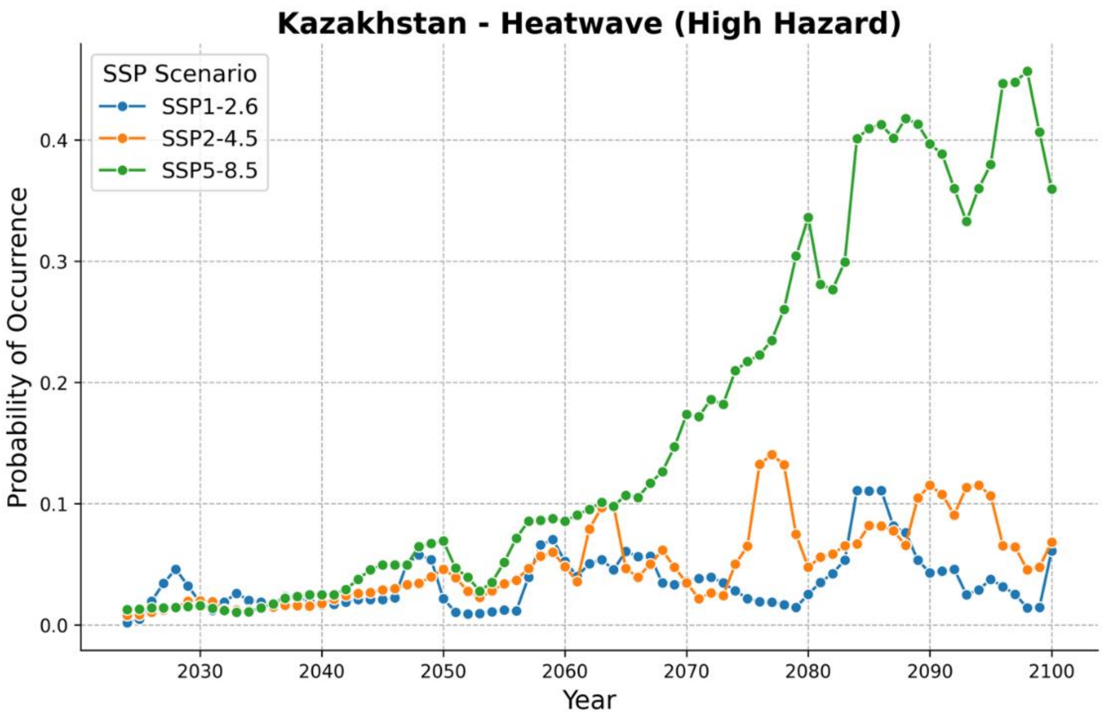


Figure 9: Probability of occurrence of heatwaves for high hazard events



5.4 Evaluation

Projected water hazards under climate change for Kazakhstan reveal increasing risks of heatwaves, droughts, and riverine floods under most of the scenarios, with SSP 5-8.5 indicating potentially severe outcomes. These findings highlight the urgent need for Kazakhstan to adopt both adaptive strategies and support global mitigation to avoid intensifying climate hazards.

Kazakhstan is projected to experience substantial increases in both the frequency and intensity of heatwaves across all climate scenarios, with the highest probabilities under SSP 5-8.5. While SSP 1-2.6 presents a scenario where heatwave probabilities could stabilize and even decline slightly by the century's end, SSP 2-4.5 and 5-8.5 indicate that even moderate heatwaves will become more likely, occurring every few years or more frequently. In SSP 5-8.5, extreme heat events could occur almost half the time by the end of the century.

For Kazakhstan, these changes could strain public health systems, increase heat-related illnesses, and elevate energy demands for cooling, especially during prolonged and intense heatwaves. Additionally, extreme heat could impact agricultural productivity, given that much of Kazakhstan's economy relies on climate-sensitive sectors.

Kazakhstan's historical vulnerability to drought is expected to persist and even worsen under the SSP 5-8.5 scenario, which projects a significant increase in drought probabilities. Under both SSP 1-2.6 and SSP 2-4.5, drought levels are relatively stable but still above the historical baseline, emphasizing that even low-emission pathways might not fully eliminate drought risks. By the century's end under SSP 5-8.5, the frequency of all drought hazard levels rises considerably, with nearly half of all years projected to experience at least low-hazard drought conditions.

This poses serious implications for Kazakhstan's water resources, which are already under pressure. Increased drought frequency could impact drinking water supplies, reduce arable land, and force shifts in agricultural practices. Such trends may also accelerate land degradation and desertification in Kazakhstan's dryland areas, potentially driving rural-to-urban migration and pressuring urban infrastructure.

Flooding risks in Kazakhstan show considerable variation across scenarios, with SSP 5-8.5 again projecting the most dramatic increase. While SSP 1-2.6 suggests that flood probabilities could eventually decrease from mid-century peaks, SSP 2-4.5 and especially SSP 5-8.5 forecast an upward trend in flood occurrences, particularly for low- and medium-hazard events. By the century's end in SSP 5-8.5, low-hazard floods could occur in more than three-quarters of all years, posing significant risks to infrastructure, communities, and agriculture, particularly in river-adjacent regions. Frequent flooding could degrade soil quality, disrupt agriculture, and damage infrastructure, from roadways to residential areas. Furthermore, Kazakhstan's rural and urban areas alike could see rising costs from flood mitigation and repairs, especially if flooding becomes frequent.

These projections underscore the pressing need for Kazakhstan to adopt robust climate adaptation and resilience strategies. The SSP 1-2.6 scenario highlights that emission reductions could stabilize some climate risks, suggesting that global climate policies will play a key role in minimizing hazard frequencies.

However, even under moderate and high-emission scenarios, Kazakhstan must prepare for increased heatwave, drought, and flood probabilities. Enhancing drought-resistant agriculture, improving irrigation practices, and investing in water conservation measures could mitigate drought impacts. In addition, infrastructure reinforcement and flood management systems will be critical for reducing flood-related damages, particularly under scenarios with high flood recurrence.

In conclusion, Kazakhstan's climate outlook illustrates the importance of global emission reductions and national-level adaptation measures. Combining both approaches offers the best hope for protecting the country's population, ecosystems, and economic stability in the face of escalating climate hazards.

6. ECONOMIC DAMAGES

The economic implications of the above described climate-induced water risks are profound. Kazakhstan faces significant challenges related to water scarcity and climate change impacts, which could affect its water availability and economic growth in the coming decades. The agricultural sector is particularly vulnerable, as it heavily relies on irrigation, accounting for 60% of total water withdrawal in 2020-2022 (FAO, 2022). Crop water requirements are projected to increase by 15% by 2050 compared to the 1990 reference period (USAID, 2017). This, coupled with the fact that irrigation water productivity in Kazakhstan is six to eight times lower than in other countries (FAO, 2013)., poses significant challenges to food security as agricultural productivity declines and food supply and prices become more volatile (FAO, 2024).

Also, the droughts have significant implications for Kazakhstan's agricultural sector. Farmers growing moisture-intensive crops face clear water deficits seasonally. These shortages have led to below-average cereal production in recent years (FAO, 2024). For instance, in the Kostanay region, grain yields dropped significantly below the regional average (Rashid & Isakodzhaev, 2021).

The impacts of drought extend beyond agriculture, affecting various aspects of Kazakhstan's socio-economic landscape. Drought events have led to increased livestock mortality, water shortages, and accelerated desertification processes. These factors contribute to rural migration and depopulation, as well as economic hardship in affected regions. In conclusion, drought represents a significant and growing challenge for Kazakhstan, with far-reaching implications for its environment, economy, and society. Addressing this issue will require comprehensive strategies that consider both immediate mitigation efforts and long-term adaptation to changing climate conditions.

The impacts of flooding are also far-reaching, threatening infrastructure, agricultural land, and communities. Recurring floods lead to the displacement of rural and urban populations, increase poverty, and ultimately result in lost livelihoods (UNDRR, 2024a). The economic losses associated with disaster recovery are substantial, underscoring the need for improved flood management strategies. The unprecedented event in 2024 that affected over 6,000 households and led to the evacuation of 117,000 residents, demonstrates the substantial economic and social costs associated with climate-related disasters (UNDRR, 2024a).

The reduction of overall water availability is likely to overwhelm the water management infrastructure. Additionally, pollution of water resources is a concern, exemplified by the Balkhash Mining and Metallurgical Plant discharging about 600,000 tons of industrial waste annually into Lake Balkhash (UNDP Kazakhstan, 2023). These water-related hazards pose significant challenges to Kazakhstan's environmental and socioeconomic stability, necessitating comprehensive water management strategies and international cooperation.

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 Riparian Buffer Zones

Sector: Habitat, Water Management

Hazard: Floods, Desertification

Region: Country-wide around crucial water bodies

Background: Riparian buffer zones and protected areas around bodies of water offer manifold benefits for the environment and act as a natural protection barrier in water management. They are vegetated areas adjacent to rivers, lakes, and streams and provide functions such as erosion control, pollution filtration and temperature regulation. Kazakhstan's riparian areas are primarily found along major rivers such as the Syr Darya, Amu Darya, Chu, and Ile. These zones, known as "tugai," are gallery forests that provide essential habitat for diverse wildlife (UNEP-WCMC 2024). These zones in Kazakhstan offer biodiversity conservation, water regulation, provision of critical habitat and carbon sequestration (FAO 1993).

Current Efforts: The government of Kazakhstan has recognized the importance of these zones around their great bodies of water and introduced several nature reserves and wildlife sanctuaries as well as bird areas and has ratified international agreements with neighboring countries (UNDP 2024).

Suggestion: Expansion, improvement and establishment of riparian buffer zones around all great bodies of water.

Suggested Measures:

- Identification of needs and site assessment by local governments to centralize plans for protection.

- Expansion of existing areas to minimize costs.
- Implementation of reforestation and habitat restoration projects in areas affected by deforestation and water diversion.
- Engagement of local communities in planning and maintaining these zones. Education about the benefits of riparian buffers can encourage stewardship and reduce potential conflicts over land use.
- Enforcement of stricter regulations on land use and resource extraction in and around riparian buffer zones

Expected Benefits:

- Water quality improvement as buffer zones can act as natural filters and thus lower Nitrogen and filter phosphorus.
- Buffer zones would reduce the force, height, and volume of floodwaters by allowing them to spread horizontally across floodplains.
- Microclimate regulation: The shading effect of buffers would help create microclimates, cooling water bodies and stabilizing temperatures

7.2 Agroecological practices

Sector: Agriculture

Hazard: Droughts, Desertification

Region: Country-wide

Background: Agroecology in Kazakhstan has been shaped by the country's unique geographical and historical context. As the world's largest landlocked country and the ninth-largest overall, Kazakhstan possesses diverse agricultural landscapes, ranging from vast steppes to irrigated farmlands. The country's agricultural sector has undergone significant transformations over the past century, influenced by social and institutional changes (Yan 2020). Kazakhstan's agricultural sector faces challenges such as water scarcity, soil degradation, and climate change impacts, particularly in the form of severe droughts (GIZ 2021). In response to these challenges, there has been a growing interest in agroecological approaches. The government has recognized the need for sustainable agricultural practices, as evidenced by the "Green Economy Transition Concept" which aims to address agricultural productivity and environmental issues (GIZ 2021). Additionally, research institutions like the Kazakh Research Institute of Soil Science and Agricultural Chemistry are working on soil resource management and reproduction, contributing to the development of agroecological practices in the country.

Current Efforts: Currently, Kazakhstan is actively pursuing various initiatives to promote sustainable agricultural practices and address environmental challenges such as the carbon farming project "CarbonIQ", which assesses Kazakh soils to store carbon, several sustainable education programs, studies on climate-resistant crops in dry areas and government programs such as "The Green Economy Transition Concept" and several ecologisation processes to promote sustainable agricultural practices.

Suggestion: Strong focus on agroecological practices by the government and international donors/partners.

Suggested Measures:

- An increase in crop diversification to improve soil health with financial incentives from the government.
- Subsidies on no-till machinery to promote practices like strip tilling and no-till farming in arid or semi-arid areas (Central Kazakhstan) to avoid soil erosion and desertification.
- Regulations on integrated pest management near or around great bodies of water to prevent further salination and soil contamination.

- Government-initiated installation of rainwater harvesting systems.

Expected Benefits:

- Environmental resilience: The combined measures are expected to improve soil health and combat both wind and water erosion which would make areas less perceptible for desertification.
- Economic security as reduced dependence on chemical inputs and enhanced soil productivity can lower costs and increase profitability for farmers.
- Improved water quality around large bodies of water.

7.3 Additional suggested adaptation measures

► The introduction and adaptation of full integrated water management. Kazakhstan is currently making greater efforts to improve its integrated water management through the implementation and update of new water legislation (Satulbadina, 2024), has established new institutions for water management and is introducing water monitoring systems (GWP 2024), but is not yet on par with international standards. The country's revised Nationally Determined Contribution (NDC) acknowledges these challenges (rising temperature and heat waves) and includes adaptation components focusing on agriculture, water, forestry, and disaster risk management (UNDP, 2023c).

► Improved early warning systems for floods. The government is in the process of revising the Water Code in order to strengthen its capabilities in flood forecasting and preventatve measures including IT solutions such as the Skymax early warning system and a digital map-chart of flood water passage (Prime Minister of Kazakhstan, 2024). This process should be accelerated with additional measures such as local river monitoring and international donor mobilization to emphasize the focus on long-term solutions which would also include the development of predictive models and tools to mitigate the impact of future floods. Examples for this include a recent collaboration with the Netherlands that aims to implement advanced flood risk management technologies to improve Kazakhstan's ability to predict, respond to, and adapt to flood hazards (Haidar, 2024; UNDRR, 2024b). This initiative includes developing models and tools to enhance flood resilience and improve interagency collaboration (UNDRR, 2024b).

► One of the primary culprits in agriculture for water waste are irrigation techniques and the inefficient use of water. The government is currently working on improved irrigation systems such as drip irrigation, but there is still significant potential for improving water use efficiency and agricultural productivity through modernization of irrigation systems and better water management practices. (FAO, 2023).

► Intensification of rainwater harvesting: Kazakhstan has recognized the need for improved water saving techniques but initiatives to save rainwater more efficiently have been comparably slow. Currently the government is investing in water-saving technologies and subsidies for drilling irrigation wells (Times of Central Asia, 2024), but existing water infrastructure and practices are too focused on conventional sources such as rivers and public awareness is limited.

8. CONCLUSION

Kazakhstan's vulnerability and approach to climate-related water hazards show the escalating risks posed by climate change and the urgent need to act fast in order to mitigate, and adapt to, the worst repercussions. As global temperatures rise, water resources and related hazards have started to become significant issues worldwide. Kazakhstan, already facing immense challenges such as desertification, drought, and extreme heat, is particularly vulnerable to these risks and global consequences.

Based on these trends, the project identified droughts, riverine floods and heatwaves as imminent threats to Kazakhstan. 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.

The study findings highlight that heatwaves are likely to become both more frequent and severe under all climate scenarios, with the highest risks occurring under SSP 5-8.5. Intense heatwaves could become a regular occurrence, posing serious threats to both humans and the economy. Similarly, Kazakhstan's vulnerability to drought, especially in its arid and semi-arid regions, is expected to persist or worsen. Under the SSP 5-8.5 scenario, drought probabilities are projected to increase significantly, underscoring the likelihood of prolonged dry periods that could severely impact agriculture, exacerbate land degradation, and heighten water scarcity. Even under low-emission pathways, drought risks remain above historical baselines, emphasizing the need for ongoing drought management and adaptation strategies.

Flooding, although more variable across scenarios, also presents a growing concern for Kazakhstan. Particularly in the northern and eastern regions, where spring thaw and riverine flooding from the Irtysh, Syr Darya, and Ishim rivers are already prevalent, climate change-induced factors like earlier snowmelt, ice jams, and intense rainfall are compounding flood risks. Scenarios such as SSP 5-8.5 predict an upward trend in flood occurrences, especially for low- and medium-hazard events. Given Kazakhstan's infrastructure vulnerabilities, these risks demand enhanced preparedness and improved flood mitigation strategies to protect communities and ecosystems.

Adaptation measures suggested, such as riparian buffer zones and agroecological practices, could provide effective, sustainable solutions for managing these impacts. Riparian buffers stabilize riverbanks, reduce erosion, and act as natural flood defenses, while agroecological practices promote sustainable land use and resource management, minimizing the impacts of drought and desertification. These strategies emphasize working with natural systems, creating cost-effective and environmentally friendly solutions that not only protect against immediate hazards but also promote long-term resilience.

Kazakhstan's approach demonstrates a proactive commitment to addressing the challenges posed by climate change. By strengthening its capacity to predict, respond to, and adapt to climate hazards, Kazakhstan is building a foundation for reducing the potential devastation of floods, droughts, and heatwaves. Continued investment in climate resilience and adaptation will be essential to safeguarding communities, ecosystems, and the economy in the coming decades. This project serves as a meaningful step toward sustainable adaptation and highlights the importance of national efforts in tackling the global climate crisis.

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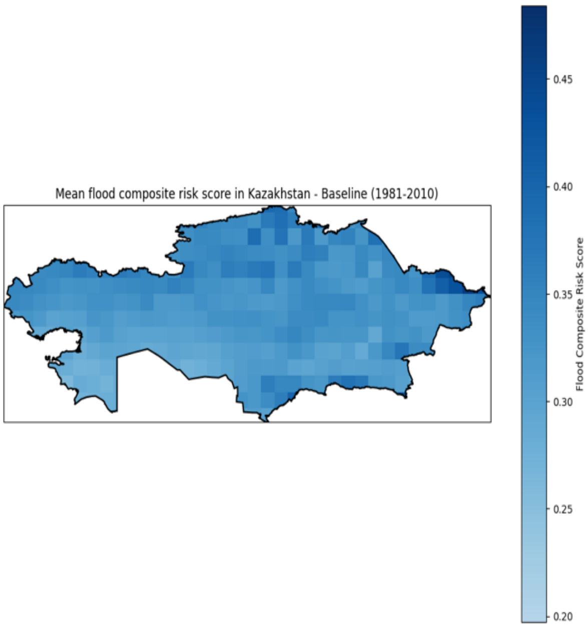
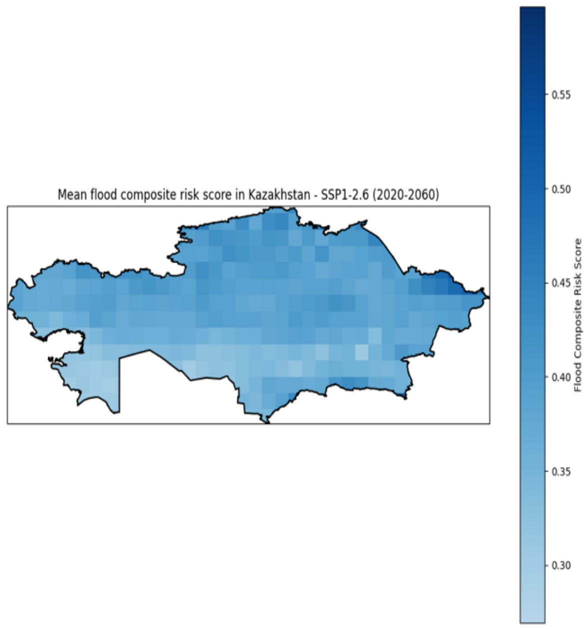
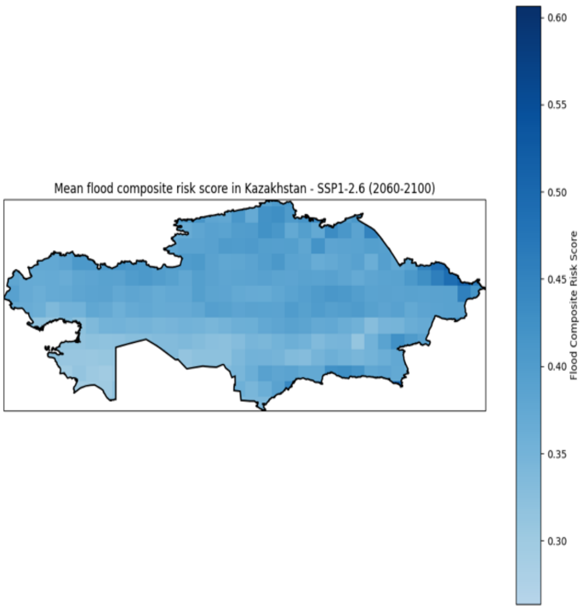
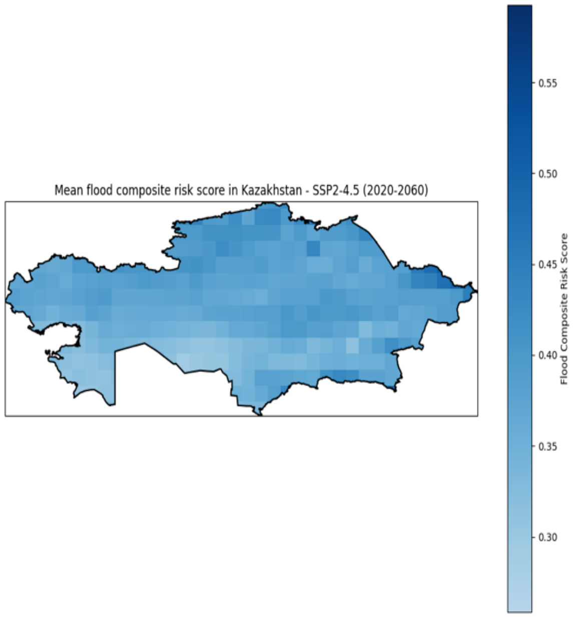
10. ANNEX

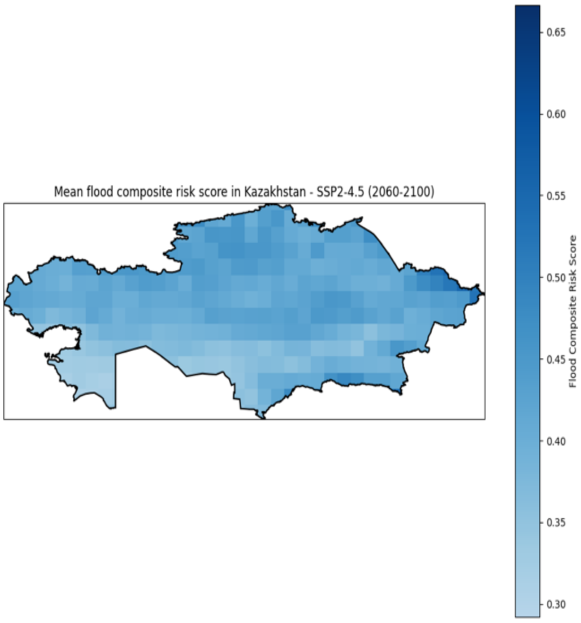
10.1 Mean flood composite risk score

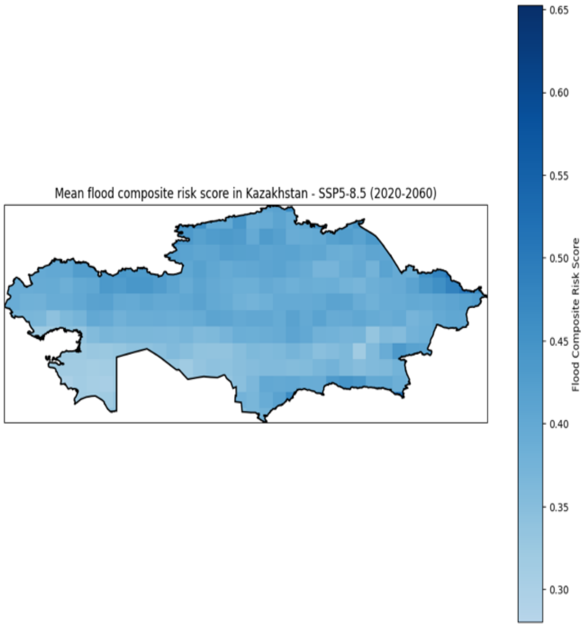


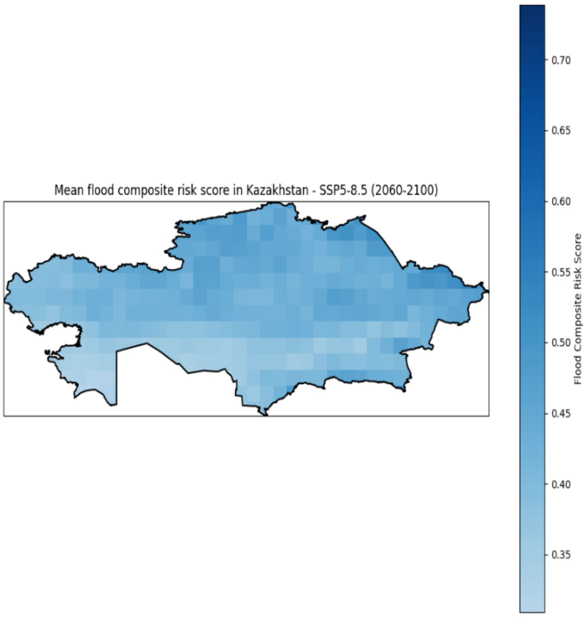




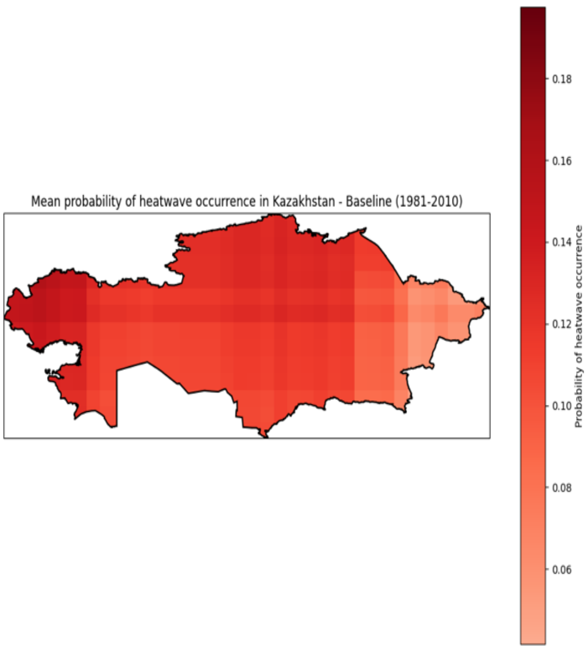


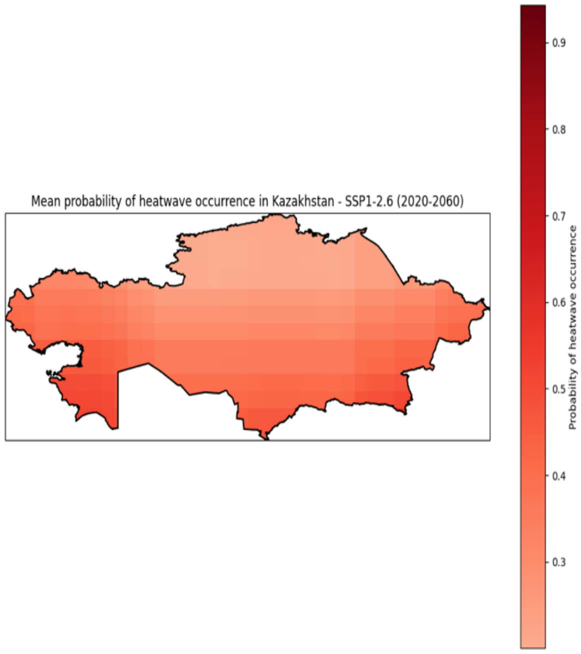

Mean flood composite risk score in Kazakhstan - SSP2-4.5 (2060-2100)
Flood Composite Risk Score
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30

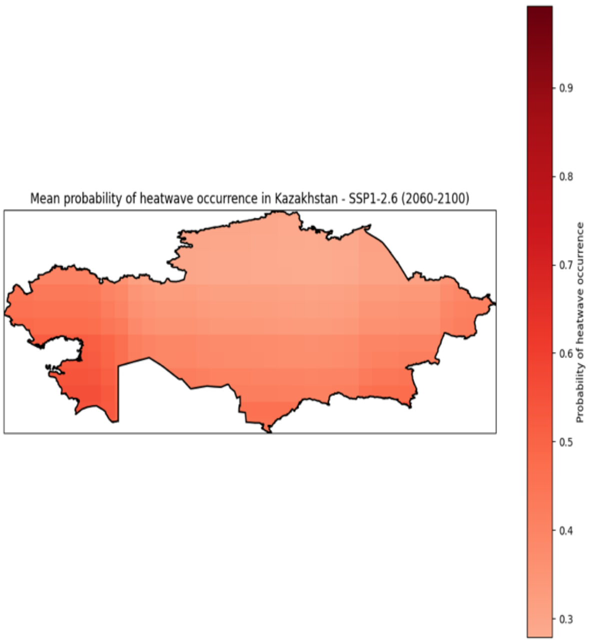

Mean flood composite risk score in Kazakhstan - SSP5-8.5 (2020-2060)
Flood Composite Risk Score
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30

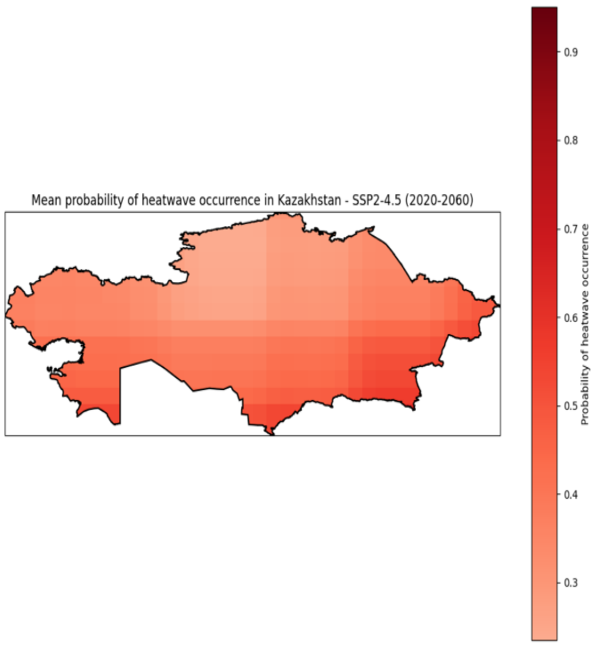

Mean flood composite risk score in Kazakhstan - SSP5-8.5 (2060-2100)
Flood Composite Risk Score
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35

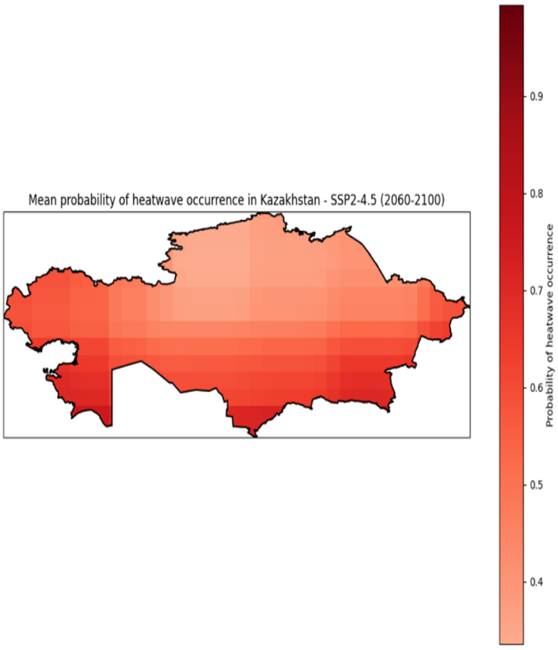
10.2 Heatwave probability

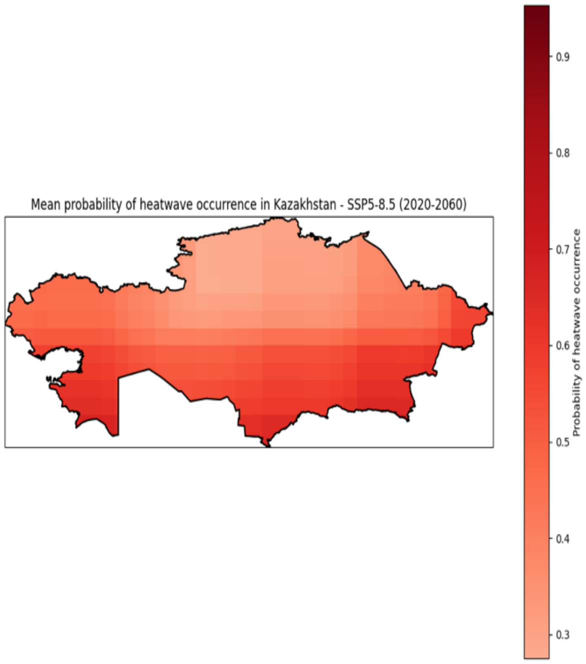


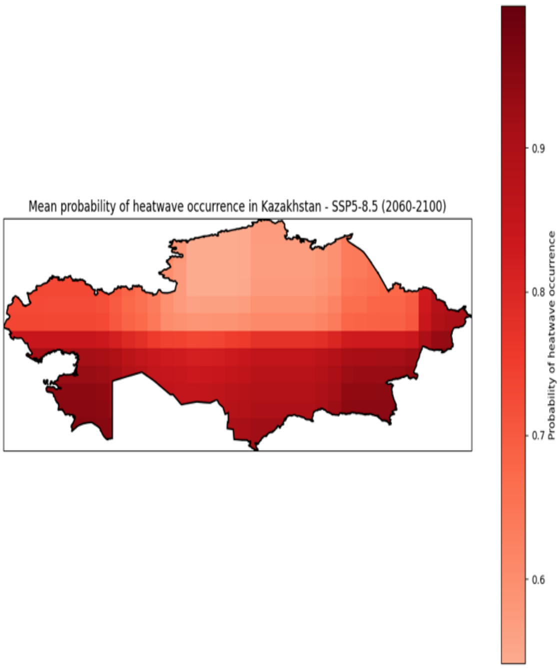




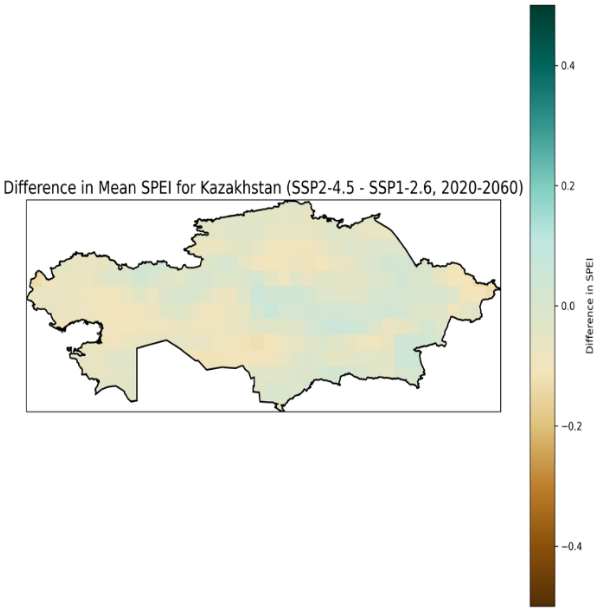


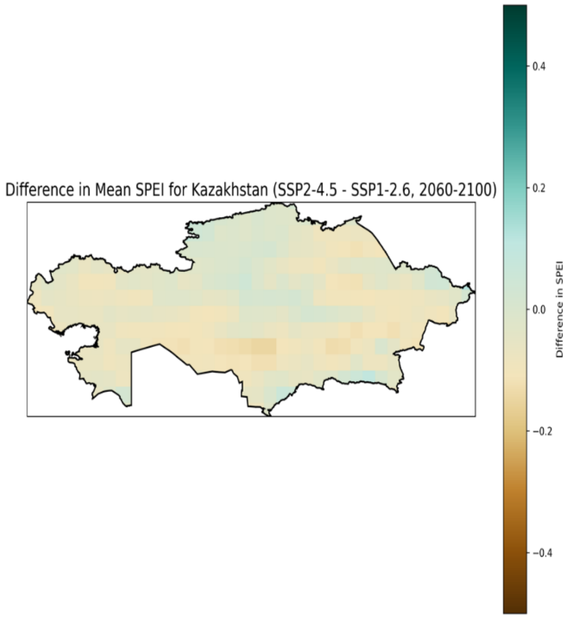

Mean probability of heatwave occurrence in Kazakhstan - SSP2-4.5 (2060-2100)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6
0.5
0.4

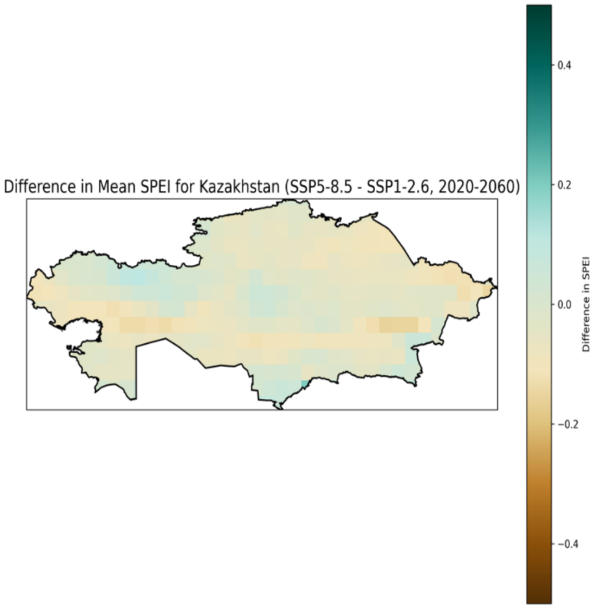

Mean probability of heatwave occurrence in Kazakhstan - SSP5-8.5 (2020-2060)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6
0.5
0.4
0.3

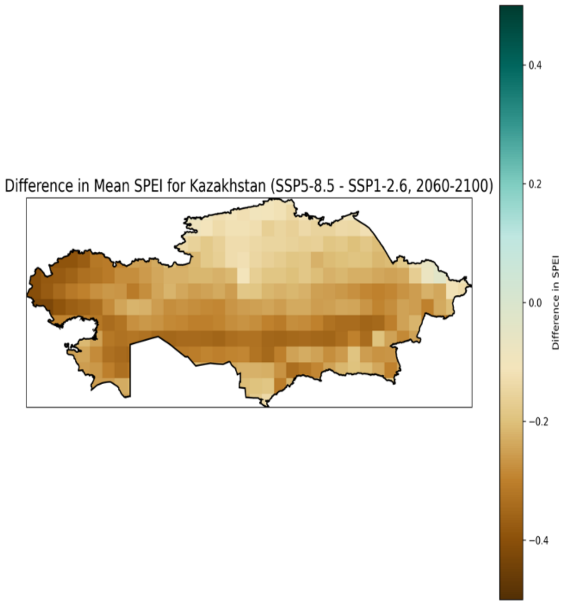

Mean probability of heatwave occurrence in Kazakhstan - SSP5-8.5 (2060-2100)
Probability of heatwave occurrence
0.9
0.8
0.7
0.6

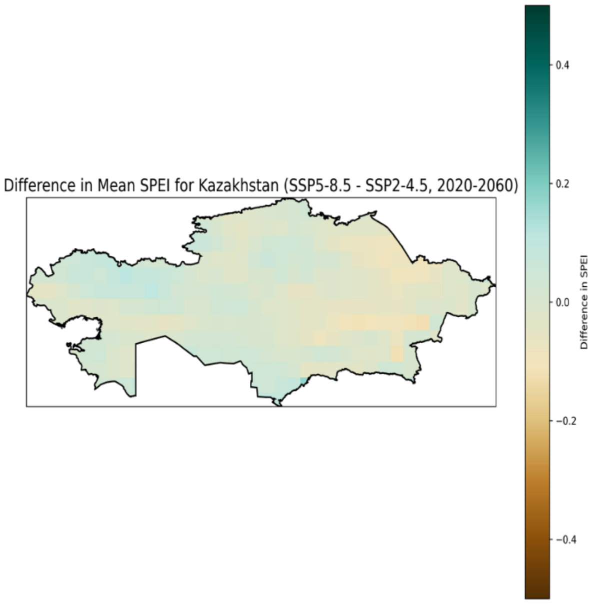
10.3 Differences in mean SPEI

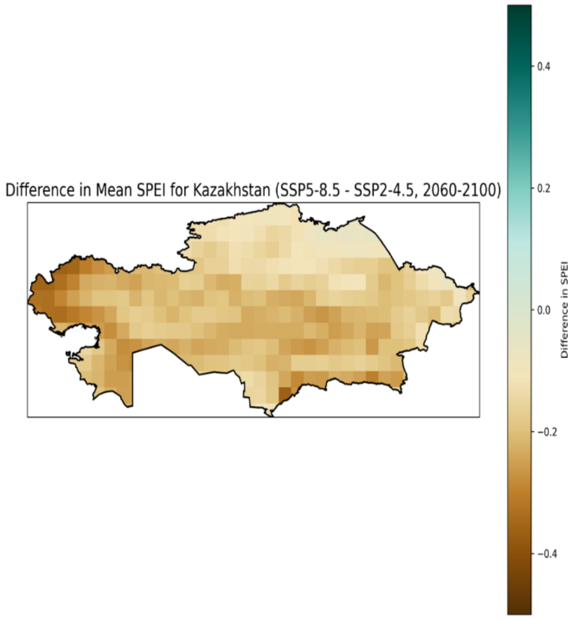









Difference in Mean SPEI for Kazakhstan (SSP5-8.5 - SSP2-4.5, 2020-2060)
Difference in SPEI
0.4
0.2
0.0
−0.2
−0.4


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