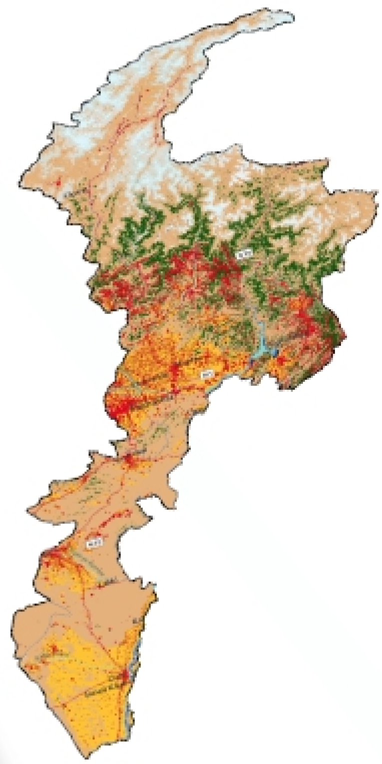
german cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by
giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Ministry of Climate Change



CLIMATE RISK PROFILE FOR KHYBER PAKHTUNKHWA PAKISTAN

Published in 2024

By

Global Change Impact Studies Centre

On behalf of

Ministry of Climate Change and Environmental Coordination

Design: Mr. Zaka ul Rasool

PROLOGUE

As we stand at the precipice of climate uncertainty, Pakistan faces an urgent call to action. The recent floods, droughts, and other extreme weather events are stark reminders of the far-reaching consequences of climate change. These challenges not only threaten our environment but also pose significant economic and social risks to our nation.

In this critical juncture, it is imperative that we equip ourselves with the necessary tools to confront the impending climate crisis. The Climate Risk Profile of Khyber Pakhtunkhwa (KP), presented here, serves as a vital resource in our endeavour to understand and mitigate the impacts of climate change. Developed through rigorous research and analysis, this profile offers valuable insights into projected climate parameters and their implications for various sectors across KP.

I commend the efforts of the German government and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) for their unwavering support in advancing climate resilience in Pakistan. Their commitment to strengthening climate knowledge, fostering organizational development, and facilitating political change processes is commendable. Through collaborative initiatives and cross-sectoral approaches, we strive to harness the potential of mitigation and adaptation measures, paving the way for sustainable development in alignment with the Paris Climate Agreement and Agenda 2030.

The Climate Risk Profile of KP, mainly developed by our Global Climate-Change Impact Studies Centre (GCISC), serves as a cornerstone in our collective efforts to build a resilient and sustainable future. It provides a comprehensive overview of climate risks and opportunities, empowering decision-makers at all levels to make informed choices. Moreover, it lays the foundation for further research and refinement, facilitating adaptive planning and proactive measures to address evolving climate challenges.

As we embark on this journey towards climate resilience, let us embrace the spirit of collaboration and innovation. Together, we can navigate the complexities of climate change and forge a path towards a brighter, more sustainable tomorrow.

Romina Khursheed Alam
Coordinator to the Prime Minister
Ministry of Climate Change & Environmental Coordination
Government of Pakistan

FOREWORD

It is with great pleasure and a sense of responsibility that I introduce the Climate Risk Profile of KP. As the custodian of environmental stewardship in the province, it is incumbent upon us to understand and address the multifaceted challenges posed by climate change.

KP, as one of the populous provinces of Pakistan which and represent a range of diversified hydroclimatic and topographic features, is particularly vulnerable to the impacts of climate variability and change. From extreme weather events to shifting precipitation patterns, the manifestations of climate change are increasingly evident in our daily lives.

The Climate Risk Profile of KP represents a significant milestone in our ongoing efforts to enhance climate resilience and sustainability. Developed in collaboration with esteemed partners such as the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on behalf of the German Development Cooperation, this profile provides a comprehensive assessment of projected climate parameters and their implications for KP's environment, economy, and society.

I extend my sincere appreciation especially to GCISC and to all those involved in the development of this invaluable resource. Their dedication and expertise have ensured the accuracy and relevance of the information presented herein. By offering a nuanced understanding of climate risks and opportunities, this profile equips policymakers, planners, and stakeholders with the insights needed to formulate effective strategies and interventions.

As we navigate the complex terrain of climate change, it is essential that we adopt a proactive and collaborative approach. The Climate Risk Profile of KP serves as a catalyst for informed decision-making and coordinated action, fostering resilience and sustainability across our province.

I encourage all stakeholders to utilize this profile as a guiding tool in our collective efforts to build a climate-resilient KP. Together, let us embrace the challenges and opportunities presented by climate change, forging a path towards a greener, more prosperous future for generations to come.

Zahid Pervez
Secretary,
Environment Protection and Climate Change Department
Government of Punjab, Pakistan

FOREWORD

As the global climate crisis continues to escalate, the imperative for action becomes increasingly urgent. In Pakistan, the impacts of climate change are acutely felt, with regions like KP facing multifaceted challenges that threaten livelihoods, infrastructure, and ecosystems alike.

As the Coordinator of the Energy, Climate Change & Just Transition Cluster at GIZ Pakistan, it is my privilege to introduce this comprehensive Climate Risk Profile for KP. This document represents the culmination of rigorous research, collaboration, and expertise from various stakeholders, aimed at understanding and addressing the climate risks facing this vital region.

Khyber Pakhtunkhwa (KP), often referred to as the lifeline of Pakistan's water resources, plays a pivotal role in the nation's agricultural sector. However, the changing climate poses significant threats to agricultural productivity, water availability, and food security. Furthermore, the impacts ripple across other sectors, including water resources management, public health, infrastructure resilience, and ecosystem integrity.

This Climate Risk Profile delves into the current climate trends, projected future scenarios, intensity and frequency of climate extreme indices, and the potential impacts on key sectors. By examining the intricate interplay between climate variables and socio-economic factors, it provides a nuanced understanding of the vulnerabilities facing KP. Importantly, it also paves the way for adaptation and mitigation strategies to build resilience and mitigate the adverse effects of climate change.

At GIZ, we are committed to supporting Pakistan in its efforts to address climate change and build a sustainable future. Through collaborative initiatives, capacity building, and innovative solutions, we strive to empower communities, government agencies, and private sector stakeholders to tackle climate risks effectively.

I extend my gratitude to all the contributors, researchers, and partners who have dedicated their time and expertise to the development of this Climate Risk Profile. May this document serve as a valuable resource for policymakers, planners, and practitioners in crafting evidence-based strategies to safeguard the future of KP and its inhabitants.

Wolfgang Hesse
Cluster Coordinator
Energy, Climate Change & Just Transition
GIZ Pakistan

PREFACE

In a world increasingly defined by the impacts of climate change, understanding the unique risks and vulnerabilities faced by nations is paramount. Pakistan, with its diverse geography, complex socio-economic landscape, and growing population, stands at the forefront of this global challenge. The need for a comprehensive understanding of Pakistan's climate risk profile has never been more urgent.

This study report on the climate risk profile of KP represents a culmination of rigorous research, data analysis, and stakeholder engagement aimed at unravelling the intricacies of climate vulnerability within the country. Developed through collaboration between experts, policymakers, and community representatives, this report endeavors to provide a holistic perspective on the multifaceted risks posed by climate change across various sectors and regions of Pakistan.

Through detailed examination and analysis, this report sheds light on the evolving climate patterns, extreme weather events, and their cascading impacts on agriculture, water resources, infrastructure, human health, and ecosystems. Moreover, it delves into the socio-economic implications of climate risks, highlighting disparities, vulnerabilities, and adaptive capacities within different segments of society.

While the findings presented in this report may paint a sobering picture of the challenges ahead, they also serve as a clarion call for action. By identifying key risk factors, hotspots, and priority areas for intervention, this report aims to inform evidence-based policymaking, foster resilience-building efforts, and catalyze transformative actions towards a more climate-resilient future for KP, Pakistan.

As we navigate the complexities of climate change, let this report serve as a guiding beacon, illuminating pathways for sustainable development, adaptation, and mitigation. Together, let us embark on a journey of collective action, collaboration, and innovation to safeguard our planet and ensure a prosperous tomorrow for all.

Muhammad Arif Goheer
Head – Agriculture & Coordination
Global Climate-Change Impact Studies Centre (GCISC)
Islamabad, Pakistan

ACKNOWLEDGMENTS

This profile is part of the German Development Cooperation's endeavour to bolster the Pakistani governments' access to precise information regarding climate change's far-reaching impacts across diverse economic sectors. We extend heartfelt appreciation to all reviewers, with special recognition to Mr. Muhammad Arif Goheer, whose unwavering commitment significantly shaped this pivotal resource.

In seamless collaboration with federal and provincial stakeholders, including the Provincial Planning and Development Board (P&D Board), Agriculture and Health departments, Provincial Disaster Management Authorities (PDMA), and other pertinent entities, GIZ Pakistan on behalf of the German Development Cooperation takes pride in presenting these Sub-National Climate Risk Profiles.

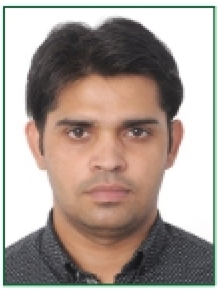
Crafted through the joint efforts of GIZ and the Global Climate-Change Impact Studies Centre (GCISC) in tandem with the Ministry of Climate Change and Environmental Coordination (MoCC & EC), these profiles offer a structured framework for comprehending and evaluating the multifaceted risks posed by climate change. Acknowledging the diverse regional and sectoral impacts, these profiles empower stakeholders with invaluable insights into the specific vulnerabilities, exposures, and potential consequences confronting their communities, economies, and ecosystems.

The profiles received further enrichment through a dedicated launch event convened on March 20, 2024, fostering collaboration and knowledge exchange among representatives from provincial and federal departments, thereby fortifying our collective efforts to enhance national resilience against climate change.

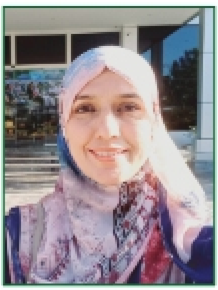
By furnishing decision-makers with comprehensive insights into current and projected climate conditions, sector-specific risk assessments, and an overview of vulnerabilities and priorities, these profiles aspire to guide resource allocation and shape effective national adaptation strategies.

We heartfully acknowledge the invaluable contributions of the following:

CONTRIBUTORS:



Dr. Muhammad Azmat
Sector Specific Climate Impacts



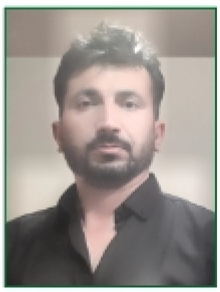
Ms. Qurat-ul-Ain Ahmad
Projected Climate Change patterns

Ms. Nuzba Shaheen
Climate Extreme Indices, Indicators

Dr. Muhammad Abid
Provincial Context

Mr. Sanaullah Khan Hassanzai
Provincial Context

Ms. Aruba Irfan
Proof Reading and Validation



Mr. Zaheer Abbass
Design and Proof Reading

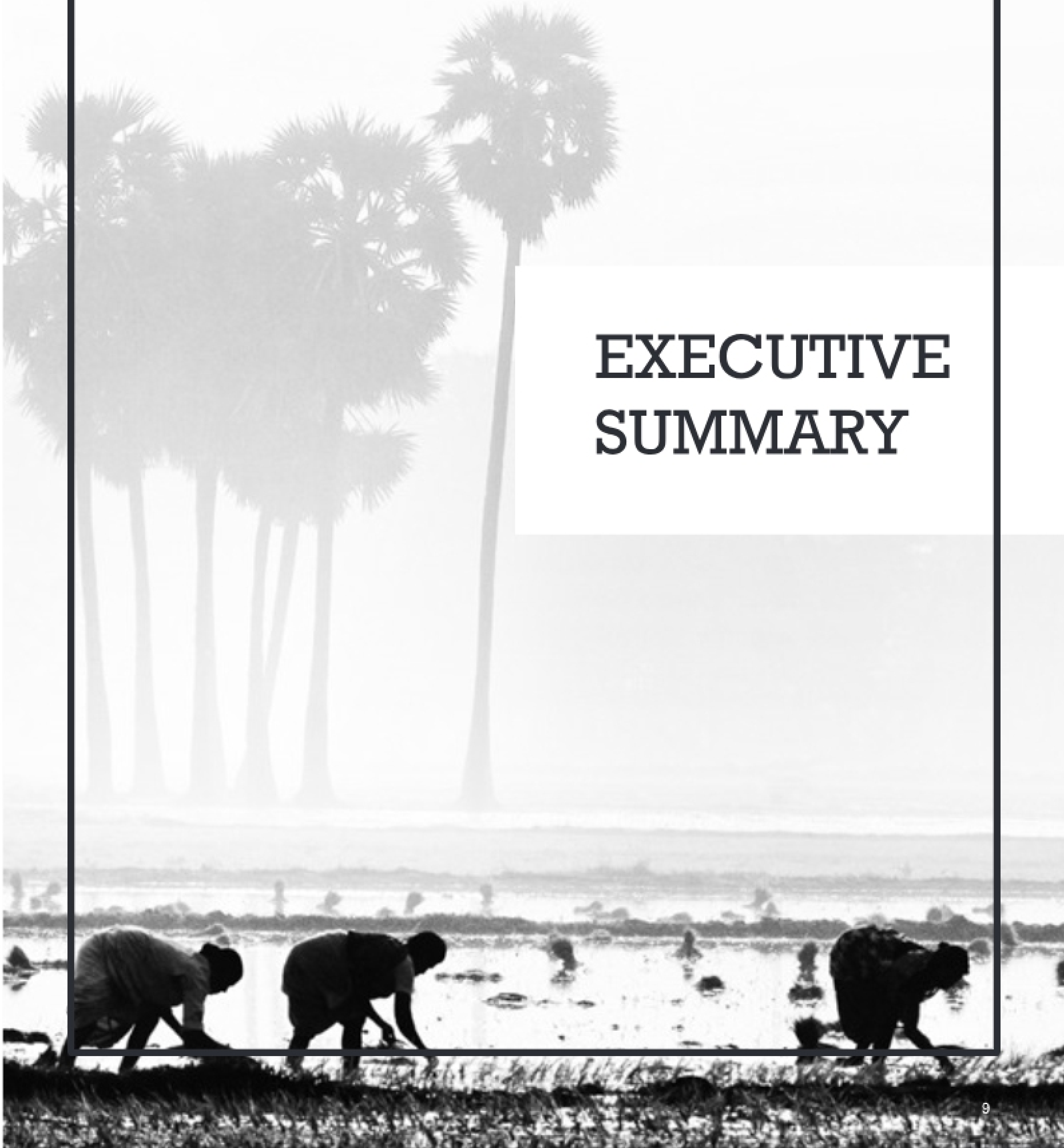
Ms. Swera Javed
Validation and Design

ABBREVIATIONS

BMZ	German Federal Ministry for Economic Cooperation and Development
CRP	Climate Risk Profile
CMIP	Coupled Model Intercomparison Project
GCISC	Global Climate-Change Impact Studies Centre
FAO	Food and Agriculture Organization of the United Nations
GCMs	Global Climate Models
GDDs	Growing Degree Day
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GIZ	Gesellschaft für Internationale Zusammenarbeit
GLOFs	Glacial Lake Outburst Floods
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
KP	Khyber Pakhtunkhwa
MoCC &EC	Ministry of Climate Change and Environmental Coordination
RCPs	Representative Concentration Pathways
SSPs	Shared Socioeconomic Pathways
LULUCF	Land use, Land-Use Change and Forestry
mm	Millimeters
MW	MegaWatts
PET	Potential Evapotranspiration
PERI	Punjab Economic Research Institute
PITB	Punjab Information Technology Board
PRECIP	Precipitation
SPEI	Standardized Precipitation Evapotranspiration Index
TAVG	Average Temperature
TMAX	Maximum Temperature
TMEAN	Mean Temperature
TMIN	Minimum Temperature
TX10P	10th percentile of TX (Cold Days)
TX99P	99th percentile of TX (Warm Days)
USD	United States Dollar

TABLE OF CONTENTS

TABLE OF FIGURES



EXECUTIVE SUMMARY

According to the Global Climate Risk Index, Pakistan is currently the eighth most climate-affected country in the world. Pakistan contributes little to global CO2 emissions (0.75% with just under 3% of the world's population) but is one of the countries most affected by the impacts of climate change. Pakistan is particularly vulnerable to flash floods, heavy monsoon rains, cyclones, droughts, and heat waves due to extreme weather events. Melting glaciers in the Himalayas threaten flooding in the short to medium term and droughts in the long term. Extreme weather events already cause an average economic loss of almost EUR 3 billion per year. **If Pakistan did not take measures to adapt to climate change, more than 21,000,000 people, or 10% of the country's population, could face additional poverty by 2050.** At the same time, the technical and financial capacity to adapt to the adverse effects of climate change is very low. Heatwaves in rapidly and unsustainably growing cities, as well as extreme weather events and natural disasters, particularly affect the poor population dependent on local livelihoods and natural resources.

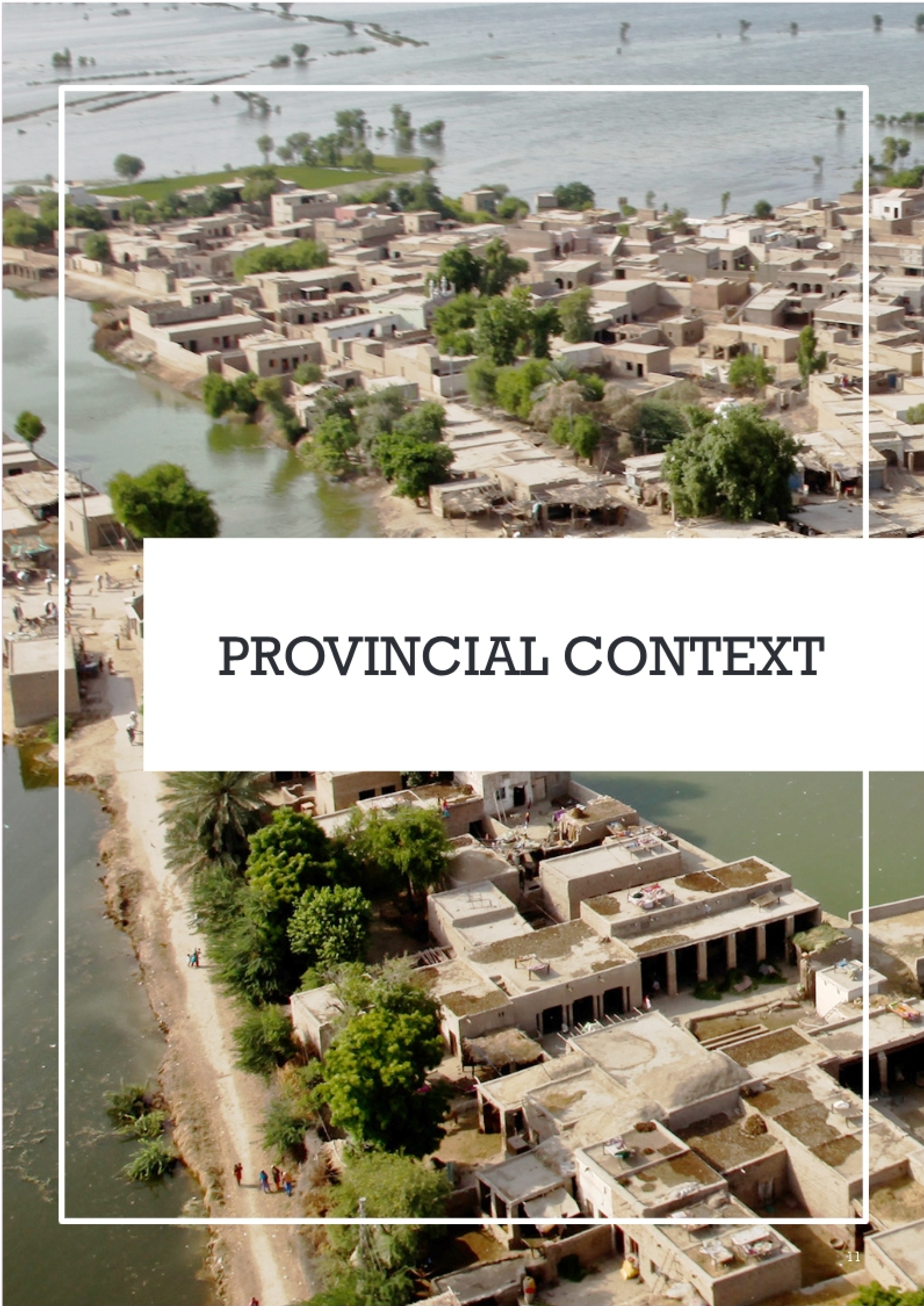
In Pakistan, water resources, agriculture, infrastructure, ecosystems, biodiversity, and public health are all vulnerable to the impacts of climate change. **The country's Climate Change Policy, National Adaptation Plan, and Nationally Determined Contributions (NDCs) prioritize adaptation efforts in these sectors, particularly focusing on agriculture and energy due to their significant emissions.** This sub-national climate risk profile meticulously utilizes the **latest CMIP6 climate change scenarios tailored to KP's unique context. It encompasses critical climate extreme indicators across various spatial and temporal scales.** Importantly, this sub-national profile supplements existing national-level climate risk assessments conducted by reputable organizations such as PIK, the World Bank, and the Asian Development Bank, which mainly relied on CMIP5 IPCC climate change scenarios.

This sub-national profile offers an overview of projected climate change trends and their related impacts on various sectors within Khyber Pakhtunkhwa (KP), Pakistan, by the end of the 21st century. **The analysis is conducted under different climate change and socio-economic scenarios, including Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs). Specifically, this report presents findings based on RCP-SSP 2.4.5** (a world with moderate emissions, approximately 2.7°C warmer than pre-industrial levels) **and RCP-SSP 585** (a world with very high emissions, approximately 4°C warmer than pre-industrial levels – an unlikely scenario) **). It is unlikely). Khyber Pakhtunkhwa, like the rest of Pakistan, is highly vulnerable to climate change due to its topography, demography and heavy reliance on agriculture and water resources from the HKH region in the North. Understanding the projected climate change patterns and associated impacts under RCP 2.4.5 and RCP 5.8.5 on Khyber Pakhtunkhwa is essential for informed decision-making and effective policy formulation.** By delineating the differences between various climate change scenarios, stakeholders can devise robust strategies to mitigate risks and enhance resilience across key sectors in the region.

The large and positive increase **of > 5.5 °C in seasonal temperature is observed during summer in the Northern parts of KP during F2 (2061-2100) under RCP-SSp 585**. In winter, a uniform increase of **more than 4.5 °C is observed in the whole KP during the late century** period under a high emission scenario.

There is a large variation in the spatial distribution of precipitation both in terms of quantity and location during both seasons with the largest change in F2 (2061-2100) under RCP-SSP585. **In KP, the positive increase in precipitation is large during summer as compared to winter. During summer, the largest increase in precipitation is observed in the Southern Parts (> 110 mm).**

In KP under 585 scenarios wheat yield will be a bit stable with no significant changes while sharp decrease with high variability in 245 yields**. No significant changes (7%) in wheat yield for SSP-245 and 25 % decline in Rice yield in KP for SSP-585**



PROVINCIAL CONTEXT

Khyber Pakhtunkhwa, situated in the northwestern region of Pakistan, is one of the country's four provinces. Although it is the smallest province geographically, it ranks third in population, with approximately **35 million residents, comprising about 15% of the nation's population. Economically, Khyber Pakhtunkhwa contributes significantly, accounting for 10.5% of Pakistan's total economy.**

The rugged terrain of Khyber Pakhtunkhwa, compounded by the integration of the Merged Areas, has intensified the vulnerability of its rural population. Particularly in the Merged Areas and remote regions, internally displaced individuals and those who recently returned face heightened risks from climate hazards and consequent food insecurity. **As of August 2020, 1.18 million people, constituting 23% of the Merged Areas' population**, are grappling with crisis and emergency-level food insecurity due to prolonged conflict, which has disrupted food and livestock production, infrastructure, and markets. Concurrently, the province's population is growing at a rate of about 2.4%, underscoring the urgency of ensuring agricultural self-sufficiency. The province witnesses significant out-migration, primarily of young males seeking better economic prospects elsewhere, leaving the responsibility of farm management to female family members. The province's economy is diversified, with key sectors including forestry, mining, agriculture, and manufacturing. Agriculture, particularly focused on major crops like wheat, maize, tobacco, rice, sugar beets, and various fruits and vegetables, is a vital component. To support these economic activities, a reliable transportation network is essential. Khyber Pakhtunkhwa heavily relies on road transport, serving as a crucial transit corridor to Afghanistan through the Khyber Pass. The province boasts a well-developed road infrastructure, including a network of over 15,000 kilometres of classified paved roads. The capital of the province Peshawar extends northward along the Kabul River. It contains about half of the province's total population even though it covers one-tenth of the total covered area by the Khyber Pakhtunkhwa. In the west of Peshawar, the Iconic Khyber Pass is an easy route between Afghanistan and the Indian subcontinent. Peshawar's climate is warm and temperate.

Khyber Pakhtunkhwa consists of mountain ranges, undulating submontane areas, and plains surrounded by hills. The mountain ranges generally run in the north-south which is the south of the River Kabul. It divides the Khyber Pakhtunkhwa from east to west. The Hindu Kush region in the North is known for its exotic beauty. The highest peak of the northern Hindu Kush is the Tirich Mir. The rugged basins of the Panjkora, Swat, and Kandia rivers lie in the south of the Hindu raj.

Agricultural development stands as a pivotal cornerstone for Khyber Pakhtunkhwa's food security and economic self-reliance. Despite encompassing only 8.4% of Pakistan's agricultural land, Khyber Pakhtunkhwa's agricultural sector employs a significant 33% of its labor force. However, the province heavily depends on neighboring regions, particularly Punjab, for essential food commodities like wheat, rice, citrus, and vegetables. Home to around 35.5 million people, with 81% residing in rural areas and a substantial 27% living below the national poverty line, Khyber Pakhtunkhwa faces considerable development challenges.

Conflict-affected Merged Areas rely heavily on subsistence agriculture, but economic activities have been severely disrupted. The region's human development index, particularly in the Merged Areas, is notably low, exacerbating multi-dimensional poverty.

Topography and Environment

Geographically, the province of Khyber Pakhtunkhwa is divided into two zones, the northern zone, and the southern zone. **The northern zone scopes from the Hindu Kush to the borders of the Peshawar basin. The climate of the northern zone is snowy and cold with heavy rainfall in winter. It has pleasant summers with moderate rainfall** excluding the Capital Peshawar which is hot in summer. The southern zone ranges from Peshawar to the Derajat basin. It has hot summers with relatively cold winters with minimal rainfall.

The climate in the province exhibits significant variation based on elevation. **Mountainous regions experience cold winters and mild summers, whereas temperatures tend to rise towards the southern areas.** Precipitation levels fluctuate across the province, averaging around 16 inches annually. The period from January to April typically sees the most significant rainfall. The northern mountain slopes are characterized by dense oak and pine forests, as well as expansive grasslands. Peshawar, in particular, receives notable rainfall throughout the year, with even the driest months experiencing some precipitation. **The average temperature in Peshawar is 22.3°C (72.1°F), with annual precipitation ranging from 817 mm to 32.2 inches.**

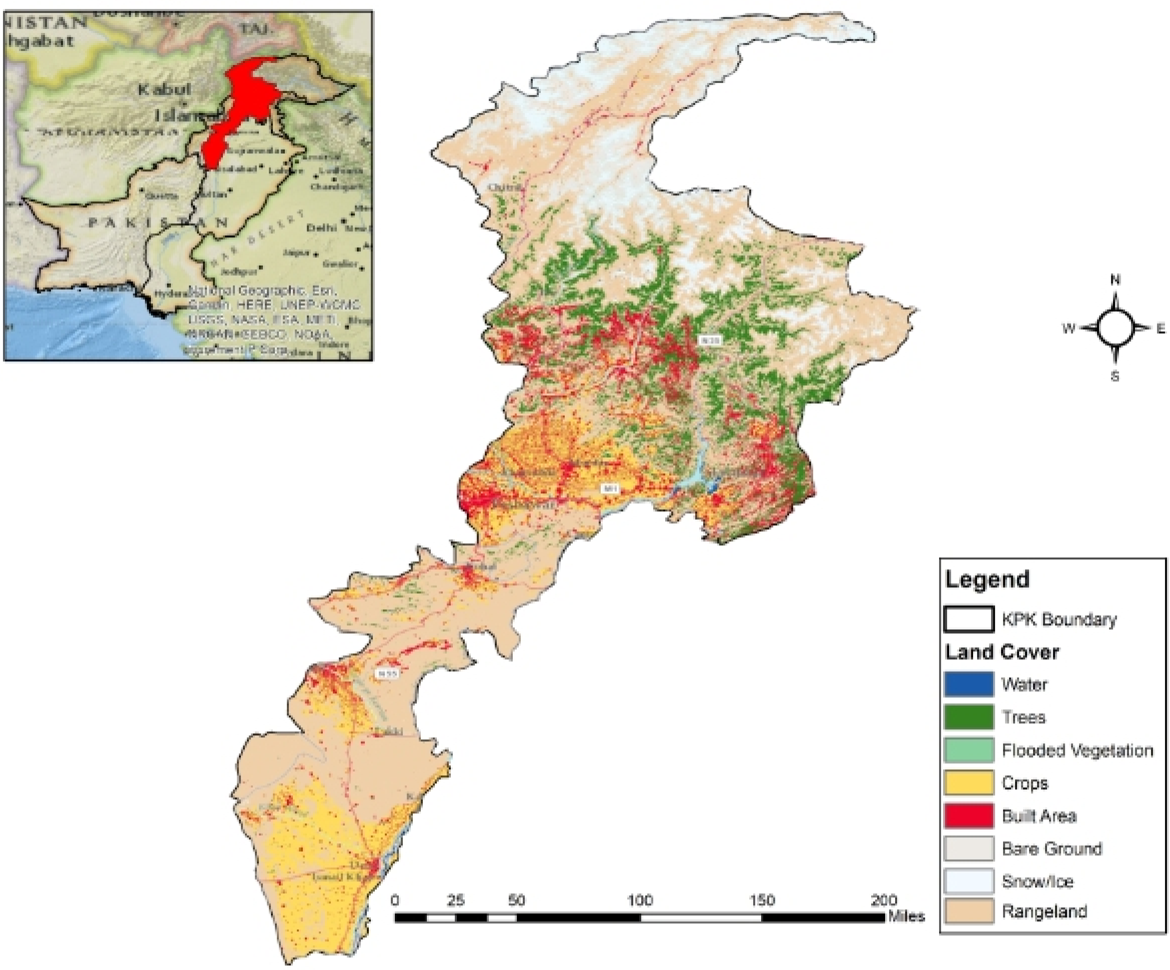


***Figure 1: Location of Khyber Pakhtunkhwa Province in Pakistan** (Source: Land Cover Atlas of Pakistan, The Khyber Pakhtunkhwa Province, and Federball Administered Tribal Areas)*

Current Climate

The climate of the province varies with elevation. **The mountain ranges encounter cold winters and cool summers,** whereas the temperature rises towards the south. **Precipitation of the province is fluctuating; roughly it averages about 16 mm annually.** The most active duration for the precipitation occurs from January to April. The mountain slope in the north is known for oak and pine. The area is also filled with immense grasslands.

Temperature

In the lower parts of KP, particularly in the southern regions, the **mean summer temperature remains relatively stable at around 30 degrees Celsius**. However, as we move towards central KP, there is a noticeable variation in summer temperatures, especially from south to north.

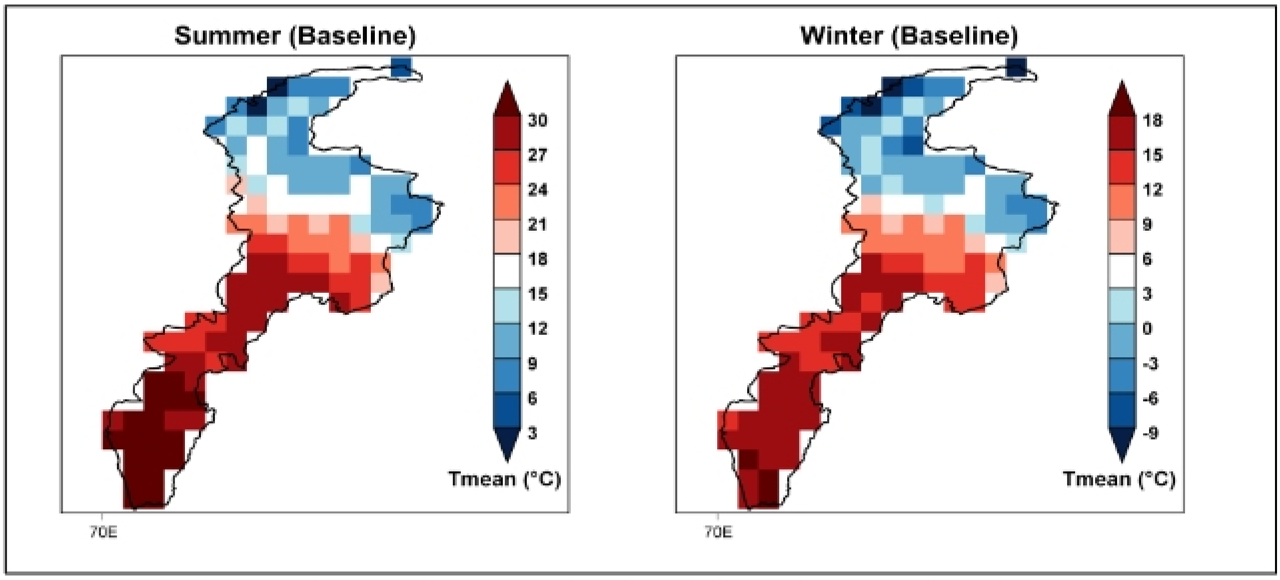


Figure 2: Seasonal (Summer (April – September) and Winter (October – March) patterns of mean temperatures (Tmean ^{o}C) of KPK province during the baseline period (1974-2014)

Overall, the figure highlights the diverse climatic conditions within KP province during the winter season, with warmer temperatures in the lower regions and much colder temperatures in the central and northern mountainous areas. Furthermore, as we ascend towards the Himalayan ranges in the northern parts of KP, there is a significant drop in mean winter temperatures. **In these mountainous areas, the mean winter temperatures plummet to as low as -9 degrees Celsius**. Similarly, in the upper parts of KP, there is a notable decrease in temperatures, with mean **winter temperatures ranging from -3 to -6 degrees Celsius**. **In the lower parts of KP, such as the southern areas, the mean winter temperature typically falls within the range of 15-18 degrees Celsius.**

In central KP, as we progress from the southern areas towards the northern regions, there is a significant change in the mean summer temperatures. Towards the southern parts of central KP, temperatures may be comparable to the lower regions, **around 30 degrees Celsius**. However, as we move northward, towards the upper parts of central KP, the temperatures exhibit a notable decrease. **In these upper regions, the mean summer temperatures range between 6 to 9 degrees Celsius.**

Precipitation

Large precipitation amount (> 500 mm) is observed in the central KP region during both seasons with a larger spatial extent during winter.

A substantial decrease in precipitation is observed in both seasons as we move from central parts to the South.

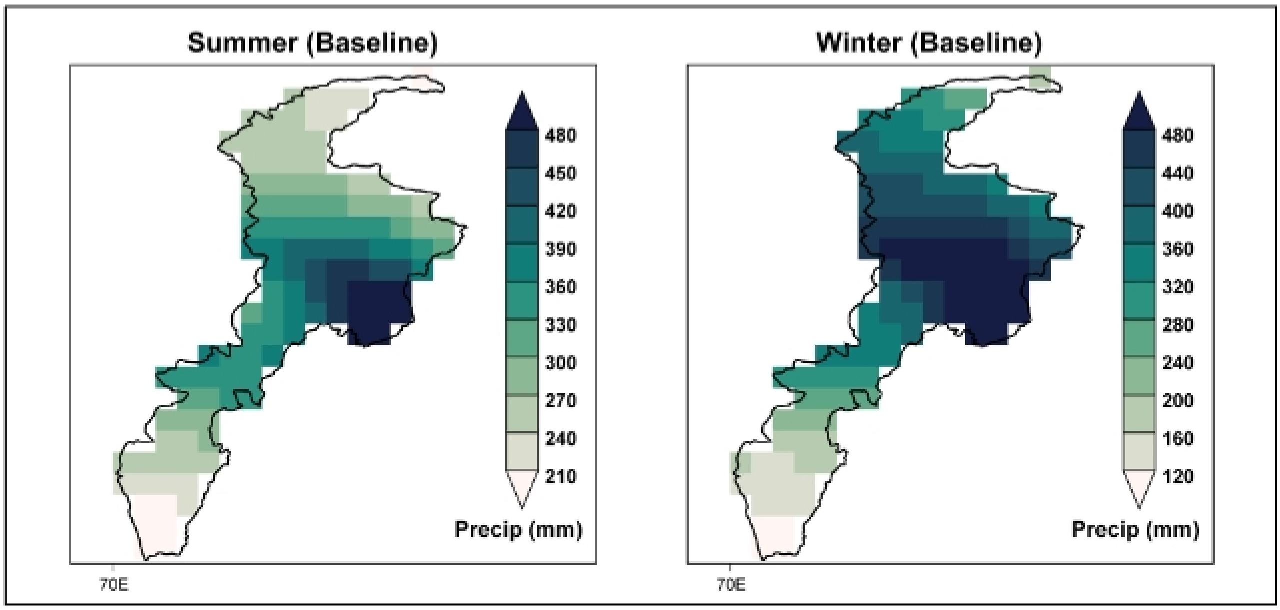


Figure 3: Seasonal (Summer (April – September) and Winter (October – March) patterns of total precipitation (mm) of KP province during the baseline period (1974-2014)

PROJECTED CLIMATE CHANGES

Temperature

Projections for seasonal temperatures in KP province indicate notable upward trends under both emission scenarios, with more pronounced increases anticipated during winter months. Particularly, the most substantial rise in average temperatures (Tmean) is forecasted for the summer season, exceeding 6 degrees Celsius in the latter half of the century (2061-2100) under the RCP-SSP585 scenarios.

Conversely, **in the northern parts of Pakistan, including KP (Khyber Pakhtunkhwa) and adjoining areas, the figure suggests a comparatively lower but still notable range of temperature changes, varying from 1 degree Celsius to 3.8 degrees Celsius.** While these increases are relatively less extreme compared to the southwestern regions, they still carry implications for local ecosystems, water resources, and socio-economic activities.

The future mean temperature spatial distribution in the KP (Khyber Pakhtunkhwa) district of Pakistan during summer season reveals a notable discrepancy in temperature changes between the northern and southern parts. According to the figure, **the northern regions are projected to experience a higher degree of temperature increase, reaching up to 4 degrees Celsius, as we transition from historical to end-century periods under the SSP585 scenario**. During the winter season, the spatial distribution of mean temperatures exhibits significant variations and diversity at the local scale as one moves from north to south in the KP district of Pakistan. This variation suggests that different regions within the district experience distinct changes in winter temperatures, influenced by a range of factors such

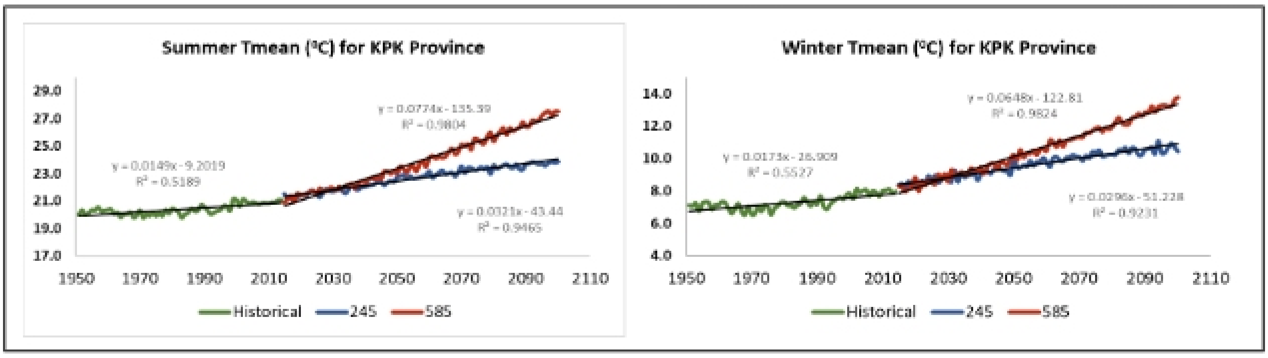


Figure 4: Future changes in the temporal distribution of seasonal (Summer (April – September) and Winter (October – March)) temperatures (Tmean °C) of KP province during the 150 years from 1950–2100

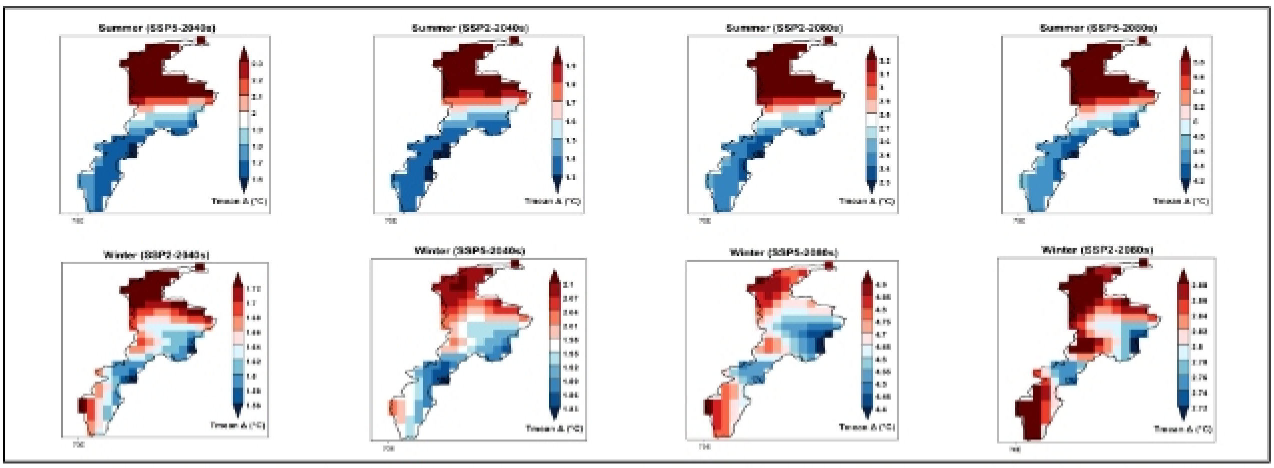


Figure 5: Future changes in the spatial distribution of seasonal (Summer (April – September) and (Winter (October – March) temperatures (Tmean °C) of KP province during the 2040s and 2080s under SSP2 and SSP5 emission scenarios.

as elevation, proximity to water bodies, and local geography. In contrast, **the southern parts of KP show comparatively lower temperature changes, with increases of up to 3.2 degrees Celsius over the same period**. This gradient of temperature changes from north to south underscores the complex interplay of geographical and climatic factors shaping regional climate trends.

Precipitation

In the context of seasonal temperature trends in Khyber Pakhtunkhwa (KP) under two emission scenarios (RCP-SSP585 and RCP-SSP245) from 1951 to 2100, it's important to note that these scenarios represent different trajectories of future greenhouse gas emissions and socio-economic development.

Analysing the trends in summer and winter temperatures reveals a consistent pattern of linear and significant increases over time under both emission scenarios. This means that, regardless of the specific pathway of emissions and socio-economic conditions, temperatures in both summer and winter seasons are projected to rise steadily throughout the 21st century. The implications of these temperature trends are particularly significant for various sectors, including agriculture, water resources, and public health. As temperatures increase, the agricultural sector may face challenges such as changes in growing seasons, increased water demand for irrigation, and shifts in the distribution of pests and diseases.

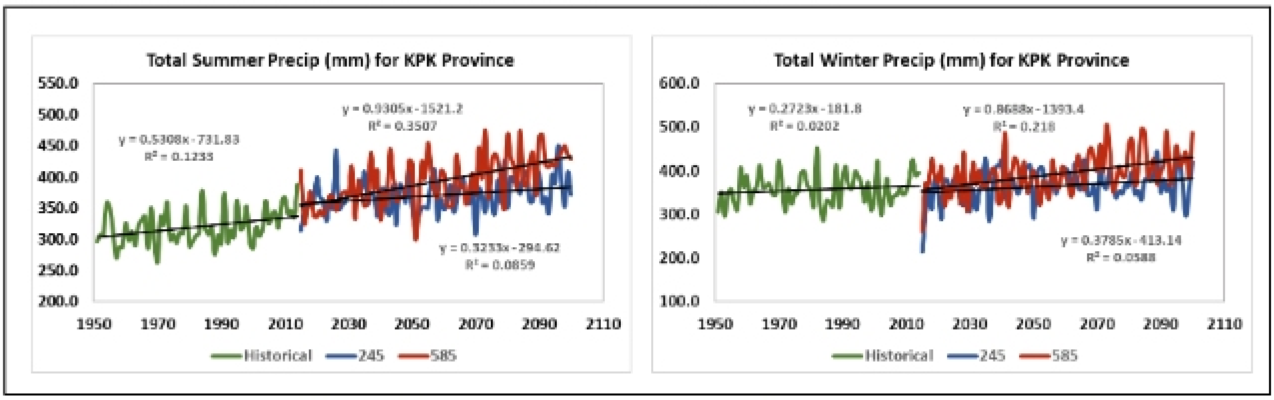


Figure 6: Future changes in the temporal distribution of seasonal (Summer (April – September) and Winter (October – March)) precipitation (mm) of KP province during 150 years from 1950–2100

Water availability, crucial for agriculture and other sectors, may also be affected, especially during the times of the year when it is most needed. Changes in precipitation patterns, coupled with rising temperatures, can alter the timing and magnitude of river flows, affecting irrigation schedules and water supply for domestic and industrial use. Additionally, the impact on public health cannot be overlooked. Rising temperatures can exacerbate heat-related illnesses and increase the frequency and intensity of heatwaves, posing health risks, particularly to vulnerable populations.

Moreover, the observed large inter-annual variation suggests a degree of unpredictability and variability in future climate conditions, which further complicates adaptation planning and resilience-building efforts. Overall, the linear and significant increase in temperatures, particularly towards the end of the century, underscores the urgent need for proactive measures to adapt to climate change impacts in KP. This may involve implementing strategies to enhance water management practices, improve agricultural resilience, and strengthen public health systems to mitigate the adverse effects of rising temperatures on communities and ecosystems.

Our analysis of seasonal precipitation patterns in Khyber Pakhtunkhwa (KP) reveals notable trends for the future periods F1 (2021-2060) and F2

(2061-2100) under RCP-SSP 245 and 585 emission scenarios. Spatial maps depicting precipitation distribution during the summer and winter seasons demonstrate distinct patterns across the province. In the summer season, characterized by monsoon rainfall, higher precipitation levels ranging from 10 mm to over 100+ mm are observed, particularly in the northeastern regions of KP. This heightened precipitation intensity and frequency are consistent with monsoon rains, contributing significantly to the overall precipitation levels.

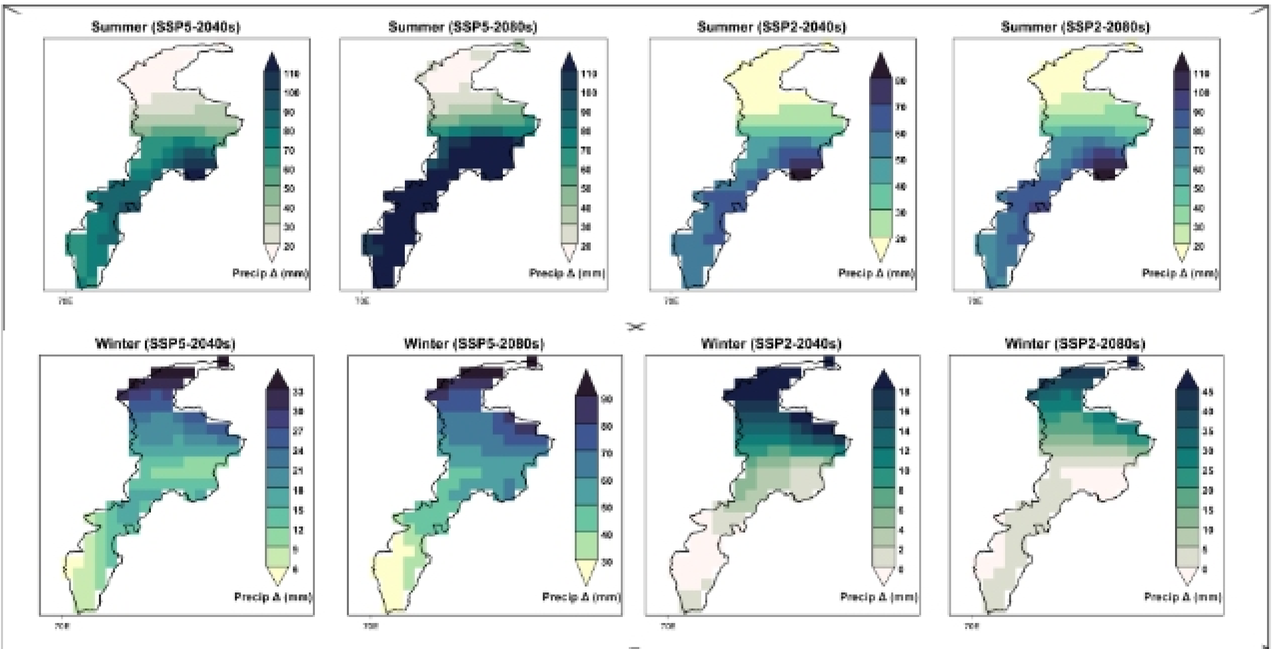


Figure 7: Future changes in the spatial distribution of seasonal (Winter (October – March) and (Summer (April – September)) precipitation (mm) of KP province during 2040s and 2080's under SSP2 and SSP5 emission scenarios.

In contrast, **winter precipitation exhibits a more uniform distribution, with levels typically up to 20 mm across the province**. Looking towards the future, our analysis indicates a substantial increase in precipitation levels during the **Kharif season towards the end of the century, with a more pronounced rise under the RCP-SSP 585 emission scenario**. These findings underscore the need for adaptive strategies and sustainable development practices to address the challenges posed by climate change and ensure the resilience of KP's ecosystems and communities.

Climate Extreme Indices

Very Hot Days

As temperatures continue to increase, the frequency of extremely hot days, defined as days with a daily maximum temperature exceeding 35°C, is expected to increase significantly across KP. This trend is particularly pronounced in the central and southern parts of the province. Our analysis of spatial maps depicting the distribution of hot days in the future provides crucial insights into the changing climate dynamics of KP province. Hot days are estimated using daily maximum temperatures of KP province with the threshold of 35 °C for the control period (1974-2014) and for two future periods F1 (2021-2060) and F2 (2061-2100) under two emission scenarios i.e., RCP-SSP 245 and RCP-SSP 585.

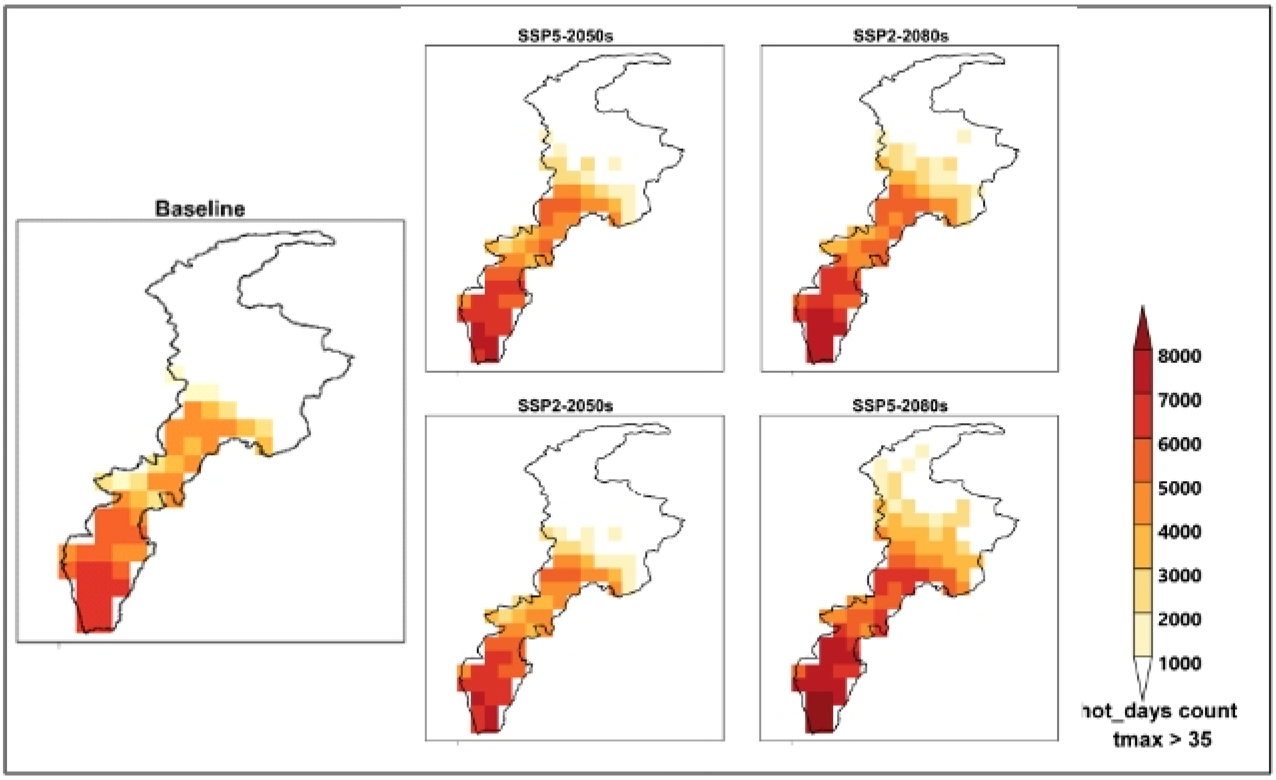


Figure 8: Future changes in the spatial distribution of hot days of KP province during the baseline period 1974–2014 and F1 (2021-2060) and F2 (2061-2100) under two emission scenarios i.e., RCP-SSP 245 and RCP-SSP 585

The maps reveal a higher number of hot days observed in the southern parts of KP. The hilly and mountainous terrain of KP experiences fewer hot days as compared to the southern parts of the province, attributed to its cooler microclimate. **The maps also illustrate that the increasing temperatures projected under the RCP-SSP585 emission scenario are reflected in the distribution of hot days.** Furthermore, the spatial maps provide a comparison of **hot day frequency and intensity under two emission scenarios (RCP-SSP245 and RCP-SSP585) and two future periods (F1: 2021-2060 and F2: 2061-2100),** offering valuable insights into the regional variations and impacts of climate change on temperature extremes.

Cold Nights

Cold nights are defined as the number of days over a period where the daily minimum temperature is below 0 degrees C of a five-day window centered on each calendar day of a given 40-year climate reference period.

From the historical period until the late century, the occurrence of cold nights, defined as nights with temperatures falling below a certain threshold, is **relatively low in the lower parts of Khyber Pakhtunkhwa (KP), numbering less than 1000.** However, in the upper parts of KP, there is a notable increase in the frequency of cold nights. Here, the count of cold nights surpasses 10,000 days, indicating a substantial rise in the prevalence of colder temperatures, particularly at higher elevations.

It's essential to note the significant spatial variability across the region, highlighting the diverse climatic conditions within KP. This increase in the frequency of cold nights, especially in the upper regions, may have implications for various sectors, including agriculture, human health, and infrastructure. Agricultural practices, for instance, may need to adapt to colder conditions, affecting crop selection and cultivation methods. Additionally, the health sector may need to prepare for increased demand related to cold-related illnesses. Understanding these trends and spatial variations is crucial for effective climate change adaptation planning and resilience-building efforts in KP.

Climate Extremes (Warm, Dry, Wet and Cold)

Under a changing climate, climate extremes, including warm, dry, wet, and cold, are projected to increase across the entire KP Province, with significant variations (both spatially and temporally) under RCP-SSP 2.4.5 and RCP-SSP 5.8.5. This analysis presents the seasonal trends, changes and frequency and intensity of climate extremes over KP Province. The temperature extremes are based on averaged anomalies of seasonal temperature using TX10p (cold) and TX99p (warm) relative to mean values of maximum temperature for the control period (1974–2014).

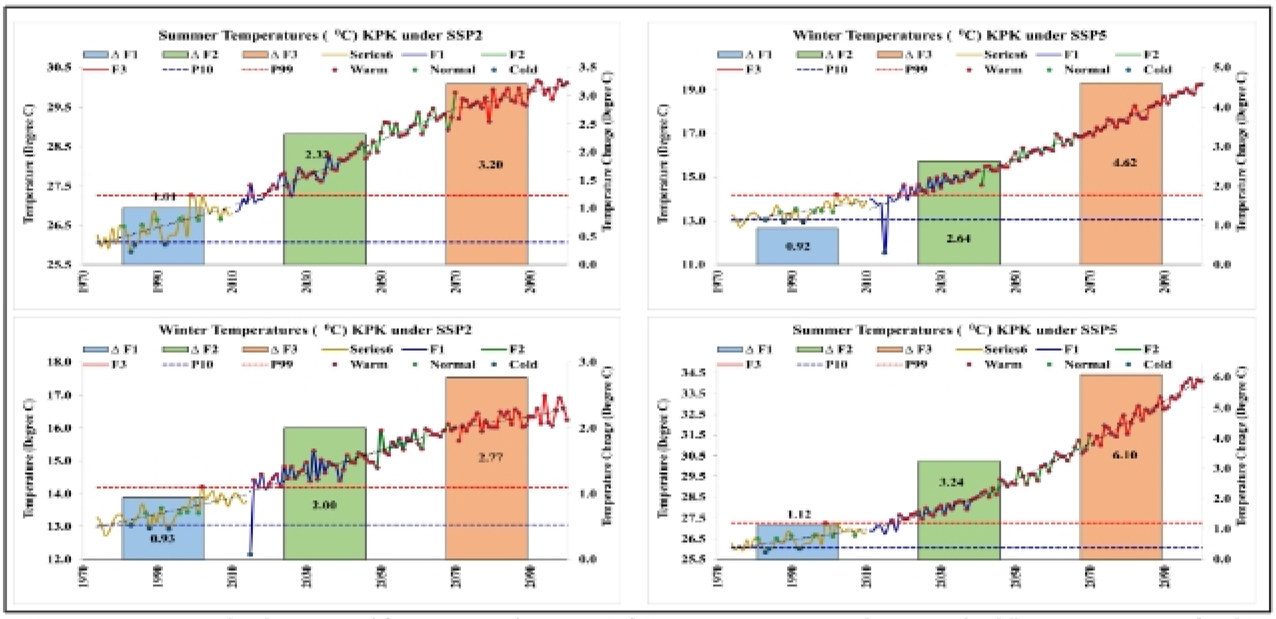


Figure 9: Future trends, changes and frequency and intensity of temperature extremes (warm and cold) over KP Province for the period from 1981-2100 under two emission scenarios (RCP-SSP 245 and RCP-SSP 585

The linear graphs depicting temperature trends in Khyber Pakhtunkhwa (KP) provinces provide valuable insights into climate patterns. In these plots, we illustrate the linear trends of maximum temperature (Tmax) during summer and winter seasons, along with the values corresponding to the 99th percentile (P99) and 10th percentile (P10). Values exceeding P99 represent Warm extremes, while those falling below P10 denote cold extremes. Our analysis reveals notable future changes in temperature compared to the baseline period. Particularly concerning is the significant rise in the number of Warm extremes towards the end of the century, with the most substantial increase observed in the last 40 years of the projection period. **This rise is more pronounced under the RCP-SSP 585 emission scenarios, indicating a higher emission trajectory**. Such findings highlight the urgency for robust mitigation and adaptation strategies to address the escalating risks associated with climate change, emphasizing the need for proactive measures to mitigate the adverse impacts on ecosystems and human well-being in both provinces.

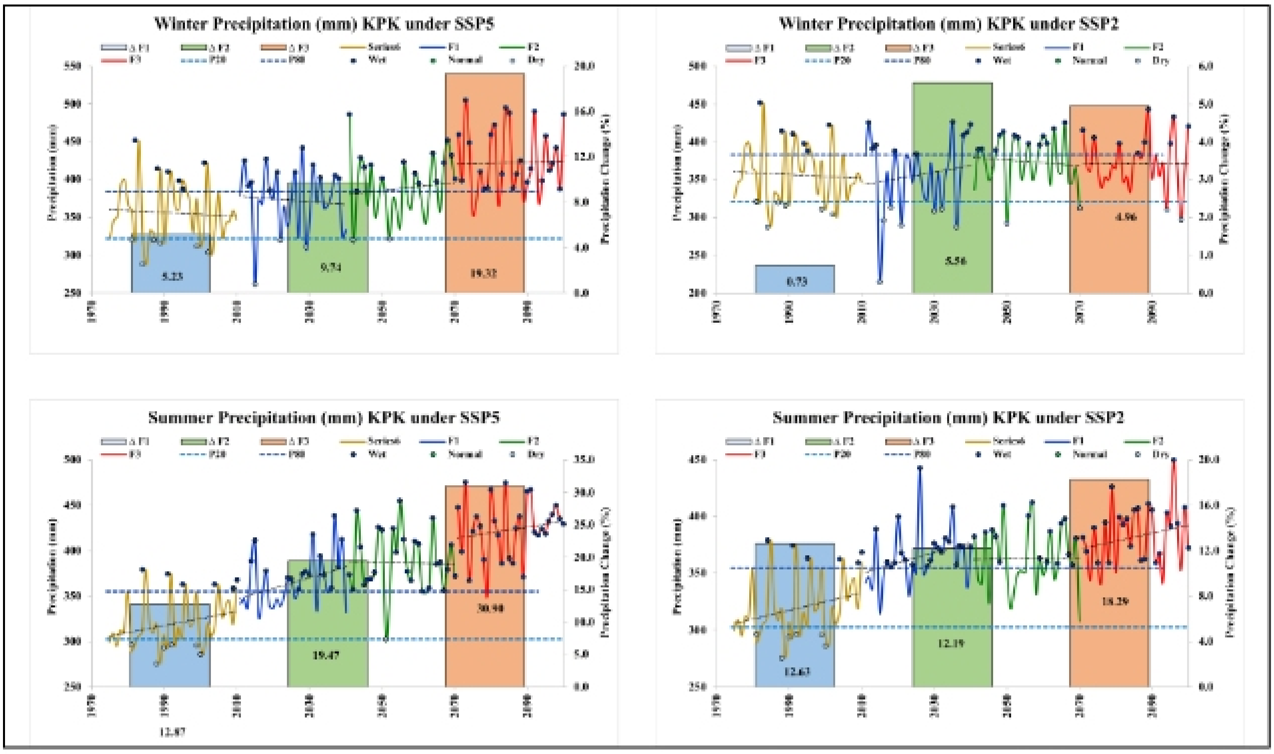


Figure 10: Future trends, changes and frequency and intensity of precipitation extremes (wet and dry) over KP Province for the period from 1981-2100 under two emission scenarios (RCP-SSP 245 and RCP-SSP 585)

The linear graphs depicting precipitation trends in Khyber Pakhtunkhwa (KP) provinces provide valuable insights into climate patterns. In these plots, we illustrate the linear trends of precipitation levels during summer and winter seasons, along with the values corresponding to the 80th percentile (P80) and 20th percentile (P20). Values exceeding P99 represent wet extremes, while those falling below P10 denote dry extremes. Our analysis reveals notable future changes in precipitation compared to the baseline period. Particularly concerning is the significant rise in the number of wet extremes towards the end of the century, with the most substantial increase observed in the last 40 years of the projection period. This rise is more pronounced under the RCP-SSP 585 emission scenarios, indicating a higher emission trajectory. Such findings highlight the urgency for robust mitigation and adaptation strategies to address the escalating risks associated with climate change, emphasizing the need for proactive measures to mitigate the adverse impacts on ecosystems and human well-being in both provinces.

Growing Degree Days

The growing degree days (GDD) is considered an important parameter determining the crop growth and development under different temperature regimes (Kalra et al., 2008; Kingra & Kaur, 2012; Meena & Rao, 2013). It assumes a direct and linear relationship between growth and temperature (Nuttonson, 1955). The crops sown on the recommended time have a higher heat requirement than those of later sown crops. This happens because of the lower temperatures during the early vegetative growth stages and comparatively higher temperatures at the time of reproductive stage (Khichar & Niwas, 2007)

In the realm of climate change, the Growing Degree Day (GDD) index plays a pivotal role by aiding in several key agricultural aspects. Firstly, it assists in estimating the growth stages of crops, providing valuable insights into their development. Additionally, it helps assess the suitability of a region for the production of specific crops, guiding farmers in selecting the most appropriate varieties for their local conditions. Moreover, the GDD index aids in predicting crucial milestones such as crop maturity stage, enabling farmers to plan their harvests effectively. Furthermore, it facilitates determining the optimal timing for fertilizer or pesticide application, optimizing resource utilization and minimizing environmental impact.

Lastly, the GDD index serves as a valuable tool in estimating the heat stress experienced by crops, allowing farmers to implement mitigation measures and safeguard their yields against adverse weather conditions. Accumulated Growing Degree Days (GDD) were calculated using a base temperature of 5°C with the help of the following equation,

$$GDDk=\sum Dn=1max\{(TMAXnk+TMINnk2-B),0\}$$

where GDDk is the growing degree days accumulated through the growing season for the k-th weather station, TMAXnk and TMINnk are defined as the maximum and minimum temperatures, respectively, for the n-th day of the m-th month for the k-th weather station, B is a baseline temperature below which it is assumed that no growth occurs, and D represents the number of days in the growing season.

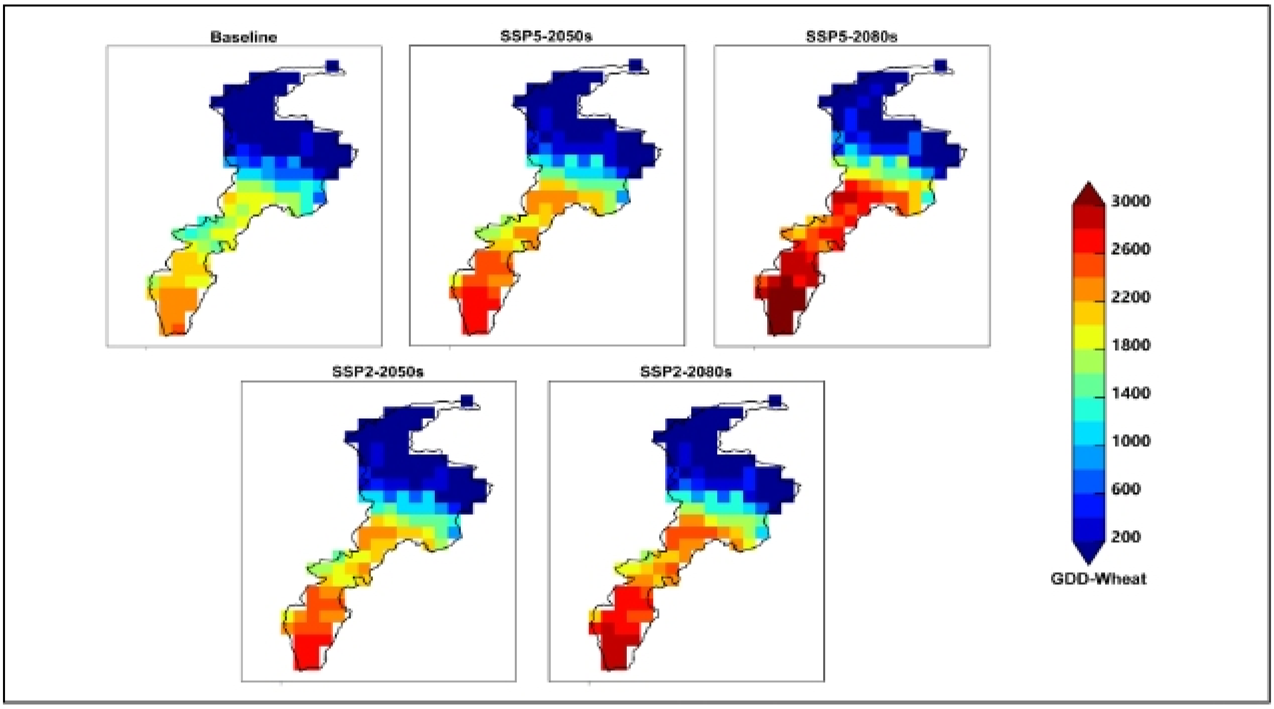


Figure 11: Spatial distribution of Growing Degree Days (GDD) over KP during the baseline period (1974-2014) and F1 (2021-2060) and F2 (2061-2100) under two emission scenarios (RCP-SSP 245 and RCP-SSP

For optimal growth and development, plants require heat. Each plant transitions through distinct stages of development, or phenophases, which necessitate specific amounts of heat. In the northern region of Khyber Pakhtunkhwa (KP), our **analysis indicates an accumulation of 400 growing degree days (GDD) throughout the growing cycle**, due to colder temperatures prevailing in the region, from historical to future period, for both emission scenarios. This amount of GDD supports wheat plants in reaching the tillering stage, yet to complete the normal cycle for optimal yield, an additional 1200 to 1500 GDD is required.

Looking ahead to the latter part of the century, **increasing temperatures in the northern region are projected to raise the accumulated growing degree days by an additional 200 units,** which remains insufficient for optimal growth. However, in the central western parts of KP, including Kurram, Orakzai, and Hangu, warming conditions are forecasted to become more favorable for wheat production.

Standardized Precipitation Evapotranspiration Index (SPEI)

The Standardized Precipitation Evapotranspiration Index (SPEI) is an extension of the widely used Standardized Precipitation Index (SPI). The SPEI is designed to take into account both precipitation and potential evapotranspiration (PET) in determining drought. (SPEI) is a drought index that combines precipitation and potential evapotranspiration (PET) to assess drought severity and duration. SPEI is standardized to have a mean of 0 and a standard deviation of 1, making it comparable across regions and time periods. SPEI values indicate the number of standard deviations by which the observed precipitation and PET deviate from the long-term climatological mean.

SPEI can be used for determining the onset, duration and magnitude of drought conditions concerning normal conditions in a variety of natural and managed systems such as crops, ecosystems, rivers, water resources, etc. It's crucial to comprehend the historical spatiotemporal drought patterns and their impact on potential evapotranspiration (PET) and vegetation coverage changes. This understanding is vital for developing effective drought mitigation policies in the face of climate change.

In this sub-national Climate Risk Profiling, to explore the provincial-scale dry and wet annual changes across KP province, we used the standardized precipitation evapotranspiration index (SPEI) at multiple timescales, such as SPEI-03, SPEI-06, SPEI-12, and SPEI-24 for 150 years from 1951 to 2100 under RCP-SSP 245 and RCP-SSP 585 emission scenarios.

In our case, we have estimated SPEI-03, SPEI-06, SPEI-12, and SPEI-24 with the following thresholds:

Categories	SPEI Values
Extreme drought	Less than -2.00
Severe drought	-1.99 to -1.50
Moderate Drought	-1.49 to -1.00
Near Normal	-0.99 to 0.99
Moderately wet	1.00 to 1.49
Severely wet	1.50 to 1.99
Extremely wet	More than 2.00

Floods and droughts are often perceived as significant natural calamities with high levels of risk. Given the rugged and mountainous terrain of KP and its heavy reliance on water from snow, glaciers, and rainfall, analyzing drought using the Standardized Precipitation Evapotranspiration Index (SPEI) is essential for efficient water resource management.

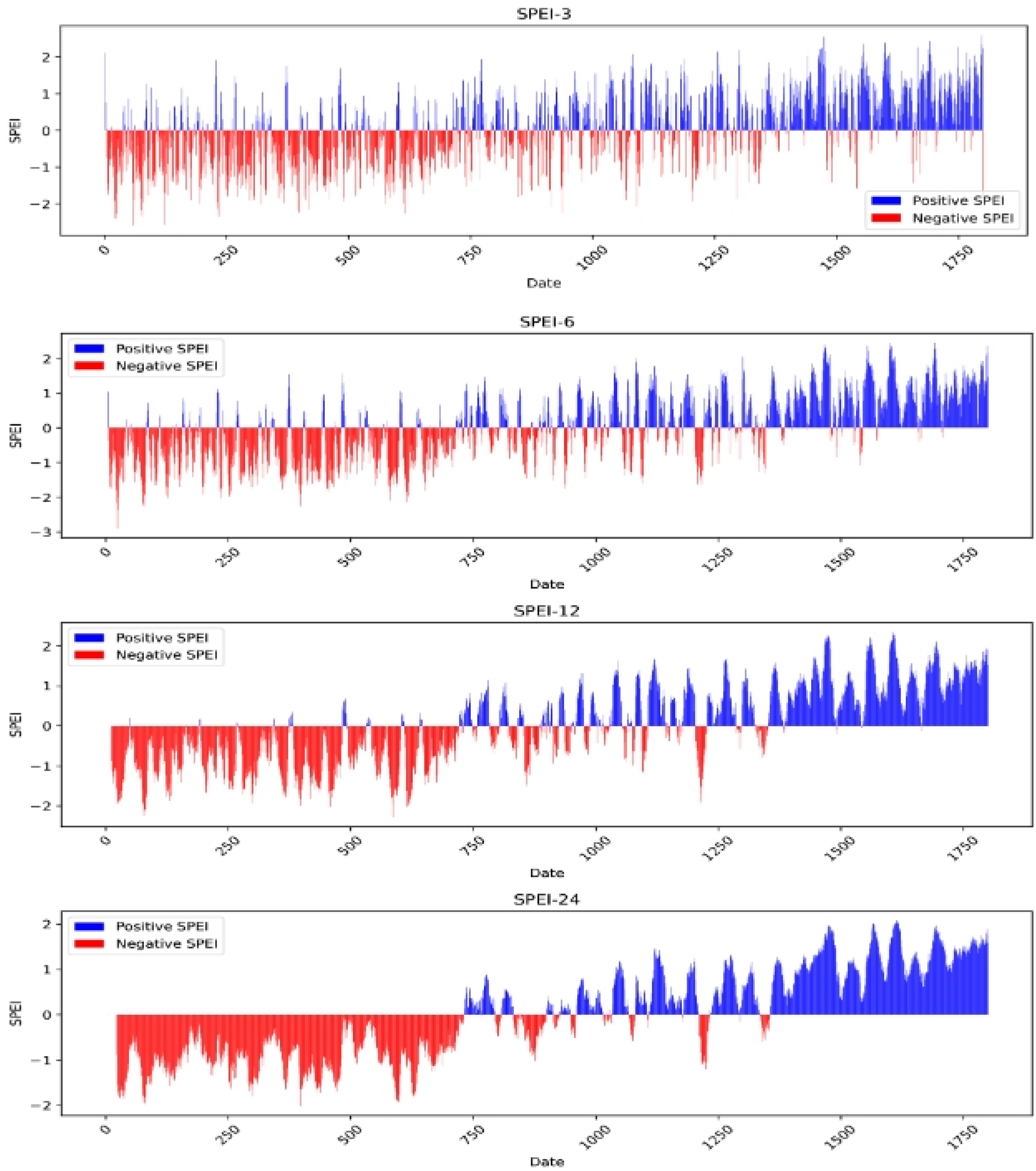


Figure 12: Standardized Precipitation Evapotranspiration Index (SPEI) over Punjab estimated at multiple timescales, such as SPEI-03, SPEI-06, SPEI-12, and SPEI-24 for 150 years from 1951 to 2100 under RCP-SSP 245 emission scenario.

The above two panels presented above illustrates the fluctuations in drought and flood occurrences throughout the years 1951 to 2100, as measured by SPEI-3 and SPEI-6 in KP province. **We observed that the frequency of drought condition decreases gradually as we move after 2020 under short term droughts estimated with SPEI-3 and SPEI-6. By 2020, severe drought conditions are evident under RCP-SSP245 emission scenarios**. However, post-2021, there is a notable increase in the frequency of wet extremes with random droughts under both emission scenarios, with the most significant rise observed in the late century under RCP-SSP585 scenarios, particularly reflected in SPEI-12 and SPEI-24 values (as shown in the lower figure). These higher flood and drought index values have direct consequences on crop production and water availability for agriculture. The long-term trends in SPEI values underscore the regional challenges faced by the agriculture sector, where reduced drought frequency with larger SPEI timescales poses serious and potentially irreversible threats to food and water security.

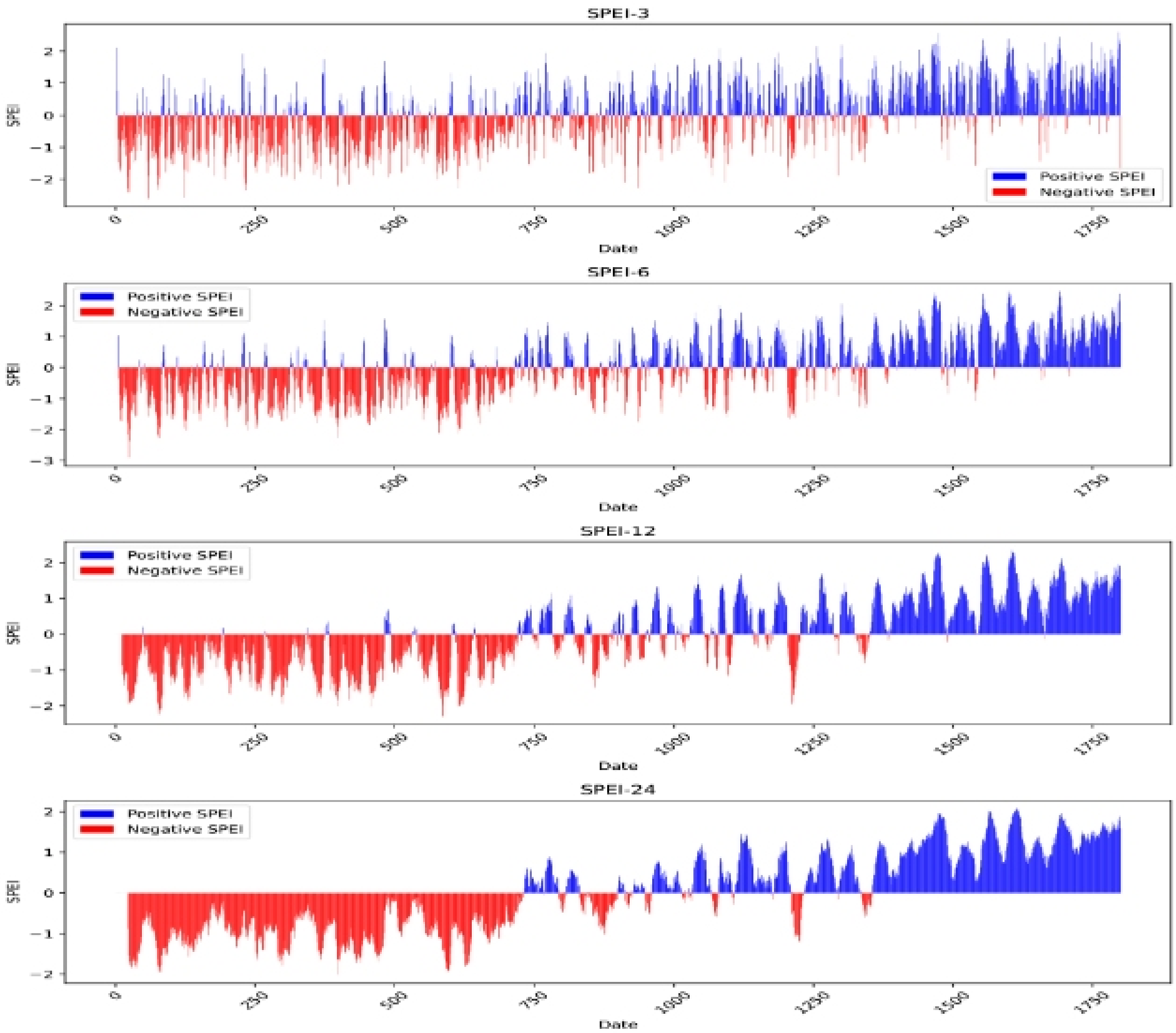


Figure 13: Standardized Precipitation Evapotranspiration Index (SPEI) over KP estimated at multiple timescales, such as SPEI-03, SPEI-06, SPEI-12, and SPEI-24 for 150 years from 1951 to 2100 under RCP-SSP 585 emission scenario.

Agriculture

Climate change has profound impacts on agriculture in Pakistan, particularly in relation to water resources (Azmat et al. 2021). One of the most significant effects is the alteration in precipitation patterns and temperature over mountainous regions (Ahmad et al. 2022). Consequently, climate change has caused rainfall to become irregular and unpredictable, disrupting the traditional agricultural calendar. Currently, farmers often face challenges with sowing and harvesting as rains come either too early or too late, potentially damaging crops yield (Azmat et al. 2019 and 2021). Additionally, the increased frequency and intensity of extreme weather events such as floods and droughts further exacerbate the situation resulting sever impacts on infrastructure. These events can destroy crops, wash away topsoil, and disrupt irrigation infrastructure, making agricultural activities highly uncertain.

Pakistan's agriculture system heavily depends on glacial meltwater from the Hindukush, Karakoram, and Himalayas. These glaciers feed the rivers, particularly the Indus River and its tributaries like the Kabul River, which are the lifelines of the agricultural sectors in Punjab and KP provinces. Rising global temperatures are accelerating glacial melt, which initially increases water flow in rivers (Jamal et al., 2023; Lutz et al., 2014). However, this is followed by a long-term reduction in glacial volume (Bajracharya et al., 2019), ultimately leading to decreased water availability during crucial growing seasons (Azmat et al., 2020). The reduced flow of surface water forces farmers to rely more on groundwater, which is being rapidly depleted (Hassan and Hassan, 2017). Over-extraction of groundwater not only lowers the water table but also increases salinity, rendering the water unsuitable for irrigation in many areas.

Climate change also directly impacts crop yields such as higher temperatures result in heat stress for crops, significantly reducing their productivity (Ahmad et al. 2023; Abbas, 2022; Gul et al., 2022; Jan et al., 2021). Staple crops such as wheat and rice are particularly vulnerable to temperature increases. Furthermore, climate change can lead to the proliferation of pests and diseases, which thrive in warmer conditions and can devastate crops. The combined effect of reduced water availability, irregular rainfall, and increased pest pressures creates a challenging environment for agriculture.

The agriculture sector in Khyber Pakhtunkhwa (KP), Pakistan, is facing significant threats from climate change. Changes in optimal temperatures are projected to drastically reduce the yields of spring maize and wheat, as shown in Figure 16. By the end of the 21st century, spring maize yields are expected to decline by 40% under the SSP 2080s scenario. This decline is anticipated to be more pronounced from north to south across KP, correlating with temperature shifts due to changes in altitude from high to low regions.

Similarly, wheat yields are projected to decrease by 45% under the SSP5 scenario by the 2080s. Like maize, the reduction in wheat yields will follow a north-to-south gradient, corresponding with temperature patterns affected by topographical variations. Overall, the yields of both maize and wheat are expected to gradually decline, considering current agronomic and water management practices, due to the impacts of climate change under SSP2 and SSP5 scenarios. Similar results depicting crops yield decline has been reported by Jan et al. (2021) over northern areas of Pakistan under climate change scenarios.

As crop yields decline, Figure 16 illustrates the potential changes in major crop areas (wheat and maize) in KP under various climate change scenarios, depicting loss, gain, and retention. The KP province is projected to lose 0.6% and 1.8% of its current wheat area under SSP2 during the 2050s and 2080s, respectively, with a maximum decline of 5.2% expected under SSP5 by the 2080s. Conversely, several regions in KP are anticipated to gain wheat area by 8.2% and 6.9% under SSP2 during the 2050s and 2080s,

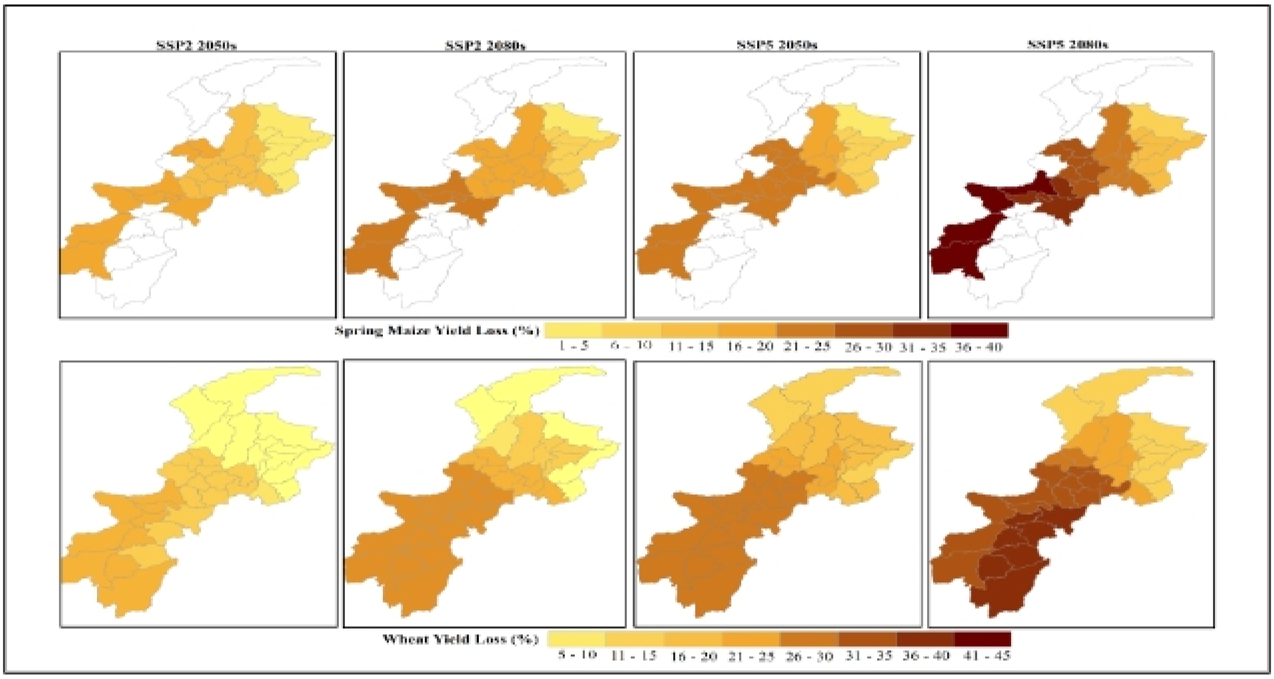


Figure 14: Potential loss of wheat and spring maize yield under climate change scenarios.

respectively. The gain in wheat area is slightly lower under SSP5, possibly due to the significant rise in temperature associated with this extreme climate change scenario. For spring maize, a substantial area gain of 11.1% and 29.3% is projected under SSP2 and SSP5 during the 2050s. However, a significant loss of maize area is expected under both SSP2 and SSP5 by the 2080s, indicating that spring maize is highly sensitive to temperature increases. The spring season is anticipated to shorten significantly due to extreme temperature rises by the end of the 21st century, leading to a considerable loss of spring maize area (Figure 16). If the SSP5 scenario materializes, spring maize could potentially vanish from the KP province, as climate change challenges toward agriculture sector in Pakistan has been reported by Syed et al. (2022).

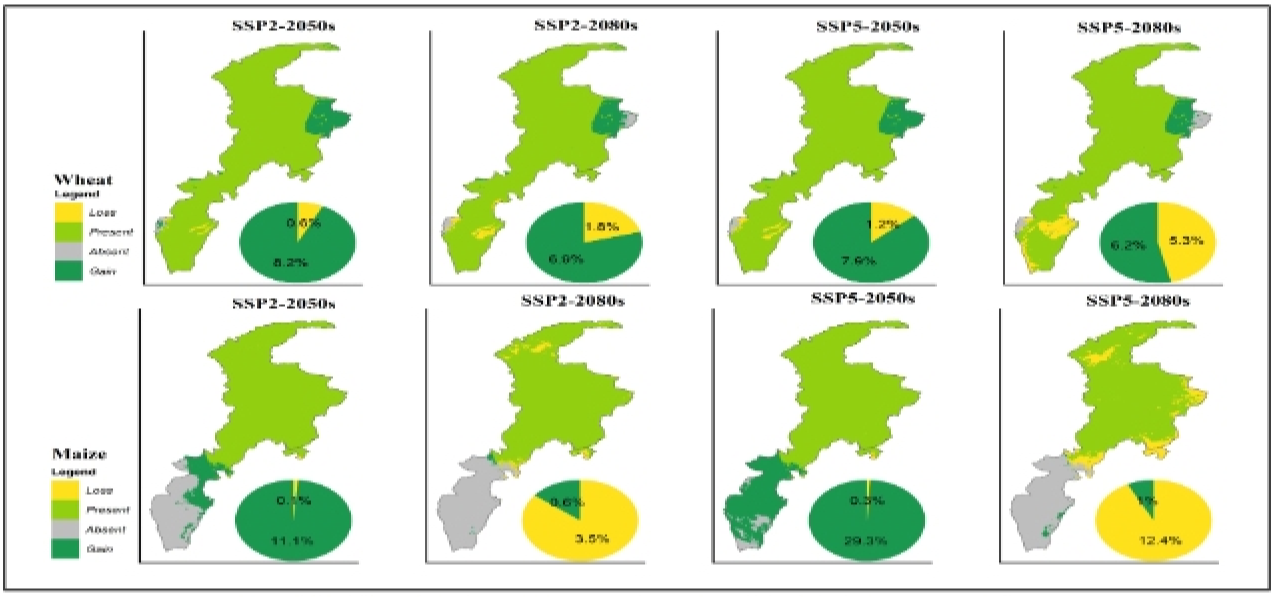


Figure 15: state of wheat and maize cropping area under climate change scenarios.

Considering the loss of maize and wheat areas shown in Figure 17, the extended outcomes in Figure 18 and Figure 19 illustrate the suitability levels for major crops (rice, cotton, wheat, and sugarcane) under climate change scenarios. Currently, the KP province is entirely unsuitable for cotton cultivation. However, with temperature shifts, some areas, particularly in southern KP, are expected to develop less to moderately suitable hotspots for cotton under future climate change scenarios.

Similarly, a very small part of southern KP is currently under less suitable conditions for rice cultivation. However, this area is expected to increase significantly, shifting towards moderately to highly suitable conditions under SSP2 and SSP5 during the 2050s and 2080s. Figure 19 shows that a large area in southern KP is projected to become moderately suitable for rice cultivation.

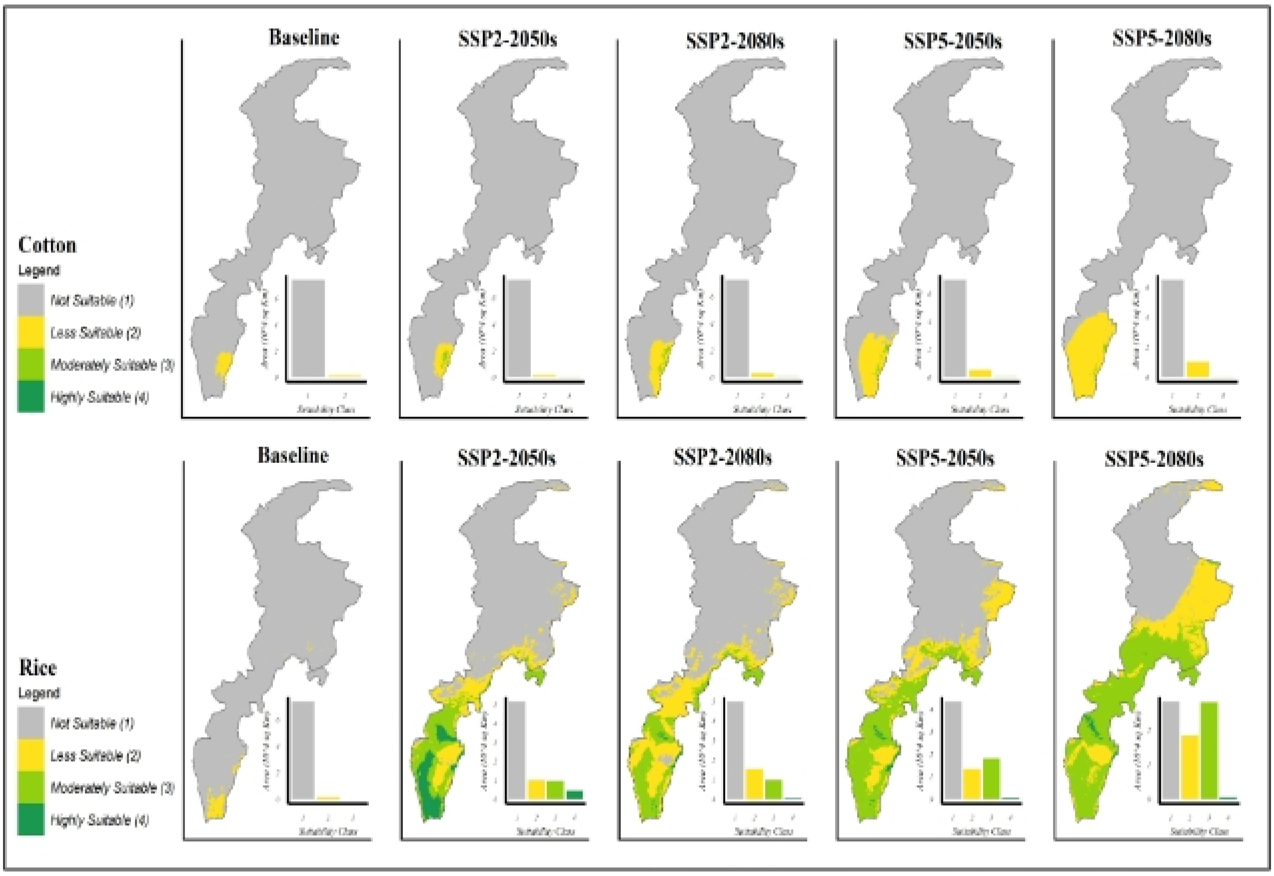


Figure 16: Suitability levels of rice and cotton climate change scenarios.

Figure 19 illustrates the changes in suitability levels for wheat and sugarcane crops in KP province under various climate change scenarios, compared to the baseline. Rising temperatures are expected to shift highly suitable regions for sugarcane to moderately and less suitable regions over different future periods. Moderately suitable regions for sugarcane will likely shrink and be confined to the southern part of KP. Notably, the most suitable areas for maize in KP are projected to vanish by the end of the 21st century.

For wheat, the suitability is expected to remain relatively stable across most of KP, with a slight decrease in suitability in the southern regions. However, this decrease will cover a much smaller area compared to the baseline, with almost the entire province remaining highly suitable. Additionally, there will be a slight gain in suitable areas in the northern part of KP (Figure 19).

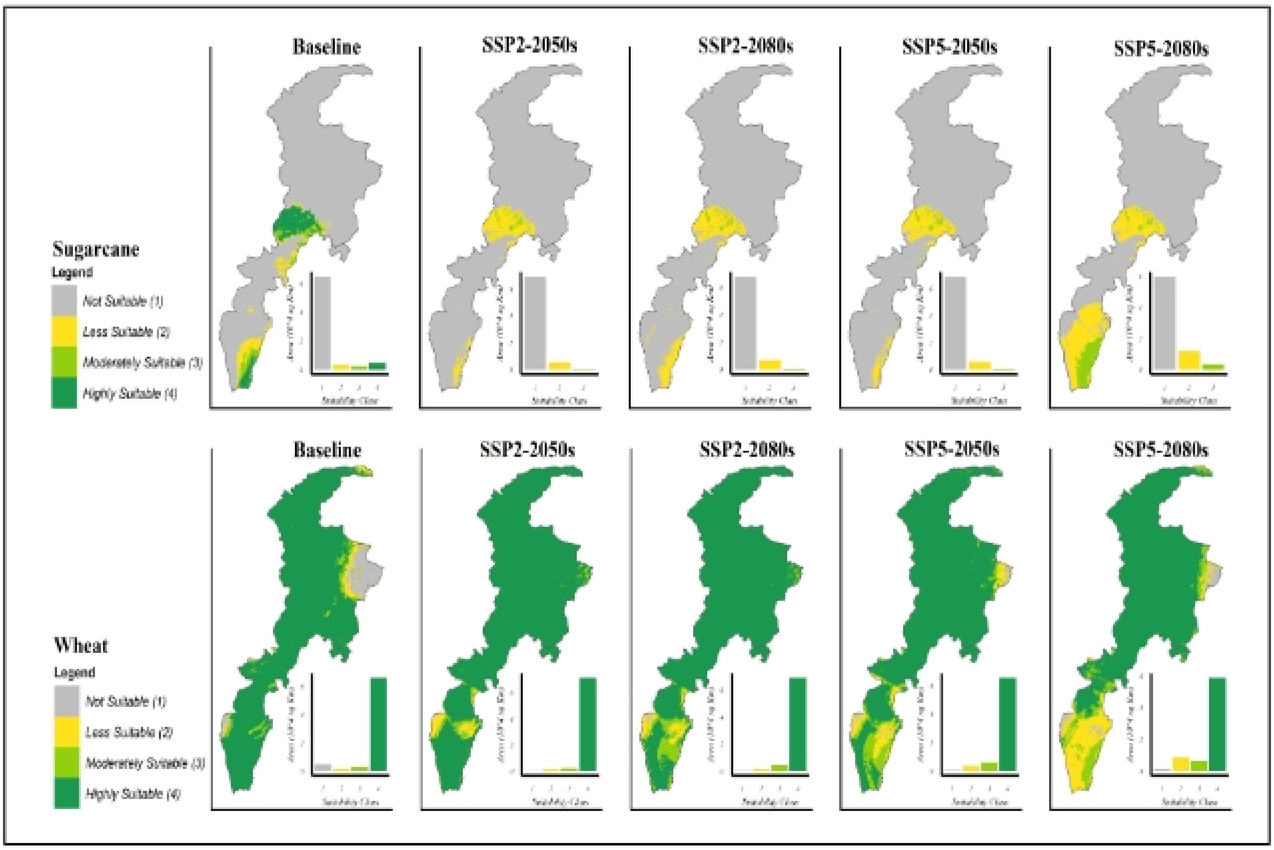


Figure 17: Suitability levels of wheat and sugarcane climate change scenarios.

Considering the significant loss of agricultural areas for various Rabi and Kharif crops, it is crucial to rezone cropping suitability under climate change. Figure 5 illustrates the suitability of Kharif and Rabi crops under future climate scenarios. Climate change is affecting the overall cropping zones, patterns, and intensity in KP province. For example, under baseline conditions, wheat and sugarcane (Rabi) and maize (Kharif) zones are dominant. However, by mid-century, the cotton crop zone is expected to expand into maize areas, creating mixed cropping zones of cotton and maize.

The situation becomes particularly interesting in the late-century scenarios, where both cotton and maize cropping zones are anticipated to cover a large area of KP. For the Rabi season, there is a gradual decrease in wheat and sugarcane areas from mid to late-century scenarios. However, the cropping zone boundaries for wheat and sugarcane are expected to become more distinct. The highly suitable zones for sugarcane and wheat are projected to shift towards the south of KP.

Regarding the Rabi season in Khyber Pakhtunkhwa (KP), wheat cultivation is predominant, with 81% of the region's area considered suitable. Only 10% of the area supports combined wheat and sugarcane cultivation, while 9% is deemed unsuitable for any crop cultivation. Projections under the Shared Socioeconomic Pathway 2 (SSP2) and SSP5 scenarios indicate a potential increase in the area suitable for wheat cultivation by the 2050s, reaching 97% of the region. However, this expansion comes at the expense of the combined wheat and sugarcane cultivation area, which is projected to decline to 1%. By the 2080s, the trend is expected to slightly reverse, with the wheat cultivation area decreasing to 94%, and 6% of the land becoming unsuitable.

In contrast, the SSP5 scenario presents a more drastic shift in climate suitability patterns. Projections for the 2080s indicate a decrease in the wheat cultivation area to 83%, accompanied by a slight increase in the area unsuitable for any crop cultivation, rising to 12%.

During the Kharif season in KP, the current scenario shows that 75% (76,306 sq km) of the region's area is climatically suitable for maize cultivation. However, 25% (25,435 sq km) of the area is not suitable for the cultivation of maize, cotton, or rice during this season.

Projections indicate that by the 2050s, the area suitable for maize cultivation is expected to increase to 81% (82,410 sq km) under SSP2 and 93% (94,619 sq km) under SSP5. Additionally, 9% (9,157 sq km) under SSP2 and 1% (10,171 sq km) under SSP5 of the region are projected to become suitable for cotton cultivation, and an additional 2% (2,035 sq km) under SSP2 and 4% (4,070 sq km) under SSP5 will be suitable for the combined cultivation of maize and cotton. The area not suitable for any of these crops is anticipated to decrease to 8% under SSP2 and 2% under SSP5.

By the 2080s, the trends are projected to shift. The area suitable for maize cultivation is expected to decrease to 72% (73,254 sq km) under SSP2 and 60% (61,045 sq km) under SSP5, while the suitability for cotton cultivation remains at 9% (9,157 sq km) under SSP2 and increases to 13% (13,226 sq km) under SSP5. The combined cultivation of maize and cotton is projected to become minimal under SSP2, accounting for only 1% (1,017 sq km) of the region's area and 7% (7,122 sq km) under SSP5. Significantly, the area not suitable for any of these crops is projected to rise to 18% under SSP2 and 19% under SSP5.

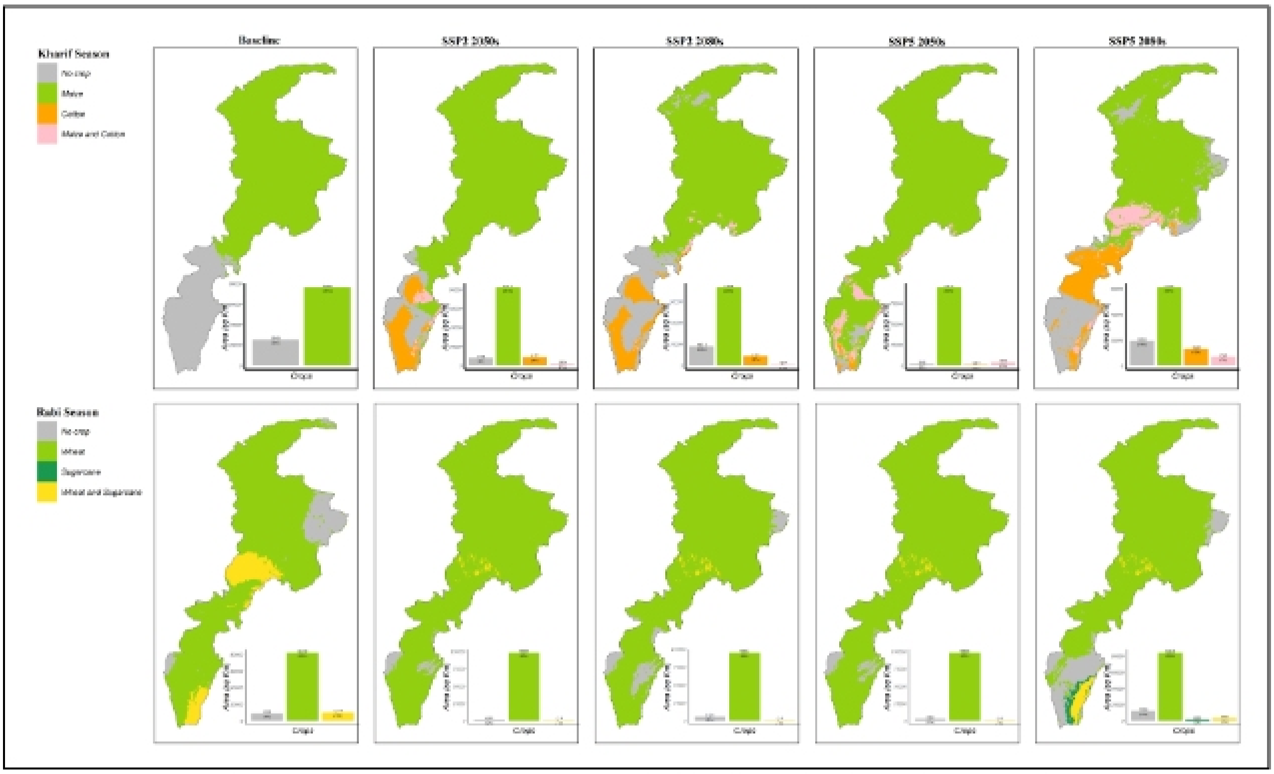


Figure 18: Potential cropping zones of Kharif and Rabi crops for climate change scenarios.

Water Resources

The agriculture sector in Khyber Pakhtunkhwa (KP), Pakistan, is significantly threatened by climate change. Altered precipitation patterns, including irregular and unpredictable rainfall, present major challenges by disrupting sowing and harvesting cycles and leading to both floods and droughts. Rising temperatures exacerbate water scarcity by accelerating glacial melt, initially increasing water flow but ultimately reducing long-term water availability as glaciers shrink (Ahmad et al. 2022; Biemans et al. 2019). This strain on water resources is compounded by the depletion of groundwater, which becomes increasingly saline and less suitable for irrigation. Addressing these threats requires adaptive strategies, improved water management, and resilient agricultural practices to mitigate the adverse effects of climate change on KP's agriculture.

Agriculture in most regions of KP relies heavily on rainfall, but the province's rivers and irrigation systems play a crucial role in irrigating agricultural lands. For instance, the Tarbela Dam, strategically positioned on the Indus River, is pivotal in irrigating various regions of KP. The dam's inflows are meticulously managed to support an extensive network of canals that distribute water across the province. Key agricultural areas benefiting from this irrigation include the fertile plains of Peshawar, Mardan, and Swabi. These regions are known for their rich agricultural output, including crops like wheat, maize, sugarcane, and various vegetables. The regulated water supply from the Tarbela Dam ensures consistent irrigation, enhancing crop yields and supporting the livelihoods of countless farmers. Importantly, the dam's ability to store and release water according to seasonal demands helps mitigate the effects of erratic rainfall and droughts, providing a reliable water source essential for maintaining agricultural productivity and food security in KP. This irrigation infrastructure is vital for sustaining the province's agrarian economy and ensuring the well-being of its rural communities. However, even a small change in river flow regime can disturb peak water availability, leading to significant losses in yield or agricultural areas.

Figure 21 illustrates significant changes in Indus River flows at Tarbela Dam under changing climate scenarios. Notably, peak flows in July and August are increasing abruptly under SSP2, with peak flows shifting from August to July under SSP5. A long-term trend shows a gradual increase in flows

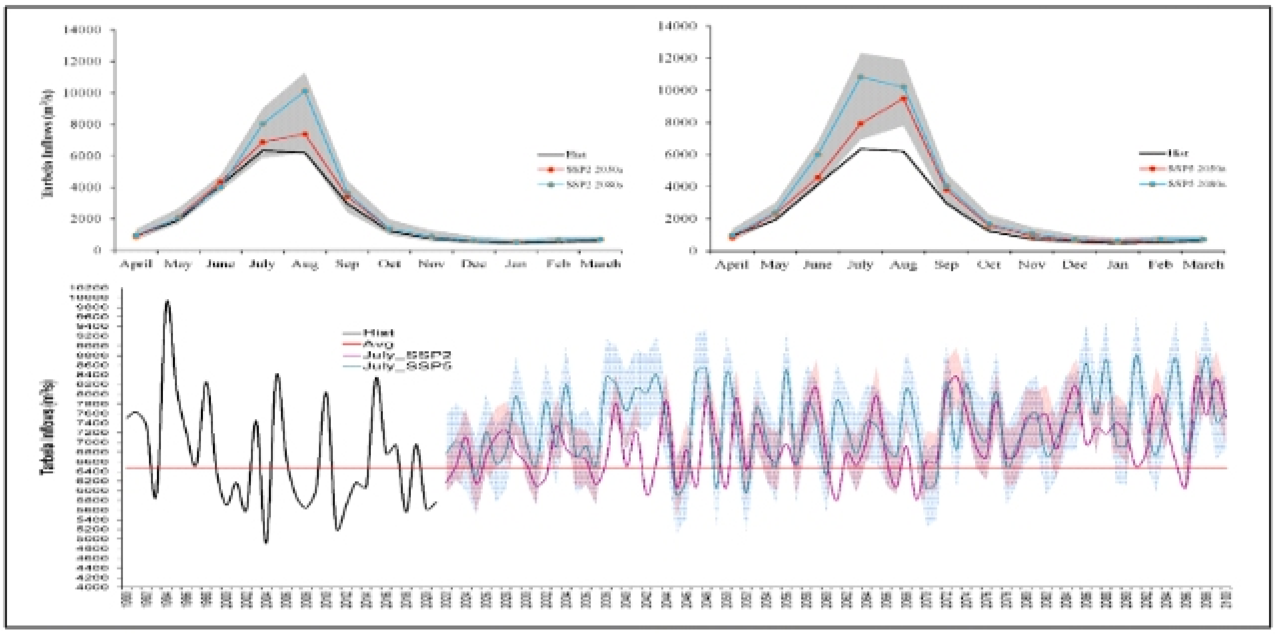


Figure 19: Change in Tarbela monthly inflows (Indus River) and during July (peak month) under climate change scenarios.

suggests extensive glacier melt during peak summer months (June and July). Such changes are alarming for the current water management system in KP, which may need to adapt to these future trends.

Similarly, for the Kabul River, peak flows are expected to increase significantly during the peak inflow months, as shown in Figure 22. Notably, flows during June and July are projected to increase gradually under future scenarios (2024 to 2100), mainly due to early seasonal snowmelt and glacier melt in later months. This change could potentially alter downstream water delivery and storage, making it challenging to meet water requirements for agriculture during drought or dry seasons. Similar trends in Indus River flows have been reported by researchers such as Lutz et al. (2014) The Kabul River is indispensable for the irrigation of several regions in Khyber Pakhtunkhwa (KP), Pakistan. Originating from the Hindu Kush mountains in Afghanistan, the river provides a crucial water source for the fertile lands of Peshawar Valley, Nowshera, Charsadda, and parts of Swabi. During the monsoon season, the Kabul

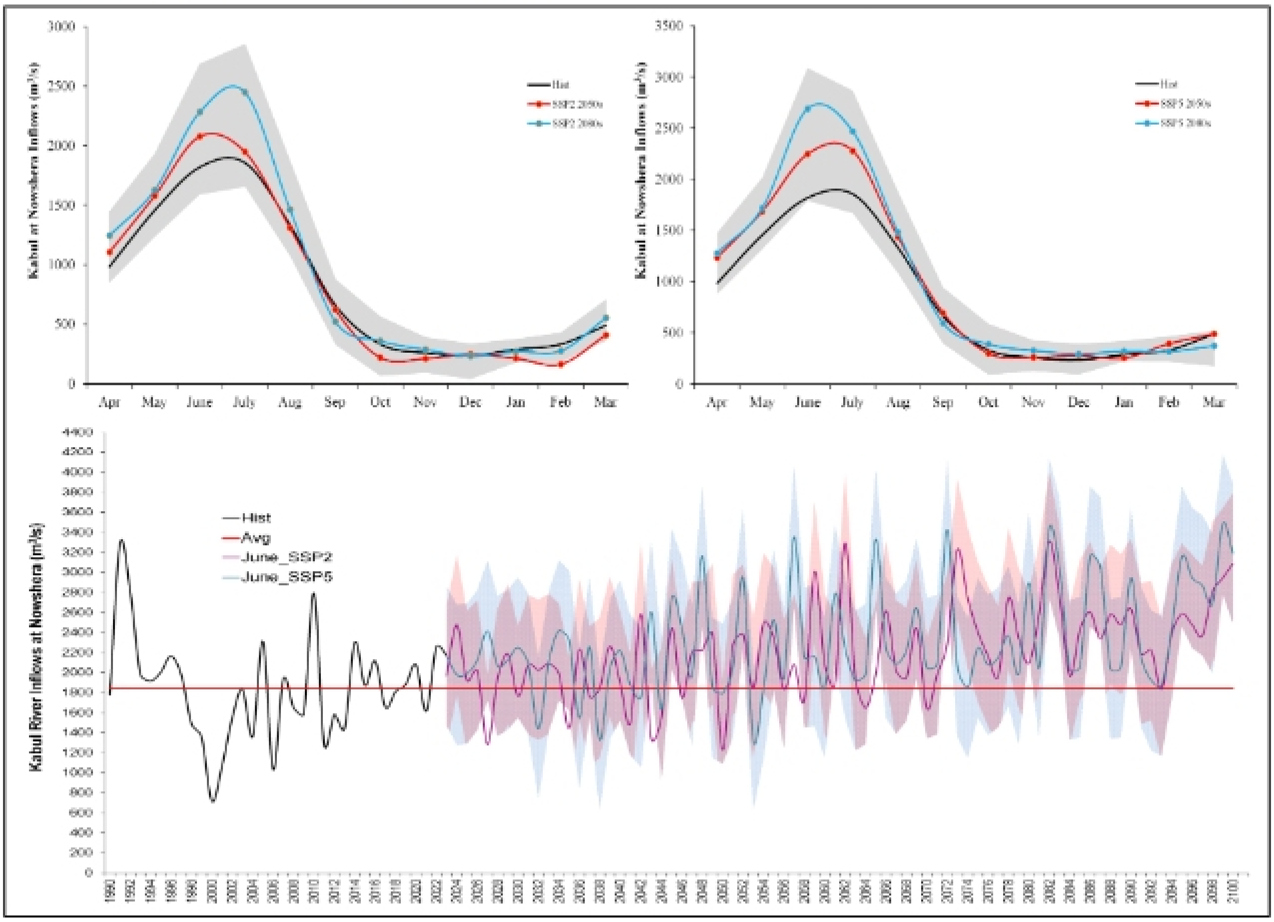


Figure 20: Change in Kabul monthly inflows (Nowshera) and during month of June (peak month) under climate change scenarios.

River's high flows are managed for flood irrigation, enriching the soil with nutrients and boosting crop yields. By ensuring a reliable water supply, the Kabul River supports the livelihoods of thousands of farmers, underpinning the economic stability and food security of the region. Therefore, even a slight change in Kabul River flows can significantly impact the agricultural area in KP.

Figure 21 illustrates a clear increase in river flows during the summer months, particularly June and July, under SSP2 and SSP5 climate change scenarios. Interestingly, the peak of monthly flows occurs in July under SSP2, while this peak potentially shifts to June under the SSP5 scenario. Similarly, the long-term flow regime for June shows a clear increase in Kabul River flows

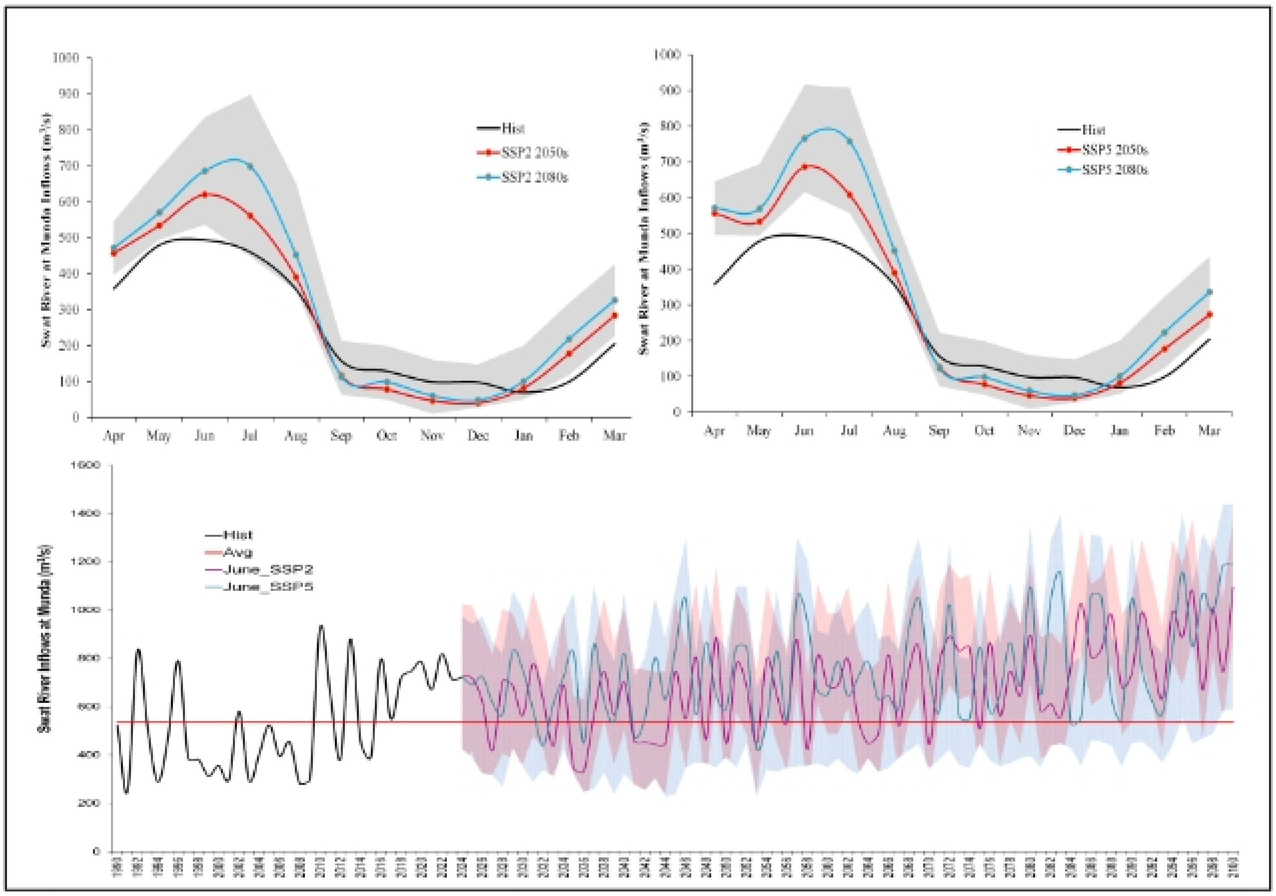


Figure 21: Change in Swat River monthly inflows (Munda Dam) and during month of June (potentially peak month) under climate change scenarios.

compared to the June average under both SSPs.

The completion of the Munda Dam is anticipated to significantly transform irrigation in the Khyber Pakhtunkhwa (KP) regions. Located on the Swat River, the dam's inflows will greatly enhance the water supply for irrigation, particularly benefiting the agricultural lands in districts such as Charsadda, Peshawar, and Nowshera. By storing and regulating river flows, the Munda Dam will provide a consistent and reliable source of water, crucial for cultivating various crops, including wheat, maize, sugarcane, and vegetables. This regulated water supply will help mitigate the effects of seasonal variations in rainfall and reduce dependence on erratic weather patterns, ensuring that farmers have a steady irrigation source year-round. Additionally, the dam will help control flooding during the monsoon season, protecting farmlands from flood damage and enhancing soil fertility through managed flood irrigation. Overall, the Munda Dam's inflows will bolster agricultural productivity, improve water management, and support the economic stability and food security of the KP region.

Figure 22 shows a significant alteration in monthly streamflows at the Munda Dam site, with an increase during the peak months of June and July under SSP2 and SSP5 scenarios for the 2050s and 2080s. There is an abrupt rise in streamflows under SSP5 scenarios, while a slight decline in streamflows is potentially observed during the winter months from September to February. This increase in summer peak flows is likely due to the early and rapid melt of seasonal snow and permanent glacier mass. The Munda Dam catchment currently receives a significant proportion of snow and glacier melt, which is gradual, as evidenced by the steady peak flow regime during May, June, and July. However, these peak months show a clearly different picture under future climate change scenarios.

A similar trend can be observed in the lower panel of Figure 23, which illustrates the streamflow regime for June until the end of the 21st century. A significant increase in streamflows at the Munda Dam is expected during June under SSP2 and SSP5 scenarios, which will impact agricultural water availability during the peak water demand months in the future.

Evapotranspiration is a key indicator for agricultural water management, and with rising temperatures, estimating evapotranspiration is crucial to addressing climate change challenges related to agricultural water management. Figure 24 demonstrates spatio-temporal changes in potential evapotranspiration (ETp) under SSP2 and SSP5 for future scenarios (2050s and 2080s). The figure shows that ETp is likely to increase across KP province, particularly in the southern part, indicating a higher crop water requirement under future climate change scenarios (mid and late century). As ETp increases, the water demand for agriculture will rise significantly, leading to decreased soil moisture reliability over time. This can pose serious challenges for the water-agriculture sector.

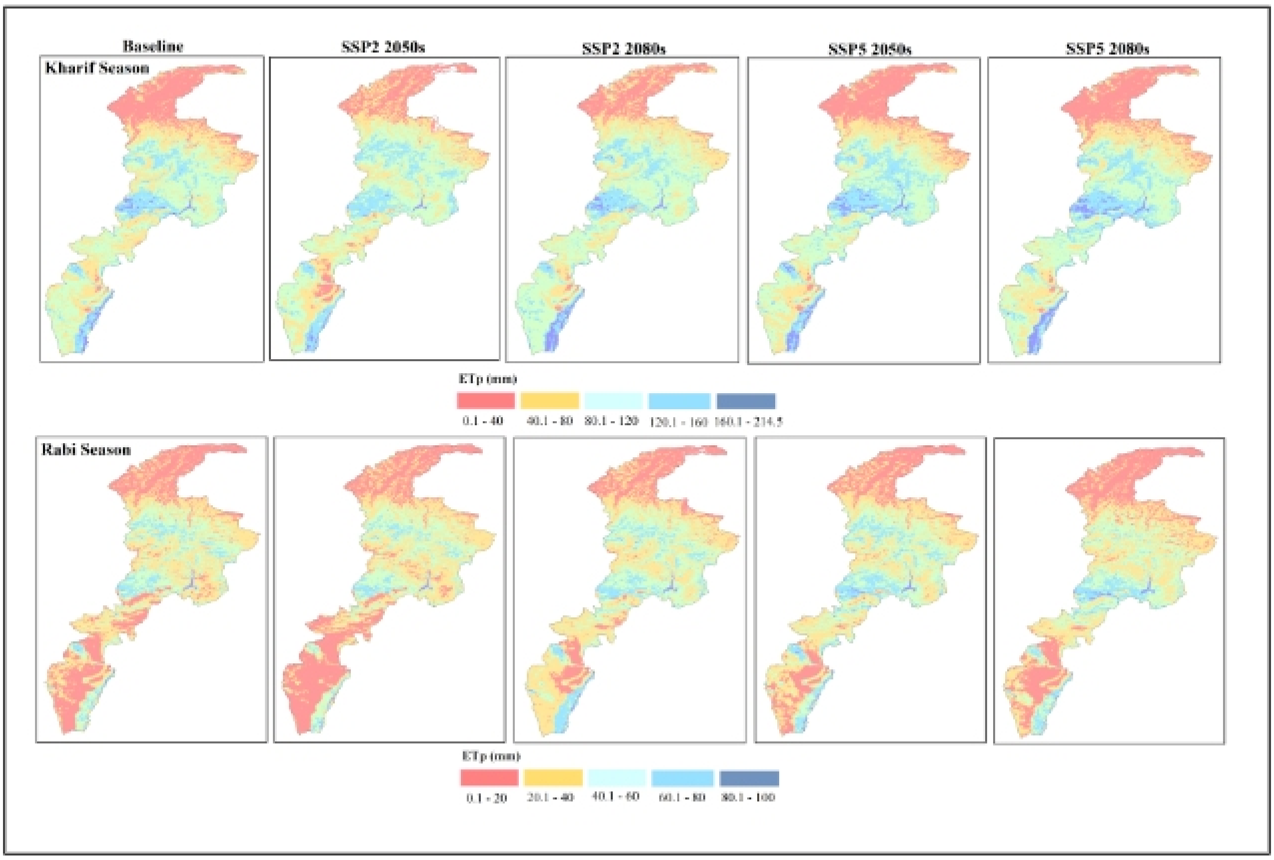


Figure 22: Change in Potential Evapotranspiration under future scenarios.

Health

Climate change significantly impacts the health sector in Khyber Pakhtunkhwa (KP), Pakistan, posing severe risks to the well-being of its population. The region experiences an increased frequency and intensity of waterborne diseases, such as cholera and diarrhea, due to the contamination of water sources. Additionally, shifting climate patterns affect the spread of vector-borne diseases like malaria and dengue, as warmer and wetter conditions provide ideal breeding grounds for mosquitoes . Several studies have reported that climate change significantly impacts the spread and intensity of dengue viruses, primarily through its influence on the habitat and behavior of Aedes mosquitoes, the primary vectors of the disease . Pakistan, being one of the most vulnerable countries to climate change, faces significant impacts on the intensity and spread of dengue outbreaks.

The number of dengue transmission suitable days (DTSD) is a key metric for assessing the spread of dengue in a region. For KP province, temperature data from CMIP6 under SSP2 and Climate change significantly impacts the health sector in Khyber Pakhtunkhwa (KP), Pakistan, posing severe risks to the well-being of its population. The region experiences an increased frequency and intensity of waterborne diseases, such as cholera and diarrhea, due to the contamination of water sources. Additionally, shifting climate patterns affect the spread of vector-borne diseases like malaria and dengue, as warmer and wetter conditions provide ideal breeding grounds for mosquitoes (Campbell-Lendrum et al., 2015). Several studies have reported that climate change significantly impacts the spread and intensity of dengue viruses, primarily through its influence on the habitat and behavior of Aedes mosquitoes, the primary vectors of the disease (Huber et al., 2018; Mordecai et al., 2017). Pakistan, being one of the most vulnerable countries to climate change, faces significant impacts on the intensity and spread of dengue outbreaks.

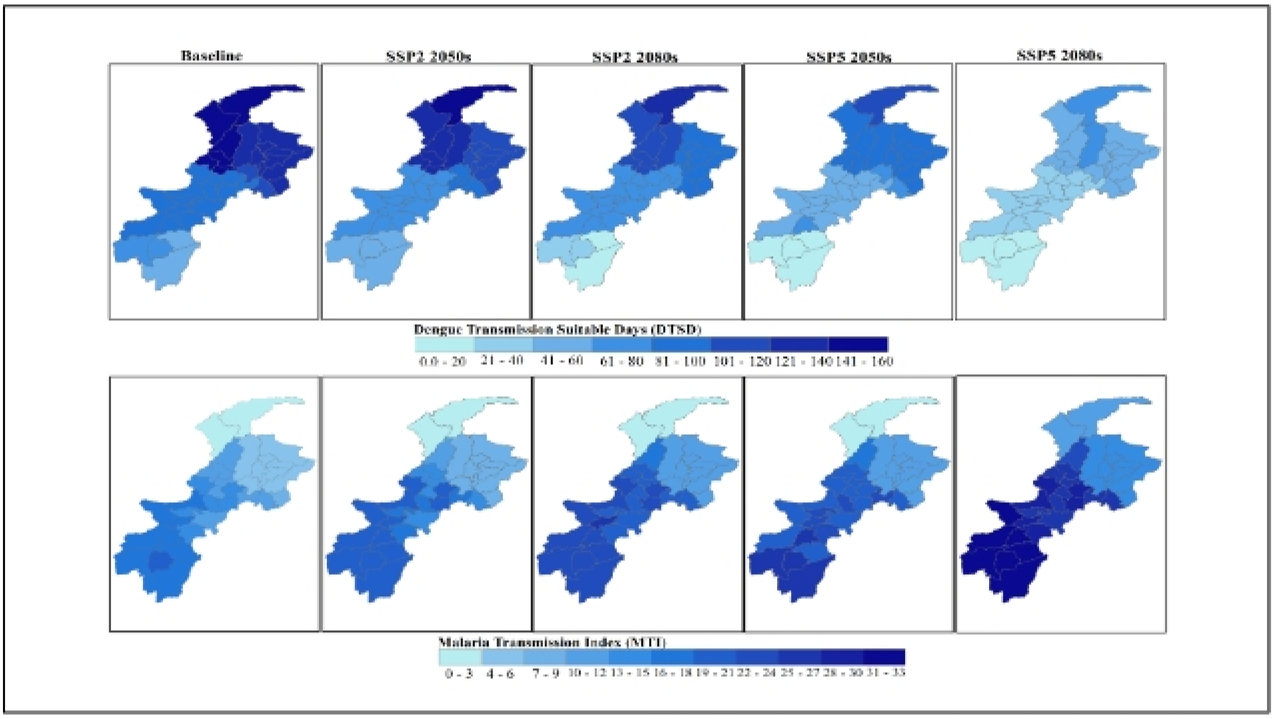


Figure 23: climate change impact on Malaria transmission in KP Province under future scenarios.

The number of dengue transmission suitable days (DTSD) is a key metric for assessing the spread of dengue in a region. For KP province, temperature data from CMIP6 under SSP2 and SSP5 scenarios was used to identify dengue hotspots using DTSD values. These hotspots were then interpolated for adjoining districts of KP. The analysis revealed that the density of cases is potentially higher in the northern (colder) part of KP, while dengue cases are declining in the southern part of KP. Overall, it was observed that dengue cases are inversely proportional to temperature rise, meaning that as temperatures increase, dengue cases will decline. Figure 25 shows that dengue cases will be minimal by the end of the 21st century under the SSP5 scenario (extreme scenario), with a higher number of cases in the mid-century under SSP2 (mitigation scenario). High-altitude regions of KP are more vulnerable to dengue compared to low-altitude or plain regions, demonstrating a clear inverse relationship between temperature rise and dengue cases.

Conversely, malaria is an extremely climate-sensitive tropical disease, making the assessment of potential changes in risk due to past and projected warming trends one of the most important climate change health questions. Meteorological factors such as rainfall, temperature, and humidity are known to be associated with malaria incidence from both temporal and spatial perspectives. These factors, when acting synergistically, increase the duration of larvae development, shorten the incubation period of parasites, prolong mosquito survival, provide favorable swampy habitats for the vectors, and increase the number of mosquitoes and their bites, thus being positively related to high malaria risk. Malaria is moderately endemic in Pakistan; however, its transmission is unstable, with the disease burden ranging from very high to low. Erratic malaria transmission patterns due to climatic changes can be assessed using the Malaria Transmission Index (MTI).

The MTI values presented in Figure 18 (lower panel) clearly depict the direct relationship between climate change and the spread of malaria from north to south in KP. There is a clear trend of increasing MTI values from the north (high elevation) to the south (low elevation) regions of KP province. An important insight is that the MTI is significantly increasing over time under climate change scenarios (SSP2 and SSP5) during the 2050s and 2080s. There is also a spatial trend of increasing MTI values from high-altitude to lower-altitude regions. These trends have been documented in several studies (Pascual et al., 2006; Patz and Olson, 2006). These studies highlight the importance of understanding the nonlinear and threshold responses of malaria (a biological system) to regional temperature changes. Remarkable findings show that the biological reaction of mosquito populations to warming can exceed the measured temperature change by more than tenfold, which is crucial for advancing the assessment of climate change risks. Indeed, these findings indicate that even small shifts in temperature should be a cause for concern. As Pascual et al. (2006) reported, a mere half-degree (0.5°C) increase in temperature can translate into a 30–100% increase in mosquito abundance, a phenomenon known as the "biological amplification" of temperature effects.

Ecosystem

Climate change is causing a global redistribution of plant and animal species, leading to the formation of new ecosystems and ecological communities, which will have significant impacts on human society. Although the geographical ranges of species are dynamic and fluctuate over time, climate change is driving a universal shift in the distribution of life on Earth. For birds, the primary response to warmer and drier conditions caused by climate change is often a shift in location to maintain preferred environmental conditions. At the cooler edges of their distributions, species are moving towards more favorable conditions. Conversely, their range limits are contracting at the warmer edges. This contraction occurs where environmental conditions—such as temperatures, precipitation, and rainfed croplands—have become unfavorable.

Different species respond at varying rates and to different extents, often disrupting key interactions among species and leading to the development of new interactions. These unique responses can result in the formation of novel biotic communities and rapid changes in ecosystem functioning. The consequences of these changes can be widespread and sometimes unexpected, affecting both biological and human communities.

Pakistan is situated at the intersection of three zoogeographic regions—Oriental, Palearctic,

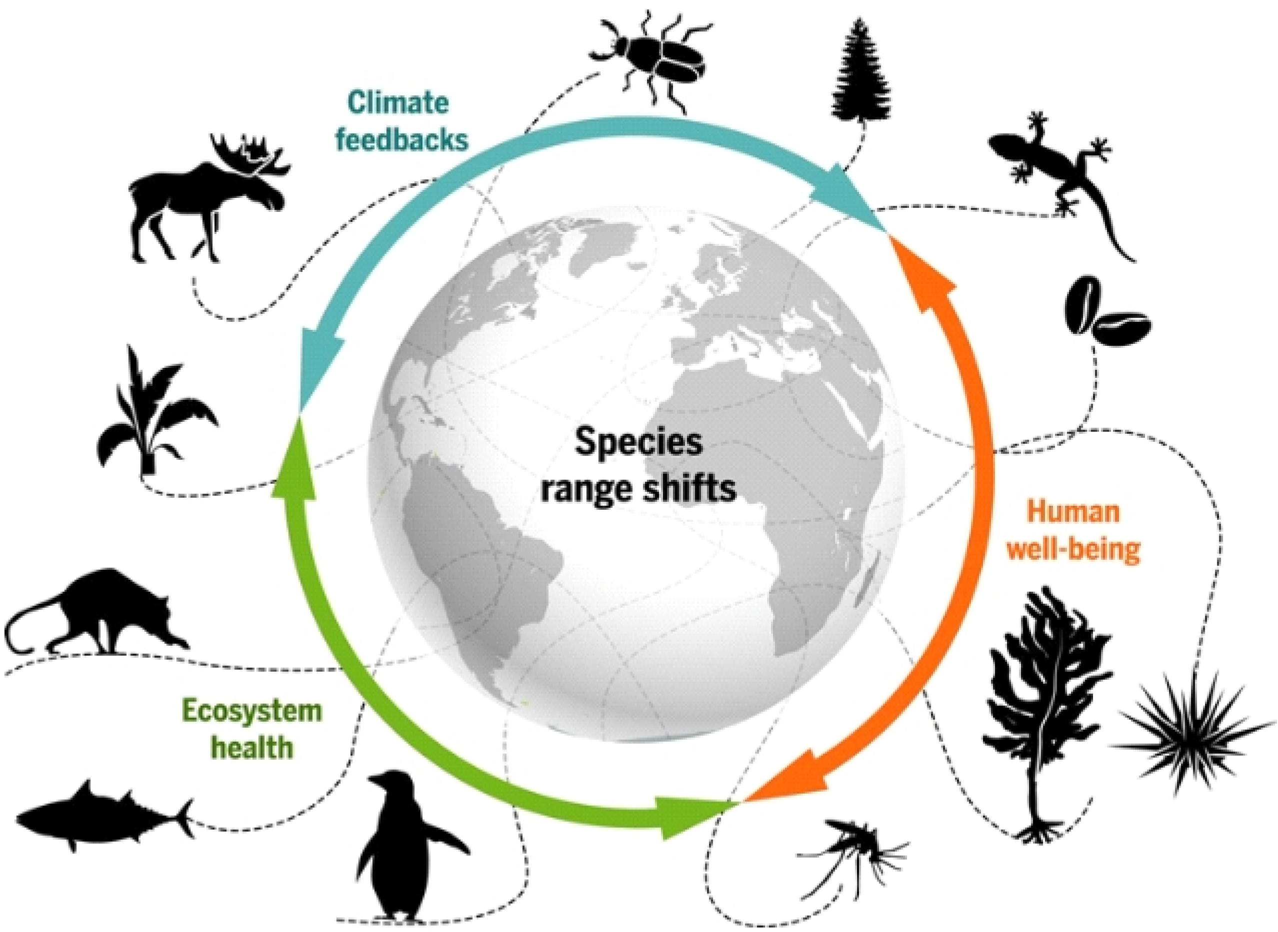


Figure 24: Climate-driven changes in species distributions, or range shifts, affect human well-being both directly (for example, through emerging diseases and changes in food supply) and indirectly (by degrading ecosystem health).

and Ethiopian—and boasts significant altitudinal variation and a diverse range of ecological zones (Anwar et al., 2022). Pakistan's forests are home to a rich diversity of flora and fauna, including several endangered and endemic species. Climate change disrupts the delicate balance between these species and their habitats. Rising temperatures, altered precipitation patterns, and changes in rainfed cropland significantly affect the breeding and wintering species richness across different provinces of Pakistan. These key factors—particularly precipitation, temperature, and rainfed cropland—have a pronounced impact on the breeding and wintering species richness (Figure 26), especially in the KP Province.

Climate change poses significant threats to the ecosystem of Khyber Pakhtunkhwa (KP), Pakistan, a region known for its diverse landscapes and rich biodiversity. Rising temperatures and altered precipitation patterns can lead to habitat loss and shifts in species distributions, particularly affecting endemic and endangered species in the mountainous areas. The increased frequency and intensity of extreme weather events, such as floods and droughts, exacerbate soil erosion, disrupt agricultural practices, and reduce water availability, impacting both terrestrial and aquatic ecosystems. Additionally, the melting of glaciers in the Hindu Kush and Karakoram ranges threatens the downstream water supply, which is crucial for maintaining the ecological balance in the region. The cumulative effects of these changes can lead to the degradation of natural habitats, loss of biodiversity, and diminished ecosystem services, highlighting the urgent need for adaptive conservation strategies and sustainable resource management in KP.

Considering the specific impacts of climate change on species richness in breeding and wintering birds, the impact values represent the predicted changes in species richness due to projected environmental changes. Bird species richness varies significantly across seasons due to the seasonal presence of migratory species in winter. Therefore, we compared both wintering (migratory plus resident species) and breeding (resident species only) bird richness. The richness of breeding and wintering species is correlated with sensitivity to temperature, precipitation, and rainfed cropland, showing positive relationships with these factors.

Exposure varied regionally, with the most significant projected temperature changes occurring in northern regions and the strongest projected precipitation changes also in northern regions of KP. The projected impact of future environmental changes was highly heterogeneous across the country and differed between wintering and breeding communities. Overall, the most negatively impacted region was projected to be the Khyber Pakhtunkhwa province in northern Pakistan, due to reductions in precipitation and rainfed cropland, resulting in a projected negative impact, especially on wintering species richness (Figure 27).

Figure 27 depicts the impacts on breeding birds in the KP province under climate change scenarios (SSP2 and SSP5). The impact values for breeding birds range between -3000 to 1200, with negative severity over the southern part of KP and positive severity over the northern part. Moreover, the most northern, high-altitude regions of KP show mid-range impact values.

Most climate change impact models on ecosystems primarily focus on natural losses without accounting for the additional factors contributed by human activities, such as infrastructure development, rapid urbanization, and deforestation. For example, Ali et al. (Ali et al., 2020) estimated the forest carbon stocks in KP in the context of climate change mitigation and reported that due to extensive deforestation, approximately 96% of trees are immature (young) with only 4% being mature trees. This has resulted in a decrease in carbon stock in KP from 144.71 million tons to 127.6 million tons. In contrast, Punjab Province has only 4% forest cover with limited carbon stock capacity '(Khan et al., 2021).

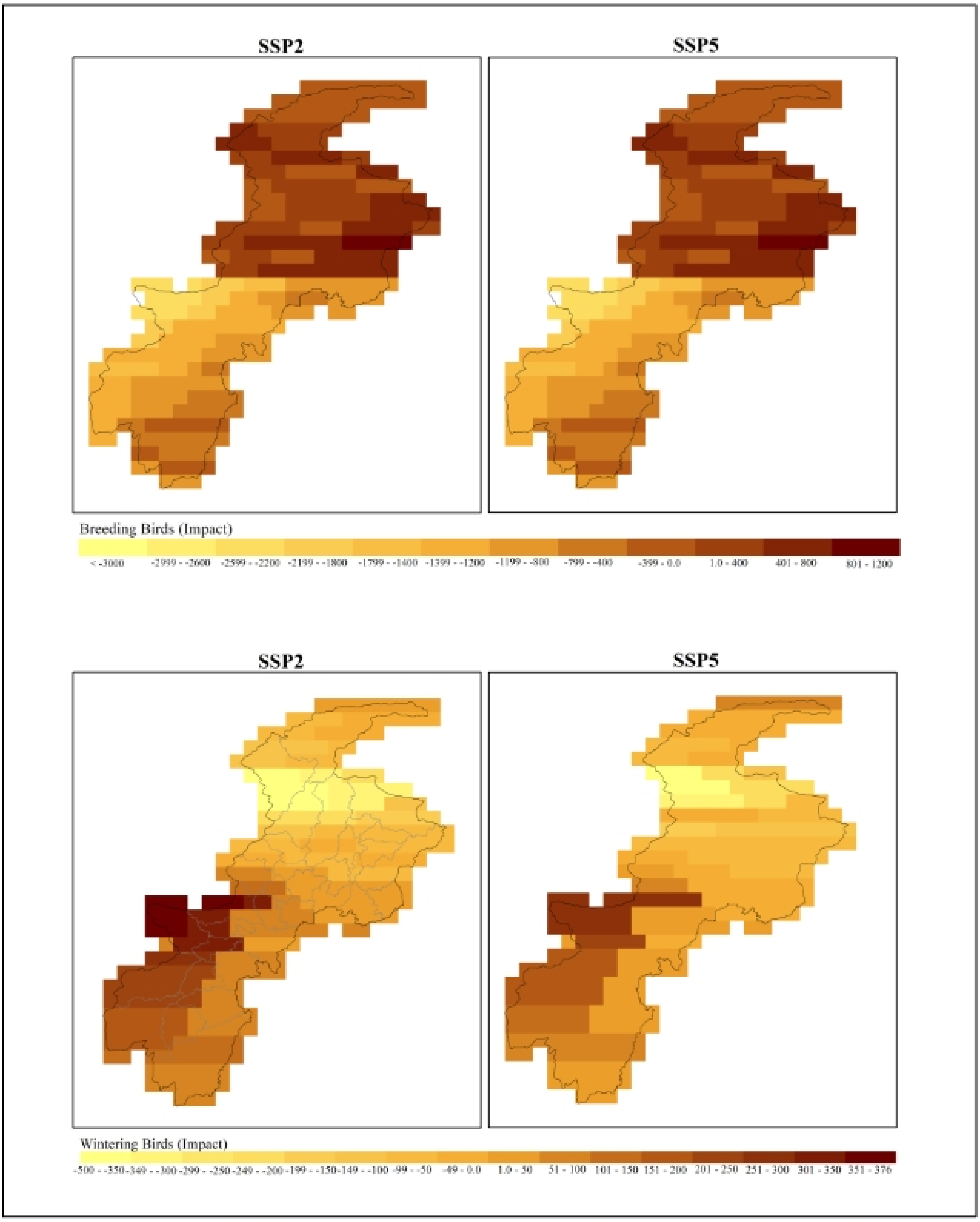


Figure 25: Combined impact of the projected changes on breeding birds and wintering birds due to significant drivers (precipitation, temperature and rainfed cropland) in different provinces of Pakistan, under RCP2.6 and RCP6.0.

Infrastructure

The major reason for floods in Pakistan is primarily due to intense and prolonged monsoon rains, which cause rivers, particularly the Indus and its tributaries, to overflow. This situation is exacerbated by the rapid melting of glaciers in the northern regions during summer months, leading to increased water flow in rivers due to intensive change in climate. Additionally, deforestation reduces the land's ability to absorb water, resulting in higher runoff. Poor water management infrastructure, unplanned urbanization, and inadequate drainage systems further contribute to the severity of floods. Climate change has intensified these factors, bringing about more extreme and unpredictable weather events. The combination of these elements makes Pakistan particularly Khyber Pakhtunkhwa (KP) province even more vulnerable to frequent and severe flooding.

In KP, Climate change impacts on infrastructure are well connected through extreme events such as a combination of highly intensive rainfall and rapid snow and glacier melt due to rise in temperature (Azmat et al., 2018; Azmat et al., 2020). High intensity precipitation can cause of devastating floods such as 2010 and 2022 which are live examples of climate change induced floods, consequently, sever damage to the national (i.e. roads, bridges, railway tracks, agriculture fields etc) and private infrastructure (urban areas etc), ultimately can damage the urban settlements and country's economy. The high temperatures can impact infrastructures in a dual way, by expediting snow and glacier melt process which can cause of riverine, flash flooding, glacier lake outbursts (GLOFs) and can cause of cracks in roads, bridges and coastal infrastructures and degrade more quickly, as reported a study by Tomalka (2022).

The 2010 flood is an example of high intensity rainfall, which damaged infrastructure of different regions of the country's infrastructure severely. Just an example of 2010 flood which was mainly due to 4-day wet spell of Monsoon particularly over the north-west of Pakistan with combination of rapid snow and glacier melt, generated a massive flash flood in the eastern Hindukush region, and the foothills of Suliman Ranges followed by disastrous fluvial flood as reported by Shakeel et al. (2019). The flood 2010 reportedly damaged agriculture, road network, canal network, houses, electric supply feeders, livestock with total cost 783,997 USD just in one district Muzaffargarh, Punjab. While, reportedly approximately 57% (2.8 million ha) of the cropland was affected out of the 4.9 million ha of agricultural area in Sindh. The analysis indicated expected production losses of 88% (3.1 million bales), 80% (1.8 million tons), and 61% (10.5 million tons) for cotton, rice, and sugarcane, were damaged due to 2022 floods in Pakistan (Qamer et al., 2023). Moreover, In boreal summer of 2022, Pakistan experienced extremely high rainfall, resulting in severe flooding and displacing over 30 million people (Hong et al., 2023). Considering this the 2022 flood, is a true example of climate change induced highly intensive sequential rainfall in Pakistan (Nanditha et al., 2023).

Figure 28 illustrates the extensive infrastructure at risk (including settlements, bridges, roads, health units, and schools) due to climate change-induced floods under SSP2 and SSP5 scenarios for future periods. Multiple devastating floods are anticipated, particularly towards the end of the 21st century, potentially surpassing the severity of the 2010 and 2022 floods.

Potentially, several extreme flood events are expected under future climate change scenarios due to increase in hydrological regime of the rivers, as shown in Figures 22-23 in the water resources sector section highlight a significant increase in peak flows at Munda, Kabul River (at Nowshera), and Tarbela Dam gauging stations during summer months, leading to substantial infrastructure damage in Punjab province. In some cases, the projected infrastructure loss exceeds that of the catastrophic 2010 flood. Specifically, Figure 28 presents the estimated loss values under SSP2, including a population of 0.26 million, 215 settlements, 68 bridges, 06 health units, 75 communication towers, 33 schools, and 42 roads for a selected lowest future extreme event. Under SSP5, the projected losses include a population of 2.04 million, 1703 settlements, 526 bridges, 116 health units, 1410 communication towers, 698 schools and 129 roads, for a selected future flood.

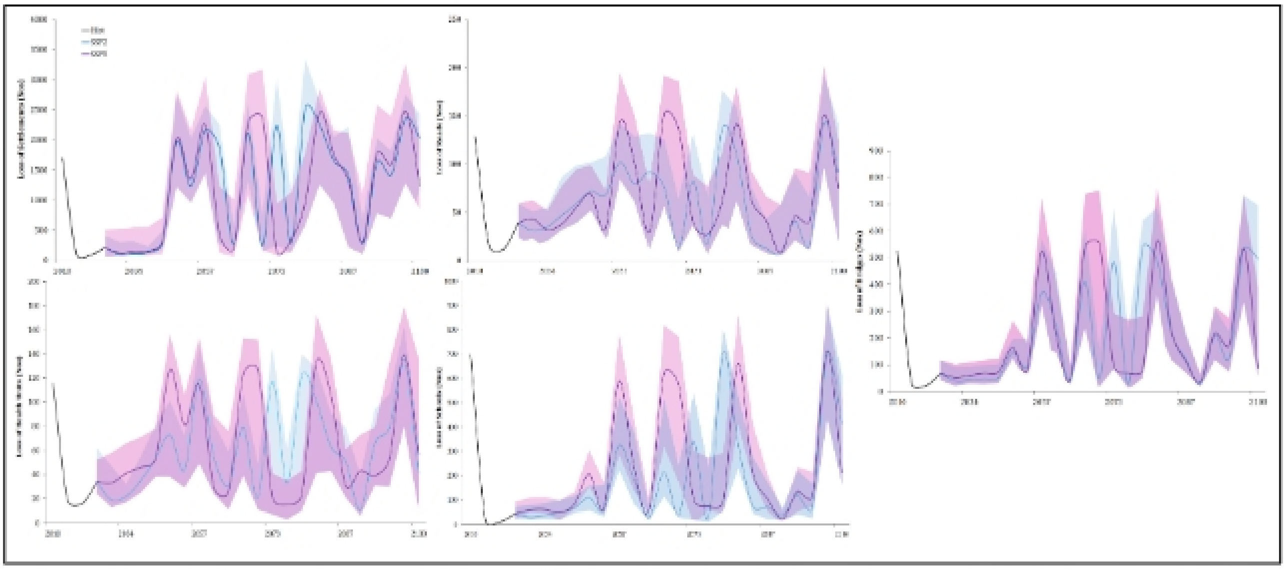


Figure 26: Loss Settlements, Human units, Bridges, Schools and Roads under climate change scenarios (SSP2 and SSP5) during 2050s and 2080s.

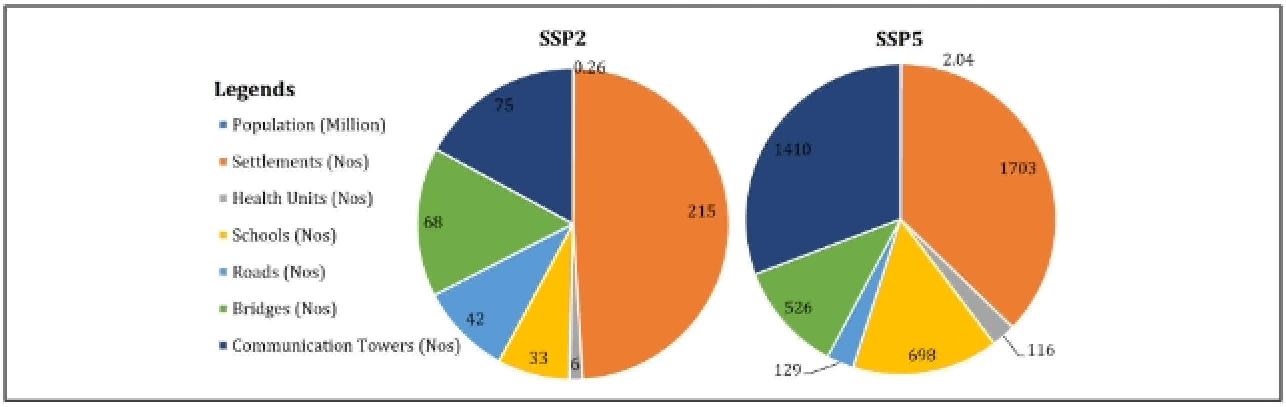


Figure 27: Infrastructures loss due to floods in KP province under SSP2 and SSP5 scenarios.

REFERENCES

Abbas, S. (2022). Climate change and major crop production: evidence from Pakistan. Environmental Science and Pollution Research, 29, 5406-5414.

Ali, A., Ashraf, M.I., Gulzar, S., Akmal, M.J.E.m., assessment (2020). Estimation of forest carbon stocks in temperate and subtropical mountain systems of Pakistan: implications for REDD+ and climate change mitigation. 192, 1-13.

Anwar, M., Rais, M., Baig, M.B., Behnassi, M., (2022). Impacts of climate change on biodiversity in Pakistan: current challenges and policy recommendations, The Food Security, Biodiversity, and Climate Nexus. Springer, pp. 101-123.

Azmat, M., Qamar, M.U., Huggel, C., Hussain, E. (2018). Future climate and cryosphere impacts on the hydrology of a scarcely gauged catchment on the Jhelum river basin, Northern Pakistan. Science of the Total Environment, 639, 961-976.

Ahmad Q-u-A, Biemans H, Moors E, Shaheen N, Masih I. The Impacts of Climate Variability on Crop Yields and Irrigation Water Demand in South Asia. Water. 2021; 13(1):50. https://doi.org/10.3390/w13010050

Ahmad, Q. ul A., Moors, E., Biemans, H., Shaheen, N., Masih, I., ur Rahman Hashmi, M.Z., 2023. Climate-induced shifts in irrigation water demand and supply during sensitive crop growth phases in South Asia. Climatic Change (2023) 176:150. https://doi.org/10.1007/s10584-023-03629-7

Qurat-ul-Ain Ahmad, Eddy Moors, Ilyas Masih, Nuzba Shaheen, Hester Biemans, Muhammad Adnan, The coincidence of Climate extremes with sensitive crop growth phases: Projected impact on sustainable crop water use and crop yield in the IGB river basins, Science of The Total Environment, Volume 916, 2024, 169680, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.169680.

Azmat, M., Wahab, A., Huggel, C., Qamar, M.U., Hussain, E., Ahmad, S., Waheed, A. (2020). Climatic and hydrological projections to changing climate under CORDEX-South Asia experiments over the Karakoram-Hindukush-Himalayan water towers. Science of the total environment, 703, 135010.

Bajracharya, S.R., Maharjan, S.B., Shrestha, F., (2019). Glaciers in the Indus basin, Indus River Basin. Elsevier, pp. 123-144.

Biemans, H., Siderius, C., Lutz, A.F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R.R., Wester, P., Shrestha, A.B., Immerzeel, W.W., 2019. Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. Nat. Sustain. 2, 594–601. https://doi.org/10.1038/s41893-019-0305-3

Campbell-Lendrum, D., Manga, L., Bagayoko, M., Sommerfeld, J. (2015). Climate change and vector-borne diseases: what are the implications for public health research and policy? Philosophical Transactions of the Royal Society B: Biological Sciences, 370, 20130552.

Gul, A., Chandio, A.A., Siyal, S.A., Rehman, A., Xiumin, W. (2022). How climate change is impacting the major yield crops of Pakistan? an exploration from long-and short-run estimation. Environmental Science and Pollution Research, 29, 26660-26674.

Hassan, G., Hassan, F.R. (2017). Sustainable use of groundwater for irrigated agriculture: A case study of Punjab, Pakistan. European Water, 57, 475-480.

Hong, C.-C., Huang, A.-Y., Hsu, H.-H., Tseng, W.-L., Lu, M.-M., Chang, C.-C.J.n.C., Science, A. (2023). Causes of 2022 Pakistan flooding and its linkage with China and Europe heatwaves. 6, 163.

Huber, J.H., Childs, M.L., Caldwell, J.M., Mordecai, E.A. (2018). Seasonal temperature variation influences climate suitability for dengue, chikungunya, and Zika transmission. PLoS neglected tropical diseases, 12, e0006451.

Jamal, K., Li, X., Chen, Y., Rizwan, M., Khan, M.A., Syed, Z., Mahmood, P. (2023). Bias correction and projection of temperature over the altitudes of the Upper Indus Basin under CMIP6 climate scenarios from 1985 to 2100. Journal of Water and Climate Change, 14, 2490-2514.

Jan, I., Ashfaq, M., Chandio, A.A. (2021). Impacts of climate change on yield of cereal crops in northern climatic region of Pakistan. Environmental Science and Pollution Research, 28, 60235-60245.

Khan, I.A., Khan, W.R., Ali, A., Nazre, M.J.F. (2021). Assessment of above-ground biomass in pakistan forest ecosystem's carbon pool: A review. 12, 586.

Lutz, A., Immerzeel, W., Shrestha, A., Bierkens, M. (2014). Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. Nature Climate Change, 4, 587-592.

Mordecai, E.A., Cohen, J.M., Evans, M.V., Gudapati, P., Johnson, L.R., Lippi, C.A., Miazgowicz, K., Murdock, C.C., Rohr, J.R., Ryan, S.J. (2017). Detecting the impact of temperature on transmission of Zika, dengue, and chikungunya using mechanistic models. PLoS neglected tropical diseases, 11, e0005568.

Nanditha, J., Kushwaha, A.P., Singh, R., Malik, I., Solanki, H., Chuphal, D.S., Dangar, S., Mahto, S.S., Vegad, U., Mishra, V. (2023). The Pakistan flood of August 2022: causes and implications. Earth's Future, 11, e2022EF003230.

Pascual, M., Ahumada, J.A., Chaves, L.F., Rodo, X., Bouma, M. (2006). Malaria resurgence in the East African highlands: temperature trends revisited. Proceedings of the National Academy of Sciences, 103, 5829-5834.

Patz, J.A., Olson, S.H. (2006). Malaria risk and temperature: influences from global climate change and local land use practices.

Proceedings of the National Academy of Sciences, 103, 5635-5636.
Qamer, F.M., Abbas, S., Ahmad, B., Hussain, A., Salman, A., Muhammad, S., Nawaz, M., Shrestha, S., Iqbal, B., Thapa, S. (2023). A framework for multi-sensor satellite data to evaluate crop production losses: the case study of 2022 Pakistan floods. Scientific Reports, 13, 4240.
Syed, A., Raza, T., Bhatti, T.T., Eash, N.S. (2022). Climate Impacts on the agricultural sector of Pakistan: Risks and solutions. Environmental Challenges, 6, 100433.
Tomalka, J., Lange, S., Gleixner, S., Ostberg, S. & Gornott, C. (2022). Climate Risk Profile for Pakistan, Potsdam : A joint publication by the Potsdam Institute for Climate Impact Research (PIK), the German Federal Ministry for Economic Cooperation and Development (BMZ), the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and the Ministry of Planning, Development and Special Initiatives of Pakistan.