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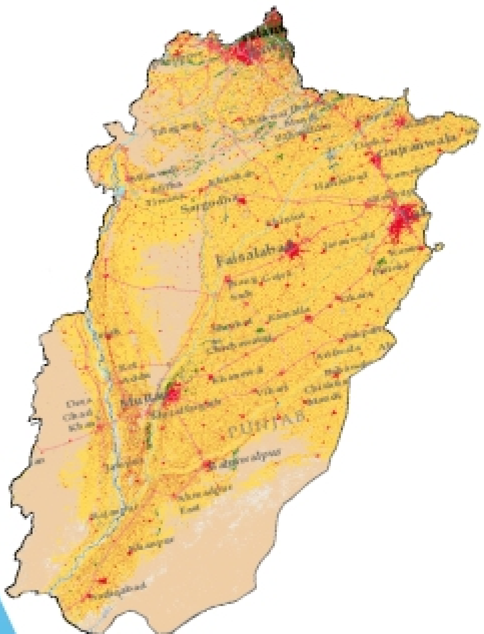


# CLIMATE RISK PROFILE FOR PUNJAB, PAKISTAN

Published in 2024

By

Global Change Impact Studies Centre

On behalf of

Ministry of Climate Change and Environmental Coordination

**Design: Mr. Zaka ul Rasool**

**DISCLAIMER**

This Publication has been developed and produced with the support of the German Federal Ministry for Economic Cooperation (BMZ) through the Support to Strengthening Climate Adaptation and Resilience (SAR) project implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. The views expressed in this publication do not necessarily represent those of GIZ Pakistan.

# 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 Punjab, presented here, serves as a vital resource in our endeavour to understand and mitigate the impacts of climate change in the local context. Developed through rigorous research and analysis, this profile offers valuable insights into projected climate parameters and their implications for various sectors across Punjab.

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 Punjab, mainly/principally developed by 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 Punjab. 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.

Punjab, as one of the most populous and agriculturally productive regions of Pakistan, 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 Punjab represents a significant milestone in our ongoing efforts to enhance climate resilience and sustainability. Developed in collaboration with esteemed partners such as 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 Punjab's environment, economy, and society.

I extend my sincere appreciation especially to GCISC and to all those involved in the creation 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 Punjab 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 Punjab. 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 Punjab 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 Punjab. 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.

Punjab, often referred to as the breadbasket of Pakistan, 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, 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 Punjab. 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 Punjab 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 Punjab 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 from diversified fields of research, , this report endeavours 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 policy-making, foster resilience-building efforts, and catalyse transformative actions towards a more climate-resilient future for Punjab, 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 authors and 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.

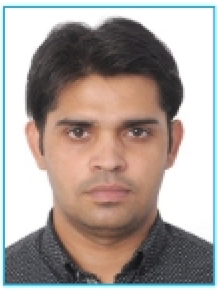
Crafted through the joint efforts of GIZ and the Global Climate-Change Impact Studies Centre (GCISC) in tandem with the Ministry of Climate Change and Environmental Coordination (MoCC & EC), these profiles offer a structured framework for comprehending and evaluating the multifaceted risks posed by climate 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.

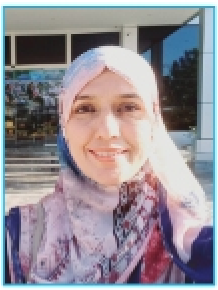
By furnishing decision-makers with comprehensive insights into current and projected climate conditions, sector-specific risk assessments, and an overview of vulnerabilities and priorities, these profiles aspire to guide resource allocation and shape effective national adaptation strategies.

We heartfully acknowledge the invaluable contributions of the following:

**CONTRIBUTORS:**



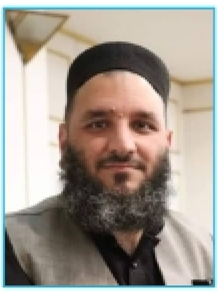
**Dr. Muhammad Azmat**
Sector Specific Climate Impacts



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

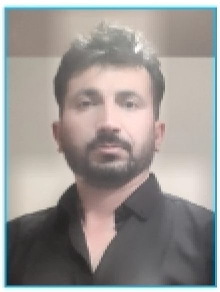
**Ms. Nuzba Shaheen**
Climate Extreme Indices, Indicators

**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 |
| NDCs | Nationally Determined Contributions |
| IPCC | Intergovernmental Panel on Climate Change |
| KPK | 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 |

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# 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 $CO_2$ 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.

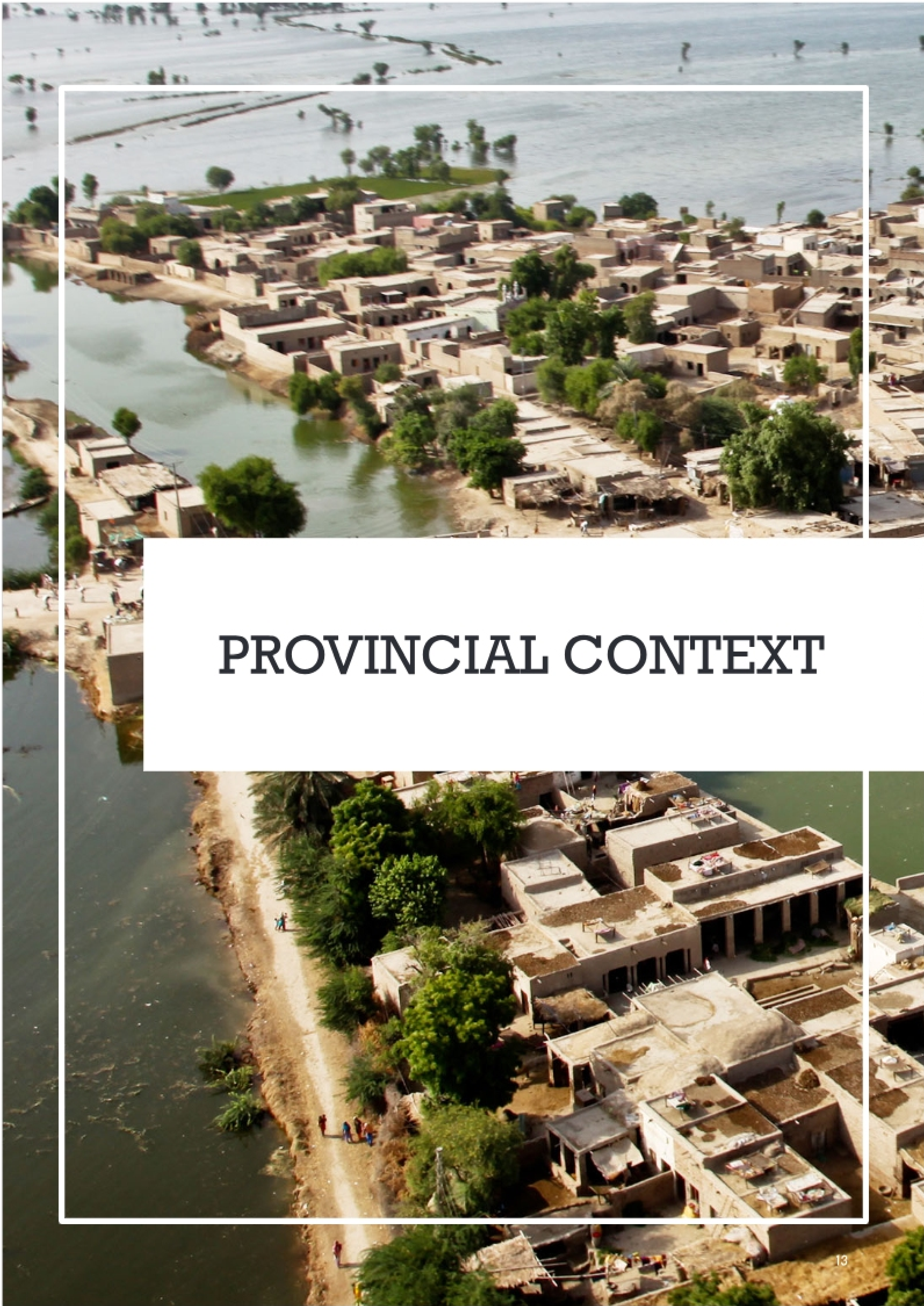
Punjab being the second largest province has experienced severe droughts, followed by devastating floods. This unpredictable cycle of climatic extremes has severely impacted agriculture production and the supporting irrigation systems. **This sub-national profile provides an overview of projected climate change patterns and associated impacts on different sectors (including agriculture, water, health, eco-system, biodiversity and infrastructure) in Punjab, Pakistan by the end of 2100 century under different climate change and socio-economic scenarios (i.e., Representative Concentration Pathways (RCPs) and Shared socio-economic pathways (SSPs) based on latest available IPCC AR6 climate models. In this report, findings are based on RCP-SSP 245** (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).** Pakistan is highly vulnerable to climate change due to its large population, high dependence on agriculture, water resources, and coastal areas, as well as existing socio-economic challenges. **Assessing the differences between RCP 245 and 585 allows policymakers and planners to identify the level of adaptation and resilience required to cope with various climate change scenarios**. This includes strategies for water management, agriculture, infrastructure development, disaster risk reduction, and public health interventions.

Water, agriculture, infrastructure, ecosystems, biodiversity, and health are all highly susceptible to the impacts of climate change in Pakistan. **Adaptation in these sectors is emphasized in Pakistan's Climate Change Policy, National Adaptation Plan, and Nationally Determined Contributions (NDCs).** These documents prioritize agriculture and energy as key sectors contributing to the emissions. This sub-national climate risk profile has been meticulously developed using the **state-of-the-art latest CMIP6 climate change scenarios**, tailored to Pakistan's unique circumstances. It considers essential climate extremes indicators across spatial and temporal scales. Importantly, this sub-national profile complements existing national-level climate risk profiles developed by organizations such as PIK, the World Bank, and the Asian Development Bank, which mainly relied on CMIP5 IPCC climate change scenarios.

The seasonal temperature changes show diverse patterns over different areas in Punjab. **Summer temperatures show an increase of 3.5 °C in the North with the largest increase of 4 °C** in the South. **During winter, there is more warming expected with a higher increase above 4 °C across the whole Punjab** under extreme climate scenarios.

Precipitation trends are uncertain and show distinct patterns in future across seasons in the province. **Summer precipitation is projected to increase significantly (150 mm to 300 mm) in upper Punjab during the late century period under RCP-SSP 585.** Future dry and wet periods are likely to become more extreme.

In the Punjab agricultural sector, the environmental indicators, including extreme precipitation and temperature, are no longer conducive to the current cropping patterns and intensities across the province. This situation necessitates the redistribution of cropping zones based on altered climate variables and adaptation measures.



# PROVINCIAL CONTEXT

Punjab is Pakistan's second largest province by area after Baluchistan with an **area of 205,344 square kilometres**. According to the latest population census of 2023, Punjab has a population of **128 million**, which is growing at a rate of 2.53 (PGS, 2023). The total share of the population to the national population has declined from 52.95% to 52.87% due to slightly lower population growth rate than the national population growth rate of 2.55% (PGS, 2023). Majority of the population in Punjab lives in rural areas alongside the Indus River and its tributaries. However, the urban population in Punjab is also gradually increasing at the rate of 3%, slightly higher than the country's urban growth of 2.67%. Lahore is the largest city in Punjab, counting around 11.3 million inhabitants. It is followed by Faisalabad with a population of 3.2 million people (Economic survey of Pakistan 2023). Rawalpindi, Multan, Gujranwala, and Sialkot are the other major cities of the Punjab with significant contributions to the provincial economy.

Punjab is a major contributor to the national economy by sharing 54.2% of the national Gross Domestic Product (GDP). The growth rate of Punjab's economy has been close to the national growth rate. During the last five years since 2017, the average annual provincial GDP growth rate has been 4.9 percent. Services (62.4%), Agriculture (20%) and Industry (17.6%) are the three major economic sectors in Punjab. Recent trends and projections show that as development proceeds, the share of employment in agriculture will further decline. For instance, the share of agriculture in Punjab has fallen relatively fast from 45% in 2012-13 to 38.5% in 2017-18. Urbanization and industrial growth are the major factors behind this overall shift of labour from agriculture to other sectors. On the other hand, climate change over the past few decades has emerged as another contributing factor to this decline by increasing uncertainty in the agriculture sector and negatively impacting the yields of major crops and reducing the profit

@ *Syed Bilal Javed / Unsplash*

margins for farmers.

Despite of its declined share in the overall provincial economy, the agriculture sector remains the major employer for Punjab's population (38.5%) and the source of livelihood for majority of the population resided in rural areas ((Government of Pakistan, 2021)). Agriculture is also one of the largest sectors in term of women employment by engaging 28% of the economically active women in the province (PERI, 2021). Given the direct and indirect dependency of populations, the concerns are increasing over the negative impacts of climate change on agriculture including increases in temperature, changes in rainfall patterns, and occurrence of extreme weather events i.e., riverine and flash floods and droughts. Agriculture production in the province is primarily irrigated and dependent on surface and groundwater-fed by the Indus River and its tributaries. The average farm size in Punjab is 7.57 hectares, which is 3 times higher than the national average (Asad et al., 2016). However, more than 42% of the farmers own less than one hectare of land and are currently facing a lot of challenges in terms of sustaining their livelihood under changing climate. The major crops of Punjab are wheat, cotton, rice, sugarcane, grams and fodder (PITB, 2021). However, the adaptive capacity of the agriculture sector in Punjab is limited due to limited access to resources especially quality inputs, agricultural credit and access to market services which are often exploited by middlemen. This limited access to resources coupled with the negative impacts of climate change may put small farmers in a difficult situation while reducing their food supply and increasing the risk of becoming poor.

Further, it is also important to mention that all other sectors especially the industrial sector are directly or indirectly connected to the agriculture sector for the supply of raw materials to major industries, i.e., textile, leather, rice processing, edible oil, sugar, and various food processing industries. Any negative impact on agriculture will directly impact the people employed in other sectors as well.

*@Kashif Shah / Unsplash*

# Topography and Environment

The province is predominantly on a plain level, however, there are some mountainous areas in the northwest called the Margalla Hills and extreme South-West named Sulaiman Mountains. There is also a plateau adjacent to the mountains known as the Potohar plateau and a desert belt in the Southeastern part known as Cholistan. Punjab also contains part of the Thal desert. In the South, Punjab's elevation reaches over 2000 metres near the hill station of Fort Munro in Dera Ghazi Khan (Saif Ur-Rehman et al., 2020).

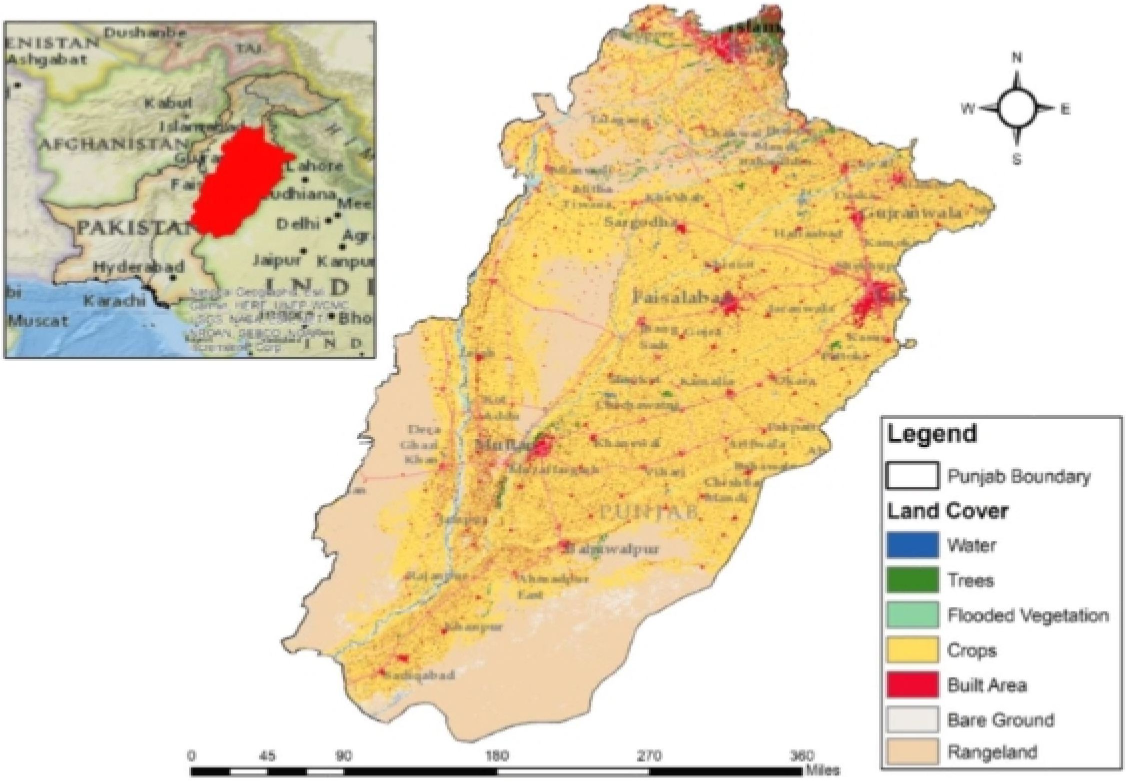



Figure 1: Location of Punjab Province within Pakistan

Punjab is characterised by a semi-arid climate with increasing aridity from east to west and from north to south. Punjab province can be divided into fourteen Agroecological zones depending on climate and other factors (FAO, 2018). Each of the agroecological zones is unique in terms of its climatic conditions, land resources and ecological factors allowing the region to follow specific patterns of crop production and pastoral activities.

**Punjab has one of the largest irrigation systems supported by a thousand canals to serve the 21.71 million acres of cultivable command area with cropping intensities between 120-150% .** The main source of water for Punjab is the Indus River and its tributaries i.e., the Jhelum, Chenab, Ravi and Sutlej rivers. **The Indus is fed by melting snow and glacial meltwater from the Himalayas and runs southward, ultimately discharging into the Arabian Sea**. However, climate change has impacted the water availability in the Indus and its tributaries through changes in rainfall patterns and has led to increased reliance on groundwater resources which is also evident from the rapid growth of tubewells across the province. Unsustainable agricultural practices, inadequate reforestation techniques as well as poor watershed protection and excessive water abstraction for irrigation have resulted in major environmental issues in the province, including salinity, soil erosion and desertification.

@ Abdul Hameed / Unsplash

Extreme weather events, including heavy precipitation and droughts, are expected to intensify in the context of climate change, highlighting the need for adaptation measures to protect biodiversity and maintain fragile ecosystems and their services.

@Arshad Jamil / Unsplash

# Current Climate

In Punjab, there is a huge gradient/ variation in temperature from North to South and between the seasons i.e., Summer (April-September) and Winter (October-March).

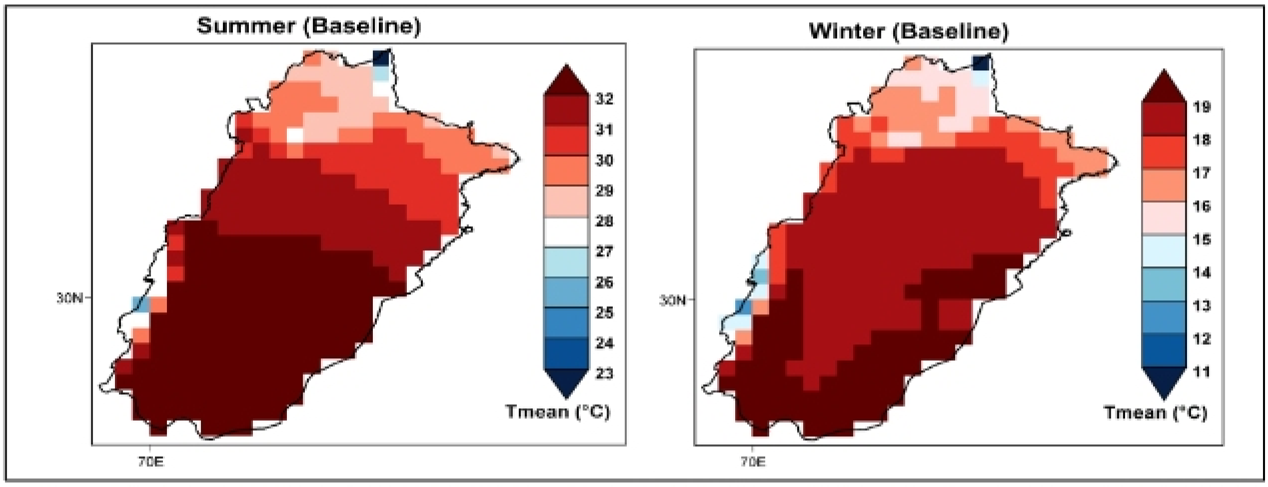



*Figure 2: Seasonal Winter ((October – March) and (Summer (April – September) patterns of mean temperatures (Tmean 0C) of Punjab province during the control period 1974–2014*

Figure 2 shows a gradient in temperature across the province, with warmer conditions prevalent in the southern regions compared to the relatively cooler northern areas during the summer season.

In the lower parts of Punjab, which encompass regions closer to the south, **the mean summer temperature typically ranges between 32 to 34 degrees Celsius**. Conversely, in the upper parts of Punjab, comprising areas towards the north**, the mean temperature tends to vary within a slightly lower range of 28 to 30 degrees Celsius**.

In the southern parts of Punjab, **the mean winter temperature hovers around 19-20 degrees Celsius, indicating relatively warmer winters**. Moving towards central Punjab, we see a slight decrease in temperatures, with mean temperatures averaging around 18 degrees Celsius**. Finally, as we move further north into the upper regions of Punjab, particularly in the northern parts, temperatures drop further, ranging between 15-17 degrees Celsius.**

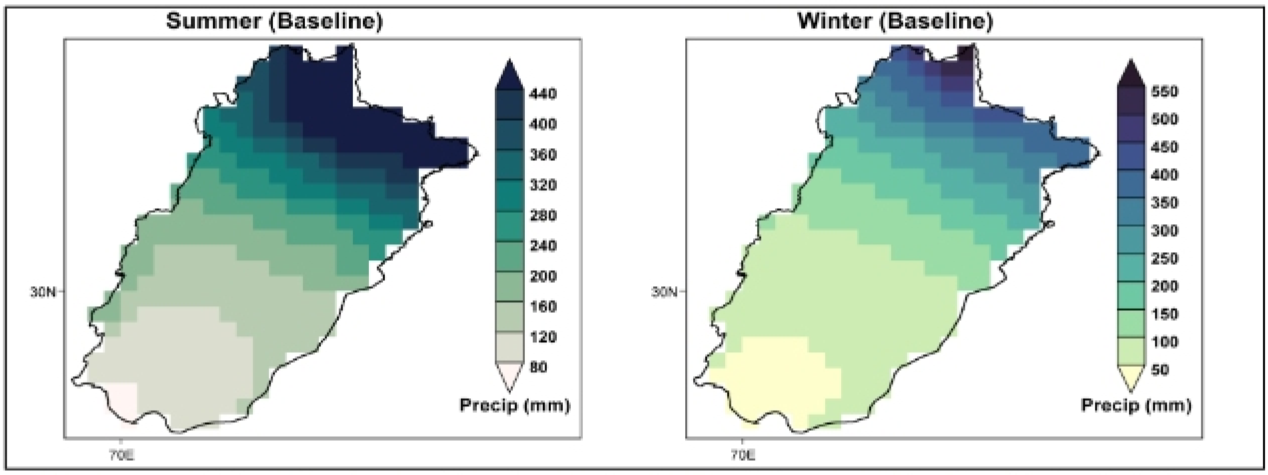



*Figure 3: Seasonal (Winter (October – March) and Summer (April – September) patterns of total precipitation (mm) of Punjab province during the control period 1974–2015*

Seasonal total precipitation during the control period shows a large spatial gradient decreasing from North to South. **The highest precipitation (> 600 mm) is observed during summer in the Northern parts of Punjab linked with regional monsoon patterns**. Lowest precipitation (< 50 mm) is observed in Southwest parts of Punjab during Winter.

Punjab's seasonal precipitation paints a picture of contrasting extremes Figure 3. A clear north-south gradient dictates rainfall amounts, with totals steadily decreasing as you travel southward. This pattern aligns perfectly with regional weather systems, specifically the summer monsoon.

During this monsoon season, the northern regions of Punjab benefit from its full force, leading to the highest seasonal precipitation, exceeding a generous 600 millimeters. In stark contrast, the southwestern parts of Punjab experience the other end of the spectrum, receiving the lowest seasonal precipitation. Here, winter reigns supreme as the driest season, with precipitation dipping below a meagre 50 millimeters. This dramatic difference highlights the undeniable impact of the monsoon on Punjab's precipitation patterns, creating a north wet, south dry scenario.

*@Abdul-Rauf-Khalid / Unsplash*

# PROJECTED CLIMATE CHANGES

This section presents a spatial and temporal pattern in seasonal temperature and precipitation for Punjab province in Pakistan, focusing on both summer and winter months. Two different emission scenarios, SSP245 and SSP585, are considered to assess the range of potential outcomes for the future periods F1 (2021-2060) and F2 (2061-2100).

# Temperature

Seasonal temperature projections for Punjab province over the span of 150 years, from 1951 to 2100, depict a clear and consistent trend of increasing temperatures under both emission scenarios. These projections reveal a linear and significant rise in temperatures, particularly pronounced towards the end of the century, with the most notable changes occurring under the RCP-SSP585 emission scenarios. The observed increase is especially pronounced during the summer season, with temperatures surpassing 5 degrees Celsius above historical averages during the period from 2061 to 2100.

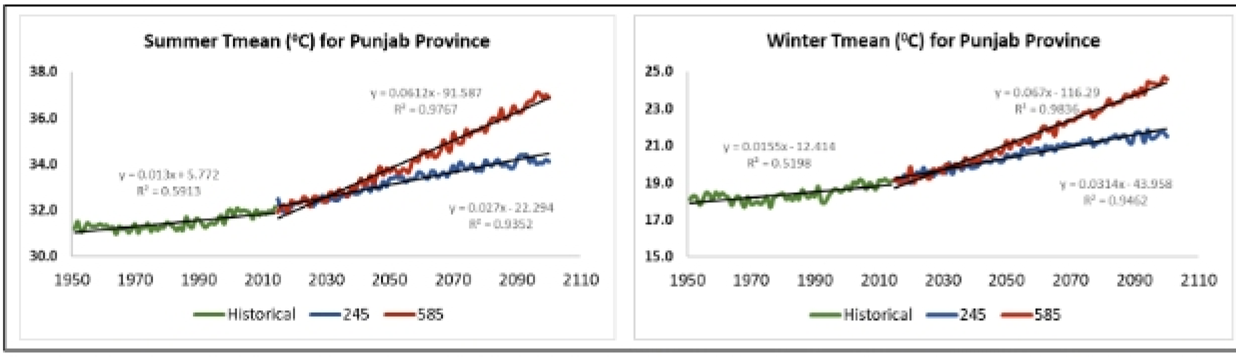



Figure 4: Future changes in the temporal distribution of seasonal (Summer (April – September) and Winter (October – March)) temperatures (Tmean 0C) of Punjab province during the control period 1974–2014.

Seasonal temperature projections over Punjab province show significant increasing trends in both emission scenarios with a larger increase during winter. **The largest change in Tmean is observed during the summer season (> 5 °C) in F2 (2061-2100) under RCP-SSP585 scenarios**.

This significant rise in temperatures has multifaceted implications for the region's climate dynamics. It not only impacts seasonal variations but also leads to pronounced fluctuations in annual temperatures. **The warmer winters may disrupt traditional agricultural practices and crop cycles, affecting planting and harvesting schedules**. Conversely, hotter summers could exacerbate heat stress on crops and livestock, potentially leading to reduced yields and increased vulnerability to pests and diseases.

Moreover, the increasing temperatures can also have far-reaching consequences for the region's water resources and ecosystems. **Higher temperatures may accelerate the melting of glaciers in the Himalayas, leading to changes in river flow patterns and affecting water availability for irrigation and other essential needs.** Additionally, rising temperatures can exacerbate the frequency and intensity of heatwaves, posing significant risks to human health and well-being.

In Punjab, particularly in the **southwestern region** encompassing districts like Muzaffargarh, Multan, Lodhran, and nearby areas, the results indicate the highest projected increase in mean temperatures. The summer temperature in Punjab is projected to increase under both emission scenarios, i.e., SSP245 and SSP585. **Under the SSP585 scenario, these areas could experience temperature rises of up to 4.5 degrees Celsius by the end of the century.** Such significant temperature changes pose substantial challenges for agriculture and other sectors, potentially leading to adverse effects on productivity and livelihoods.

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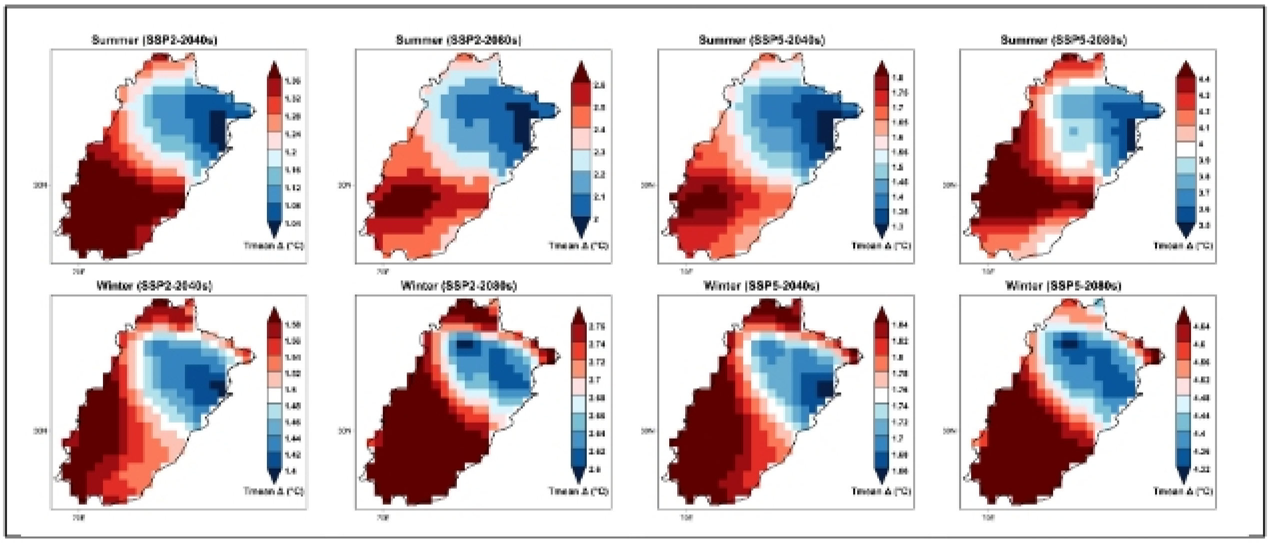



Figure 5: Future changes in the spatial distribution of seasonal (Winter (October – March) and (Summer (April – September) temperatures (Tmean 0C) of Punjab province during the control period 1974–2014.

indicate the highest projected increase in mean temperatures. The summer temperature in Punjab is projected to increase under both emission scenarios, i.e., SSP245 and SSP585. Under the SSP585 scenario, these areas could experience temperature rises of up to 4.5 degrees Celsius by the end of the century. Such significant temperature changes pose substantial challenges for agriculture and other sectors, potentially leading to adverse effects on productivity and livelihoods.

The figure 5 indicates that the projected changes in mean temperatures during the winter season are notably more substantial compared to those during the summer months, particularly in the southwestern parts of Punjab. **In these regions, the anticipated temperature increases range between 1.6 to 4.8 degrees Celsius by the end of the century.**

Overall, the figure 5 highlights the urgency of addressing climate change impacts, particularly in regions like southwestern Punjab, where the projected temperature rises could have profound consequences for the environment and human well-being. These findings emphasize the need for targeted adaptation and mitigation strategies to minimize the adverse effects of climate change on vulnerable communities and sectors in Pakistan.

Conversely, **in the northern parts of Punjab, the results suggest 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.

# Precipitation

Precipitation shows a linear, non-significant increase in summer in Punjab. However, there is no significant change observed during winter for both emission scenarios. Inter-annual variation is large in Precipitation with the largest increase under RCP-SSP585.

Our investigation into the seasonal precipitation patterns in Punjab also unveils significant trends for the future periods F1 (2021-2060) and F2 (2061-2100) under RCP-SSP 245 and 585 emission scenarios. Spatial maps depicting the distribution of precipitation during the summer and winter seasons showcase distinct patterns across the province.

The spatial distribution of precipitation during the summer season highlights higher levels of rainfall, particularly in regions influenced by the monsoon rains. This heightened precipitation is primarily observed in the northeastern part of Punjab province, coinciding with the onset of the monsoon

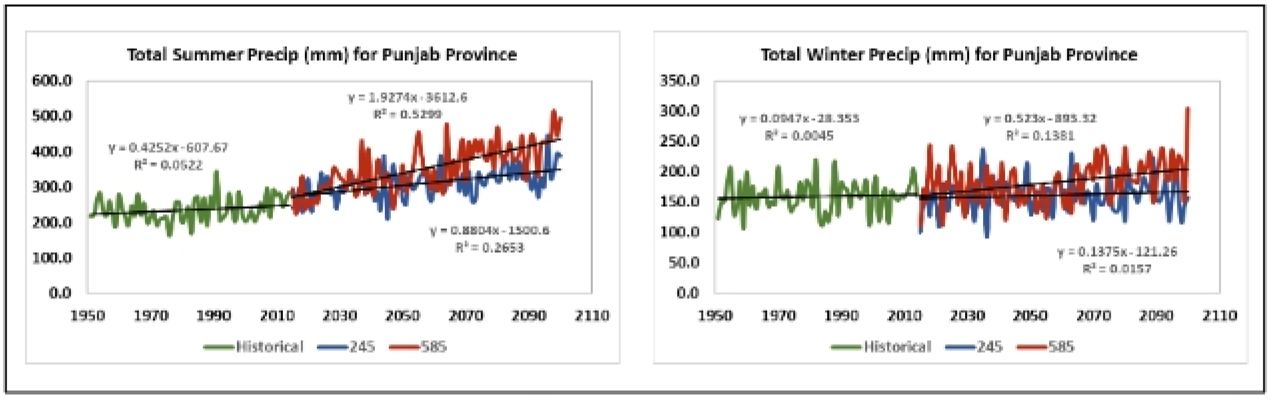



Figure 6: Future changes in the temporal distribution of seasonal (Summer (April – September) and Winter (October – March) total precipitation (mm) of Punjab province during the control period 1974–2014..

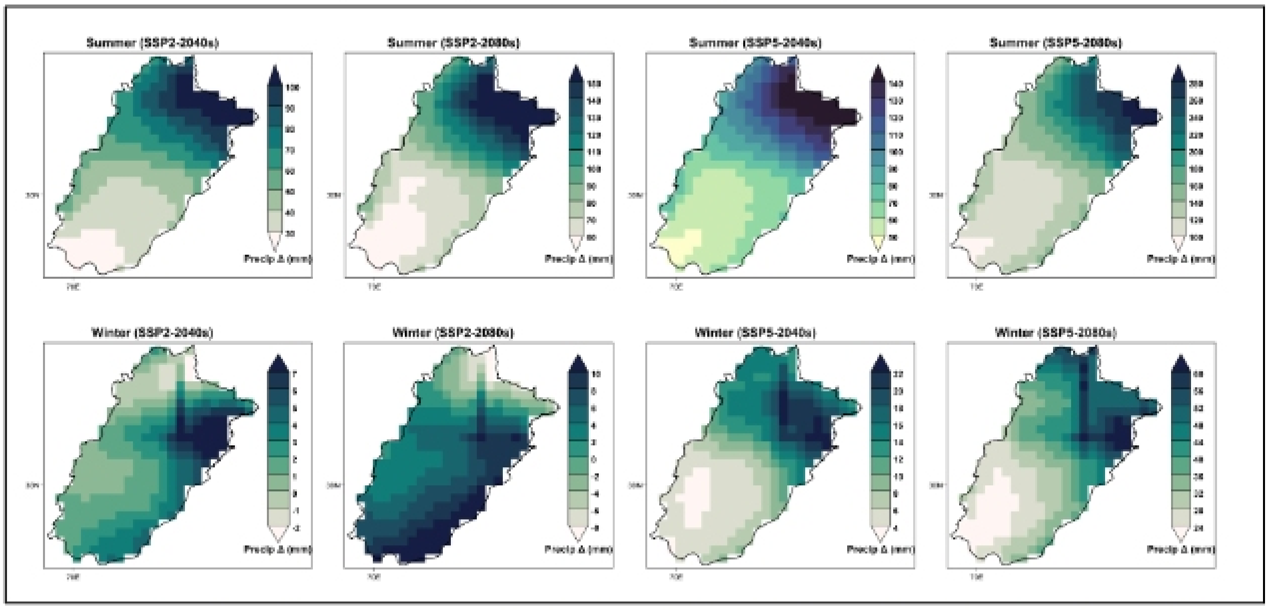



Figure 7: Future changes in the spatial distribution of seasonal ( Winter (October – March) and Summer (April – September)) total precipitation (mm) of Punjab province during the control period 1974–2014.

In contrast to the summer season, the winter precipitation distribution in Punjab exhibits lower levels of rainfall, typically ranging up to 20 mm. The spatial distribution of winter precipitation indicates a more uniform pattern across the province, with relatively consistent levels of rainfall observed throughout. The winter months experience reduced precipitation intensity and frequency compared to the summer season, reflecting the diminished influence of monsoon rains during this period.

# 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 Punjab. 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 Punjab provinces. Hot days are estimated for Punjab province using daily maximum temperatures with the threshold of 35 0C under both RCP-SSP 245 and RCP-SSP 585 emission scenarios for future periods F1 (2021-2060) and F2 (2061-2100).

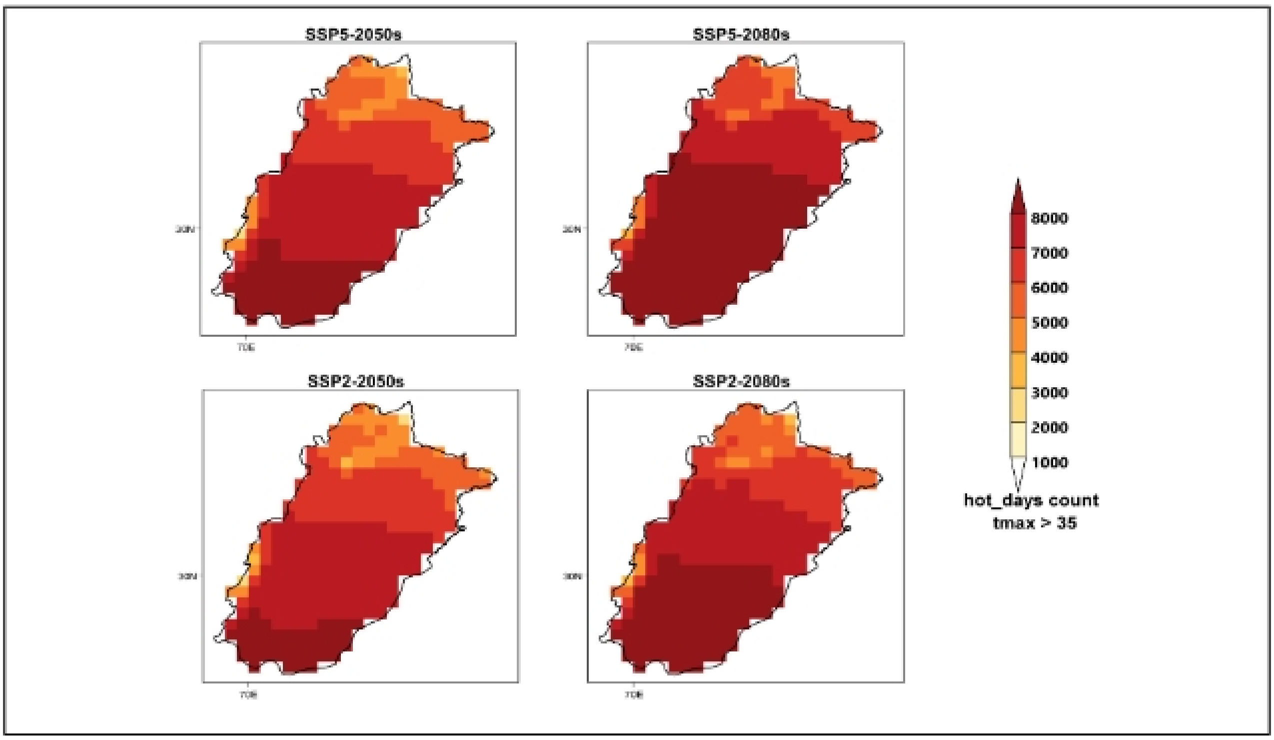



Figure 8: Future changes in the spatial distribution of hot days of Punjab province during the control period 1974–2014 and F1 (2021-2060) and F2 (2061-2100) under two emission scenarios i.e., RCP-SSP 245 and RCP-SSP 585.

The frequency of hot days is projected to be notably higher (> 8000 days during the late century under RCP-SSP 585) in the southern regions, which are characterised by highly cultivated land areas. Conversely, the northern parts of Punjab are likely to experience fewer hot days (less than 3000 days), attributed to its cooler micro-climate. The maps also illustrate that the increasing temperatures projected under the RCP-SSP585 emission scenario are reflected in the distribution of hot days.

The Punjab province is highly regarded for its agricultural potential, characterised by diverse land use/land cover (LULC) patterns and human settlements. The southern regions of the province boast some of the most fertile lands, ideal for cultivating a variety of crops such as wheat, rice, cotton, sugarcane, and maize. However, the projected increase in extreme heat in these southern areas is expected to have detrimental effects on crop yields and water availability, particularly during critical crop growth stages.

# 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 centred on each calendar day of a given 40-year climate reference period.

Under rising temperatures, cold nights are

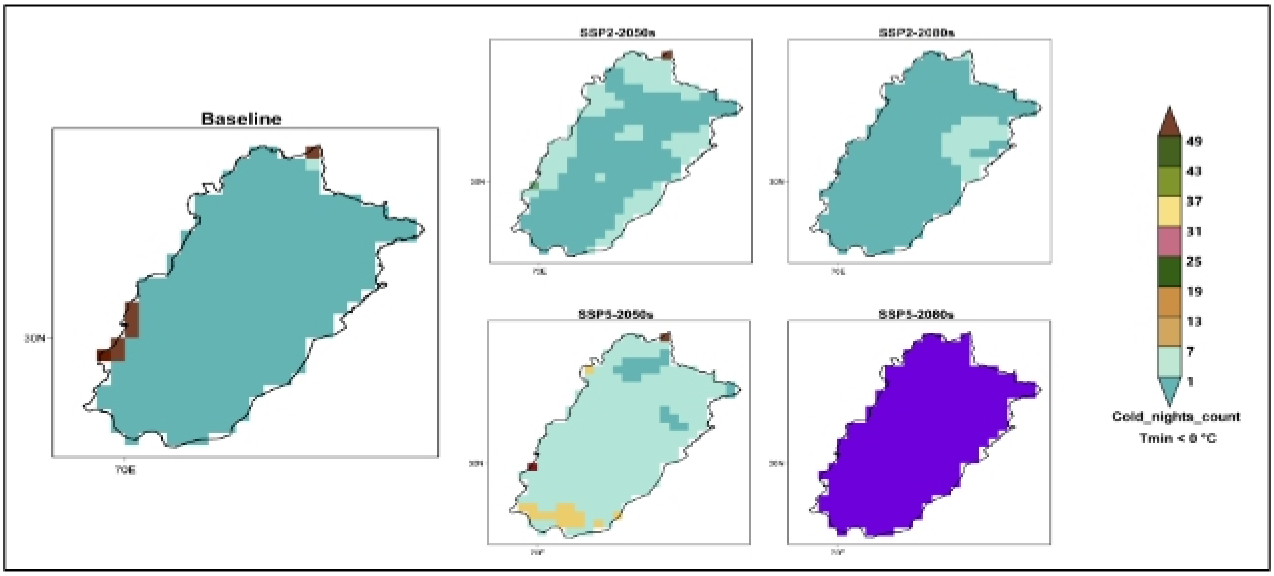
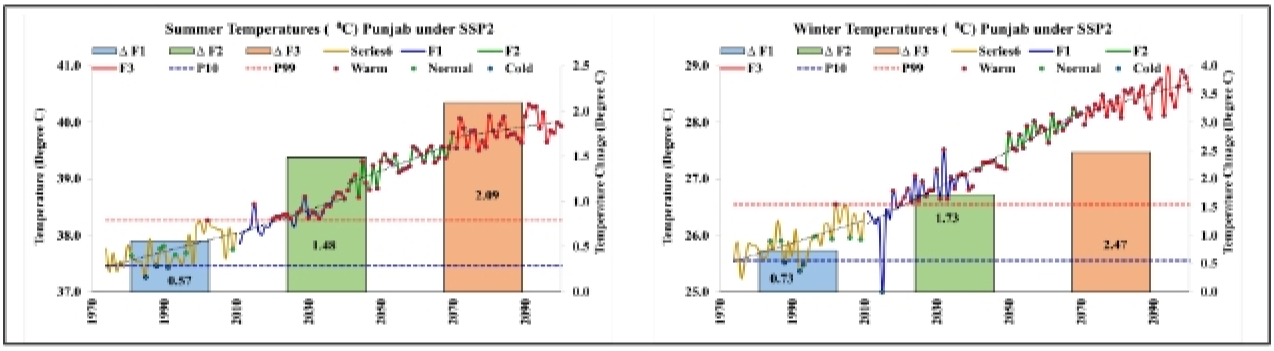



Figure 9: Future changes in the spatial distribution of Cold nights of Punjab province during the control period 1974–2014 and F1 (2021-2060) and F2 (2061-2100) under two emission scenarios i.e., RCP-SSP 245 and RCP-SSP 585.

projected to decrease substantially by the end of the century under both emission scenarios. **In the mid-century period, there is a greater spatial variability in cold nights while by the end of the century under extreme scenarios warming will increase and cold nights will be diminished.**

# Climate Extreme (Warm, Dry, Wet and Cold)

Under a changing climate, climate extremes, including warm, dry, wet, and cold, are projected to increase across the entire Punjab 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 Punjab 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).



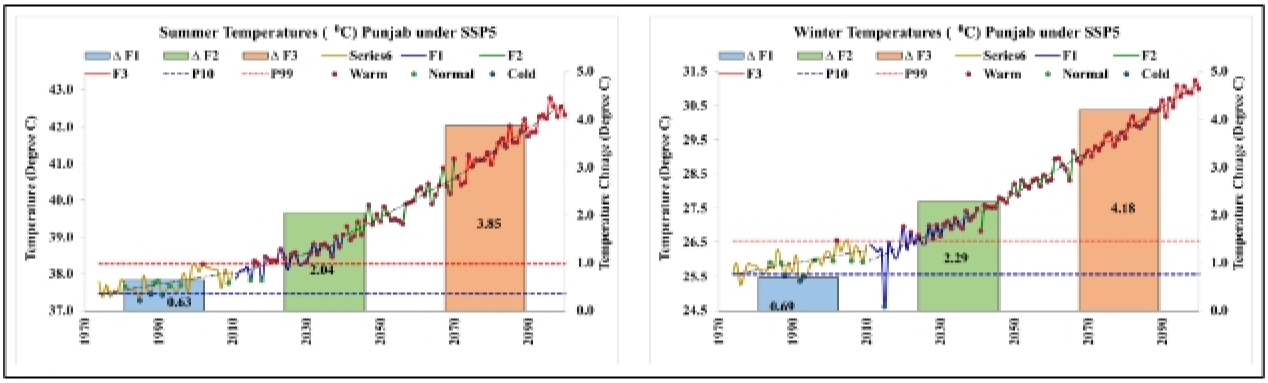



Figure 10: Future trends, changes and frequency and intensity of warm climate extremes (warm and cold) over Punjab Province for the period from 1981-2100 under two emission scenarios (RCP-SSP 245 and RCP-SSP 585.

The linear graphs depicting temperature trends in Punjab provide valuable insights into climate patterns. These plots illustrate the linear trends of maximum temperature (Tmax) during the 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 control period. **Particularly concerning is the significant rise in the number of Warm extremes towards the end of the century for both seasons, with a substantial increase (4.18 °C) observed during winter in the last 40 years of the projection period. However, cold extremes show non-significant trends in both seasons under both emission scenarios. 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.

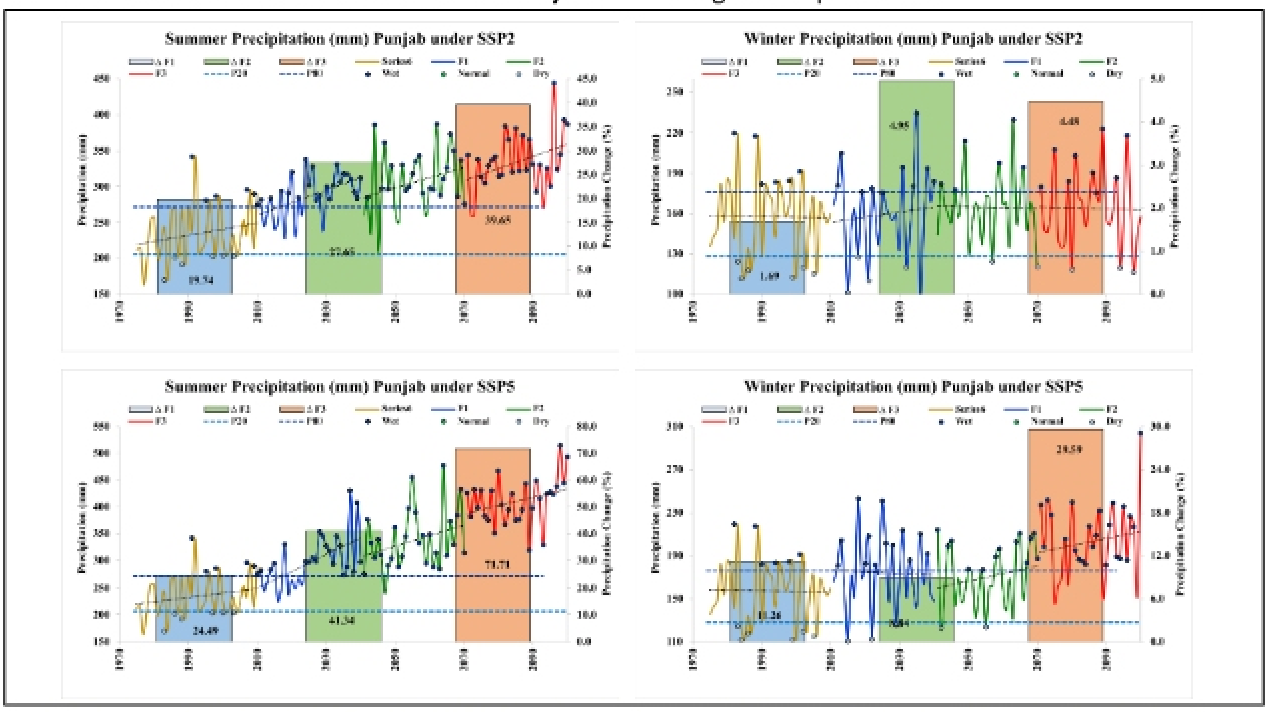



Figure 11: Future trends, changes and frequency and intensity of cold climate extremes (wet and dry) over Punjab Province for the period from 1981-2100 under two emission scenarios (RCP-SSP 245 and RCP-SSP 585).

The linear graphs depicting precipitation trends in Punjab province provide valuable insights into precipitation patterns Figure 11. In these plots, we illustrate the linear trends of precipitation levels during the summer and winter seasons, along with the values corresponding to the 80th percentile (P80) and 20th percentile (P20). Values exceeding P80 represent wet extremes, while those falling below P20 denote dry extremes. **Our analysis reveals linear and non-significant trends during summer under both emission scenarios. While the winter season is characterised by non-linear and non-significant trends. The largest positive change in precipitation is observed during the summer season (72%) under RCP-SSP 585 by the end of 2100 century.** Such findings highlight the urgency for robust adaptation strategies to address the ever-rising impacts and risks associated with precipitation extremes.

# 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 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)

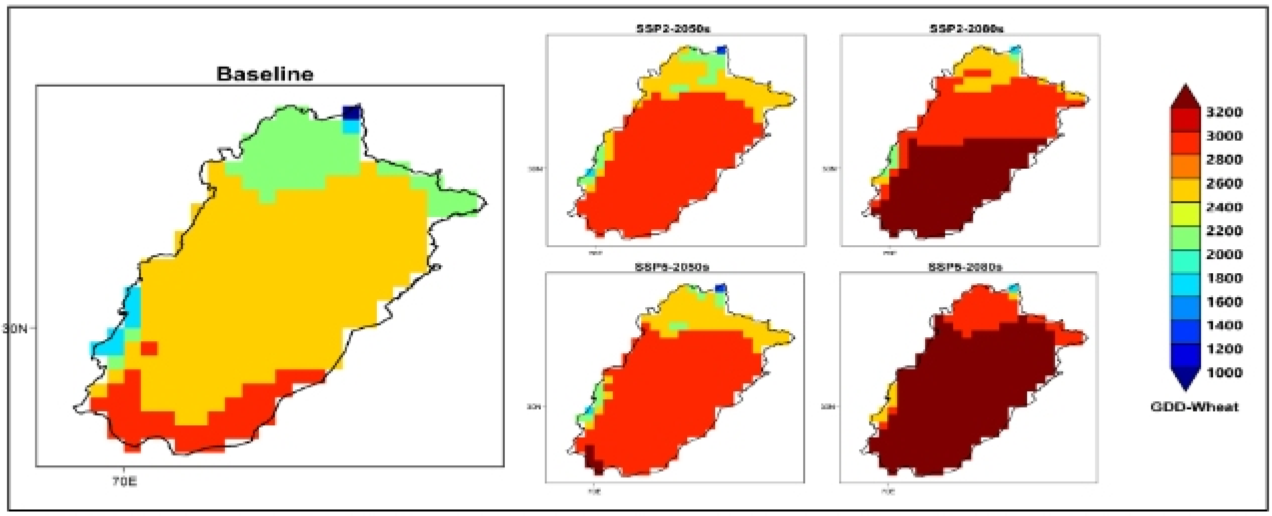



Figure 12: Spatial distribution of Growing Degree Days (GDD) over Punjab during the control period (1974-2014) and F1 (2021-2060) and F2 (2061-2100) under two emission scenarios (RCP-SSP 245 and RCP-SSP 585).

Growing degree days analysis represents an increase in accumulated growing degree days for both scenarios (RCP 4.5 and RCP 8.5) and time periods (F1 & F2) in all major Wheat producing zones of Punjab including the Potohar region, Central and Southern Punjab.

However, **this increase is more intense in RCP 8.5 during the late century period. There is an overall increase of 800-1000 Growing Degree Days (GDD) between the historical and late-century extreme scenarios in the central and southern parts of Punjab**. Results indicate that the major irrigated wheat-producing areas of Punjab are poised to face heightened challenges due to escalating temperatures, particularly during critical crop growth stages marked by high temperatures and water stress. This scenario is anticipated to result in diminished productivity.

**In the extreme southern parts of Punjab, there's been a notable surge of 800-1000 growing degree days, while the northern regions of Pakistan are anticipated to experience an increase of nearly 600**. Consequently, the lower southern areas may become less conducive to crop production due to the intensifying heat in late century period, in the absence of mitigation measures and appropriate adaptation strategies.

## Standardised 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 consider 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 is 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 Punjab 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 |

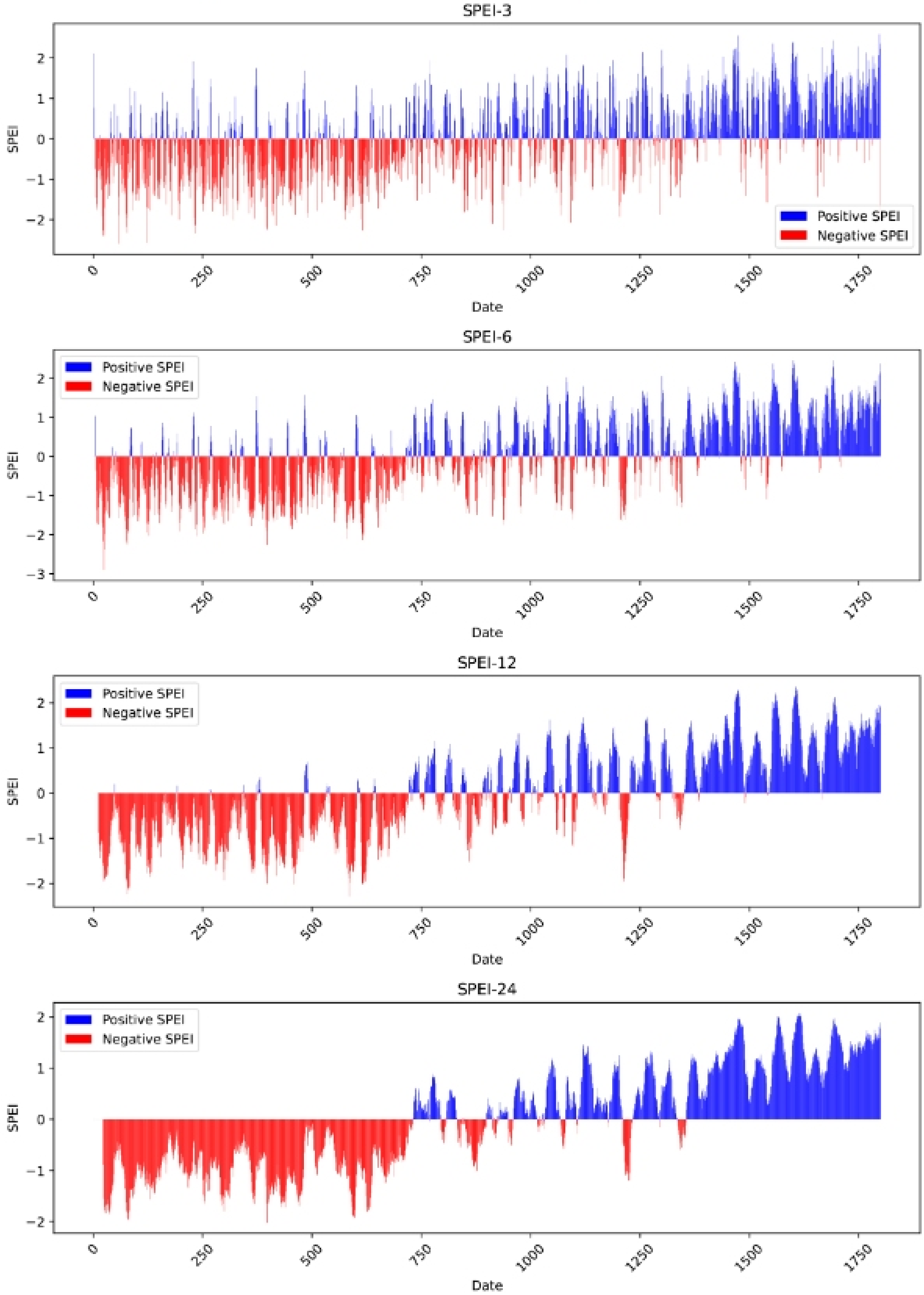



Figure 13: Standardized Precipitation Evapotranspiration Index (SPEI) over Punjab estimated at multiple timescales, such as SPEI-03, SPEI-06, SPEI-12, and SPEI-24 for 150 years from 1951 to 2100 under RCP-SSP 245 emission scenario.

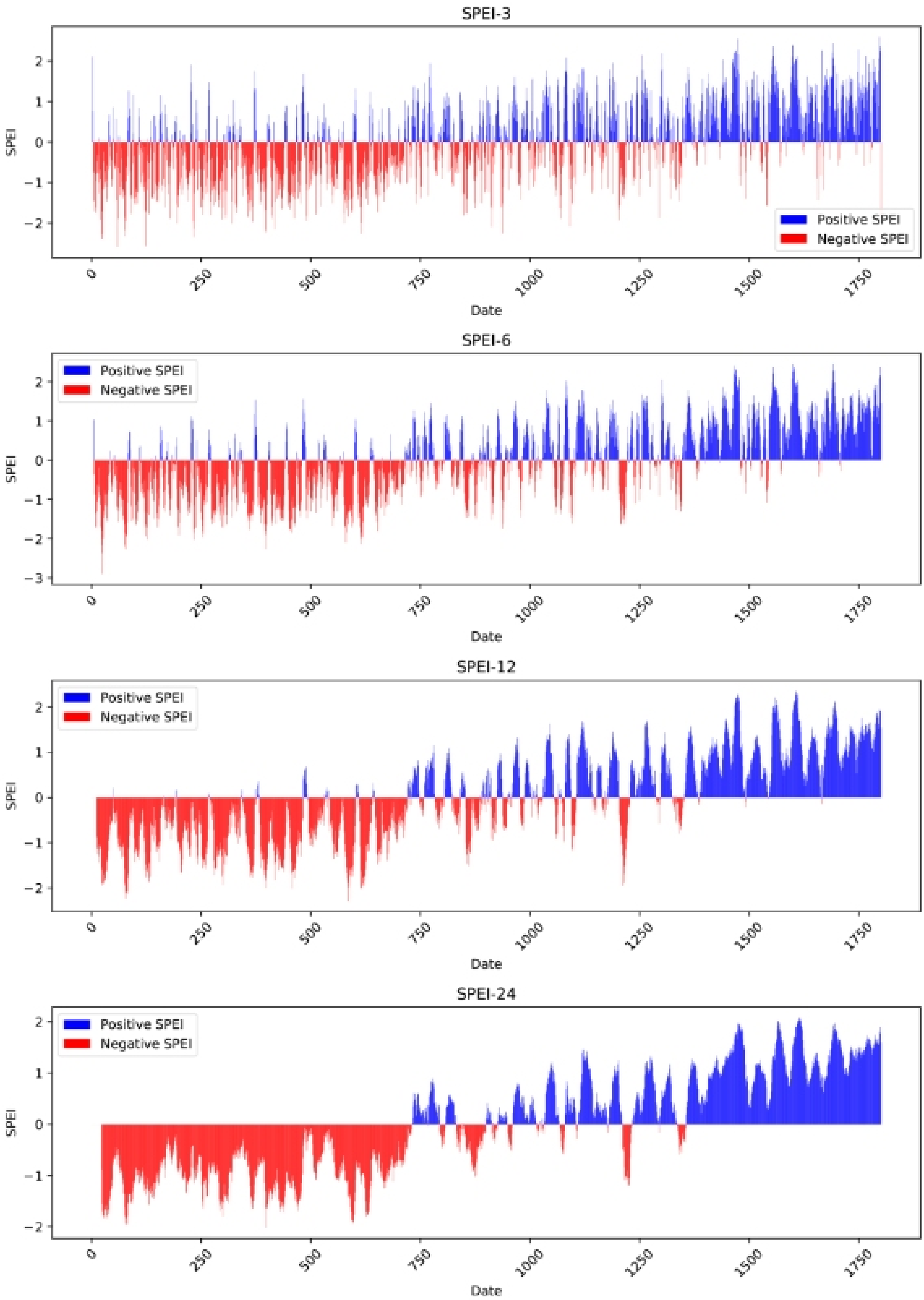
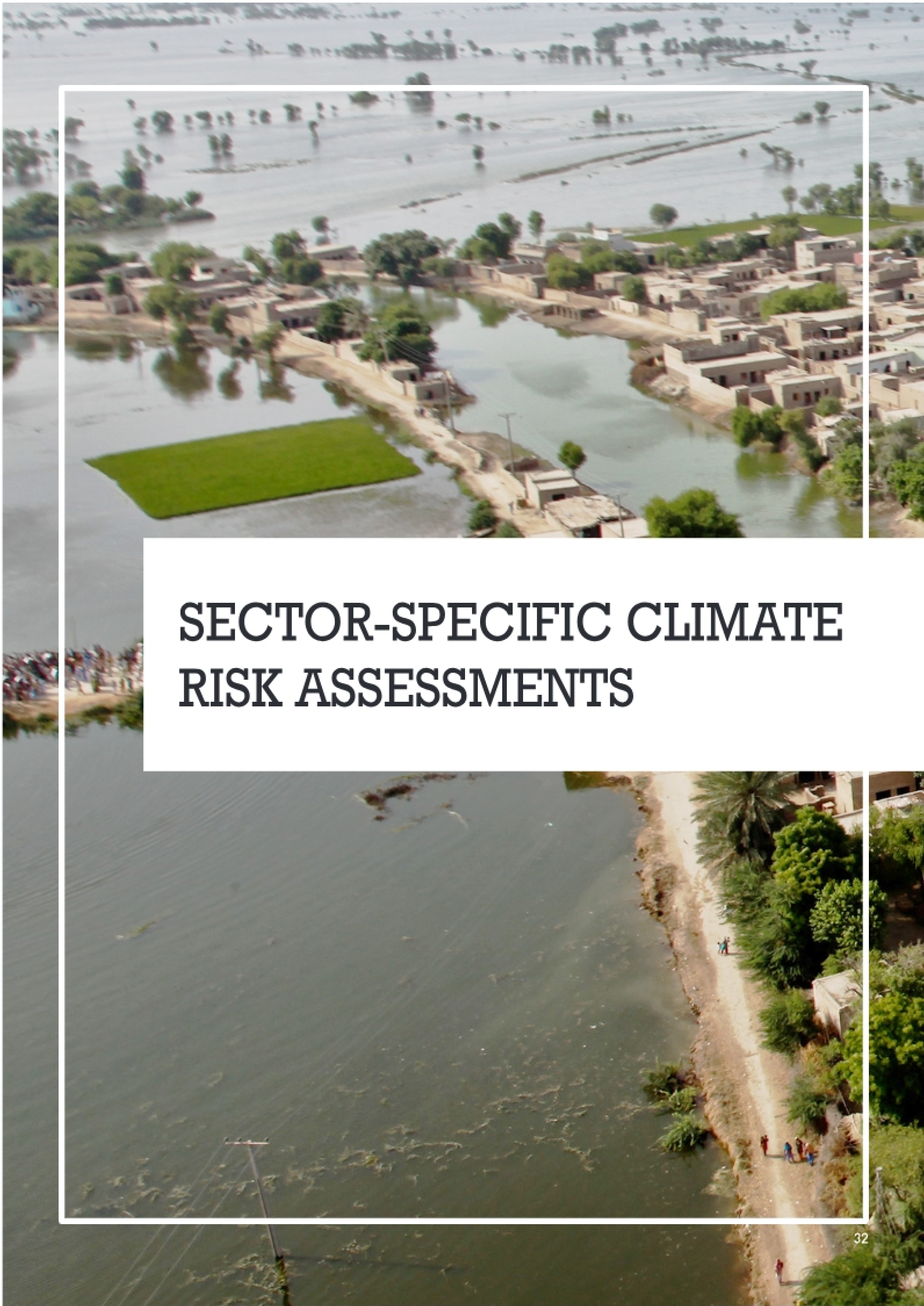



Figure 14: Standardized Precipitation Evapotranspiration Index (SPEI) over KPK estimated at multiple timescales, such as SPEI-03, SPEI-06, SPEI-12, and SPEI-24 for 150 years from 1951 to 2100 under RCP-SSP 585 emission scenario.

The graphs above depict the alternating frequency and severity of droughts and flood conditions from 1951 to 2100 using SPEI-3 and SPEI-6, with extreme droughts notably observed by 2020 under the RCP-SSP245 emission scenarios. However, following 2021, the frequency of both wet and dry extremes increases significantly under both emission scenarios, with the most substantial rise occurring in the late century under the RCP-SSP585 emission scenarios, as indicated by the SPEI-12 and SPEI-24 values (lower figure). These long-term SPEI values bear regional implications for the agricultural sector. The decreased frequency of droughts with longer SPEI timescales poses serious and potentially irreversible threats to food and water security.



# SECTOR-SPECIFIC CLIMATE RISK ASSESSMENTS

# AGRICULTURE

Agriculture is one of the key sectors being significantly impacted by the climate change due to alteration in optimum temperature required for crops growth. Importantly, the agriculture sector contributing largely to Pakistan's economy with approximately 25% of population is directly linked with this sector. However, the change in climate is affecting Pakistan's cropping patterns and intensity, particularly in Punjab, a major contributor in country's agriculture sector. Any change in temperature and precipitation over the Punjab province under climate change scenario can redistribute crops suitability zone geographically.

The first response of crops to climate change is a decline in yields. Evidence of significant declines in wheat, rice, and cotton yields confirms these adverse effects on crops, consequently disrupting the food supply chain. Such decline is mainly triggered due to rise in temperature far above the optimum values suitable for crop growth. Consequently, this leads to a decrease in the length of phenological stages, such as days to anthesis, maturity, and harvesting. A significant decline in wheat crop yield is expected over Punjab starting from north to south of Punjab province (Figure 15). Similar trend has been reported by several researchers Azmat et al. (2021) for the significant decline of wheat yield over irrigated and rained regions of Punjab. Similarly in case of rice yield which is major Kharif crop of central Punjab regions is expected huge yield loss due to adverse climate change effects, as similar loss of yield has been reported by Gaydon et al. (2023) for Gujranwala and Narowal districts (key regions for rice cultivation). Cotton is one of key cash crop in Pakistan, important for Pakistan's textile and exports. However, cotton is mainly south Punjab region's kharif crop with less water requirements as compared to rice, potentially will suffer the most due to adverse effects of climate change. Figure 15 depicts a substantial decline in cotton yield, which can be a huge setback for agriculture sector of south Punjab, as reported by Samavia and Fahad (2018). By the rise in temperature, the cotton crop may need more water in south Punjab regions, which is already facing water shortage issues.

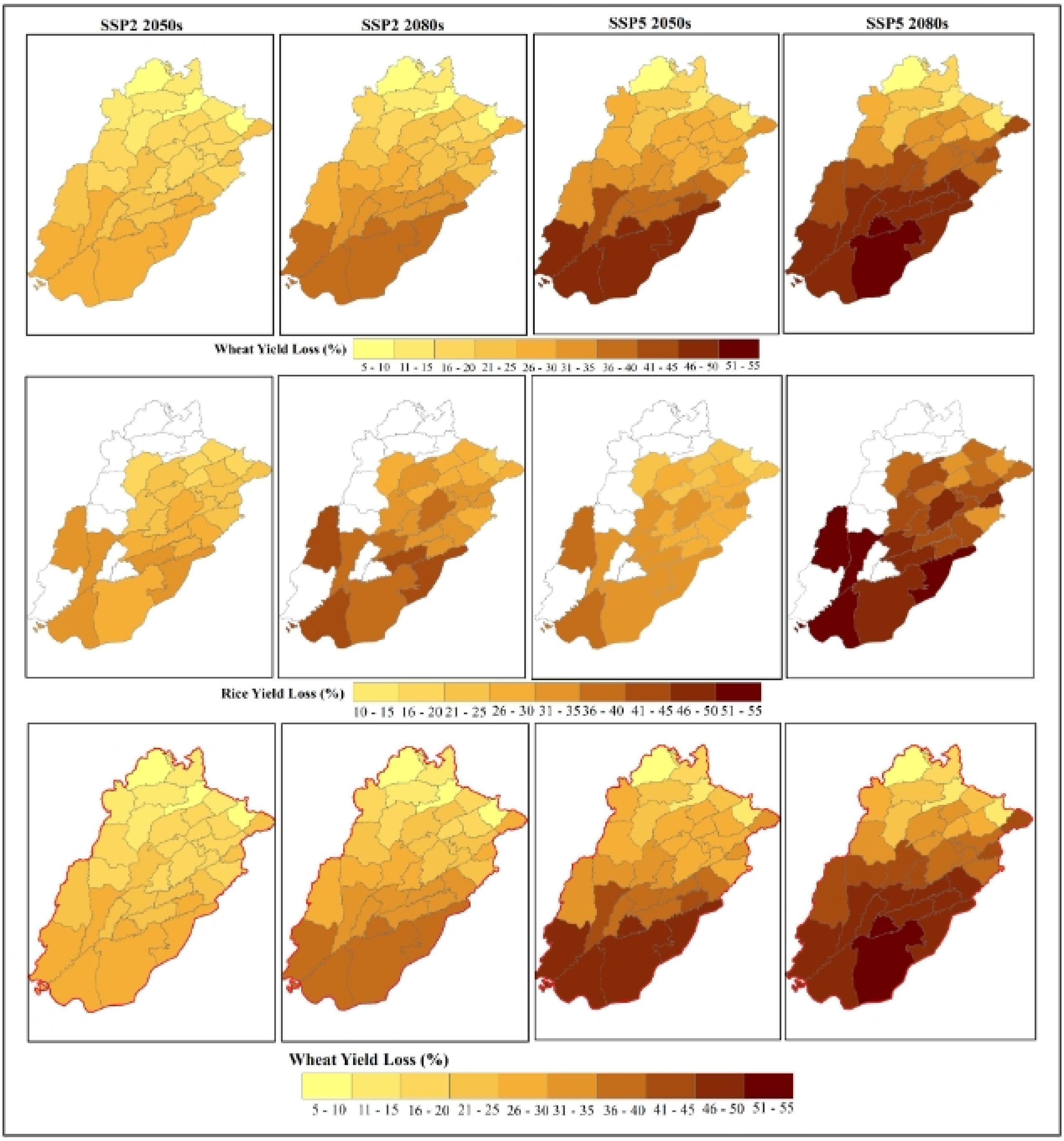



Figure 15: Potential loss of wheat, rice and cotton crops for climate change scenarios

Following the decline in crop yield, Figures 16 and 17 depict the potential shifts in the areas of major crops in Punjab—wheat, maize, cotton, sugarcane, and rice—under climate change scenarios, in terms of loss, gain, and retention. A slight loss in the wheat-growing area, which is a major food crop covering more than 95% of Punjab during the rabi season, is expected. Consequently, even this slight loss can significantly impact overall wheat production. In contrast to wheat, the maize crop is expected to face substantial area loss due to climate change in Punjab province. Considering diverse topography of Punjab province, a mix loss and gain of Maize crop area is expected, however a huge area loss can be found during 2080s.

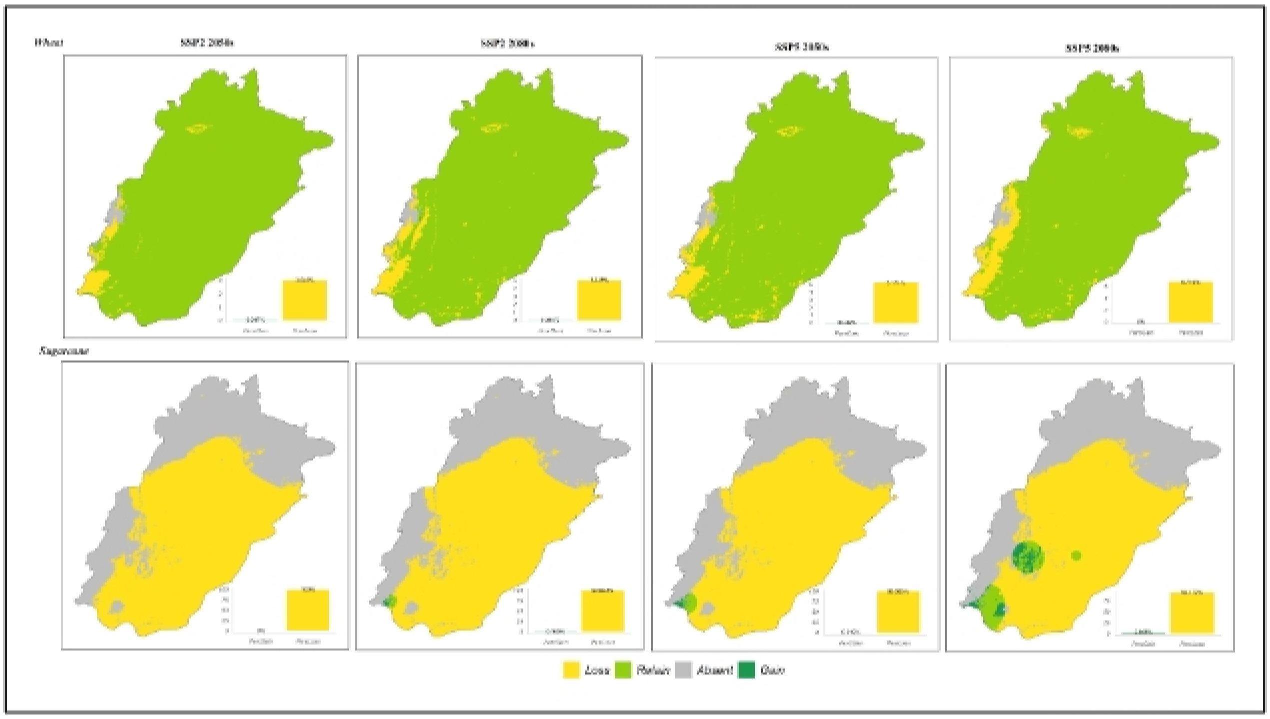



*Figure 16: State of wheat and sugarcane cropping area under climate change scenarios.*

Cotton is one of the major cash crops in Pakistan, key contributor for the textile industry and exports of Pakistan. However, the cotton crop will potentially vanish from Punjab province due to intensive climate change conditions in future particularly under dry and hot conditions (Figure 17). In contrast to cotton, the rice area is potentially gaining area under climate change scenarios, particularly during extreme climatic conditions.

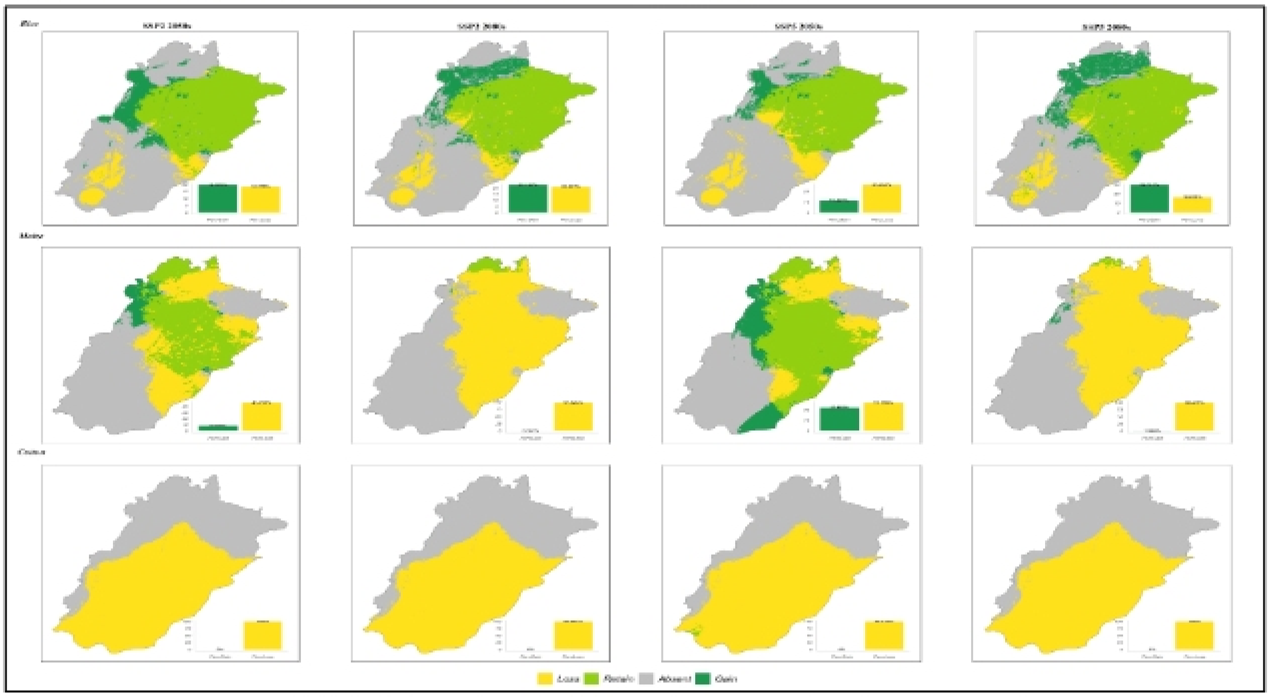



Figure 17: State of rice, maize and cotton cropping areas for climate change scenarios.

Considering the cropping area loss as shown in Figures 16 & 17, extended outcomes presented in Figures 18 & 19 depicts the suitability levels of major crops (rice, cotton, wheat and sugarcane), under climate change. Under future climate change scenarios, a considerable expanse of land currently dedicated to rice cultivation is projected to be lost. This loss is anticipated to confine rice cultivation primarily to central Punjab Additionally, in the continuation of previous results regarding cotton area loss, Figure 18 confirms huge loss of highly suitable cotton area due to intense climate in future. Although moderately suitable area for cotton can be utilized, however at the cost of low yield.

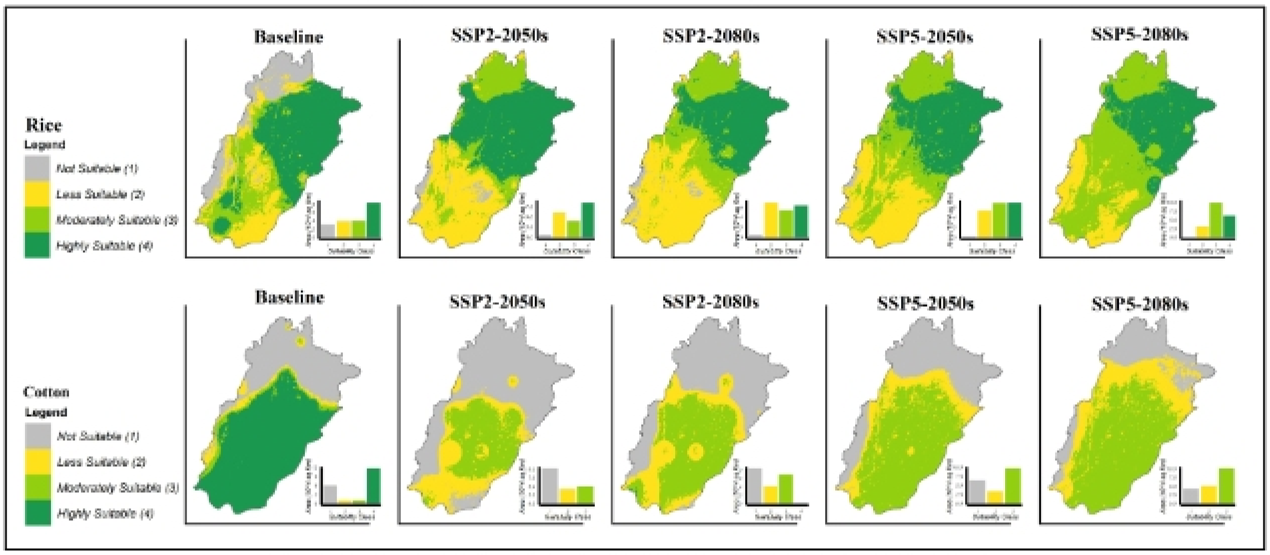



*Figure 18: Suitability levels of wheat and sugarcane climate change scenarios*

Considering loss of huge agriculture areas for different rabi and kharif crops, it is important to re-zonation of cropping suitability under climate change. Therefore, Figure 20 is depicting the suitability of kharif and rabi crops. Notably, the climate change is impacting overall cropping zones, patterns and intensity of Punjab province. For instance, while rice, maize, and cotton zones dominate in the baseline scenario, by the mid-century scenarios, the cotton crop zone disappears, leaving only the rice and maize zones. The situation is potentially alarming for late century scenario, when the cotton and maize both cropping zones are expected to vanish from Punjab province. In case of

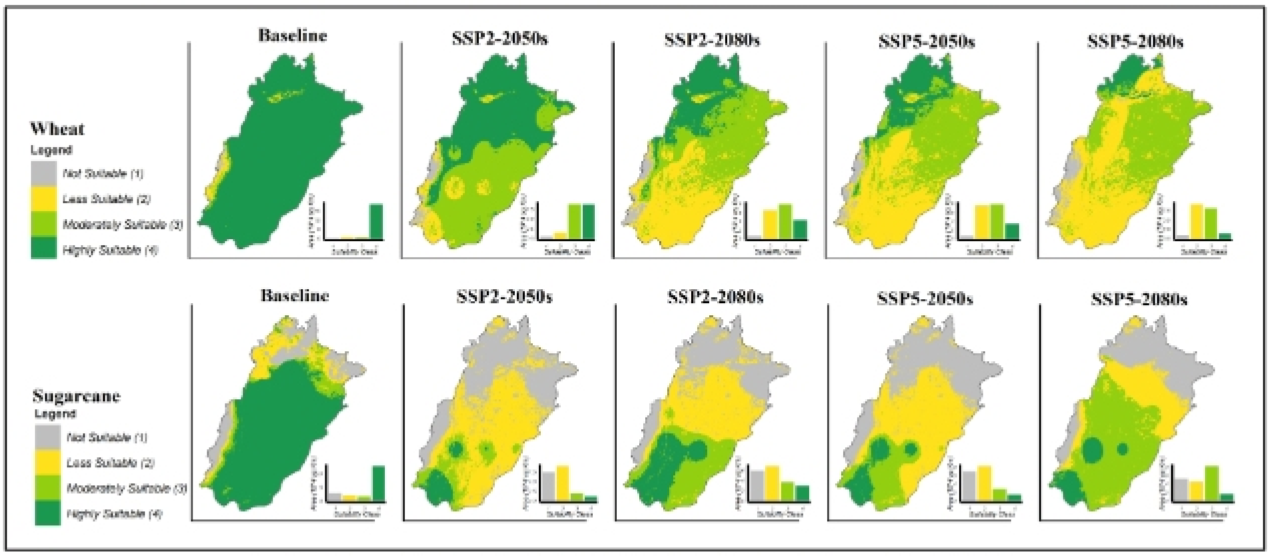



Figure 19: Suitability levels of wheat and sugarcane climate change scenarios

rabi season, the gradual decrease in wheat sugarcane areas is found during mid to late century scenarios. However, cropping zone boundary of wheat and sugarcane will is expected to define separately. Highly suitable cropping zones of sugarcane and wheat are being shifted towards south and north-central Punjab.

Rabi season in Punjab, currently exhibits a more balanced distribution, with 75% of the area suitable for both wheat and sugarcane cultivation. Additionally, 22% of the area is suitable for wheat cultivation, while 2% is deemed unsuitable for any crop cultivation. However, projections indicate a decline in combined cultivation areas by the 2050s to 9%, coupled with an expansion of wheat monoculture regions (81%). By the 2080s, these trends are expected to intensify further, with a significant portion of southern Punjab becoming climatically suitable solely for sugarcane cultivation (19%), representing a potential shift towards sugarcane monoculture in certain areas. The combined suitable area for wheat and sugarcane cultivation is projected to decrease to 2% of the total region, while the area suitable for wheat cultivation is anticipated to decline to 56%. Approximately 23% of the land is expected to remain unsuitable for either crop.

Under the SSP5 scenario by the 2050s, the combined climatically suitable area for both wheat and sugarcane cultivation is projected to reduce drastically from 75% to just 6%. This would leave 57% of the region suitable only for wheat cultivation (in upper Punjab) and 28% of the land suitable solely for sugarcane (in southern Punjab). Around 9% of the land is forecasted to become unsuitable for the cultivation of either crop. By the 2080s, under the same scenario, the area climatically suitable for wheat cultivation is expected to decrease to 34%, while suitability for sugarcane cultivation increases to 36%. Notably, the combined suitable area for wheat and sugarcane cultivation also increases to 14%, indicating the potential for co-cultivation in certain areas. However, the area unsuitable for any crop cultivation rises to 16%.

Concerning Kharif season in Punjab, the current agricultural landscape exhibits a diverse pattern of crop cultivation during the Kharif season. Approximately 25% of the total area is deemed suitable for the cultivation of rice, cotton, and maize, reflecting a multifaceted approach to agricultural practices. Furthermore, a significant portion of land, constituting 12%, exhibits suitability for both cotton and rice, highlighting the nuanced interplay between different crop types. Additionally, 20% of the area is identified as suitable solely for cotton cultivation, while maize cultivation occupies 11% of the region. Rice cultivation, comprising 8% of the total area, signifies a substantial but distinct presence within the agricultural framework. Moreover, the co-cultivation of rice and maize covers 10% of the land, showcasing an integrated approach to crop management. Notably, a mere 8% of the area is deemed unsuitable for any form of crop cultivation, emphasizing the overall suitability of the region for agricultural activities.

Looking ahead to the projected scenarios, significant transformations are anticipated by the 2050s. Under SSP2 and SSP5, approximately 39% and 31% of the area, respectively, are forecasted to become unsuitable for crop cultivation. However, the area suitable for rice is expected to rise to 28% under SSP2 and 18% under SSP5, indicating a potential shift towards rice-centric agricultural practices. Similarly, the suitability for both maize and rice is projected to increase to 29% under SSP2 and 35% under SSP5, while the suitable area for maize is anticipated to decrease to 3% under SSP2 and increase to 14% under SSP5. Furthermore, the area suitable for cotton cultivation is expected to diminish by 2050, suggesting potential advancements in cotton farming techniques.

Moving forward to the 2080s, the landscape of crop cultivation suitability in Punjab undergoes further transformation. The area unsuitable for crop cultivation is projected to escalate to 40% under SSP2 and 33% under SSP5, posing significant challenges to agricultural productivity. However, rice cultivation is anticipated to expand substantially, covering 58% of the total area under SSP2 and 65% under SSP5, signalling a pronounced shift towards rice-based agricultural practices. Conversely, maize cultivation is forecasted to decline sharply, accounting for only 1% under SSP2 and 0% under SSP5, indicating a significant decrease in its agricultural prominence. Moreover, combined maize and rice cultivation is expected to occupy a mere 1% of the area by the 2080s, reflecting a diminishing emphasis on diversification in crop cultivation.

Overall, in context of climate change impacts on agriculture sector shows that the environmental indicators such as extreme precipitation and temperature are no more favourable for current cropping pattern and intensities across the Punjab province and enforce to redistribute cropping zones based on altered climate variables and adaptation measures.

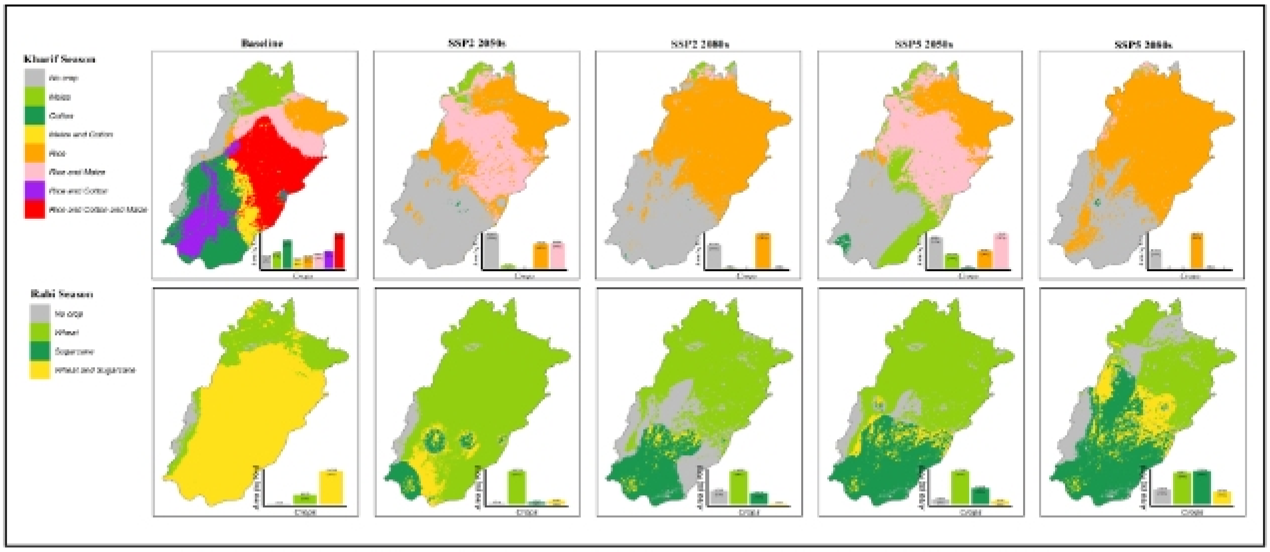



*Figure 20: Potential cropping zones of Kharif and Rabi crops for climate change scenarios.*

# WATER RESOURCES

Ensuring timely and sufficient water availability is imperative for enhancing agricultural production and ensuring its long-term sustainability. In Punjab, surface water resources are limited, posing constraints on potential water supplies. Majority of agriculture in the Punjab region relies on irrigation, contributing over 90% of agricultural output due to its economic viability. However, the expansion of cultivated land, low water management efficiency and increased cropping intensity have led to a significant deficit in irrigation water, amounting to approximately 50%. To address this growing demand, groundwater is increasingly tapped to supplement surface water supplies, playing a vital role in sustaining agricultural and rural development.

Since, the snow and glaciers located in northern areas of Pakistan are a major source of irrigation water in western rivers of Pakistan (Indus, Jhelum and Chanab Rivers), which are further supplied through two major storage structures (i.e. Tarbela and Mangla dam) along with barrages and headworks regulating through a unique network of link and irrigation canals. By the rapid increase in temperature several studies have reported that the formation of snow will decline along with acceleration of glaciers melt during mid and late century scenarios, consequently significant spatial and temporal change in inflows of western rivers, as reported by (Azmat et al., 2018; Azmat et al., 2020). Importantly, a slight change in water resources will potentially alter the large reservoirs operation, agriculture and water management dynamics at downstream agriculture areas. For example, in Punjab, the role of Tarbela Dam for irrigation agriculture is key to support several districts, including Attock, Rawalpindi, Jhelum, Chakwal, and parts of Sargodha, Khushab, and Mianwali. These areas rely largely on the water released from the Tarbela dam reservoir to support a variety of crops, including wheat, rice, sugarcane, cotton, Maize and vegetables. While, the Mangla Dam, located on the Jhelum River, serves multiple purposes including irrigation, hydroelectric power generation, and flood control. In Punjab, it benefits areas in districts like Gujrat, Jhelum, and Mandi Bahauddin. The irrigation water from the Mangla Dam supports the cultivation of various crops including wheat, rice, sugarcane, maize, and vegetables in districts of Punjab province. It plays a crucial role in enhancing agricultural productivity and supporting the livelihoods of farmers in the command areas. Similarly, the Head Marala Barrage is an important irrigation structure located on the Chenab River near Sialkot in Punjab, Pakistan. It regulates the flow of water into the Marala-Ravi Link Canal, which is part of the extensive canal network in Punjab province. The agriculture command area of the Head Marala Barrage primarily covers districts in Punjab province, including Sialkot, Narowal, Gujranwala, and parts of Gujrat. This area benefits from the irrigation water supplied by the Marala-Ravi Link Canal, which is sourced from the Chenab River. Farmers in the Marala command area rely on this irrigation water to cultivate a variety of crops, including wheat, rice, sugarcane, maize, vegetables, and fruits. The reliable water supply from the Head Marala Barrage contributes to agricultural productivity and supports the livelihoods of millions of farmers in the region.

Considering the great important role of three rivers in Pakistan's agriculture water management system, it is important to understand climate change impacts on hydrological behaviour of rivers system. Since, Pakistan's irrigation agriculture system is mainly designed based on water availability, therefore, the peak water availability is significantly important to regulate the reservoir operation and sustainable cropping pattern.

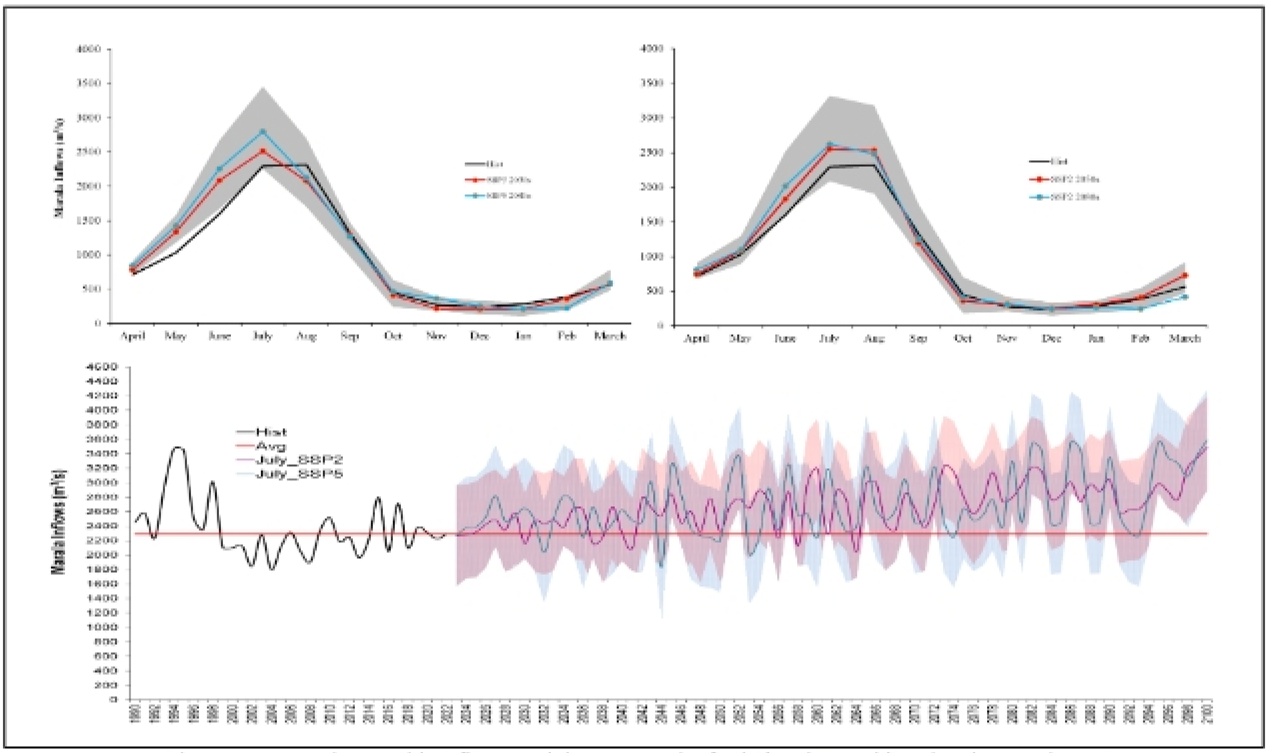



*Figure 21: changes in Marala monthly inflows and during month of July (peak month) under climate change scenarios*

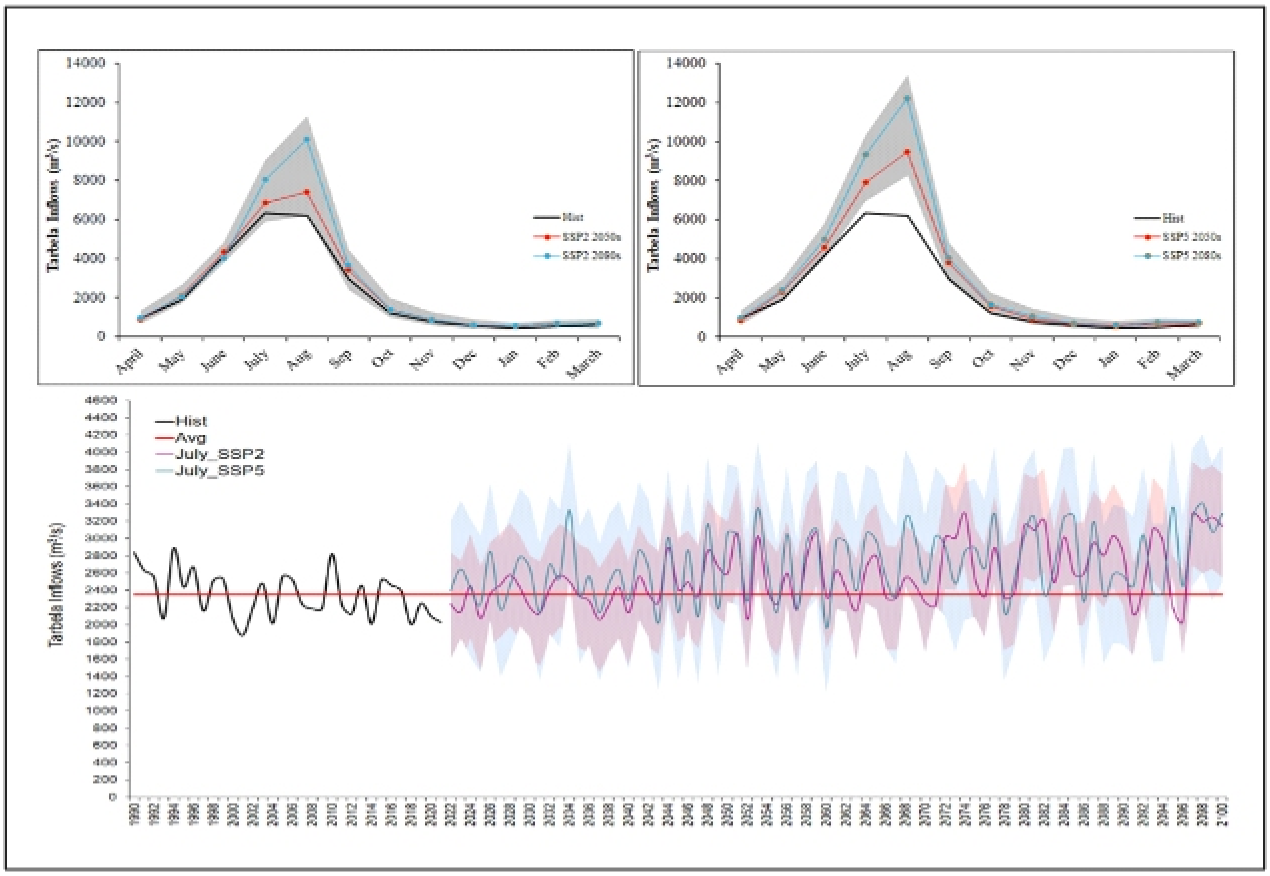



*Figure 22: change in Tarbela monthly inflows (Indus River) and during month of July (peak month) under climate change scenarios.*

Figure 22 clearly exhibits an extensive change in stream flows at Tarbela dam, which depicts a significant backward shift in inflow peaks of Indus river flows, under climate change scenarios (mid and late century). Meanwhile, a long-term trend of gradual increase in flows during July (peak month) are demonstrating a clear increase of flows over the time. This increase is more under SSP5 in comparison to SSP5, which indicates a mass melt of glaciers during peak summer season (June and July). Such extensive changes are alarming for the current water management system particularly in case of Punjab province which may need to consider for alteration as per futuristic trends. Similarly in case of Jhelum River peak flows are expected to shift at least one month backward (May to April), see Figure 23. Notably, the flows during April month are potentially increasing gradually under future scenarios (2024 to 2100) and this increase is mainly connected with early seasonal snowmelt and glacier melt during later months.

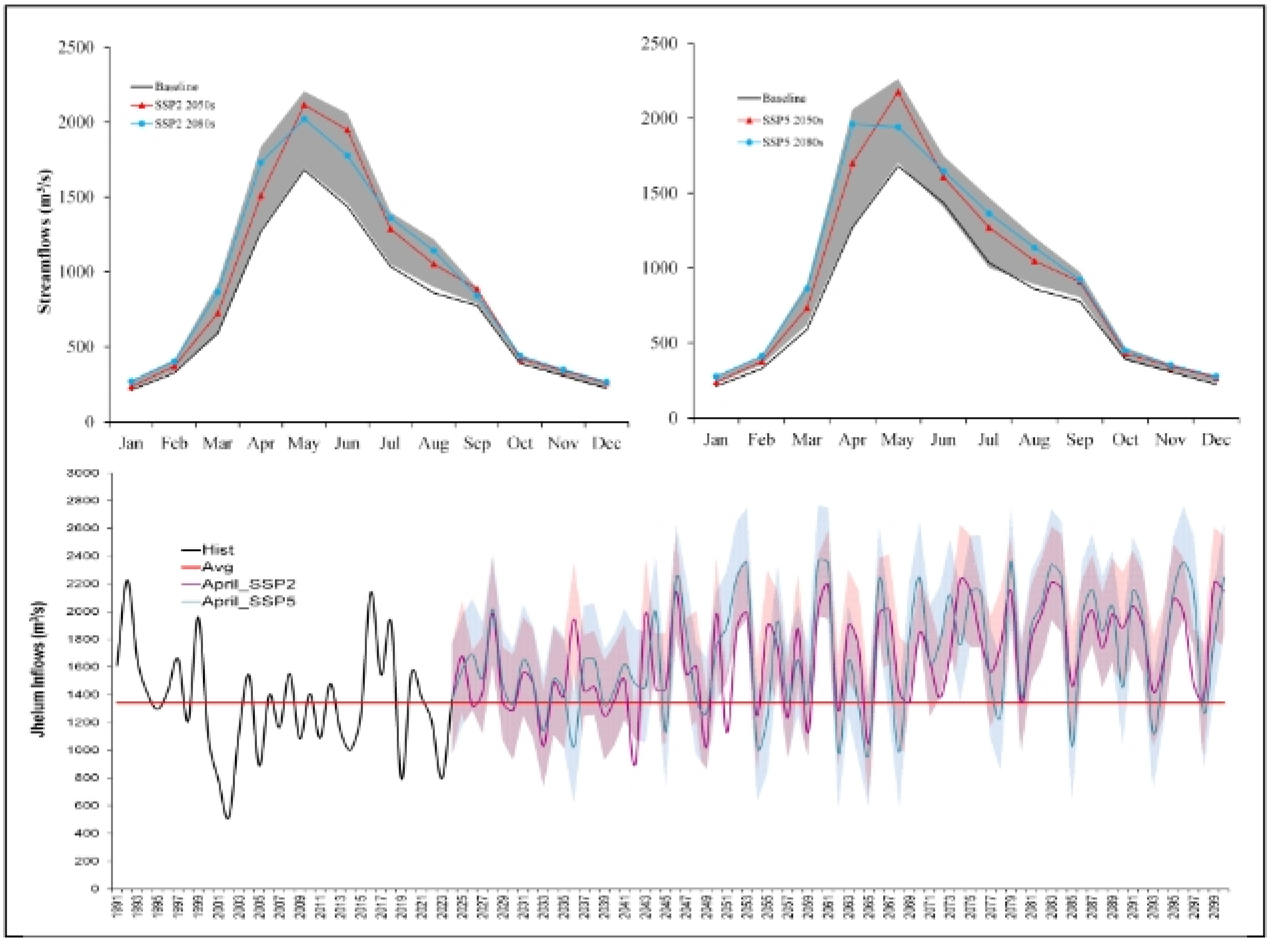



*Figure 23: change in Mangla monthly inflows (Jhelum River) and during month of April (potentially peak month) under climate change scenarios.*

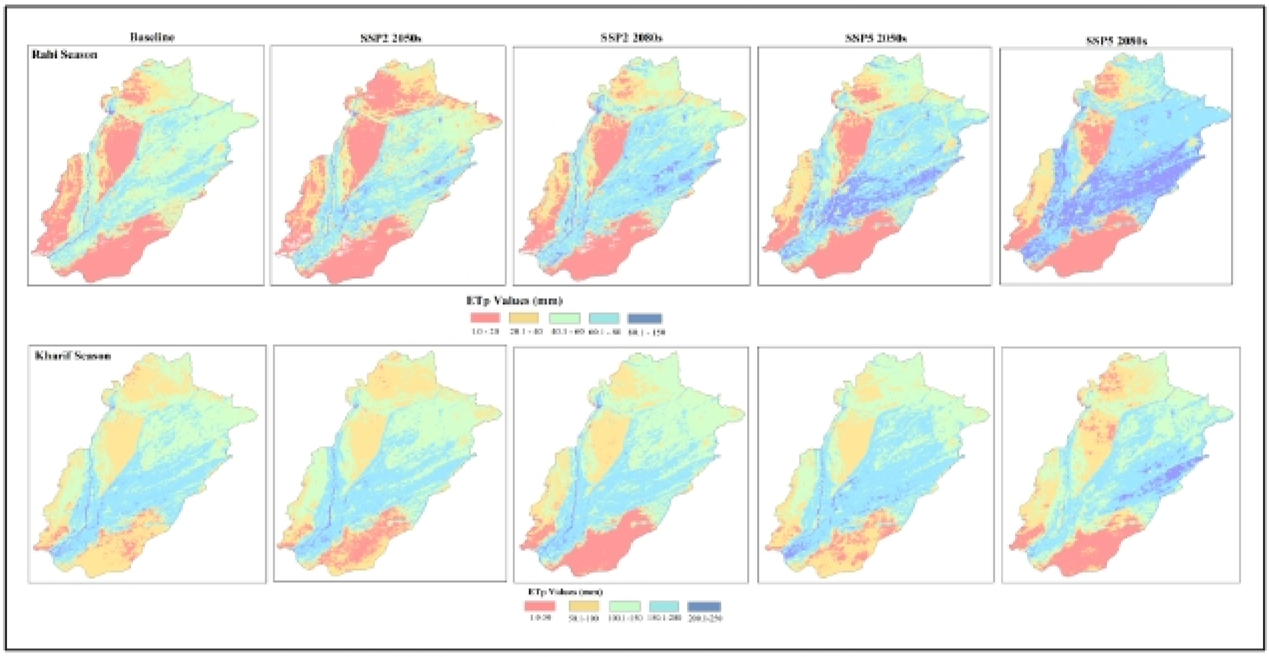



*Figure 24: Change in Potential Evapotranspiration under future scenarios*

Evapotranspiration is a key indicator for the agricultural water resources management and considering increase in temperature, the estimation of evapotranspiration is extremely important to address the climate change challenges related to agricultural water management. Figure 24 illustrates a spatio-temporal change in potential evapotranspiration (ETp). It is clear that ETp is potentially increasing in Punjab province particularly irrigated regions, thereby high crop water requirement under future climate change scenarios (mid and late century). By the increase of ET, the water demand for agriculture will increase significantly, consequently the soil moisture fluctuations and reliability over the time will decrease. This can lead to serious challenges in water-agriculture sector.

# HEALTH

Globally, the climate change has negative impact on human health and contributes to the transmission of vector-borne diseases such as dengue (Campbell-Lendrum et al., 2015) with every year, 390 million dengue cases are reported worldwide and nearly 4 billion people are at risk to the disease (Griffin et al., 2016). Several studies reported that the temperature has been found to be associated with vector survival, ovi-position, hatching development, contact, and transmission, e.g. high temperatures accelerate viral replication, shorten the extrinsic incubation period of dengue viruses, and reduce mosquito development time (Huber et al., 2018; Mordecai et al., 2017). Pakistan is one of the most vulnerable countries to climate change and its one of the adverse impacts is the spread of vector-borne diseases including dengue, thereby, climate change has a significant impact on the intensity and spread of dengue outbreaks.

Dengue Transmission Suitable Days (DTSD) serve as a crucial metric for assessing the spread of dengue across regions. In the case of Punjab province, we leveraged temperature data from CMIP6 under both SSP2 and SSP5 scenarios to identify dengue hotspots based on DTSD values. Subsequently, these identified hotspots were utilized to interpolate data for the adjoining districts of Punjab province. Analysis revealed a potentially higher density of cases in the northern and central parts of Punjab compared to the southern regions. Concerning the impact of climate change on dengue transmission, it was observed that DTSD values are expected to decrease significantly during the mid and late century under future climate change scenarios. Furthermore, the density of DTSD values diminishes from north to south of Punjab, indicating an inverse relationship between DTSD and temperature, in conjunction with the elevation of the geographical location.

Additionally, the malaria is an extremely climate-sensitive tropical disease, making the assessment of potential change in risk due to past and projected warming trends one of the most important climate change health questions to resolve. Meteorological factors, e.g., rainfall, temperature and humidity, are established in having associations with malaria incidence from temporal and spatial perspectives (Abeku et al., 2003; Reid et al., 2012). These meteorological factors when co-act synergistically, increase the duration of larvae development, shorten the incubation period of parasites, prolong mosquito survival, provide a favourable swampy habitat to the vectors, and increase number of mosquitoes and their bites, thus positively related to malaria high-risk (Adeola et al., 2017; Ikeda et al., 2017). Malaria is moderately endemic in Pakistan; yet, its transmission is unstable with disease burden ranging from very high to low (Khattak et al., 2013; Umer et al., 2018). Erratic malaria transmission patterns due to various factors like climatic changes can be attributed through Malaria Transmission Index (MTI).

The MTI values illustrated in figure: 25 (lower panel) provide a clear depiction of the impact of climate change on malaria spread from the northern to the southern regions of Punjab. There's a discernible trend of increasing malaria occurrence from the higher elevation areas in the north to the lower elevation regions in the south of the Punjab province. Importantly, an insightful observation reveals a significant temporal increase in MTI under climate change scenarios (SSP2 and SSP5) during the 2050s and 2080s, with a spatial pattern of rising MTI values observed from high altitude to lower altitude regions. These trends align with previous studies, including those by Pascual et al. (2006) and Patz and Olson (2006), which have shed light on the dynamics of malaria under changing climatic conditions. These studies have underscored the significance of recognizing the nonlinear and threshold responses of malaria, a biological system, to regional temperature changes.

One notable discovery highlighted by these studies is the fact that the biological response of mosquito populations to warming can surpass the measured temperature change by more than tenfold. This finding is pivotal in advancing the assessment of climate change risks. It serves as a clear indication that arguments downplaying concerns over minor temperature shifts should be reconsidered, especially in light of Pascual et al.'s (2006) revelation that even a mere half-degree (0.5°C) centigrade increase in temperature trends can lead to a 30–100% surge in mosquito abundance. This phenomenon underscores the concept of "biological amplification" of temperature effects and emphasizes the need for vigilant attention to even minor temperature fluctuations.

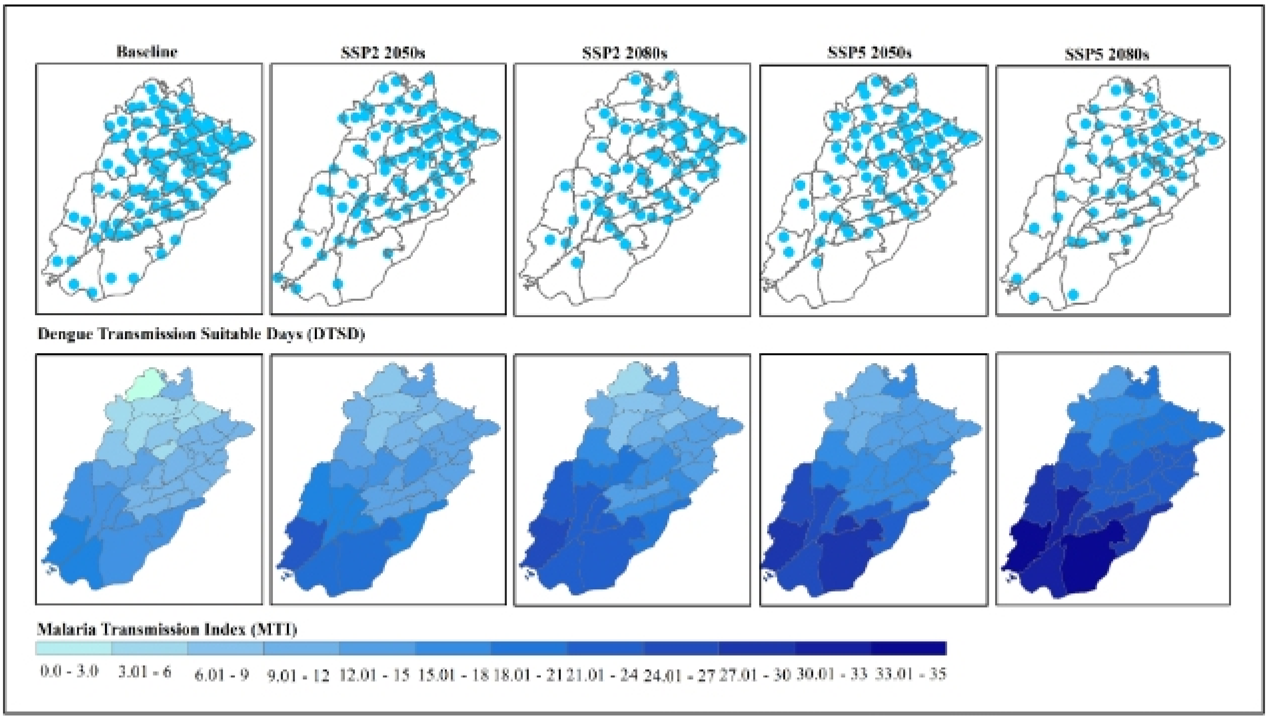



*Figure 25: Climate change impact on dengue transmission in Punjab Province under future scenarios.*

# ECOSYSTEMS

Climate change is causing geographical redistribution of plant and animal species globally. These distributional shifts are leading to new ecosystems and ecological communities, changes that will affect human societies. Although the geographical range limits of species are dynamic and fluctuate over time, climate change is impelling a universal redistribution of life on Earth (Figure 26). For birds, the first response to warmer and drier conditions resulting from climate change is often a shift in location to remain within preferred environmental conditions. Species at the cooler extremes of their distributions move towards favourable conditions, while the range limits contract at the warmer edges where temperatures, precipitation, and rainfed croplands are no longer favourable. Different species are responding at different rates and to varying degrees, key interactions among species are often disrupted, and new interactions develop. These idiosyncrasies can result in novel biotic communities and rapid changes in ecosystem functioning, with pervasive and sometimes unexpected consequences that propagate through and affect both biological and human communities.

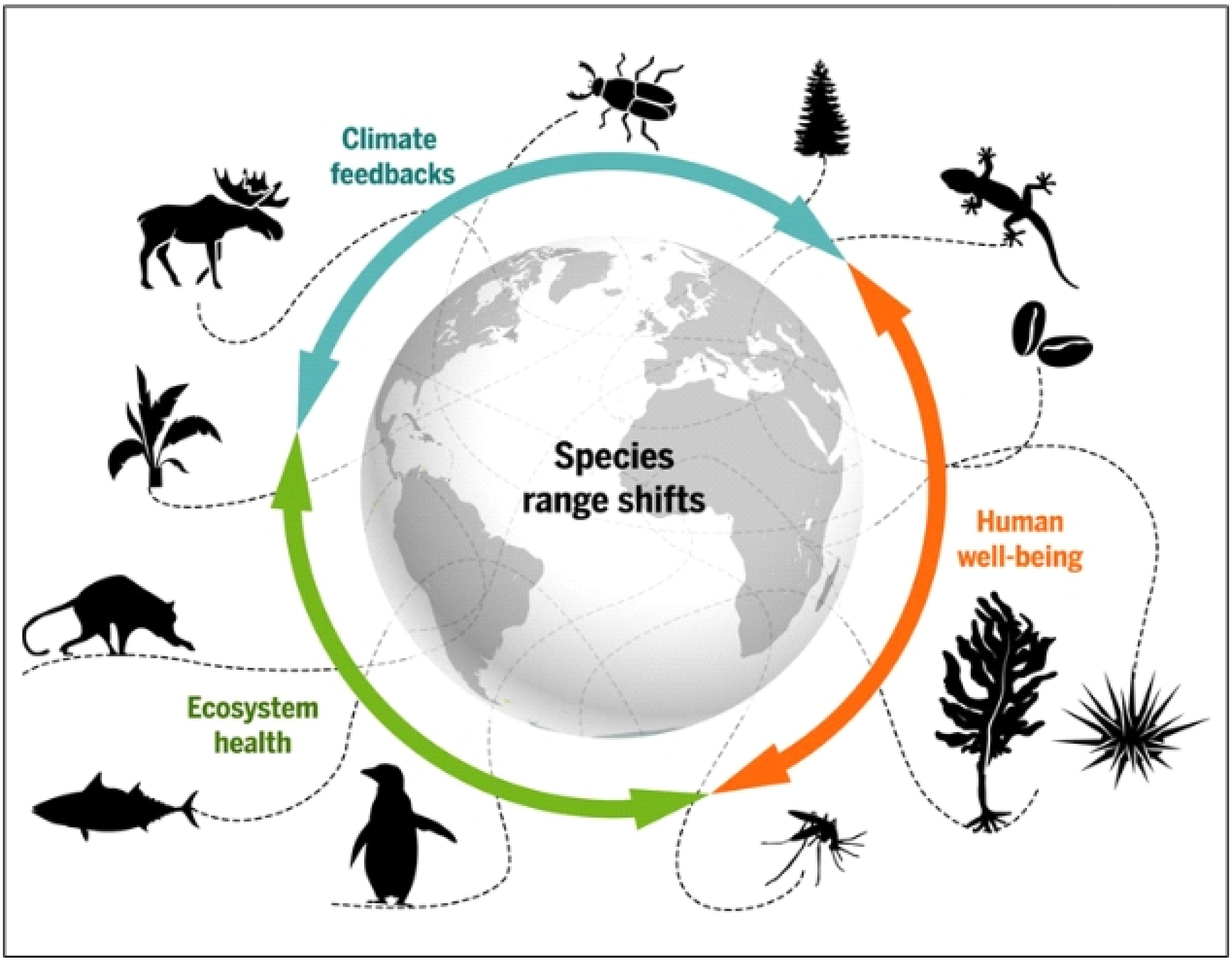



*Figure 26: Climate-driven changes in species distributions, or range shifts, affect human well-being both directly (for example, through emerging diseases and changes in food supply) and indirectly (by degrading ecosystem health). Some range shifts even create feedback (positive or negative) on the climate system, altering the pace of climate change.*

Pakistan sits at the intersection of three distinct zoogeographic regions - Oriental, Palaearctic, and Ethiopian - characterized by significant altitudinal shifts and a rich diversity of ecological zones (Anwar et al., 2022). Within Pakistan's forests reside a plethora of flora and fauna, including numerous endangered and endemic species. However, the delicate equilibrium between these species and their habitats faces disruption due to climate change. The escalating temperatures, changing precipitation patterns, and alterations in rainfed cropland profoundly affect the breeding and wintering species richness across various provinces of Pakistan (Khaliq et al., 2023).

Figure 27 demonstrates the consequential impact of significant drivers such as precipitation, temperature, and rainfed cropland on breeding and wintering species richness in Punjab, Pakistan. These impact values forecast the anticipated alteration in species richness of both breeding and wintering birds, reflecting the projected environmental conditions. Given the seasonal migration of bird species, with migratory species predominantly appearing in winter, the analysis compares both wintering (comprising migratory and resident species) and breeding (involving resident species only) bird richness.

The richness of breeding and wintering species exhibits positive correlation with temperature, precipitation, and rainfed cropland sensitivity, with these factors being key determinants. Regionally, exposure to environmental changes varies, with northern regions experiencing the most pronounced temperature shifts, while central and southern regions face the strongest projected precipitation alterations. The projected impacts of future environmental changes manifest heterogeneously across the country and differ notably between wintering and breeding bird communities.

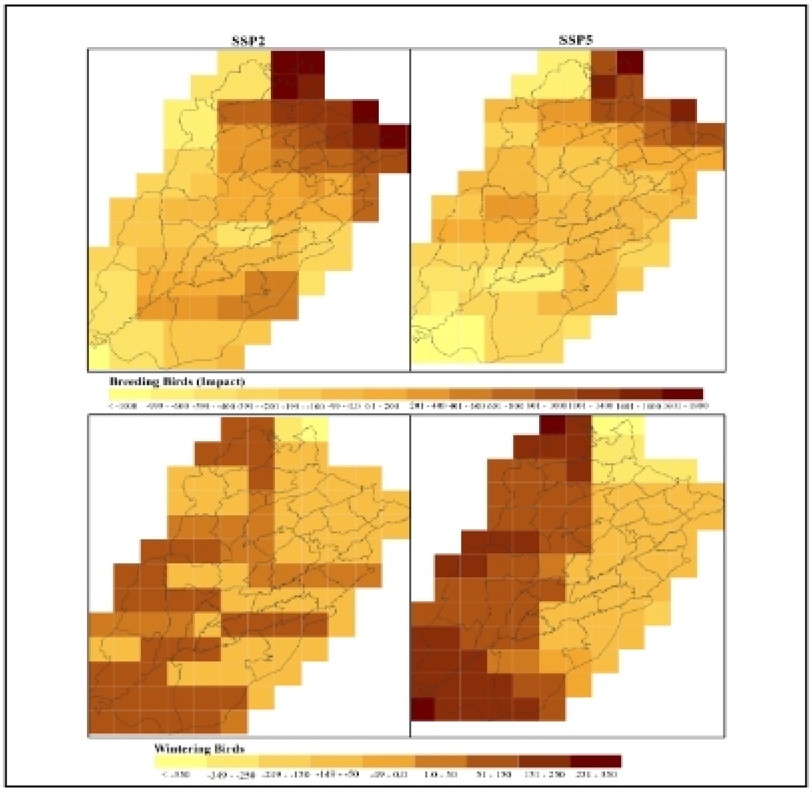



*Figure 27: Combined impact of the projected changes on breeding birds and wintering birds due to significant drivers (precipitation, temperature and rainfed cropland) in Punjab, under SSP2 and SSP5.*

# INFRASTRUCTURE

Floods are major source of infrastructure loss in Pakistan, which are mainly due to climate change induced precipitation or rapid snow and glacier melt in combination with high intensity precipitation over high altitude regions. Since, five rivers are meandering from highly populated Punjab province, thereby, apparently highly impacted province due to extreme events like floods. The 2010 and 2022 floods are living example of high intensity precipitation and rapid snow, and glacier induced floods due to climate change, consequently, severe damages to the national (i.e. roads, bridges, railway tracks, agriculture fields etc) and private infrastructure (urban areas etc), ultimately 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 riverine flooding, flash flooding, glacier lake outbursts (GLOFs) and can trigger 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 Punjab 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 flooding. The flood 2010 reportedly damaged agriculture, road and canal network, houses, electric supply feeders, livestock with total cost of 783,997 USD just in one district Muzaffargarh, Punjab (Mahmood et al., 2019). Figure 28 illustrates the repercussions of the 2010 flood in Pakistan, highlighting its effects on major cities in Sindh Province. Contrasting with previous floods, Figure 29 indicates the potential for even more severe flooding, surpassing the scale of both the 2010 and 2022 events, under future climate change scenarios. These projections suggest heightened infrastructure damage, especially under the SSP5 scenario, spanning consecutive years and extending into the last decade of the 21st century.

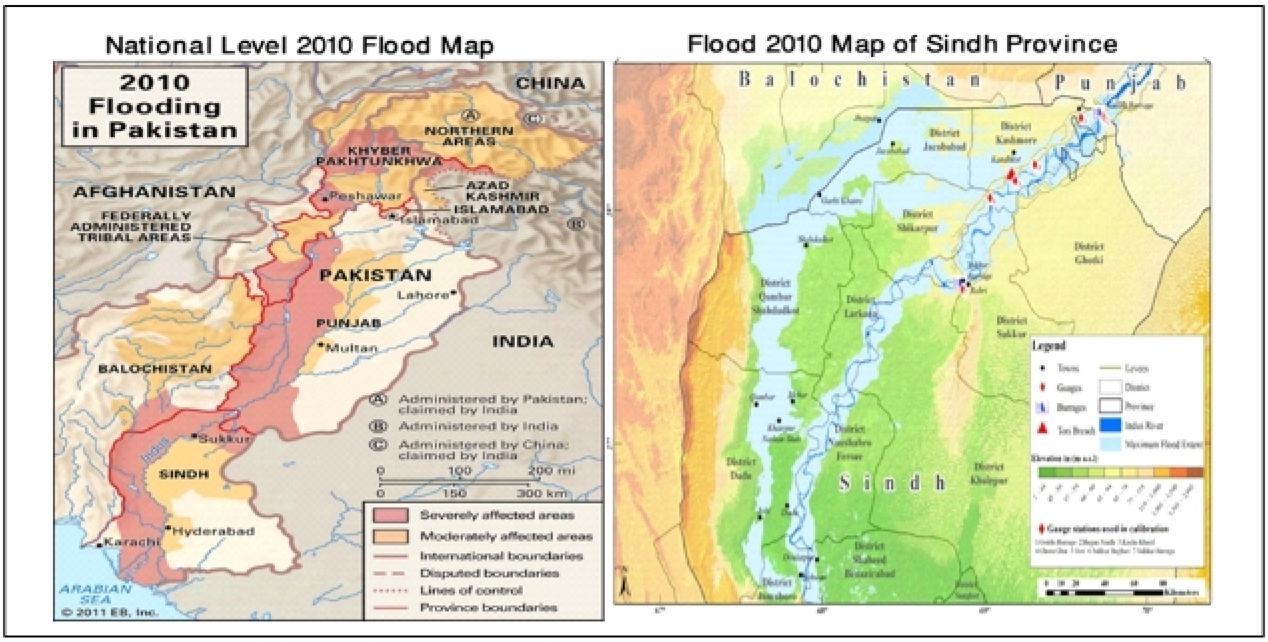



*Figure 28: Riverine 2010 flood in Pakistan (left) and in Sindh Province (right)*

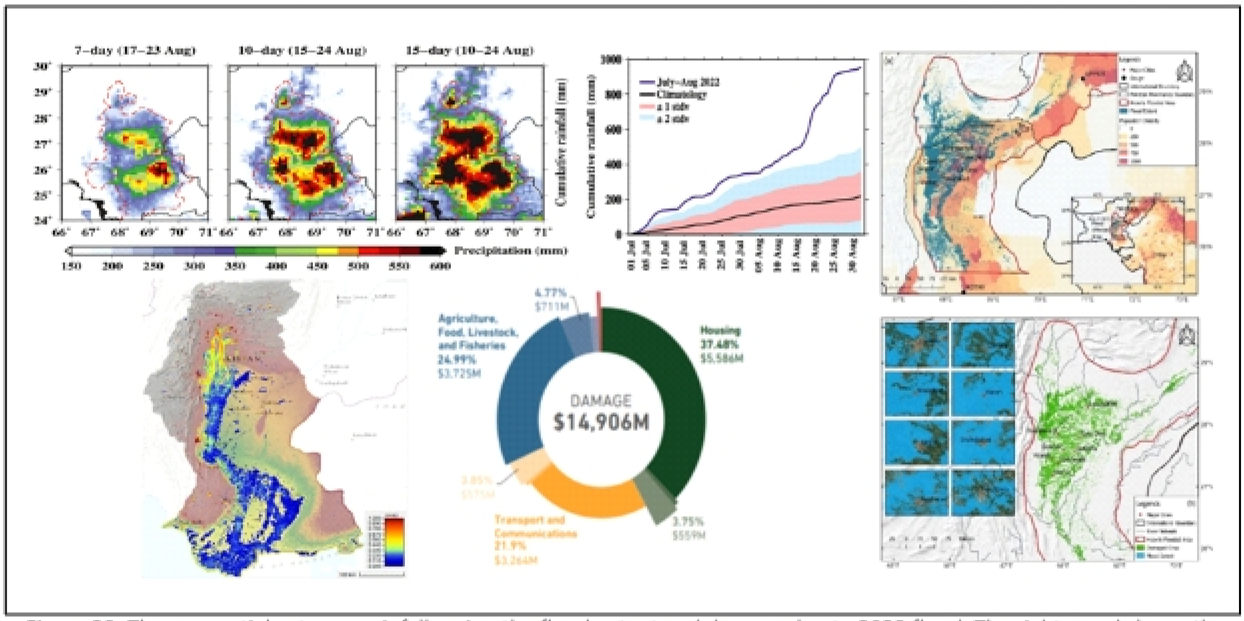



Figure 29: The sequential extreme rainfall major, the flood extent and damage due to 2022 flood. The right penal shows the population exposed to flooding in the southern provinces of Pakistan. The shading shows the population density (number of people/km$^2$) and crop damaged by the flooding.

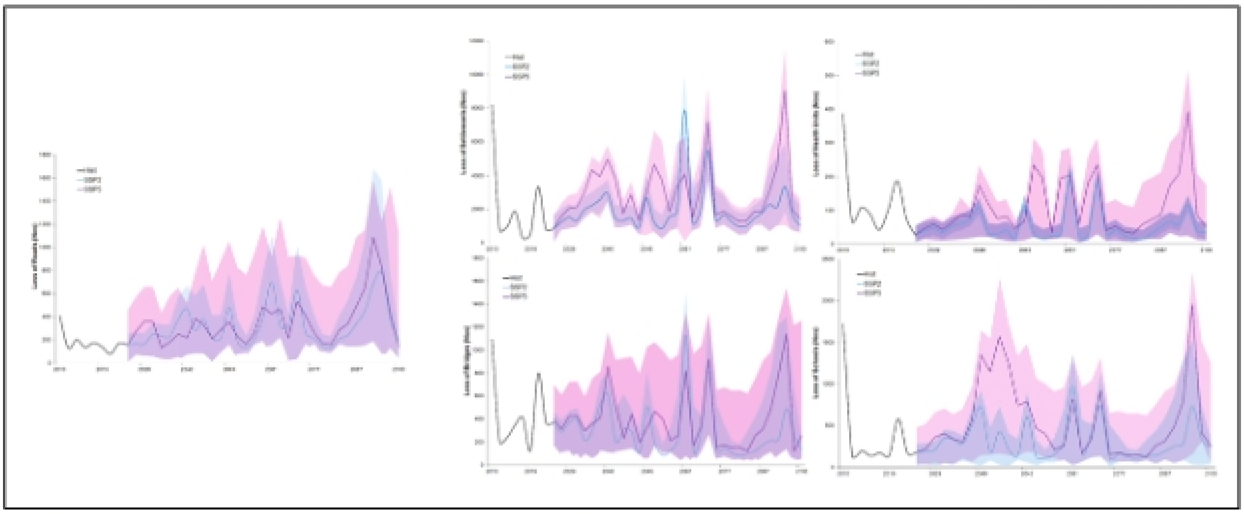


Figure 30: Loss Settlements, Human units, Bridges, Schools and Roads under climate change scenarios (SSP2 and SSP5) during 2050s and 2080s

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). At the same time, heatwaves persisted over central China and Europe. Considering this the 2022 flood, is a true example of climate change induced highly intensive sequential rainfall in Pakistan (Nanditha et al., 2023). The 2022 Pakistan flood event was an intensified manifestation of the 2010 Pakistan flood event, which was also caused by compounding factors, but occurred in a more pronounced upward trend in both tropics and extra tropics.

This disaster has demonstrated what this vulnerability looks like for the people of Pakistan particularly in Punjab and Sindh. The total damage of Khyber Pakhtunkhwa and Punjab were 935 million USD and 515 million USD, respectively. Figure 29 shows the climate change induced extreme rainfall impacted the large area of Pakistan during 2022 flood. The right penal of Figure 29 shows the population and crop lands impacted due to 2022 flood in Sindh province. The densely populated right bank of the Indus River is majorly affected by flooding.

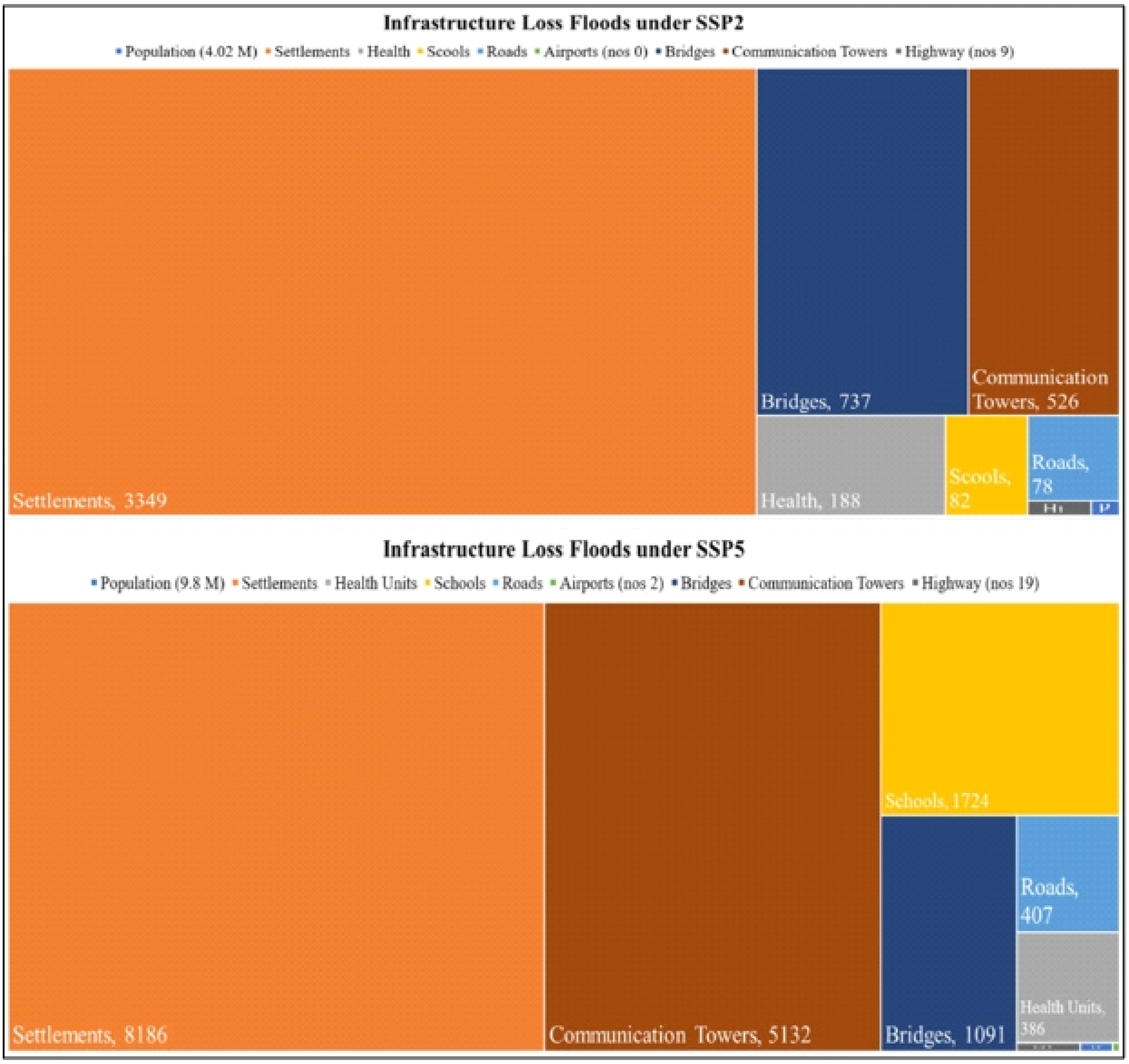



*Figure 31: Infrastructure loss due to floods in Punjab province under SSP2 and SSP5 scenarios.*

Figure 30 illustrating the vast infrastructure (settlements, bridge, roads, health and schools) damage due to climate change induced floods. Multiple devastating floods are expected under climate change scenarios particularly at the end of 21st century even worse than the 2010 and 2022 floods, as Figures 21-23 (given in section water resources sector) are evident showing a clear abrupt increase in peak flows under climate change at Marala, Tarbela and Mangla gauging stations during summer months, consequently, resulting huge damage of infrastructure in Punjab province. At few instances, the infrastructure loss is even higher than the historically devastating flood 2010. Similarly, Figure 30 shows factual loss values of population (4.02 M), settlements (3349), bridge (737), health units (188), communication towers (526), schools (82), roads (78) and highways (09) under SSP2 for a selected flood during future periods. Further, the factual loss values under SSP5 of population (9.82 M), settlements (8186), bridge (1091), health units (386), communication towers (5132), schools (1724), roads (407), highways (19) and 2 airports for a selected flood during future periods.

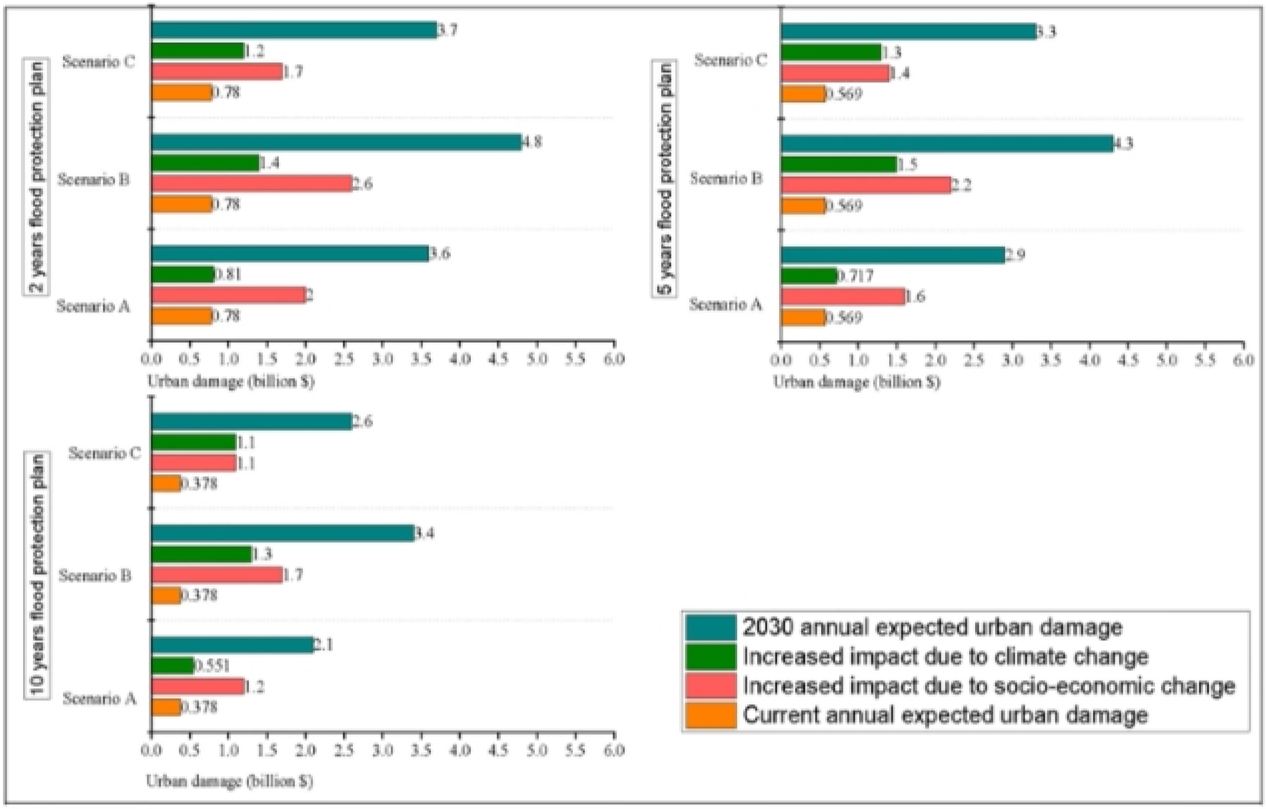



*Figure 32: Urban damage in Pakistan for 2030 based on 2-year, 5-year, and 10-year flood protection scenarios.*

Additionally, Flooding and droughts will also have an impact on hydropower generation: Pakistan draws 32 % (2020) of its energy from hydropower with a total installed capacity of 9,389 MW (2019) (Pezij et al., 2020). However, variability in precipitation and climatic conditions could severely disrupt hydropower generation. Similarly, by the alteration in peak river flows the agricultural water management will also face challenges to manage the time of peak water demand and peak water availability at downstream for agriculture purpose (Azmat et al., 2021).

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