INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE

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# Guide to Innovated Irrigation and Drainage Management under the Changing Climate

August 2025

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**INTERNATIONAL COMMISSION ON IRRIGATION AND DRAINAGE**
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International Commission on Irrigation and Drainage (ICID), established in 1950 is the leading scientific, technical, and not-for-profit Non-Governmental Organization (NGO). ICID, through its network of professionals spread across more than a hundred countries, has facilitated sharing of experiences and transfer of water management technology for over half-a-century. ICID supports capacity development, stimulates research and innovation, and strives to promote policies and programs to enhance sustainable development of irrigated agriculture through a comprehensive water management framework. The mission of ICID is to stimulate and promote the development and application of the arts, sciences and techniques of engineering, agriculture, economics, ecological and social sciences in managing water and land resources for irrigation, drainage, flood management, for achieving sustainable agriculture water management.



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# PREFACE

This publication **"Guide to Innovated Irrigation and Drainage Management under the Changing Climate",** as an output of the Working Group on Climate Change and Agricultural Water Management (WG-CLIMATE), aims to share information about the prediction of the global and regional climate change and climate variability; to explore and analyze the implications of climate change and climate variability for agricultural water management including irrigation, drainage, and flood control; to promote archiving useful information and case studies on climate change for practical use in improved impact assessment and adaptation development; to enhance discussion on climate change and water management at national and regional scales among the stakeholders including academician, practitioners, decision makers, media as well as farmers and water users in a region; and to join the international dialogue on Climate change and water management.

As per the mandate of WG-CLIMATE, the group brought out this publication to provide useful information and case studies on climate change for practical use. The Chair of the Working Group Dr. Ray Shyan Wu was pivotal in bringing out this publication by organizing numerous international workshops during the ICID annual events and eventually providing the leadership in bringing out this publication. My special thanks are due to Dr. Tsugihiro Watanabe, former Chair of WG and Vice President Hon., who drafted the outlines of the book. Thanks, are also due to the invaluable contributions of the authors, who are esteemed members of the WG-CLIMATE.

This publication will be quite helpful in understanding the complex relationship between climate change and water resource management, especially in agriculture, emphasizing the need for sustainable adaptation and mitigation strategies. It highlights global trends, including reductions in rainfall and groundwater recharge, rising temperatures, and increased demand posing challenges to water availability and quality. We hope that this publication will find a place in your library.

**Dr. R.K. Gupta**
Secretary General, ICID

# INTRODUCTION

Agriculture is a significant global user of freshwater resources, accounting for 70% of usage and contributing up to 30% of greenhouse gas emissions. Therefore, it is both a contributor to and a victim of climate change. The Working Group on Climate is dedicated to addressing the mitigation and adaptation challenges faced by agricultural water management in the context of a changing climate. The group is actively compiling valuable information and case studies on climate change to assist in impact assessments and the development of adaptation strategies.

The current urgency of climate change, highlighted by the IPCC scientists' warnings that global warming of 2°C will be exceeded during the 21st century unless immediate, rapid, and large-scale reductions in greenhouse gas emissions occur, underscores the need for immediate and effective adaptation measures. These measures must be based on the best available information, including infrastructure improvements, institutional reorganization, revised design criteria, and management strategies for extreme events. Despite the wealth of research conducted globally, the challenges posed by climate change to irrigation, drainage, and related sectors are expected to be long-lasting, necessitating focused and concerted efforts from all stakeholders.

The WG-Climate was established in 2005, coinciding with the release of the IPCC Second Assessment Report, originally named the "WG on Global Climate Change and Irrigation". This initiative was led by VPH Dr. Mark Svendsen, a devoted leader whose strategic coordination was instrumental in its formation. In 2007, the working group was renamed "WG on Climate Change and Agricultural Water Management," broadening its scope from solely "irrigation" to encompass "water management" more broadly. This shift recognized the pressing need for cross-disciplinary and institutional cooperation to address the looming impacts of climate change on agricultural water management.

In response to the climate urgency, the WG-Climate has committed to publishing this book, "Guide to Innovated Irrigation and Drainage Management under the Changing Climate," to provide useful information and case studies on climate change for practical use, especially in improving impact assessment, mitigation, and adaptation development. The initial editor is VP Dr. Tsugihiro Watanabe, former Chair of WG, who drafted the outlines of the book. As the Chair of WG-Climate and the editor of this book, I have been given the demanding tasks of overseeing the review and editing of all chapters, as well as drafting the Executive Summary. This responsibility has engaged me over the past four years, during which I have been thoroughly involved in refining the content and ensuring that the book's messages are conveyed with clarity. The completion of this book would not have been possible without the invaluable contributions of the authors, who are esteemed members of the WG-Climate. Their dedication, knowledge, and experience in their specific fields have enriched this publication, making it a comprehensive and insightful guide. We believe that the lessons and insights offered in this book will inspire and guide engineers, scientists, managers, and others facing the critical water challenges of the 21st century across various regions of the world.

**Ray-Shyan Wu (PhD)**
President of Chinese Taipei Committee on Irrigation and Drainage
Chair WG-Climate

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# EXECUTIVE SUMMARY

**CHAPTER I: General Introduction to Climate Change Effects on Agricultural Water Management**

Climate change and variability are well-documented through global climate records since the 19th century. To address the challenges needs effective adaptation and mitigation strategies, especially through sustainable water resources management. This chapter covers various topics related to optimizing and productively water resources for agriculture irrigation and drainage, focusing on adaptation and mitigation efforts. Adaptation strategies focus on decreasing risks related to climate change, such as improving soil and water management, growing biodiversity, and adopting integrated pest management. There are several methods such as value-engineering, the Water-Energy-Food (WEF) nexus, and life cycle analysis as mitigation strategies that aim to decrease greenhouse gas emissions such as decreasing fossil fuel use, shifting to sustainable dietary habits, and promoting greener cities are discussed concerning their impact on agriculture and water management.

The importance of a balanced approach that includes adaptation and mitigation is highlighted, especially in the context of institutions and governance practices supporting climate-resilient development. The water balance concept is initiated as an important tool for understanding and managing water resources at both global and local levels. The importance of potential evapotranspiration (ET) prediction using projected climate data is emphasized to anticipate future water requirements in agriculture. Developed methods both the FAO-56 and FAO-66 for crop water use calculation are recommended to assess water requirements under future climate scenarios.

In short, the increasing intensity and frequency of extreme weather events, such as floods and droughts need careful planning and adaptation measurement to manage water resources effectively. A strategic program for water storage and distribution is important to mitigate the risks of climate change on water resources. Climate services and crop modeling are brought as valuable tools for improving agricultural water management in response to climate change. Issues related to water pollution and reduced rainfall are emphasized to achieve sustainable water availability in response to the challenges of food security and safety.

**CHAPTER II: The Effects of Climate Change on Water Resources. The Distributed Catchment Scale Model, DiCaSM application in Cyprus, Italy, Brazil, and the United Kingdom**

The impact of climate change on water resources has been studied using the Distributed Catchment Scale Model, DiCaSM, across various catchments in Cyprus, Italy, Brazil, and the UK. The study findings show significant reductions in groundwater recharge and stream flow due to lower rainfall and higher temperatures, especially under high-emission scenarios. In the semi-arid northeast of Brazil and in the south of Italy, as well as in Cyprus, the gap between water supply and demand is widening with time, water scarcity and variability emphasize the need for sustainable water management strategies. In the UK, all seven catchments studied indicated potential future gaps between water supply and demand, requiring infrastructure improvements and demand reduction measures. Drought indices predicted rising evapotranspiration, soil moisture deficit, and frequency of drought events, emphasizing the urgency for adaptation and mitigation strategies. These include strengthening water use efficiency, implementing advanced irrigation systems, and adopting clean energy sources. The results underline the critical requirement for sustainable water management policies in response to the challenges posed by future climate change.

## CHAPTER III: Adaptation of Agricultural Water Management under Climate Change and Water-Related Hazards

Climate change affects all aspects of the water cycle both decreasing water availability with each degree of warming and causing significant risks. This chapter covers topics related to the impacts and adaptations of climate change on agriculture water management. The agriculture sector contributes about 22% of GHG emissions, mainly through soil management, livestock digestion processes, and crop and manure management. Climate change impacts water cycles, affecting evaporation, precipitation, runoff, and stream flow. It leads to decreased water quality due to increased runoff and saltwater intrusion. Groundwater depletion and changes in river flows are also necessary, with significant regional variations. Climate change worsens water availability issues, leading to higher risks of drought and flooding. This impacts agricultural productivity, with potential yield reductions and increased vulnerability to water scarcity by 2050**.**

Various farming practices and systems, including agroecology, conservation agriculture, and integrated production systems, can reduce emissions and adapt to changing climate conditions. Effective practices including fertilizer effective use, crop diversification, and sustainable irrigation techniques are needed. Adaptation techniques include organized irrigation practices, rainwater harvesting, conservation ponds, and using non-conventional water sources. These methods aim to increase water productivity, manage risks, and build resilience in agricultural systems. Proper irrigation scheduling based on crop needs and efficient water distribution are necessary. Challenges include treating poor-quality water in arid regions and arranging equitable water distribution. Upgrading early warning systems and improving pre-disaster preparedness in response to climate change impact are important. The 2030 Agenda for Sustainable Development, the Paris Agreement, and the Sendai Framework for Disaster Risk Reduction highlight the need for global and national strategies in response to climate change and its impacts on agriculture. Developing countries need frameworks and methodologies for effective disaster preparedness and adaptation.

Moreover, governments perform a vital role in overseeing agricultural water management, ensuring transparency, and promoting sustainable practices. Effective policies should address water use efficiency, technology adoption, and stakeholder engagement. Policy changes should focus on water-use efficiency, sustainable technologies, and addressing gender issues in water management. Engaging stakeholders and developing country-specific indicators are important for effective policy implementation.

## CHAPTER IV: Smart Water Management Against the Climate Change

The chapter on smart water management and climate change discusses the integration of advanced technologies within agriculture to optimize water usage and increase efficiency, thereby addressing the challenges presented by climate change. Smart water management, a subset of smart agriculture, uses tools such as sensors, IoT devices, and remote sensing to automate and enhance irrigation processes both on-farm and at larger scales, either at district or basin levels. This approach aims to improve productivity, reduce environmental impacts, and ensure sustainable water use in agriculture.

Climate-Smart Agriculture (CSA), as defined by the FAO, complements smart water management by focusing on three key objectives: increasing productivity, adapting to climate change, and reducing greenhouse gas emissions. CSA emphasizes the importance of locally adapted solutions and the integration of technology, policies, and institutions to build resilience in agricultural systems. The chapter highlights that while smart water management is essential, its effectiveness in extreme weather scenarios depends on its design and the extent to which it considers long-term climate risks.

Overall, the chapter disputes that while technology-driven smart water management is important, it cannot fully address the complexities of climate change on its own. A broader approach, such as CSA, which includes institutional and policy support, is needed for long-term adaptation and mitigation. The chapter recommends that integrating smart water management with concepts of both Integrated Water Resources Management (IWRM) and Integrated Disaster Risk Management (IDRM) will be vital in creating resilient agricultural systems capable of withstanding future climate challenges.

**CHAPTER V: Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Northern Taiwan**

Climate change has led to increasingly frequent occurrences of extreme weather events such as floods and droughts which cause drought events as a controversial issue in agricultural water usage in Taiwan. In Taiwan, droughts and water supply shortages generally occur in the winter and spring seasons, however, the water demand annually continues to increase. These shortages are caused by the decrease in rainfall patterns in the dry and wet seasons. Therefore, the study objective is to explore the trend of changing rainfall in northern Taiwan and analyze the impact on agricultural water usage by using the high-resolution General Circulation Model, GFDL-HiRAM, with RCP8.5 climate change scenarios. The results of the study show that there would be more water shortage in the dry season (spring and winter) due to domestic water taking priority in water supply and the significant impact on agricultural irrigation. Moreover, the water shortage could reach a peak of up to 40% in spring.

**CHAPTER VI: Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Pakistan**

Pakistan is a “water-stressed” country and its water resources are considerably vulnerable to climate change. The climate scenario assessment approach can be used for climate impact assessment. This study overviews recent advances in understanding the impact of climate change on agricultural water management and water resources of Pakistan, presents certain agricultural adaptation strategies determined in the literature studies, and uses the IDW interpolation method in the GIS environment to plot spatial patterns. The research findings emphasize that the scope of policy related to climate change adaptation should focus on the community and farm-level strategies for significant development outcomes. While analysis has identified some of the broad changes underway in Pakistan’s climate, the findings also point to the critical need to take into account regional and local trends.

**CHAPTER VII: Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Nepal**

Climate change is one of the top global issues of the current time whose impact is felt across diverse social, economic, and environmental sectors in almost every nation. Nepal’s vulnerability to climate change is widely recognized given its geographical, social, and economic realities. Nepal’s growth, achievement of SDGs, water resources development, socio-economic stability, and environmental sustainability all hinge on effectively managing, mitigating, and adapting to climate change. The objective of this study is to briefly review and identify the challenges of climate change that affect the sustainable development and management of irrigation which are determined in the literature studies. The result of the study shows the diverse facets of climate change's influence on Nepal's water resources and irrigated agriculture, analyzing its socio-economic, financial, and economic dimensions.

**CHAPTER VIII: Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in India**

Climate change affects water availability, quality, and demand, posing a significant challenge for agricultural water management. India's irrigation efficiency varies widely depending on the region and the type of irrigation used. Out of 19 Mha gap between IPC AND IPU, major and medium irrigation projects have account for 13 Mha with current rates of irrigation efficiency for surface and groundwater are roughly 30–40% and 55–60%, respectively. There are four major case studies such as climate change, water availability, extreme events, and climate-smart technology which are determined by literature review. Moreover, the studies indicate that temperatures will rise and rainwater availability will decline, leading to increased water demand for agriculture.

**CHAPTER IX: Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Iran**

Freshwater resources in arid and semi-arid countries may be severely impacted by climate change. Iran is located in the arid and semi-arid regions of the world. It is located between 25° and 40° north latitudes and 44°– 63° east longitudes in West Asia and borders the Caspian Sea, the Persian Gulf, and the Gulf of Oman. In recent years, Iran has experienced a decline in rainfall, and extreme precipitation events due to ENSO, drought, water scarcity, urban and industrial pollution, desertification, soil erosion, and biodiversity loss. The objective of this study is to briefly review the climate change impacts on agricultural water management in Iran and the Middle East North Africa (MENA) region by literature studies. The research study findings emphasize that a significant increase in potential evapotranspiration in summer causes a significant increase in crop water requirement. There are several strategies in the context of climate change such as water needs estimation, and planting less vulnerable species to climate change, such as medicinal plants.

**CHAPTER X: Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in China**

China is increasingly facing water shortage and food security challenges. In fact, drought, flood and water pollution has become the three most serious water problems in China due to the uneven spatial distribution of land and water resources and rapid industrialization and urbanization China will face great challenges in the future in terms of water availability, food security and climate change. Investing in drought-resistant crops which use less water or adopting some non-structural water-saving measures are possible options to mitigate the adverse impacts from climate change. The research utilizes the Policy Dialogue Model Simulation (PODIUMSim) to analyze and simulate future irrigation water demand, crop yield, water productivity, and food surplus or deficit in China, considering hydrology, meteorology, water and land use, and crop planting data. It also employs General Circulation Models (GCMs) and statistical downscaling to predict climate changes and their effects on agricultural water demand in China. The research findings emphasize that climate change will pose a great threat to the sustainable use of water resources in northern China. It is estimated that in the next 30 years, climate change will reduce the water availability of Haihe River basin and Luanhe River basin by 4.7% and 4-6% respectively. In addition, climate change will reduce the runoff of Haihe and Luanhe river basins by 12%. Therefore, climate change will have adverse impacts on water resources and their distribution, as well as the water availability, especially in northern China. Moreover, the effects of change in ETP on irrigation water demand and water productivity is much greater than that of change in P75 on irrigation water demand and water productivity. There are several strategies for adaptation and mitigation measures to climate change in water resources such as strengthening the protection of water resources and the control of soil erosion, building the pattern of water resources allocation and improving the flood control and drought relief system.

# CHAPTER I
# General Introduction to Climate Change Effects on Agricultural Water Management

Sue Walker[1]

## 1.1 Overview of the changing climate as one of the most serious global issues

Climate change and variability is a well-established fact from the past climate monitoring records around the world since the 19th century (WMO, 2022). However, the details of the impacts on human life are still being recorded, and more importantly, the range of interventions that can be taken to maintain sustainable livelihoods on the planet are being developed on a continuous basis. As water is the mainstay of life on the planet (GEF, 2021), it is important to make a concerted effort in developing good coping strategies for both adaptation and mitigation of climate change effects by holistic management of the limited water resources. As humans need to cultivate food to survive, therefore the wise use of water in sustainable agricultural systems should be a top priority. Therefore, this book addresses many of the relevant topics under the framework of the optimization and productive use of water for irrigation and drainage management in the agricultural sector.

### 1.1.1 Adaptation and Mitigation

The impacts of climate change affect people from all walks of life and all ecosystems in nature in a large variety of ways. Therefore, the specific goals of adaptation need to depend on the specific impact being addressed and managed and the action that can be taken (Semeraro et al., 2023). For agroecosystems, adaptation can include actions aimed at reducing a specific risk, such as construction of barriers against flooding; or aimed at multiple risks, such as a requirement for climate risk assessments in reporting in anticipation of different kinds of risk. At the local level, communities have a variety of actions including revision of land use plans, improving soil and water management, enhancing water use efficiency, increasing biodiversity, introduction integrated pest management, and taking measures to reduce poverty (Dittmer et al., 2023). In natural systems, adaptation includes changes in behavior by various components, movement to alternative locations as well as genetic modifications in response to changing climate conditions. Many goals for adaptation actions are related to water or food or livelihood security, health, employment, poverty eradication and social equity, biodiversity and ecosystem services, among others. But largely they have an intersection with the use of water on the farm as well as across the landscape or catchment, therefore there needs to be an integrated and holistic approach to the planning and implementation of such adaptation actions (IPCC-FAQ, 2022).

The purpose of adaptation is to be prepared to manage key risks by reducing vulnerability or exposure to climate hazards. In order to apply this to the irrigation and drainage sector, one needs to first establish the key risks and vulnerabilities to particular climate hazards. Furthermore, multiple pressures limit the success of some adaptation actions or hamper implementation plans, such as have already been experienced by small-scale farmers and some natural systems. Therefore, adaptation-related responses are actions that are taken with the intention of being prepared to handle risks by reducing exposure to climate hazards and/or vulnerability. This can be done by responding to impacts and future risks that are unavoidable, either due to past emissions or failure to reduce emissions.

In contrast, mitigation responses aim to reduce greenhouse gas emissions and slow global warming. For irrigation and drainage and across the water sector such mitigation responses need to be further explored. Various methods have been used to evaluate the opportunities for

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mitigation in the water sector, names value-engineering, WEF nexus, Life cycle analysis, so that possible options can be appraised and compared before implementation (El-Nashar & Elyamany, 2023; Nhamo et al., 2020; van der Laan et al., 2015).

Often it is not feasible to evaluate the adequacy of adaptation at global or regional levels, but evidence from specific localised adaptation projects have shown that adaptation-related responses reduce risk of communities. Moreover, many adaptation measures offer near-term co-benefits related to mitigation and to sustainable development, including enhancing food security and reducing poverty. Some of these examples from the irrigation and drainage agricultural sector will be described in detail in the chapters of this book.

Crucial and central to making choices about how to mitigate greenhouse gas emissions and adapt to climate change is to establish institutions and governance practices supporting climate resilient development (ICLEI Africa. 2021). This should be as a mix and sequence of mitigation and adaptation actions to be taken into considered to be fair, just and inclusive as well as technically and economically effective across successive generations.

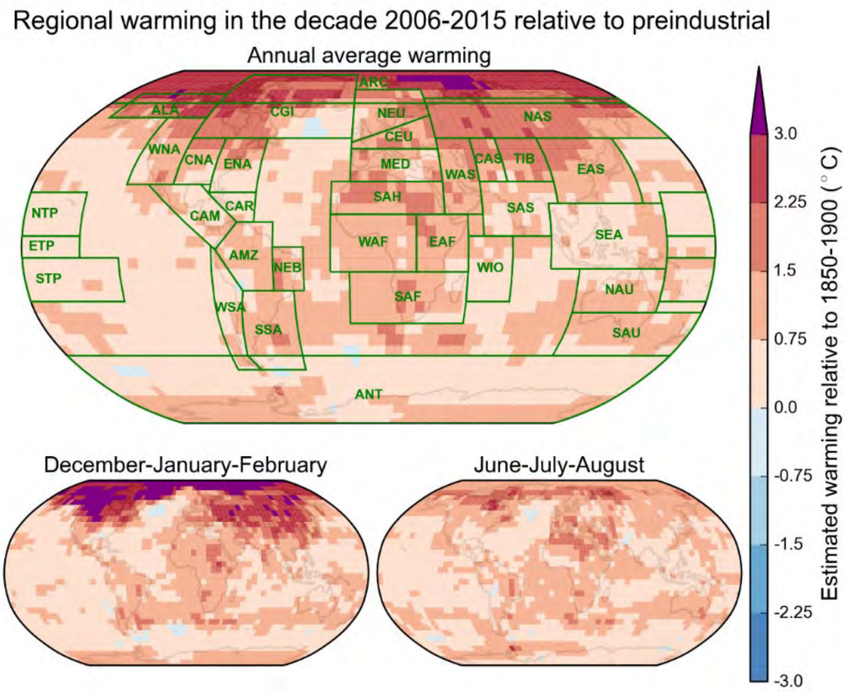
### 1.1.2 Global Temperature and Precipitation Changes

The accepted authority on the state of the earth concerning global climate change is the IPCC (Intergovernmental Panel on Climate Change) which is a scientific group that is assembled by the United Nations (UN) to do the monitoring and assessment of all global science related to climate change. IPCC has produced many reports over the last decade, as each report focuses on different aspects of climate change in order to provide scientific information and technical guidance to the United Nations Framework Convention on Climate Change (UNFCCC). The latest IPCC reports (at time of writing) are the Sixth Assessment Report – Working Group II – Impacts, Adaptation and Vulnerability released in 2022 and the IPCC Global Warming of 1.5°C Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (IPCC, 2018, 2022). These documents should be used as reference material for the background to the chapters in this book.

A significant amount of present-day warming has already occurred relative to the 1850-1900 temperatures. The map divided into regions given in the IPCC Special 1.5° C Report shows the differences particularly the values greater than 3° C in the northern polar regions (Figure 1.1). Across most part of the earth's land mass the warming for this period (2006-15) is between 0.75° C and 1.5° C, compared to lower values over the oceans. It also shows that the warming has been more noticeable during the northern winters (December, January, and February) than during the summer season (IPCC, 2018).

Figure 1.1. Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January, and February and for June, July, and August (IPCC, 2022, SR-1.5: Figure 1.3).

Basically, the projected changes in temperature and precipitation vary across the globe, but the IPCC -6AReport (2022) warned that the world is set to reach the 1.5º C level within the next two decades and that only the most drastic cuts in carbon emissions from now on would help prevent an environmental disaster. The IPCC emphasized three main special aspects that need to be addressed, namely "use of fossil fuels" which should be abandoned as soon as possible; "changes to sustainable dietary habits" by reducing livestock industry by reducing demand for meat and dairy products, and all deforestation; and "greener cities" – change traditional urban organization as soon as possible towards sustainable and more environmentally friendly urban planning. Although on the surface these do not seem to touch agriculture and irrigation or drainage, if one unpacks them then they do have an influence of the agricultural and water sectors. This can be seen for all three of the recommendations. For example, most commercial agricultural practices use fossil fuels as a major input as many of the field and pumping operations are mechanized and utilizing fossil fuel. This is also true for most of the transportation and processing of food products. Therefore, these sectors need to look for practical ways to address the reduction of the use of fossil fuels. Secondly, any proposed changes in dietary habits will have a direct effect on the agricultural production and water use. This requires a dramatic shift in many of the operations in the food and agricultural sector that is reliant on the water sector. Lastly, the greener cities proposal can also mean incorporation of more home food gardens, green buildings, and different innovative water systems – including recycling of water for irrigation and alternative drainage and sanitation systems. This could be either advantageous and beneficial or detrimental to the agricultural water sector either freeing up additional water or reducing the demand for irrigation water.




The IPCC reports propose the use of pathways showing a temporal development of natural and/or human systems towards a future state. Such pathways include a range of sets of scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Therefore, Climate Resilient Development Pathways (CRDPs) are trajectories for the pursuit of climate resilient development (CRD) while navigating the many complexities, not only the long-term concentration levels but also the trajectory taken over time to reach that outcome is of interest (Moss et al., 2010, van Vuuren et al., 2011; IPCC, 2022). CRDPs should involve ongoing processes that continue to strengthen sustainable development, eradicate poverty and reduce inequalities while promoting fair adaptation and mitigation across multiple scales. Therefore, they should include alteration to specific aspects of irrigation and drainage systems that can promote increased water conservation and use efficiencies. However, CRDPs usually involve larger-scale societal transformation, they invariably raise questions of ethics, equity and feasibility of options that are aimed to drastically reduce emission of greenhouse gasses (mitigation) that limit global warming (e.g., to well below 2°C), while achieving the desirable and liveable futures for well-being of all humanity. Therefore, a holistic approach is needed that includes the water sector as a whole and the allocation and distribution of water between sectors.

### 1.1.3 Global and Local Water Balances

In order to carefully consider the effects of climate change and variability on irrigation and drainage, one needs to take a close look at the components of the water balance. This should be addressed at several levels, but especially at the global and local levels. The earth has a finite amount of water that is cycled through the global water balance at different time steps. The concepts of water gains and losses can be considered for any ecosystem or agro-ecosystem where the inputs will be rainfall and irrigation with the outflows being evapotranspiration, runoff and drainage. Therefore, if water use is to be optimised under warming temperatures, one needs to realise that the evapotranspiration (ET) is dependent on the temperature of the surfaces and the amount of solar radiation available for latent heat conversion. One needs to make the necessary calculations of potential evaporation projections using the projected temperatures and the acceptable equations. This will give an idea of the increased demand for water by an agricultural or natural system under the warmer regime. However, one also knows that there is another driving force for evapotranspiration namely the dryness of the air or the relative humidity, this will be affected by the rainfall regime, being both amount and timing, so that the effect of projected changes in the rainfall need to be included in such an investigation. However, as the climate projection for rainfall in the future is highly variable which increases the uncertainty of the rainfall projections, this is not a simple task but one with high uncertainty.

### 1.1.4 Water Use and Irrigation

Some of the best ways to improve water use efficiency is using the water balance above together with the climatic factor inputs to the ET calculation. Much research has already been done and some of these are now generally accepted as standard methods. For example, the calculation of crop water uses via the ET using the FAO methodology in FAO-56 (Smith et a., 1998) and FAO-66 (Steduto et al., 2012). As this ET calculation are based from first principles on the meteorological parameters, one does not expect such relationships and equations to change under climate change. Therefore, the same equations can be used as long as the projected climate parameters are available at a local scale from downscaled climate models. These can then be used with confidence to make the necessary adjustments to the water requirements for an irrigated area as long as the details of the planting and harvest dates are available for the crops planted. This can then be integrated across an irrigation scheme to give a projected value (using GIS) to assist in the water demand and water allocation from the rivers and or dams suppling the water.

### 1.1.5 Extreme Events

Both the intensity and frequency of extreme event will change and probably intensify in the future. Therefore, one needs to pay particular attention to the season forecast for the upcoming three months, so as to plan correctly and take the necessary precautions. The extreme events can be large floods or severe droughts or even heavy unseasonal downpours. In particular, the management of the water storage dams should be aware of such forecasts and schedule additional water releases or reduce releases as necessary (Muchuru et al., 2016). For farmers there some adaptation that they can make such as the irrigation infrastructure; provision of, financial, technical and policy support. It has been shown that early-warning information services can help farmers to make changes in their management decisions. Analysis has shown that such adaptive response significantly mitigates yield loss and reduces the risk of crop failure (Wang et al., 2019).

### 1.1.6 Storage Capacity and Drainage

In order to reduce the risks of climate change and variability on water storage, careful planning in both long-term and medium term is a priority (World Bank, 2023). The map shows the distribution of the freshwater supplies across the world and is divided into those in ice form versus freshwater sources and ground water (Figure 2) Businesses need to participate in technical, physical and financial planning for the continued provision of water. Companies should also enhance supply reliability and/or they can reduce demand to mitigate risk by taking action at catchment and watershed scale (Larson et al., 2012). However, the allocation of water is also important, as merely purchasing water right or water trading does not reduce the overall water demand in a catchment. Therefore, a strategy such as using the WEF (Water-Energy-Food) nexus approach can assist in, managing water allocation in a catchment by using an indices methodology to assess the value of water across sectors (Adeola et al., 2022).

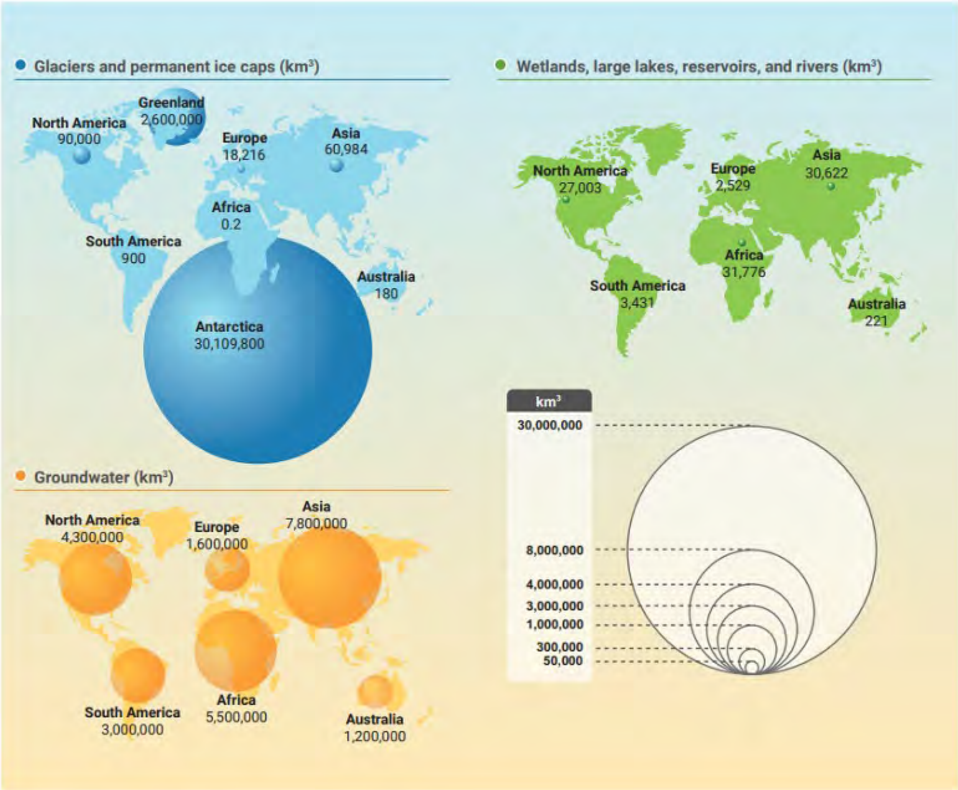



**Figure 1. 2.** Quantity and distribution of fresh water by region and place of storage (World Bank, 2023).

## 1.2 Agricultural Water Management as a Means to Adapt to Weather and Climate

Some of the impacts of climate change and variability will be discussed in the various chapters of this book. As there is much continuing work on these aspects it is not possible to describe all of them. However, a few of the more recent development will that address these aspects will be shared here.

### 1.2.1 Climate Services

Climate services are one such intervention to bring the necessary information about the climate and weather to the end users. Often in the past they were called agrometeorological advisories and distributed on a regular basis from the national meteorological services (NMS) in each country. However, in this new digital age, there are many innovative climate services being provided and a 'next-generation approach' has been proposed (Jacobs & Street, 2020). This includes supporting a broad requirement for the development and use of climate services across many sectors despite the changes being experienced. So, there is a need for a transformation that should be based on a well-coordinated network of trained, multidisciplinary science-climate service translators, preferably people who can work interdisciplinary, with good communication skills and with experience in stakeholder engagement practices (Jacobs & Street, 2020). Together with these people, one need a good well organized database of long-term climate data and good weather forecast operational models to provide updated information (Vaughan et al., 2019, Moeletsi et al., 2022). The development of such climate services can serve to address farmers need and assist in their decision making by using a variety of media channels such as group meetings, mass media (radio & TV), mobile phones, internet via computer of smart phones (Hansen et al., 2019). For example, AgriCloud, a mobile app was developed to distribute planting and spraying advice to small-scale maize farmers in South Africa (Walker, 2020, & 2021). Seasonal climate forecast has been compiled and distributed since 1990s and have assisted both farmers and water managers to make informed decisions for the upcoming rainy seasons (Hansen et al., 2019). However, further support and development was needed including downscaling and merging with the local observations, as well as making climate data more freely available. There are many examples across Africa and south east Asia where the seasonal forecast have been the basis for co-development of tailored forecasts for farmers. For example, in Senegal, the use of seasonal forecasts is generally associated with the farmers using improved seed, fertilizers together with manure, but mostly with a negative influence on limiting crop diversification. The participatory approaches to the provision of tailored climate information and advisory services lead to higher uptake and use in farm management decisions (Chiputwa et al., 2020). Another example is from Indonesia, where rice farmers formed rainfall measuring groups and received monthly seasonal forecasts in Science Field Shops (SFS). These farmers were fast learners and anticipated the changes and could then change crops or cropping systems by using the seasonal forecast and anticipating potential risks in the upcoming season (Winarto et al., 2019).

### 1.2.2 Crop Modelling for Climate Change

As crop models represent the crop growth and development though a growing season, they are useful to generate water use and predict expected changes in the future under climate change scenarios. Usually current research, an ensemble of global circulation models (GCMs) is utilized as the input to the crop models, then the uncertainties associated to their estimates are able to be calculated. Various farming systems can be described and then modelled to determine the productivity and economic viability for future climates (Beletse et al., 2015, Masikati et al., 2015, Ruane et al., 2017). It this way a holistic view of the effects of climate change and possible adaptation interventions can be assessed across wider areas (Jennings et al., 2023, Ruane et al., 2013) and therefore make policy recommendations. Various methods can be used to link climate change scenarios with hydrologic, agricultural, and planning models that can speak to the water available for agriculture under changing climate conditions. This can also take into account the changes in demand from other competing sectors like municipal and industry, to estimate changes in the amount of water available for irrigated agricultural production and the effectiveness of adaptations options and reliability (Rosenzweig et al., 2004). Crop modelling methods can be used to assess the helpfulness and effectivity of the adaptation interventions in cropping systems under the future scenarios and provide advice on water use in agricultural systems.

## 1.3 Outline of the Recent Problems in Agriculture and Water Use due to Climate Change

### 1.3.1 Challenges – to change management practices

Finding effective solutions for agricultural water use amidst climate change is imperative. Balancing the reduction of water consumption in agriculture while ensuring food security poses significant challenges. Implementing optimal irrigation strategies tailored to various climate conditions, including wet, normal, and dry seasons, presents one such solution. For instance, reducing irrigation by 50% in wheat farming could conserve 1000–1100 m3 of water per hectare. This reduction maintains a water productivity higher than 1.88 kg/m3, with wheat production decreasing by less than 5% compared to full irrigation. Similarly, during normal and dry seasons, a 25% reduction in agricultural water use sustains wheat production at around 96.35–98.3% of maximum yield. This reduction saves 650–800 m3/ha of water while achieving nearly the same water productivity as full irrigation (M. Li et al., 2024).

An essential challenge in finding optimal irrigation solutions lies in maintaining food production levels while simultaneously conserving water resources. Additionally, the issue of surface water pollution, often caused by the direct discharge of untreated wastewater in agricultural areas, further complicates matters. Given the backdrop of climate change, ensuring the availability of high-quality water resources for agriculture becomes increasingly challenging. While recycling treated wastewater for agricultural purposes presents a promising solution, it's crucial to consider the willingness of farmers to invest in such initiatives. In today's context, traditional farming methods often lack profitability, making it challenging to incentivize farmers to adopt new practices, such as utilizing recycled wastewater for irrigation. Overcoming these challenges could not only lead to more sustainable water use in agriculture but also contribute to increased food production, improved living conditions, and enhanced financial stability for farmers (Haldar et al., 2021).

### 1.3.2 Lower rainfall – less water in hydrological system

Natural rainfall plays a significant role in determining water availability within hydrological systems. Reduced rainfall can lead to decreased water availability, resulting in consequences such as deficit irrigation and diminished water-saving effectiveness. Furthermore, agricultural water demand is influenced not only by the total amount of rainfall during the growth period but also by its distribution. Hence, in order to enhance irrigation management in response to future climate change, particularly changes in rainfall patterns, it is essential to analyze how water balance elements under water-saving technologies align with the requirements for increased land productivity. Understanding the characteristics of rice irrigation demand and the interplay between crop water needs and rainfall distribution is crucial for devising water-saving management strategies amidst the impacts of climate change. Further investigation into water productivity is warranted in this context. (Luo et al., 2022) (Rodrigues et al., 2013).

### 1.3.3 Basin hydrology and water resources

The relationship between climate, basin hydrology, and water resources is significant, particularly regarding the impact of integrated extreme climate events on water yield and evapotranspiration (ETo). Evaluating these impacts is crucial for understanding potential risks and devising effective mitigation strategies in response to a changing climate. Extreme climate events, such as heatwaves, have intensified water resource depletion, while extreme cold events have predominantly negatively influenced hydrological variables. Despite a decrease in ETo, extreme precipitation events have led to increased evapotranspiration and surface runoff in certain regions, heightening the risk of disasters like floods and waterlogging. During extreme drought events, nearly all hydrological variables have decreased, indicating the severity of their adverse effects. In future periods, hydrological variables like ETo and evapotranspiration are projected to significantly increase under extreme heat, but extreme cold events will have a more pronounced negative impact on these variables. Understanding the effects of extreme climate events on hydrological variables holds significant implications for water conservation, particularly in regions like the black soil area (Zhang et al., 2023).

Furthermore, clear correlations have been observed between certain vegetation indicators and climatic or hydrological variables. To ensure the stability and sustainability of ecosystem water resources, it is essential to employ water resources judiciously, regulate water usage scales, recharge groundwater, and prevent downstream ecosystem degradation resulting from reduced upstream discharge during dry years (Lu et al., 2021).

### 1.3.4 Agricultural production

Climate change has intricated effects on agriculture and food production, primarily influenced by temperature and precipitation fluctuations. Higher temperatures coincide with decreased precipitation, impacting crop sowing and growth. This variability in climate can result in adverse effects on local crop yields, with rice, corn, and wheat experiencing varying degrees of decline over the past decade due to warming trends. Extreme events like droughts, rainstorms, and floods have become more frequent, further exacerbating yield reductions. Severe droughts significantly affect pollination and crop growth, leading to substantial yield decreases ranging from 17.86% to 36.67%. Temperature and precipitation directly influence soil moisture and adhesion, impacting crop growth. Rising temperatures intensify surface water evaporation, rendering some cultivated areas unsuitable for cropping due to soil dryness. Moreover, excessive rain or runoff can cause depressions to flood, submerging grain crops. Fertilizer use, multiple cropping, and population density are the primary drivers of food production in karst areas. Farm management practices and technological advancements, along with population growth’s demand for food have historically driven increases in food production, often outweighing the negative of climate change. Enhancing farm management efficiency within cultivated lands is crucial for sustainable food supply and environmental conservation. Farmers have improved field production systems to boost crop yields, with governmental support playing a key role in promoting sustainable production practices. However, climate change-induced temperature fluctuations negatively impact agricultural production and quality, affecting crop yields and soil fertility. Climate extremes are expected to rise in frequency and intensity, increasing irrigation water demand and potentially causing water scarcity. Reducing climate change impacts often involves adjusting farm management practices, decreasing fertilizer use, and employing new crop varieties. Intensive agricultural practices have enhanced land use efficiency, but further increases in crop yields may exacerbate the demand for irrigation water and fertilizers. Transitioning from smallholder to commercial agriculture in suitable areas is necessary for future agricultural sustainability. (Y. Li et al., 2023).

#### 1.3.5 Irrigation and drainage

The ongoing threat of climate change underscores the necessity of crafting climate-adaptive strategies to ensure that water usage and food production remain economically feasible, socially fair, and environmentally sustainable. Irrigation stands out as a valuable approach to enhance crop yields by mitigating water stress, especially in arid and semiarid areas where climate change has reduced precipitation. Through irrigation, soil moisture is directly augmented during the growing periods, impacting the surface energy balance and thereby influencing climate dynamics. These interactions and feedbacks between irrigation, climate, and hydrology emphasize the intricate relationship that must be considered in devising effective strategies (Yuan et al., 2023).

There are two main approaches to designing Sustainable Agricultural Drainage Systems (SADS) that aim to optimize surface runoff for irrigation while considering environmental constraints and cost factors: passive and active methods. Installation of SADS would have shifted water flows towards more sustainable conditions, with passive systems enhancing aquifer recharge by increasing infiltration, and active systems directing runoff towards natural watercourses. Neither method is expected to contribute significantly during the driest years, preserving natural water flows. In wet years, active systems would increase surface discharge compared to the present situation. Overall, SADS installation would reduce applied irrigation, with passive systems facilitating aquifer recharge by improving infiltration. Passive SADS, particularly those utilizing tillage practices, appear more efficient for water management than active systems or conventional irrigation techniques. Passive SADS are also better equipped to adapt to yearly changes, as they involve fewer long-term infrastructure implications and risks of over- or under-sizing (Zubelzu et al., 2022).

### 1.4 Innovated Water Management under the Changing Climate

The various chapters address a range of aspects of the effects of climate change on water resources around the world. The application of a catchment scale model shows the widening gap between water supply and demand in four countries under different climate scenarios accenting the need for viable adaptation and mitigation strategies to be developed. A range of methods and farming systems are discussed in chapter III, with a goal of increasing water productivity, and managing risks, as well as building resilience in agricultural systems. Chapter IV showcases some technologies that can be used to address climate variability in conjunction with climate-smart agricultural (CSA) interventions, concluding that both Integrated Water Resources Management (IWRM) and Integrated Disaster Risk Management (IDRM) can make good contributions to fashioning resilient agricultural systems. The remaining five chapters explain case studies from specific countries, ranging from the arid zones of Iran and Pakistan to the high mountains of Nepal to the highly populated India, China and Taiwan. Thus, many characteristics of climate change and its effects on agricultural water have been addressed, by using information from GCMs about the projected future climate and bringing examples of effective water management interventions to address the expected water shortages. Therefore, there is much to be learnt from these country specific case studies for application in other countries at a regional, catchment, farm or field level.

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# CHAPTER II
# The Effects of Climate Change on Water Resources. The Distributed Catchment Scale Model, DiCaSM application in Cyprus, Italy, Brazil, and the United Kingdom

Ragab Ragab[1]


## ABSTRACT

This chapter will briefly describe some climate change impact studies carried out in some countries Cyprus Island, Italy, Brazil and the UK. These studies were carried out at catchment scale, all used the same model, the Distributed Catchment Scale Model, DiCaSM. The results of Cyprus' two south catchments showed that by 2050, relative to baseline data, groundwater and surface water supplies would decrease by 35% and 24% for the Kouris and 20% and 17% for the Akrotiri catchments, respectively. The gap between water supply and demand showed a linear increase with time. The results of the model run for the Candelaro catchment in the south of Italy showed that by 2050 the groundwater recharge would decrease between -20% and -30% and stream flows would be reduced between -16% and -31%, relative to the baseline data. Plotting the future water supply against the projected future water demand, for the Candelaro catchment area, showed the gap between water demand and water supply (groundwater and surface water, decreasing up to 2050) would increase in all scenarios and on average by up to 15% over time. The results of Mimoso and Tapacurá catchments of the Brazilian semi-arid regions in the northeast of Brazil indicated that for the Mimoso catchment, under the average of dry high and dry low emission scenarios, a forecasted reduction by 35%, 68%, and 77%, in groundwater recharge, GWR, and by 34%, 65%, and 72% in streamflow, for the time spans 2010–2039, 2040–2069, and 2070–2099, respectively, is expected. On the other hand, the Tapacurá catchments results indicated the possibility of reduction by 13.90%, 22.63% and 32.91% in groundwater recharge and by 4.98%, 14.28% and 20.58% in surface flows for the time spans 2010–2039, 2040–2069, 2070–2099, respectively. The study on the impact of future climate change on the UK water resources, with particular interest in drought, was carried out on seven catchments from north to south and from west to east to represent the rainfall and temperature gradient across the whole UK. The results of three representative catchments (from south to middle to north) out of the seven catchments are reported in this chapter. The selected catchments are Eden in the north (Scotland), Don in the midlands, and Pang in southeast of the UK. The results of the modelling work for the Eden catchment indicated that the most significant reduction in stream flow is expected in the summer season under all emission scenarios, the summer streamflow is likely to decrease, by 9.6 to17.8% in the 2020s, by 14.9 to 21.34% in the 2050s and by up to 25.2% in the 2080s under high emission scenarios. The study also pointed out that the groundwater recharge is likely to be reduced in the future with the largest decrease in groundwater recharge expected in the second half of the century, as it may decrease by up to 20.26% under the high emission scenario in the 2080s during the summer months. Overall, groundwater recharge during the summer months is much less than other seasons. The results of the Don catchment indicated that the most significant reduction in stream flow is expected in the summer season. During the 2020s period, in summer, a significant decrease in stream flow is projected to decrease by 13 to15% while in the 2050s, a decrease is projected from 27 to 29% and during the summers of the 2080s, the stream flow is likely to decrease by 24 to 42%. The groundwater recharge projections suggest that groundwater recharge might decrease by 3.4 to 11.3% under all emission scenarios during the winter months (December, January and February). The highest decrease of over 40% in summer groundwater recharge projected for the 2080s. The results of the Pang catchment indicated that the stream flow decrease in the 2020s ranged from


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11.7% to 21.6%, in 2050s from 19.0 to 36.7% and 2080s from 21.4 to 46.6% with the lower values associated with the low emission and higher values in the range associated with the high emission. The GWR decrease in the 2020s ranged from 16.9% to 41%, in 2050s from 28.0 to 62.3% and 2080s from 28.7 to 71.7% with the lower values associated with the low emission and higher values in the range associated with the high emission scenario. The drought indices such as Standardized Precipitation Index, adjusted Standardized Precipitation Index, SPEI, which takes ET into account, Reconnaissance Drought Index, RDI and the adjusted RDI which includes actual ET instead of potential ET and net/effective rainfall instead of total/gross rainfall, Soil Moisture Deficit, Wetness Index and River Water Depth were computed for future climate change scenarios for the UK catchments. The indices were able to accurately reproduce the past drought events. In addition, they predicted the future ET, SMD, WI, RDI/RDIE, SPI/SPEI, stream depth and the future number of drought events and their severity level. The results indicated future increases in the ET, SMD and decreases in WI, SPI/SPEI. The decrease or increase gets more significant with increasing the emission level from low to medium to high and with time from the 2020s to 2080s. In addition, the RDI/RDIE analysis indicated the possibility of increasing the number of drought events, their frequency of occurrence and severity levels will increase with increasing the emission level from low to medium to high and with time from the 2020s to 2080s. The gap between water supply and demand was calculated for the Cyprus' two catchments Kouris and Akrotiri and for the Italian catchment, Candelaro, showed a widening up to 2050. Similarly, six out of the seven catchments of the UK (apart from Eden in Scotland) showed a similar widening gap between future water supply and future water demand and that gap is widening over time up to 2099 if water demand is not sustainably managed and controlled. New policies to mitigate and adapt to climate change are needed to cope with the impact of climate change in order to ensure water and food security for the 9.8 billion inhabitants by 2050.

## 2.1. Introduction

This chapter highlights the impact of future climate change on water resources. Given irrigation globally consumes on average 70% of freshwater resources (surface and groundwater), any change in the amount of water resources and availability will have impact on irrigated agriculture. Rising temperature due to greenhouse gasses would increase evapotranspiration, ET and subsequently irrigation requirement. Reduced rainfall has a negative impact on water availability in rivers, lakes, reservoirs, and aquifers. Increased $CO_2$ and radiation might encourage more photosynthesis and biomass to some extent; however, the increased temperature might increase respiration and counterbalance this increase in the biomass.

Studying the impact of future climate change on water resources is commonly carried out using suitable models and the future changes in water resources or any relevant climate dependent parameter such as evapotranspiration, ET, soil moisture deficit, SMD are expressed as % change or deviation from baseline data. The latter is a long record of observations of the stream flow, groundwater recharge, ET, SMD, and others.

The extreme events of flood and drought led to the development of relevant indicators. Some of these would apply to both, flood, and drought such as the Standardized Precipitation Index SPI and adjusted SPEI (takes into account ET). Others are more relevant to drought such as Reconnaissance Drought Index, RDI, Soil Moisture Deficit, SMD, Wetness Index, WI and more. Farmer communities will be more interested in the soil moisture status and SMD to decide when to irrigate and how much water to apply. Fishermen communities will be interested in the rivers, reservoirs, lakes water level. Some types of fish migrate from rivers to the sea (e.g. salmon), also require a certain river flow rate. Some fish require deep cold water while others require relatively shallow water.

Decision makers and water resources stakeholders and planners require information on future water availability. The latter can be compared against future water demands by all sectors. The gap between future water availability/supply and future demand will help them plan the optimal use of water resources. The water resources plan for in case if future water demand exceeds water supply, might limit the expansion of urbanization and some sectors such as tourism (limiting a number of hotels), industry (water consuming types), hospitality (e.g., restaurants), leisure (e.g., water sports) and agriculture (limiting rice areas, use of non-conventional drought-tolerant crops, limiting or abolishing surface irrigation, using efficient irrigation systems such as drip or sprinkler, etc.).

This chapter will briefly describe some climate change impact studies carried out in some countries Cyprus Island, Italy, Brazil, and the UK. These studies were carried out at catchment scale all used the same model, the Distributed Catchment Scale Model, DiCaSM which is part of the Integrated Hydrological Modelling System, IHMS (Figure 2.1), which comprises three coupled models, DiCaSM unsaturated zone model, Groundwater model MODFLOW and Sea Water Intrusion model, SWI (Ragab and Bromley, 2010).


**Figure 2.1**. The opening slides of the Integrated Hydrological Modelling System, IHMS (left) and the Distributed Catchment Scale Model, DiCaSM model (right)

## 2.2. DiCaSM Model input data

The distributed catchment scale model, DiCaSM (Ragab and Bromley, 2010) requires the following data:

- Rainfall and climate data (distributed or lumped)
- Land cover % for each grid square
- Soil Series % for each grid square
- Elevation (Digital Terrain Model, DTM) for each grid square
- Land cover properties
- Soil Series properties
- Data on water abstraction, irrigation, wastewater discharge to river (if applicable), water bodies, etc.

The model adopts a distributed approach with variable spatial scale (default is 1 km grid square) and requires daily input data of rainfall, temperature, wind speed, vapour pressure and radiation. The model runs on a daily time step, however, if hourly rainfall data is available, the model can run on hourly time step. The model calculates the flow directions using the DTM data supplied (Figure 2.2). The model also addresses the heterogeneity of input parameters of soil and land cover within the grid square using three different algorithms. More details about the model can be found in Ragab and Bromley (2010).

Model calibration: this can be conducted by running the model and adjusting the model parameters until a good agreement between the model and observation values has been achieved. If the stream flow is to be calibrated, the model calculates the Nash-Sutcliffe Efficiency (NSE) value for each iteration based on the least square of the difference between the simulated and observed streamflow values. The model optimization process helps in finding a good set of parameters that produces a good model efficiency value.

### 2.2.1 Climate change scenarios data input for the UK studied catchments:

The UK study considered three gas emission scenarios (low, medium and high) for three 30-year periods: 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099). The UKCP09 provided monthly, seasonal and annual probabilistic change factors at 25 km$^2$ grid square resolution (Figure 2.2) for precipitation and temperature (Joint Probability, JP). UKCP09 also provided generated daily weather data (Weather Generator, WG) at a 5 km$^2$ resolution. The generated data include vapour pressure and sunshine hours, in addition to rainfall and temperature. The sunshine hours were converted into total and net radiation following the methodology of Allen et al. (1998).

The joint probability plot was used to generate seasonal climatic change factors (% change in rainfall and change in temperature, °C) to apply as an input to the DiCaSM model. For the detailed weather generator simulations, multiple grid cells (cell-size: 5 km$^2$) were considered to totally cover the catchment. Also, in using the WG data, 100 realizations of the daily time series data were generated to account for the uncertainty associated with the scenarios. The daily climatic variables data generated using UKCP09 weather generator were bias corrected using observation data for the historic 1961–1990 period. The bias correction was conducted before undertaking the modelling work. This study applied bias correction method using the ‘map’ package in R statistical tool (Gudmundsson et al., 2012).

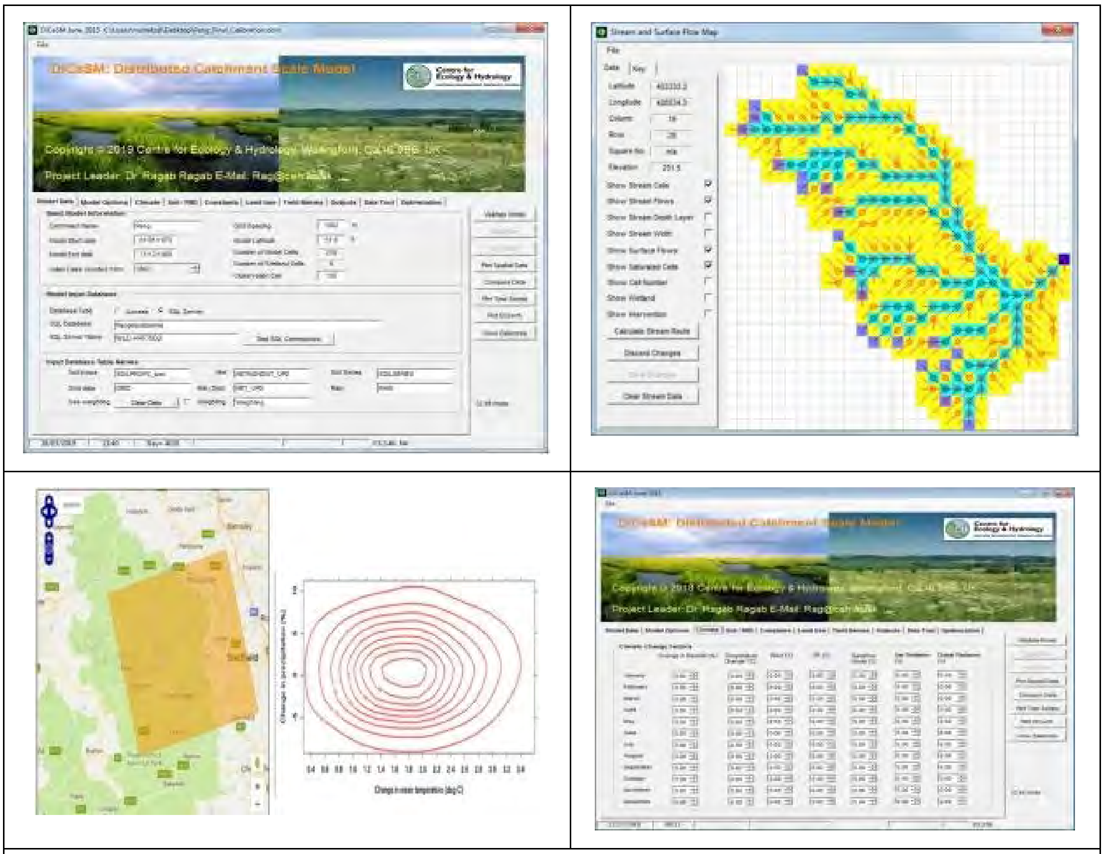


**Figure 2.2**. DiCaSM model data frame for the Pang catchment (top left), DiCaSM calculated flow directions across the Pang catchment (top right)

The Joint Probability plot to calculate the joint possible % change in rainfall that is associated with an increase/decrease in temperature ± °C (bottom left) and the monthly expected % changes in rainfall and associated increase/decrease in temperature ± °C (bottom right).

The following section will focus on studies carried out using the Distributed Catchment Scale Model (DiCaSM).

## 2.3. Results of Climate Change Scenarios in Different Countries

### 2.3.1. Cyprus, Mediterranean Island

The DiCaSM unsaturated zone model was successfully calibrated and validated against stream flows and groundwater recharge on two catchments, the Kouris (300 km$^2$) and Akrotiri catchments (123 km$^2$) in Cyprus (Figure 2.3). Once calibrated, the model was run using a number of possible future climate change scenarios for the Mediterranean region based on the UK Hadley Centre Climate Change model. The climate scenario that has been applied: by 2050, winter rain to decrease by 15%, summer rain to decrease by 10% and annual temperature to increase by 1.5 ºC.

The results showed that by 2050, relative to baseline data, groundwater and surface water supplies would decrease by 35% and 24% for Kouris and 20% and 17% for Akrotiri, respectively (Ragab et al., 2010). The gap between water supply and demand showed a linear increase with time. Following these results, some plans were developed to move away from surface irrigation and promote drip and sprinkler irrigation.

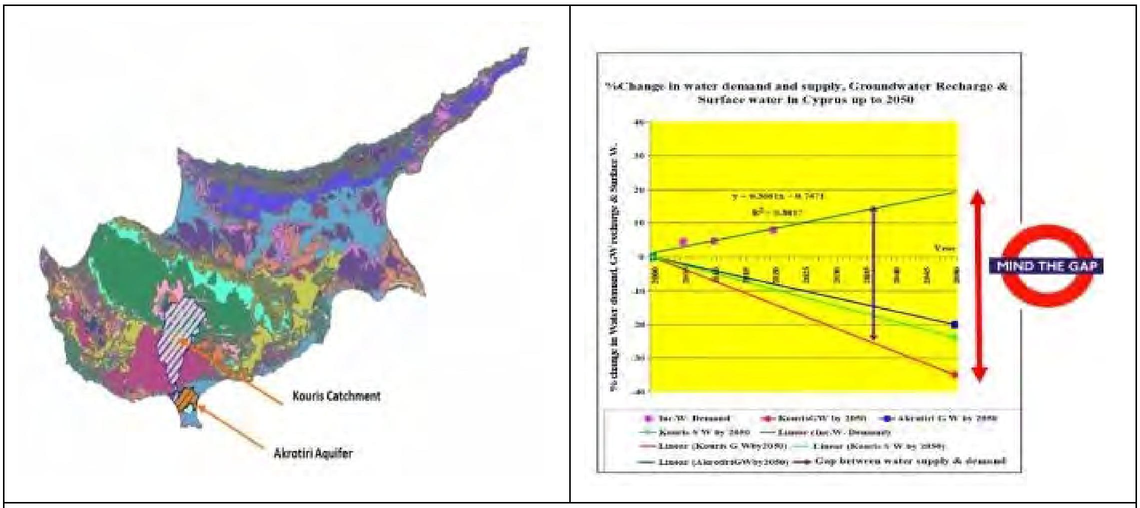



**Figure 2.3.** The study catchments in Cyprus (left) and the future gap between water supply and demand (right)

### 2.3.2. Italy

The distributed catchment scale model (DiCaSM) was employed to study the impact of climate and land use changes on the hydrological cycle and the water balance components in the Apulia region, southern Italy, specifically in the Candelaro catchment (1780 km$^2$). The DiCaSM model was run with the climate change scenarios for southern Italy (D'Agostino et al., 2010).

The future climate change scenarios indicate that, in the Candelaro area (Figure 4), rainfall will be reduced between -10% and -5% during the winter and between -20% and -15% during the summer and temperature are expected to increase between 1.25ºC and 1.5ºC during the winter and between 1.5ºC and 1.75ºC during the summer. The results of the model run showed that by 2050 the groundwater recharge would decrease between -20% and -30% and stream flows would be reduced between -16% and -31% relative to the baseline data. Plotting the future water supply against the projected future water demand, for the Candelaro catchment area, the gap between water demand and water supply (groundwater and surface water decreasing up to 2050) has increased in all scenarios and on average by up to 15% over time.

The four scenarios showed a possible future decline in water resources availability. They also showed a similar widening gap between the future water supply and future demand. An example of scenario A1 is shown in Figure 2.4.

A1 scenario (summer: temperature increase by 1.75°C and rainfall decrease by 20%; winter: temperature increase by 1.5°C and rainfall decrease by 10%). A2 scenario (summer: temperature increase by 1.5°C and rainfall decrease by 20%; winter: temperature increase by 1.25°C and rainfall decrease by 10%). A3 (summer: temperature increase by 1.75°C and rainfall decrease by 15%; winter: temperature increase by 1.5°C and rainfall decrease by 5%). A4 (summer: temperature increase by 1. 5°C and rainfall decrease by 15%; winter: temperature increase by 1.25°C and rainfall decrease by 5%). Under A1 scenario, the groundwater recharge is expected to decrease by 30% and stream flow to decrease by 28%. Under A2 scenario, groundwater recharge is expected to decrease by 29% and stream flow to decrease by 28%. Under A3 scenario, groundwater recharge is expected to decrease by 21% and stream flow to decrease by 20%. Under A4 scenario, groundwater recharge is expected to decrease by 20% and stream flow to decrease by 19%. These close results indicate that the scenarios agree on reduced groundwater recharge and stream flow due to the possible reduction in rainfall and increase in air temperature.

The results obtained by DiCaSM could be of help to stakeholders and decision makers as a support for planning intervention.

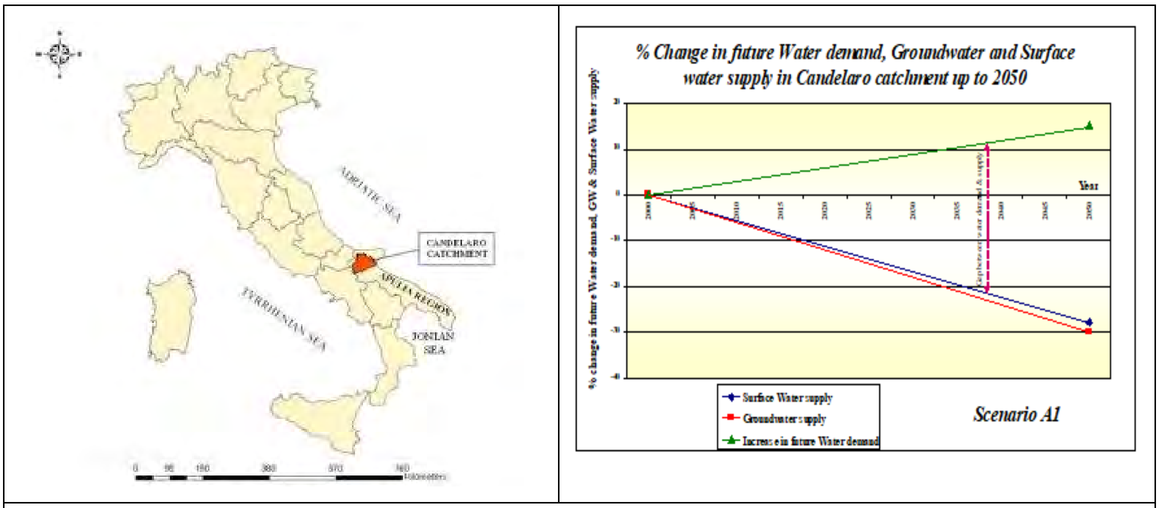



**Figure 2.4.** Candelaro catchment study site (left) and an example of percentage change in water demand and supply ("the gap") for scenario A1 (summer: temperature increase by 1.75 °C and rainfall decrease by 20%; winter: temperature increase by 1.5 °C and rainfall decrease by 10%).

### 2.3.3. Brazil

The Brazilian semi-arid regions in the northeast of Brazil are characterized by water scarcity, vulnerability to desertification, and climate variability. The hydrological distributed catchment scale model (DiCaSM) has been applied on two small representative catchments of the Brazilian northeast semi-arid region to investigate the impact of future climate change on water resources. The following sections will describe the modelling work that has been carried out on the two catchments, the Mimoso and Tapacurá catchments (Figure 2.5).

### a. Mimoso catchment, northeast Brazil

Future climate change scenarios are expected to drastically affect water resources in the northeastern region of Brazil. The DiCaSM model was run with different climate change scenarios (Montenegro and Ragab 2010). The modelling results indicated that, for the time periods of 2010–2039, 2040–2069, and 2070–2099, dry high emission future scenarios predicted a decrease in groundwater recharge, GWR, by 27%, 74%, and 71%, and in streamflow by 26%, 72%, and 68%, respectively, whereas dry low-emission scenarios forecasted a decrease in GWR by 43%, 61%, and 82%, and in streamflow by 41%, 58%, and 76%, respectively. On the other hand, if rainfall increases in the future, then for the time-slices 2010–2039, 2040–2069, and 2070–2099, wet high emission future scenarios predicted an increase in GWR by 34%, 49%, and 89%, and in streamflow by 52%, 84%, and 169%, respectively, whereas wet low emission scenarios forecasted an increase in GWR by 29%, 55%, and 59%, and in streamflow by 44%, 89%, and 101%, respectively (Montenegro and Ragab, 2012).

Taking the average of dry high and dry low emission scenarios results forecasted a reduction by 35%, 68%, and 77%, in groundwater recharge GWR, and by 34%, 65%, and 72%, in streamflow, for the time spans 2010–2039, 2040–2069, and 2070–2099, respectively, could take place under a dry future climate scenario, while on the contrary, under wet scenarios (average of wet high and wet low emission scenarios), the GWR is expected to increase by 32%, 52%, and 74% and the stream flow is also expected to increase by 48%, 87%, and 135% for the time spans 2010–2039, 2040–2069, and 2070–2099, respectively.

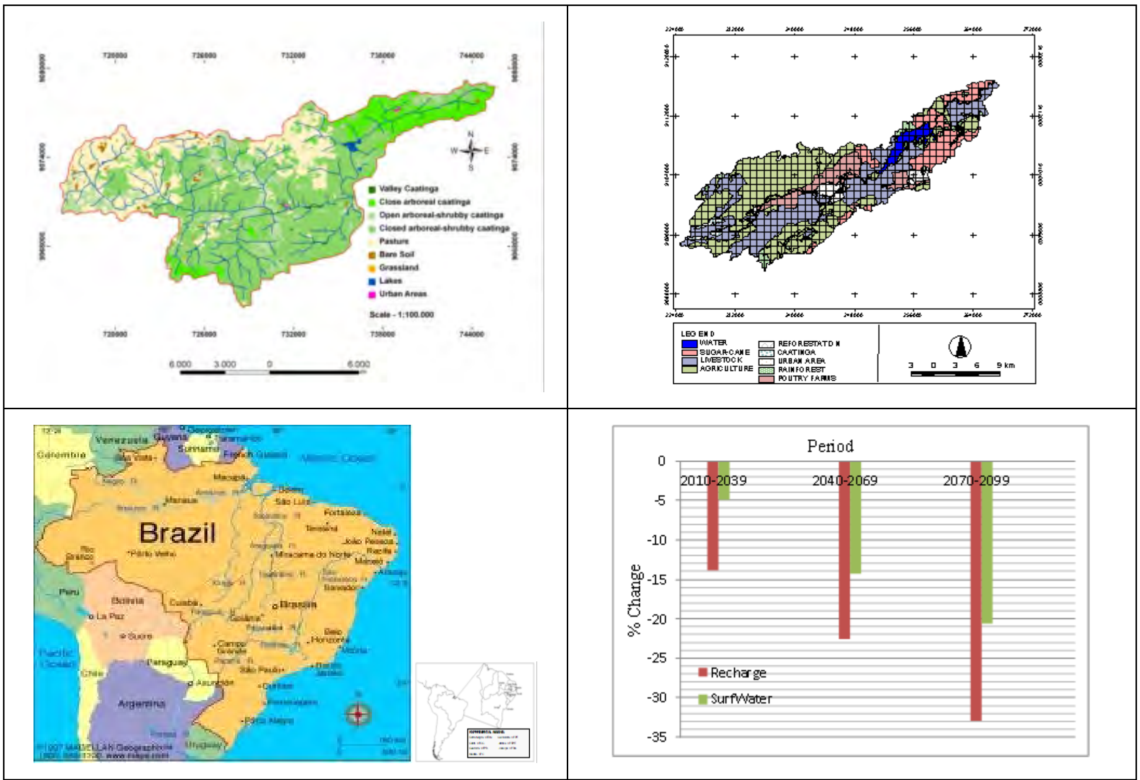



**Figure 2.5.** The Mimoso catchment - Northeast Brazil (area 149 km$^2$) (top left) and the Tapacurá catchment Northeast Brazil (area 470.5 km$^2$) (top right). The northeast region and the study basin (bottom left). The impact of climate change on surface and groundwater resources in Tapacurá catchment, under low emission (B1) scenarios (bottom right)

### b. Tapacurá catchment, northeast Brazil

The Tapacurá catchment (area 470.5 km$^2$) in the Northeast of Brazil was selected for the climate change impact study (Montenegro and Ragab, 2012). The Distributed Catchment Scale Model, DiCaSM, was calibrated and validated for the stream flows of the Tapacurá catchment.

Climate change scenarios were simulated using the calibrated parameters. Depending on the scenario, the simulated impacts of climate change predicted either a decrease in GWR and stream flow as is the case under low emission scenario B1(reduced rainfall and increased temperature) or increase in stream flow and ground water recharge as the case under high emission scenario, A2 (increased rainfall and temperature).

B1 is a dry scenario and A2 is a wet scenario. In B1 scenario, the temperature during October-March period is expected to increase by 3°C and rainfall to decrease by 18% to 45% and during April-September, the temperature is expected to increase by 2°C and rainfall to decrease by 1 to 5%. Under A2 scenario, during the October-March period the temperature is expected to increase by 3°C and rainfall to increase by 20% to 52% and during April-September, the temperature is expected to increase by 2°C and rainfall to increase between 4 to 5%.

The simulated impacts of climate change of low emission (B1) scenarios, for the worst perspective, indicated the possibility of reduction by 13.90%, 22.63% and 32.91% in groundwater recharge and by 4.98%, 14.28% and 20.58% in surface flows for the time spans 2010–2039, 2040–2069, 2070–2099, respectively (Figure 5).

For high emission scenario, A2, stream flow is expected to increase by 25.25%, 39.48% and 21.95% for the periods 2010-2039, 2040-2069, 2070-2099, respectively, and the groundwater recharge is expected to increase by 14.93%, 26.68% and 11.49% for the same time spans, respectively.

Although the dry scenarios predicted a decrease in GWR and stream flow while the wet scenarios predicted an increase in GWR and streamflow in both catchments, the past and current experience has shown a decrease rather than an increase in water resources availability in the region. Extreme events have already occurred e.g., in 1998, one of the driest years in the region with a total rainfall reduced by 50.56% below the annual average rainfall from 1952 to 2007. Tapacurá reservoir only reached 10% of its maximum storage capacity until the beginning of the following rain season in 1999. During this period, water supply for Recife Metropolitan Region was severely disrupted.

Such results are relevant for management strategies in the area. The result of climate change impact on water supply in the region show it requires a proper plan for water resources management, adaptation and mitigation strategies. This also might include a change in land use especially addressing the current deforestation and the increasing areas of sugar cane and biofuel crops.

### 2.3.4. The United Kingdom, UK

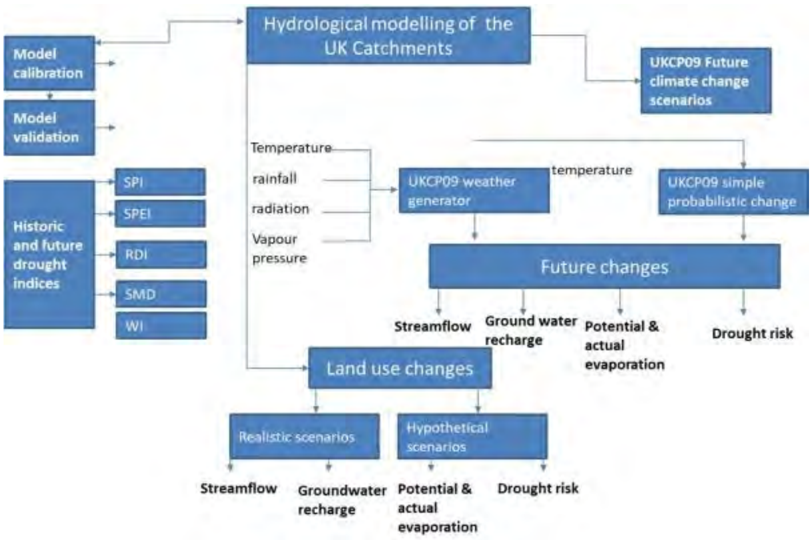
A study on the impact of future climate change on the UK water resources with particular interest in drought, was carried out as part of the DRY project, funded by the UKRI (UK Research and Innovation). The study included seven catchments from north to south and from west to east to represent the rainfall and temperature gradient across the whole UK (Figure 2.6). The selected catchments are Eden in the north (Scotland), Don in the midlands, Bevills Leam in the east midlands, Ebbw in the southwest (Wales), Frome in the southwest, Pang in the southeast and Fowey in the very south of the UK (Cornwall County). The details about those study catchments can be found at: Muhammad Afzal and Ragab (2020a) for the Eden catchment, Muhammad Afzal and Ragab (2020b) for the Don catchment, Muhammad Afzal et al. (2021) for the Ebww catchment, Muhammad Afzal and Ragab (2019) for the Frome catchment, Afzal and Ragab (2020) for the Pang catchment. DiCaSM model has been applied to 1961-1990 baseline (30 years) data as well as for future climate change scenarios. The scenarios included three 30 years' time periods, the 2020s, 2050s and 2080s time periods under High, Medium, and Low Emissions.

Scenario modelling: Two data sets were used: I. Joint Probability (JP) data: future climate change using seasonal UKCP09 simple change factors to temperature (± °C) and rainfall (%) using Joint Probability plots; II. Weather Generator (WG) data, daily prediction values of precipitation, temperature, sunshine hours, relative humidity and wind speed. Weather Generator data was based on UK base line data (1961-1990) and needed to be adjusted (bias correction) using the catchment base line data (1961-1990).

The DiCaSM model was successfully calibrated and validated, then was run with the climate change scenarios using JP and WG predictions. The impact of the climate change on the stream flow, groundwater (GW) recharge was investigated and the gap between future water demand and supply using the future scenarios was identified. In addition, drought indicators were computed, and future occurrence of drought events was investigated (Figure 2.7).


| South - North | | West –East | |
|---|---|---|---|
| Fowey | 1436 mm | Fowey | 1436 mm |
| Ebbw | 1456 mm | Frome | 792 mm |
| Don | 1009 mm | Pang | 695 mm |
| Eden | 799 mm | Bevills Leam | 630 mm |

**Figure 2.6.** The seven study catchments and their average annual rainfall.



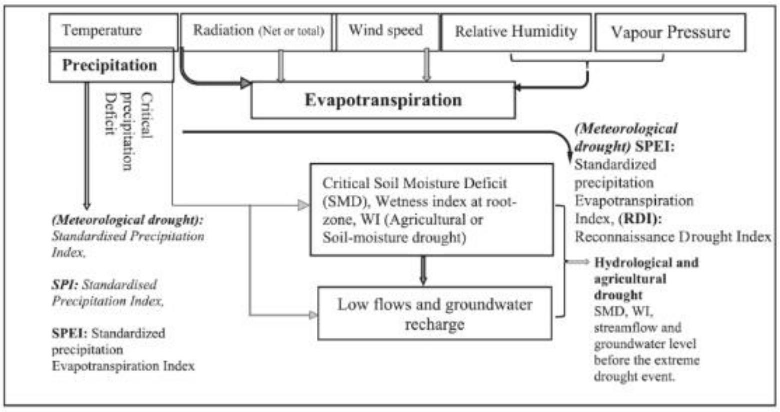



**Figure 2.7.** Schematic representation of the modelling procedure (top) and key drought drivers of meteorological, agricultural, and hydrological droughts (bottom).

In the following sections, three representative catchments the Eden catchment in the north of the UK, the Don catchment in the midlands, and the Pang catchment in the south, were selected to represent three different regional and climatic situations (Figure 2.8).

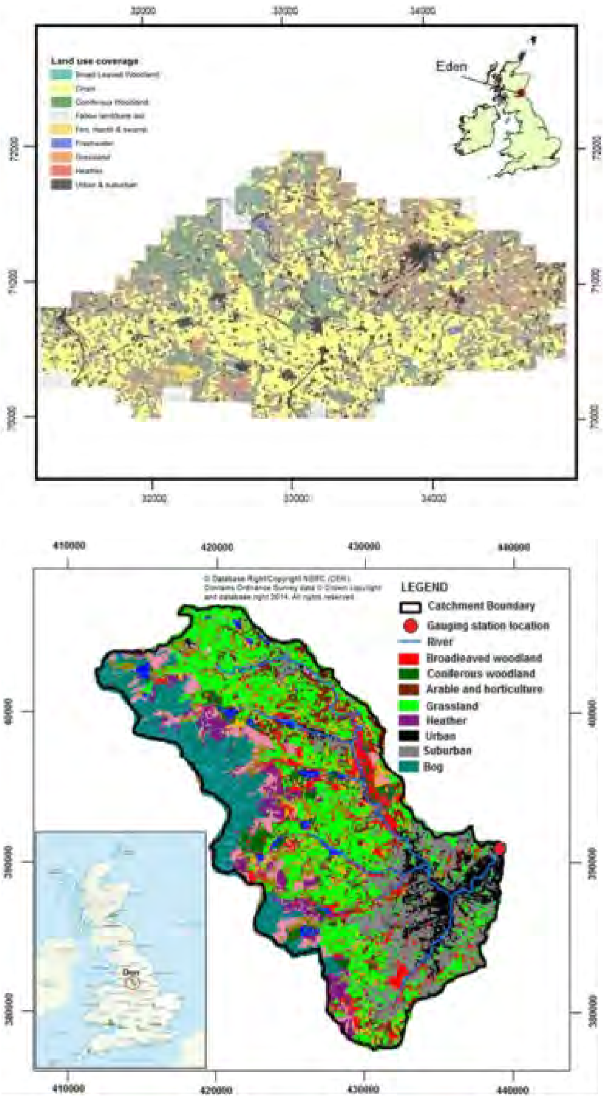



**Figure 2.8.** Three representative catchments within the UK, the Eden catchment (north, 380 km$^2$), the Don catchment (midlands, 435 km$^2$) and the Pang catchment (south, 218 km$^2$).

### a. Eden catchment

The Distributed Catchment-Scale Model, DiCaSM, was run to study the impact of climate change on the hydrology of the Eden catchment, northeast of Scotland. The model was successfully calibrated and validated for a 42-year period. The DiCaSM model was then used to study the impact of climate change on the water availability.

Data from the UKCP09 Climate Change scenarios for the 2010–2039, 2040–2069 and 2070–2099 periods, considering three gas emission scenarios (low, medium and high), were applied. More details can be found in Afzal and Ragab (2020).

The streamflow projections under both the simplified change factors and the weather generator data suggest that the streamflow is likely to be reduced by up to 27.6% during the summer months, especially by the end of the century. Under all emission scenarios, the summer streamflow is likely to decrease, by 9.6 to17.8% in the 2020s, by 14.9 to 21.34% in the 2050s and by up to 25.2% in the 2080s under high emission scenarios (Figure 2.9).

The predicted low stream flow can cause drying up of the river, possibly leading to a high risk of interruptions in domestic, industrial and agricultural water supply, given the river water abstraction is very significant during the summer months. The study also pointed out that the groundwater recharge is likely to be reduced in the future (Figure 2.9). The largest decrease in groundwater recharge is expected in the second half of the century, as it may decrease by up to 20.26% under the high emission scenario in the 2080′s during the summer months. Overall, groundwater recharge during the summer months is much less than during the other seasons. The analysis of groundwater recharge suggests that climate change is expected to have a significant impact on groundwater recharge, even though the climate models project an increase in winter precipitation.

The groundwater recharge varies according to the season, for example, the recharge during summer months with low rainfall and higher temperature could decrease by up to 20.26% under high emission scenarios of the 2080′s, whereas the increase in winter precipitation would be counterbalanced by the higher water losses due to the increased evapotranspiration. The latter leads to an increase in soil moisture deficit and subsequently low recharge particularly during dry periods. Drier summers could also lead to increased soil moisture deficit extending into the autumn and could shorten the winter recharge season. The decrease in recharge in summer could be balanced by the increased winter precipitation as projected under all emission scenarios. However, it is likely that in the future, the increase in winter precipitation would come as extreme precipitation events over a short period of time. This would lead to surface run off rather than increasing the groundwater recharge. A slight increase in groundwater recharge is projected during the winter and spring seasons by the end of this century, however, the increase would be small.

The results indicated that the greatest decrease in streamflow and groundwater recharge was projected to take place under the high emission scenarios towards the end of the century, i.e. between 2070 and 2099. This would mainly be due to the summers becoming drier. Meanwhile, the projected increase in winter precipitation did not contribute much towards groundwater recharge due to the projected increases in evapotranspiration and soil moisture deficit.

Climate change projections indicate an increasing risk of drought in the future, generally lower river flows in summer and higher flows in winter, a decrease in groundwater recharge and generally reduced soil moisture. Over annual and seasonal time scales, the severity of the drought events significantly increased over time and the drought severity was greater in the second half of the current century, as shown by several the drought indices.

All the applied drought indices (SMD, WI, and RDI) identified an increase in the severity of the drought under future climatic scenarios. Under high greenhouse emission scenarios, the drought severity was higher due to the increasing temperature and subsequent increase in water losses through evapotranspiration, thus reducing soil moisture availability, surface runoff to streams, and recharge to groundwater.

These findings help in planning for perhaps extra water infrastructure work if needed, such as constructing more reservoirs, however this option might not be acceptable by local communities due to possible environmental impact, or water transfer pipelines from water-rich to water-poor regions and planning for irrigation water demand under different climatic conditions. The findings of the study suggest increasing the storage capacity of the three main reservoirs adjacent to the catchment (Upper Glendevon, Lower Glendevon and Glensherup), which are generally considered as reservoirs at risk during droughts.

The findings of the study have broader implications in water resources management considering the future changes in climate.

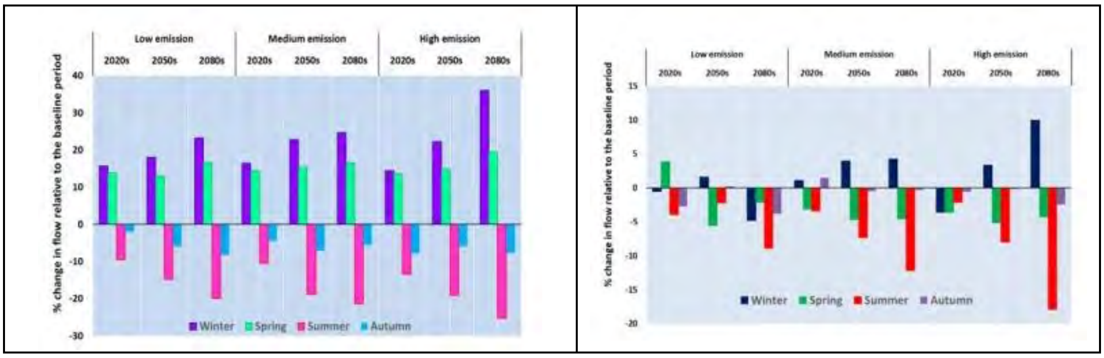



**Figure 2.9.** Eden catchment: future changes in streamflow (left) and future changes in groundwater recharge (right).

### b. Don catchment

The Don catchment in the midlands was also investigated using the same model, DiCaSM and the same climate change scenarios as those of the Eden catchment (Muhammad Afzal and Ragab 2019). The results (Figure 2.10) of the modelling work indicated that during the 2020s period, in summer, a significant decrease in stream flow is projected by 13 to15% using the joint probability approach while in the 2050s, a decrease is projected from 27 to 29% and during the summer of the 2080s, the stream flow is likely to decrease by 24 to 42%.

The low stream flows could lead to risk of inadequate domestic, industrial and agricultural water supply as river water abstraction is very significant in this catchment. The combined effect of decreasing precipitation and increasing temperature may result in higher evapotranspiration during the summer season, which in turn may result in reduced flow. This is due to the possible increase of the temperature by 4.6 °C and precipitation to decrease by up to 34% by the end of the century. With reductions in precipitation in autumn and spring, enhanced by higher evaporation, saturated conditions will occur less frequently, and precipitation events are less likely to generate significant runoff flows. The summer stream flow is more significant for the Don catchment as there are 23 reservoirs within the catchment, which significantly contribute to the water supply system.

The groundwater recharge projections under joint probability suggest that groundwater recharge might decrease by 3.4 to 11.3% under all emission scenarios during the winter months (December, January and February). Moreover, the groundwater recharge decreased for the three selected time periods, but the decrease was slightly less under low-emission scenarios, compared to medium and high emission. This is due to a smaller increase in precipitation under low-emission scenarios.

The highest decrease of over 40% in summer groundwater recharge is projected for the 2080s. Such a significant decrease may be attributed to the increased SMD. Under all emission scenarios and observed time periods, groundwater recharge is expected to decrease by 38% to 58% under low emission scenario while under medium emission scenarios the decrease in groundwater recharge would fall between 38 and 67%. The highest decrease is projected under high-emission scenarios with 39 to 76%.

In the summer months (June, July, August) enhanced evapotranspiration and reduced precipitation, would result in higher SMD and subsequently reduced stream flow and groundwater recharge under all emission scenarios. However, the severity of the decrease is much higher in the second half of the century under high-emission scenarios. Under low emission scenarios groundwater recharge might decrease by 2.2 to 12.0% while under medium emissions the likely decrease might be within the 5.9 to 14.9% range and under high-emission scenarios the projected likely decrease might be within the 4.0 to 25.8% range. The higher decrease in groundwater recharge under high emission scenarios is the result of the increase in SMD during the summer months.

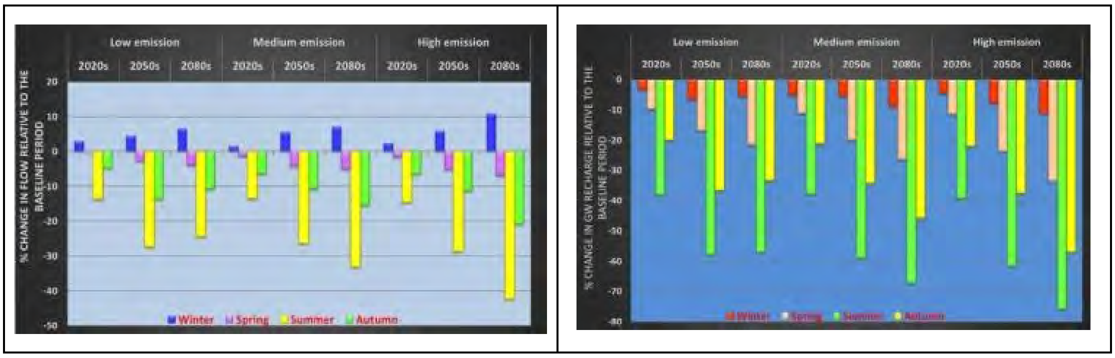



**Figure 2.10.** Don catchment: future changes in streamflow (left) and future changes in groundwater recharge (right).

### c. Pang catchment

The Pang catchment is situated in the southeast of the UK. The same study as that for the Don and Eden catchments was carried out using the DiCaSM model and the same climate change scenarios. The results indicated that by the 2080s, under high emission scenarios, streamflow could decrease by 37%, 32%, and 70% during summer-autumn, winter and spring, respectively, while the groundwater recharge could decrease by 70% and 46% during summer-autumn and winter-spring, respectively. The level of reduction in ground water recharge and stream flow increases with the increase of emission level. The stream flow decreases in the 2020s ranged from 11.7% to 21.6%, in the 2050s from 19.0% to 36.7% and in the 2080s from 21.4 to 46.6%, with the lower values associated with the low emission and higher values in the range associated with the high emission (Figure 2.11).

The GWR decrease in the 2020s ranged from 16.9% to 41%, in the 2050s from 28.0% to 62.3% and in the 2080s from 28.7% to 71.7%, with the lower values associated with the low emission and higher values in the range associated with the high emission (Figure 2.11).

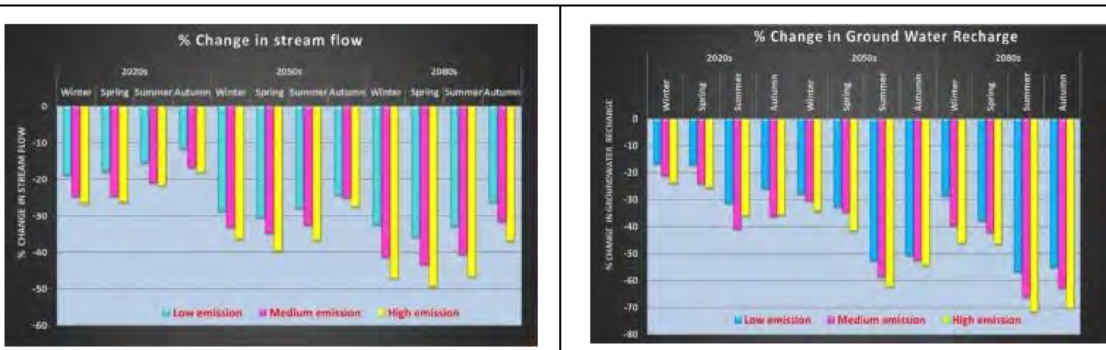



**Figure 2 .11.** Pang catchment: future changes in streamflow (left) and in groundwater recharge (right).

The Reconnaissance Drought Index, RDI projected an increase in number, severity, and frequency of drought events up to the 2080s. The results of the Pang catchment would help in future regional planning and management of the water resources in the southeast of England.

Under the UKCP09 climate change projection, the streamflow and the groundwater recharge significantly decreased with time and with emission level specifically during the summer months and the number, frequency and severity of the drought events significantly increased over time and with the increasing the emission level.

These findings would help in planning for perhaps extra water infrastructure work if needed, such as building more reservoirs or water transfer pipelines from water-rich to water-poor regions, e.g., from Wales to the South-East, and adopting a contingency plan for future irrigation water demand. The findings of the study are helpful in managing the abstraction management strategy for the studied Pang catchment and reviewing of existing licensing abstraction limits. The results of the Pang catchment are applicable to the other catchments of the region and would help in future regional planning and management of the water resources in the southeast of England.

### d. The Gap between Water Demand and Supply

The future water demand data were obtained from the local authorities, water companies, the Environment Agency, the Farmers' Union, local councils, the Public Health Authority, the Wildlife Trust, and other stakeholders. Future water demand was estimated based on future expansion of urban and new housing developments, future water demand for agriculture, industry, tourism, leisure, sports, and environmental flows,

The gap between water supply and demand was calculated for all catchments. In all 7 catchments, apart from Eden in Scotland, there will be a gap between future water supply and future water demand and that gap is widening over time up to 2099 if water demand is not sustainably managed and controlled. Figure 2.12 shows a couple of examples from the Don and Pang catchments.

In order to narrow the gap, some measures need to be considered. As an example, for the Don catchment, where the gap is widening over time due to the possible decrease in ground water recharge and stream flow and the increasing possibility of droughts in the future, new investment will be needed as the future water availability is expected to fall below the future water demand. Measures that can be applied include enhancing water use efficiency in all sectors, using alternative sources to traditional reservoirs, such as rainwater-harvesting systems or by reducing evaporation from reservoirs by, for example, using floating solar panels, spreading ecologically friendly agents on the water surfaces or an ultra-thin layer of organic molecules on their surface. The implication of surface water abstraction during drought and low-flow periods would reduce further the river flows possibly below the minimum environmental flow. Perhaps restrictions on abstraction to maintain environmental flows can be introduced, however this may restrict crop growth and yields, and food production in general. A comprehensive planning and integrated management will be needed.

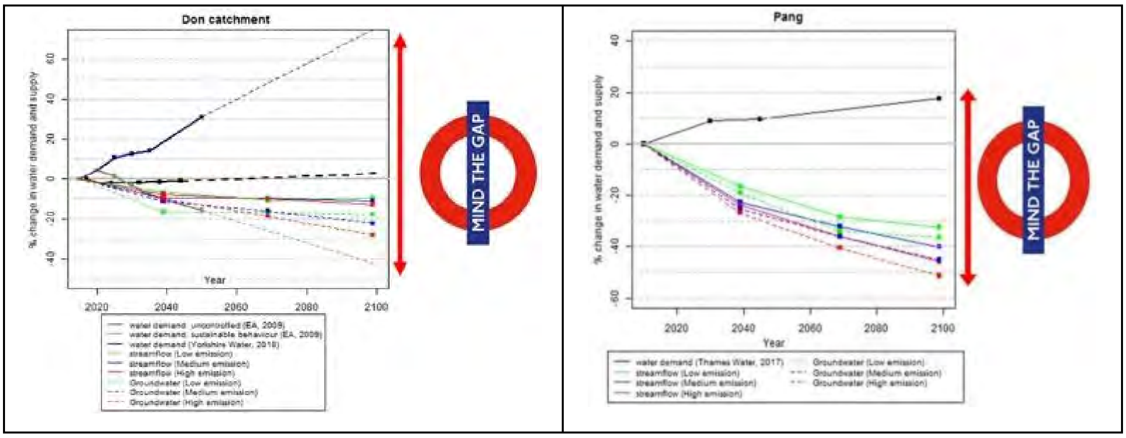



**Figure 2.12.** Two examples of the gap between future water availability (supply) and future water demand for the Don catchment (left) and the Pang catchment (right).

### 2.3.5. The Drought Indicators

The drought indices included:

I. SMD: Soil Moisture Deficit (moisture difference from field capacity)

II. WI: Wetness Index of the root zone (scaled soil moisture calculated as (current soil moisture – minimum soil moisture)/ (maximum soil moisture – minimum soil moisture).

III. RDI: Reconnaissance Drought Index calculated as (gross rain/potential evapotranspiration)

IV. Adjusted RDI: calculated as (net rain/actual evapotranspiration)

V. SPI: Standardized Precipitation Index, relative to long term average rainfall

VI. SPEI: As above but calculated as (Precipitation – Evaporation)

The Reconnaissance Drought Index, RDI, of the Pang catchment projected an increase in number, severity, and frequency of drought events up to the 2080s. The results would help in future regional planning and management of the water resources in the southeast of England. The effect of reduced rainfall and higher temperature was reflected in the RDI drought index which was able to show there will be a higher severity and frequency of drought events in the latter half of the century (Figure 2.13). Such future drought events require that the agriculture and irrigation practices need to be adapted for the future as the reduced water supply for the irrigation in summer could be problematic. The water abstractions during drought and low flow periods would reduce river flows, possibly below the minimum environmental limit. Imposing restrictions on abstraction to maintain the minimum environmental flows may restrict crop yields and food or energy production.

The RDI of Eden catchment (Figure 2.13) shows the drought events likely to occur in the future and the severity level which is low under low emission and high under high emission scenarios. RDI Scale: (2.0 + shows an extremely wet event), (1.5 to 1.99) very wet, (1.0 to 1.49) moderately wet, (0.99 to -0.99) near normal, (-1.0 to -1.49) moderately dry, (-1.5- to -1.99), severely dry (- 2 and less), extremely dry.

Figure 2.13 shows an example of Reconnaissance Drought Index, RDI calculated for the Pang and Eden catchments.

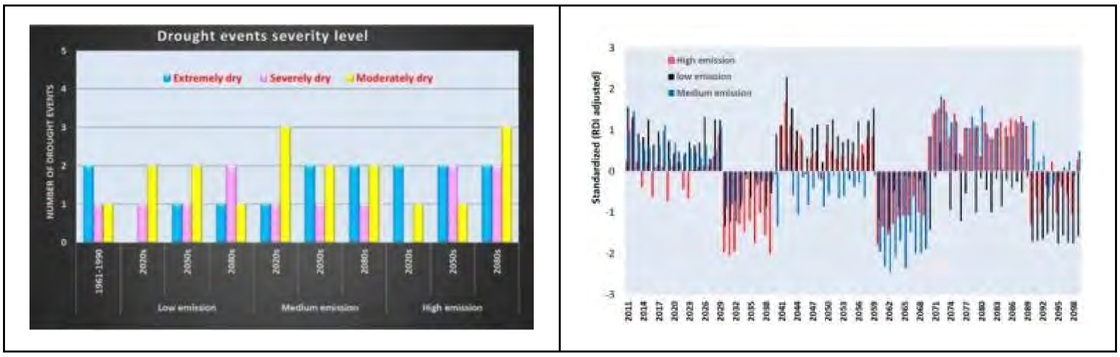



**Figure 2.13**. Number of future drought events, severity and frequency in the Pang (left) and Reconnaissance Drought Index for future years under low, medium, and high emission scenarios for the Eden catchment (right).

Similarly, for the Don catchment, the adjusted RDI calculated from the net rainfall and actual evapotranspiration of the selected time periods: 2020s, 2050s and 2080s for three emission scenarios, revealed a future increase in the number of moderate and severe drought events, more importantly under the medium- and high-emission scenarios. In comparison with the baseline period, the extreme drought events are expected to double in the later part of the century. Not only extreme dry events but also severe drought events are expected to increase in the future. Moreover, the frequency of moderate drought events (RDI −1 to −1.5) is expected to increase in the future, specifically under medium and high-emission scenarios.

### 2.3.6. Drought Indicators for the farming community

Farmers communities will be interested in the soil moisture status and SMD to decide when to irrigate and how much to apply. The general trend is that the SMD is increasing with time and with the emission level in all the UK studied catchments. Figure 2.14 shows example of the Don and Pang catchments. This trend will lead to increasing demand for irrigation water as rainfall is expected to decrease, especially during summer, and temperature is increasing leading to high evapotranspiration, ET, and subsequently, more irrigation. There will be a need to increase the water use efficiency and water productivity, to use drought tolerant crops, efficient irrigation systems, rainfall harvesting during wet periods, and to use suitable land management.

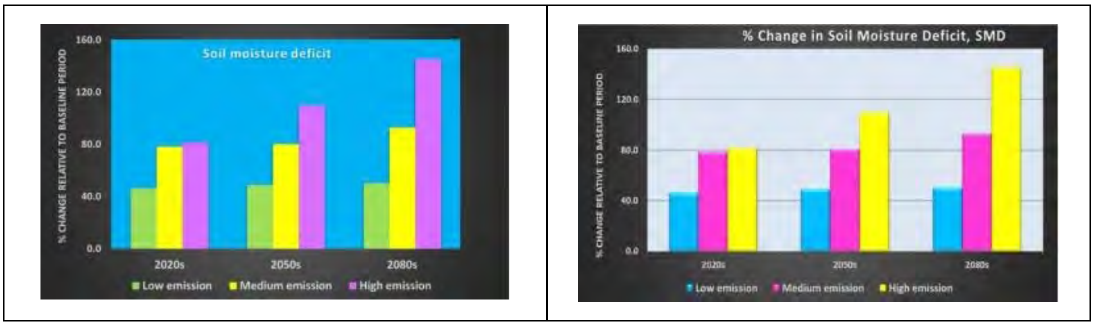



**Figure 2.14.** Future Soil Moisture Deficit of the Don catchment (left) and the Pang catchment (right) under low, medium, and high emission scenarios.

### 2.3.7. Drought indicators for the fishing community

Fishermen communities will be interested in the rivers, reservoirs, and the water level of lakes. Some type of fish that migrate from rivers to the sea (e.g., Salmon) require a certain river flow rate. Some fish require deep cold water, while others require relatively shallow water. Figure 2.15 shows two examples of impact of climate change and under low, medium, and high emission scenarios on stream depth during summer. The summer season is selected as it has the lowest stream depth among the other seasons due to the relatively greater decrease in rainfall compared with the other seasons.

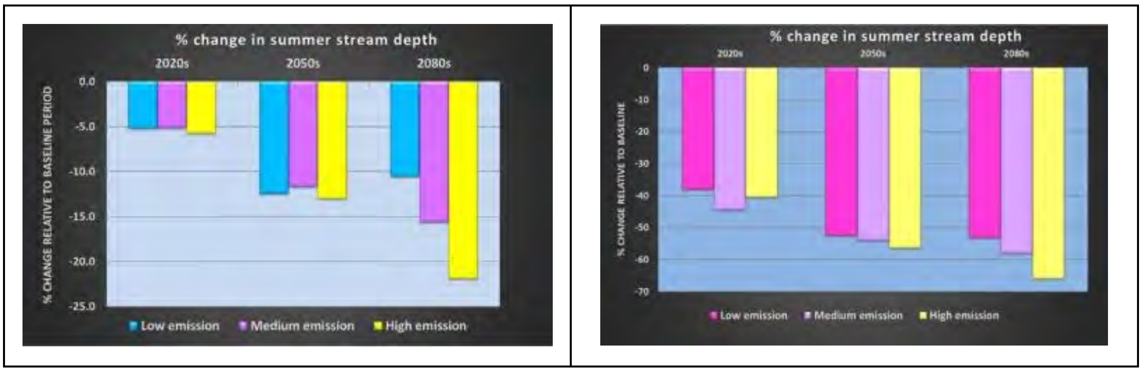



**Figure 2. 15.** The stream depth under future emission scenarios for Don catchment (left) and for the Pang catchment (right).

### 2.3.8. The Uncertainty Analysis of river flow prediction

Even with excellent calibration and validation using the baseline data, model results have a certain level of uncertainty. To quantify the uncertainty in model results, especially river flows, the Generalized Likelihood Uncertainty Estimation, GLUE, has been applied (Ragab et al., 2020). The uncertainty level decreased with increasing the time scale/step. Higher uncertainties were associated with the daily river flows and the lowest uncertainty values were associated with annual flows. The daily values have more variations (spikes), monthly values would reduce these variations as they average the daily values to produce the monthly values, similarly, the annual flow will reduce the variations further to have a smoother curve, free of spikes, as it averages the low and high values encountered during the year. As an example, the results of Don River flow indicated that the model captures above 70% of the observed daily river flow (Containment Ratio, CR) i.e., more than 70% observed values are included in the 5%-95% likelihood-weighted quantiles envelope, 76% of the observed monthly river flow and 85% of annual river flow. More details about the methodology and the results of the other catchments can be found at Ragab et al. (2020).

Generally, the results give confidence in model stream flow prediction.

It is worth to mention here that the uncertainties in climate predictions arise from:

- Our imperfect knowledge of future rates of human-made emissions and how these will change the atmospheric concentrations of greenhouse gases and how the climate will respond to these changed conditions,
- Model assumptions, processes descriptions, mechanisms, mathematical formulation and the numerical scheme,
- The fact that in nature all processes operate simultaneously while in model they don't, they follow an order of execution based on a flow chart. If evaporation comes after infiltration, expect recharge, soil moisture to be different from the processes followed different sequential order.
- The fact that linearity exists in model processes but not in nature where nothing is linear,

- Measurement accuracy (e.g., stream flow, soil moisture, groundwater levels, etc.) and parameter values (hydraulic conductivity, soil physical and plant parameters, etc.).
- The mismatch between the scale of model application (e.g. $1km^2$ and the scale of observation, e.g., plot or point scale).
- Assumptions in climate change predictions and scenarios.

## 2.4. Conclusions

The studies described in this chapter indicated that the two catchments in the northeastern semi-arid part of Brazil, Mimoso and Tapacurá, which are already suffering from reduced rainfall and water resources decline are expected to suffer a further reduction in stream flow and recharge to the groundwater aquifers under the plausible future climate change scenarios. The gap between water supply and water demand is expected to get wider with time. Similarly, the Kouris and Akrotiri catchments in Cyprus under the Mediterranean climatic condition, normally characterized by dry and hot summers and cool, mild, and wet winters, showed a possible decrease in both stream flow and groundwater recharge under future climate change and, subsequently, the gap between water supply and demand is widening over time. In Italy, there are indications that in the Candelaro catchment, under the north Mediterranean climatic conditions, stream flow and groundwater recharge will decrease under the different climate change scenarios, and subsequently, the gap between water supply and demand will widen over time.

The selected UK catchments are Eden in the north (Scotland), Don in the English midlands, Bevills Leam in the east midlands, Ebbw in southwest Wales, Frome in southwest England, Pang in the southeast and Fowey in the very south of the UK (Cornwell County). The future climate change scenarios predicted a reduction in stream flow and groundwater recharge in all catchments more significantly in the summer season. Although some scenarios predicted more rain in wintertime in the northern catchments, such as the Eden catchment, the expected increase in temperature and subsequently the increase in the losses by evapotranspiration and the increase in soil moisture deficit, SMD, did not produce a matching increase in river flow and ground water recharge.

The drought indices such as the Standardized Precipitation Index, the adjusted Standardized Precipitation Index, SPEI, which takes ET into account, the Reconnaissance Drought Index, RDI, and the adjusted RDI which includes the actual ET instead of the potential ET and net/effective rainfall instead of total/gross rainfall, the Soil Moisture Deficit, Wetness Index and River Water Depth were computed for future climate change scenarios. The Indices were able to accurately reproduce the past drought events. In addition, they predicted the future ET, SMD, WI, RDI/RDIE, SPI/SPEI, stream depth and the future number of drought events and their severity level.

In general, the results indicated future increase in the ET and SMD and decrease in WI, SPI/SPEI. The decrease or increase gets more significant with increasing the emission level from low to medium to high and with time from the 2020s to 2080s. In addition, the RDI/RDIE analysis indicated the possibility of increasing the number of drought events, their frequency of occurrence and severity levels will increase with increasing the emission level from low to medium to high and with time from the 2020s to 2080s.

The gap between water supply and demand was calculated for all catchments. In all 7 catchments, apart from Eden in Scotland, there will be a gap between future water supply and future water demand and that gap will widen over time up to 2099 if water demand is not sustainably managed and controlled. To narrow the gap, the two options are to increase water supply and reduce water demand. Increasing water supply implies building more reservoirs, rainfall/runoff water harvesting, desalination of sea/brackish water, treating and reusing wastewater, reuse of drainage water, recycle water in industry, leisure, sports, hospitality (hotels, restaurants, etc.), cooling towers, mining industries, and more. Reducing water demand by all sectors could be achieved through increasing water use efficiency, recycling/reusing water, water saving using smart sensors, and more as given in the last paragraph hereunder.

The results of the different study countries and sites highlight the need for action to mitigate and adapt to climate change. Mitigation will include tailoring policies towards “net zero emission”. The latter could include the gradual decrease of fossil fuels, eliminating paddy rice cultivation in favour of dry rice cultivation, use clean energy (wind and solar), better management of livestock, and more. Adaptation will require more efficient use of water resources in all sectors. In agriculture this could include, for example, the use of more efficient irrigation systems (drip, sprinkler, nano irrigation, subsurface drip, low nozzle centre pivot, variable rate irrigation VRI, centre pivot, etc.), use of less water consuming crops, use of crops with shorter growth seasons, use of deep rooted crops after shallow rooted crops in a rotation, managing soil to prevent losses by evaporation from soil surface (mulching, amendments, mixing crop residues with soil surface, etc.), accurately calculate the crop water requirements, use automated irrigation networks, use sensors to monitor soil moisture and salinity, use drones to identify the nutrients and water deficiencies, and more.

## Acknowledgement

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# CHAPTER III
# Adaptation of Agricultural Water Management under Climate Change and Water-Related Hazards

Waleed H. Abou-El Hassan, Amani Alfarra[1], Mohamed Farig, George Akoko

## 3.1 Introduction

In the past decades, from 1827 to 1956, numerous reports confirmed the fact of climate change (Fourier 1827; Foote 1856; Tyndal 1863; Milanković 1941) until Gilbert Plass (1956) formulated the theory of Carbon Dioxide on climate change. Over time, in 1970, climate change evolved from theory to fact with the establishment of the 'Intergovernmental Panel on Climate Change (IPCC). Hence, meticulous scientific analyses were performed and the contribution of human activity to climate change was considered. Water which is a crucial necessity for survival, is always known as a part of climate change where water and climate change are inextricably linked. Climate change is always mediated by water, such as changes in precipitation (Dore 2005; Trenberth 2011; Pino-Vargas et al., 2022), patterns of glacier melting (Kalugin 2023; Li and XU 2023; Wang et al., 2023), frequent occurrence of droughts and floods (He and Sheffield 2020; Tabari 2020), variations in river flow (Petra and Müller 2012; Kay et al., 2021), groundwater depletion (Tixier et al., 2009; Sayed et al., 2020; Jannis et al., 2021; Gona et al., 2022), sea level rise (Mimura 2013; Palm and Bolsen 2020; Roy et al., 2023), and evaporation (Qin et al., 2021; Helfer et al., 2023).

Climate change will worsen the existing severe global impact on water resources. Globally, climate change has an impact on every region. More than 40% of people on the planet are impacted by water scarcity, and 70% of all deaths resulting from natural catastrophes are caused by water disasters (World Bank 2022). Extreme rainfall and weather events are growing more frequent in some regions, while extreme heat waves and droughts are becoming more frequent in others. Every report from 2012 to 2020 of the World Economic Forum has included the water problem as one of the top five global risks (WEF 2015; WEF 2016; WEF 2017; WEF 2018; WEF 2019; WEF, 2020). Extreme weather events are becoming more common and intense worldwide as a result of the global climate crisis. These climate extremes, such as droughts, hurricanes, and floods, are pushing more people into extreme hunger and poverty, in many regions around the world (U.N.WFP 2023). In Western Europe, China, Japan, the USA, Peru, Brazil, and Australia, recently several heavy precipitation events occurred, and caused substantial flooding, while drought hit Africa, such as Somalia, Burkina Faso, Niger, and Mali (IPCC 2022; U.N.WFP 2023). With frequent droughts, high rainfall variability, and an economy heavily dependent on natural resources, climate change affects all aspects of life (UNEP 2023). A total of 1083 $km^3$ of blue water resources are used annually to irrigate 23% of the world's farmland regions (Rosa et al., 2020), 68% of these farmlands experience blue water scarcity in one-month $yr^{-1}$ and 37% up to five months $yr^{-1}$ (Rosa et al., 2020; Caretta et al., 2022).

The term water resources management is defined based on the World Bank (2017) as "The process of planning, developing, and managing water resources, in terms of both water quantity and quality, across all water uses. It includes the institutions, infrastructure, incentives, and information systems that support and guide water management (Bekele and Tilahun 2006; Norman et al., 2008; Ghazouani et al., 2014; Mole et al., 2019). For best adaptation to climate change, participation, collaboration, and bottom-up involvement are essential (Butler et al., 2015; Braunschweiger 2022). Adequate and appropriate financing in water management is considered in the World Bank agenda, of about 13% of the investments made from the adaptation fund went towards water management (Adaptation Fund 2018). Water-related adaptation in the agricultural sector has been extensively documented in relation to irrigation and agricultural water management (Frisvold and Bai 2016; Rosa 2022; Zhao et al., 2022; El-Nashar and Elyamany 2023). For adaptation to changing conditions to be successful, careful management compatible with local conditions is necessary. Relevant stakeholders can learn valuable lessons from the next generation of water sector

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adaptation strategies to climate change by implementing conceptually sound, multifaceted, and empirically relevant strategies. Additionally, future water-related impacts of climate change are likely to reduce the global GDP by mid-century if effective adaptation is not made, with higher projected losses expected in low- and middle-income nations (Caretta et al., 2022). This chapter addresses a range of lessons and case studies from different regions, showing adaptation strategies for key stakeholders. This is in an attempt to implement the next generation of agricultural water management adaptation policies.

## Glossary terms of climate change and agricultural water management

The following definitions of key procedures were taken and outlined through different sources:

- ***Climate Change:*** defined as *'A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes, external forcings, or persistent anthropogenic changes in the atmosphere's composition or land use* (IPCC 2012).
- ***GHG:*** '*Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, which absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, by the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H2O), carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and ozone (O3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO2, N2O, and CH4, the Kyoto Protocol deals with the greenhouse gases sulfur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbon (PFCs)* (IPCC 2012).
- ***Carbon sequestration:*** *'The process of capturing and storing atmospheric carbon dioxide. It is one method of reducing the amount of carbon dioxide in the atmosphere with the goal of reducing global climate change* (USGS; https://www.usgs.gov/)
- ***Adaptation:*** *'In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate*(IPCC 2012).
- ***Mitigation:*** *'A human intervention to reduce the sources or enhance the sinks of greenhouse gases* (IPCC 2012).
- ***Vulnerability:*** *'The propensity or predisposition to be adversely affected (IPCC 2012).*
- ***Substitutability:*** *'The extent to which an agent can replace adaptation with mitigation or vice versa to produce an outcome of equal value* (Klein et al., 2007).
- ***Ecosystem:*** *'Living elements which interact with each other and their non-living environments – provide benefits, or services, to the world (FAO 2023).*
- ***Drought:*** *'A period of abnormally dry weather long enough to cause a serious hydrological imbalance* (IPCC 2012).
- ***Flood:*** *'The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods* (IPCC 2012).
- ***Water security:*** *'It is the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability (Grey and Sadoff 2007)*

- ***Blue water scarcity:*** *'When irrigation is unsustainable and renewable blue water availability is insufficient to sustainably meet CWR. In these cases, irrigation impairs environmental flows and depletes freshwater stocks. BWS has been defined as the ratio between societal blue water demand and renewable blue water availability (Liu et al., 2017; Vanham et al., 2018; Rosa et al., 2020).*

- ***Irrigated agriculture:*** *'It refers to an area equipped to provide water (via artificial means of irrigation such as by diverting streams, flooding, or spraying) to the crops. In non-irrigated agricultural areas, the production of crops is dependent on rain-fed irrigation (World Bank 2023).*

- ***Watershed:*** *'Surface area drained by a specific stream, large or small, or draining into a lake (FAO 1960).*

- ***Rainwater harvesting:*** *'It is the collection of rainfall runoff for subsequent beneficial use. Farmers worldwide have been using it for centuries to both reduce erosion and increase crop yields and production reliability (FAO 2021).*

- ***Water conservation ponds:*** *'Water conservation ponds are a strategic way to store water, replenish groundwater reserves for the dry season, and protect hillsides from landslides during the rainy season (FAO 2020).*

- ***Groundwater recharge schemes:*** *'This is the perimeter within which all aquifer recharge (whether derived from precipitation or surface watercourses) will be captured in the water supply under consideration. This area should not be confused with the area of hydraulic interference caused by the pumping borehole, which is large on the down gradient side (World Bank 2002).*

- ***Climate-smart agriculture (CSA):*** *'An integrated approach to managing landscapes—cropland, livestock, forests, and fisheries--that address the interlinked challenges of food security and climate change (World Bank 2021).*

- ***Telecommunications systems:*** *'Systems designed for the exchange of information among users. This information exchange can take place in a variety of ways, for example, multiparty voice communications, television, electronic mail, and electronic message exchange (Daigle and Daigle 2003).*

## 3.2 Impacts of climate change on agricultural water management

### 3.2.1 Global climate change (GHG emissions) and agricultural activities

By the early 1970s, global GHG emissions had almost doubled. Current policies may cause them to increase by more than 70% between 2008 and 2050, as shown in Figure 3.1. Further, it was previously understood that industrialized countries were the source of GHG emissions; nevertheless, in recent years, developing countries have accounted for two-thirds of the flow of new emissions into the atmosphere. GHG is generally produced because of several economic activities. The agriculture sector (crop cultivation and livestock) contribute 22% of GHG (IPCC 2022), as shown in Figure 3.2.

According to the EPA 2021 and IPCC (2022), there are numerous factors contribute to $CO_2$ emissions from crop and livestock production in the agricultural sector (Figure 3.2), including; ***i)*** Agricultural soil management techniques can increase the amount of nitrogen available in the soil and cause nitrous oxide ($N_2O$) emissions. For example, the use of chemical and organic fertilizers, the growth of plants that fix nitrogen, the degradation of organic soils, and irrigation practices management, ***ii)*** Livestock, Methane ($CH_4$) which is produced as a natural byproduct of the digestion process in ruminants like cattle. This process is called Enteric fermentation (Grossi et al., 2019). Emissions of $CH_4$ and $N_2O$ are also influenced by how cattle manure is handled. The amount of this greenhouse gases produced varies depending on the manure treatment and storage practices used, ***iii)*** Smaller sources of $CO_2$ emission from liming and urea fertilizer, rice cultivation produces $CH_4$, burning crop residues produce $CH_4$ and $N_2O$, and ***iv)*** Croplands management also lead to emissions or carbon dioxide sequestration. Biological carbon sequestration is the term used to describe the storage of carbon in soil, dead organic matter, and plants. Crop and livestock management that is more effective and sustainable, as well as carbon sequestration in agriculture (which includes managing soil carbon in croplands and grasslands, agroforestry, and biochar), can reduce $CO_2$ emissions by 1.8 to 4.1 $GtCO_2$-eq per year (IPCC 2022).

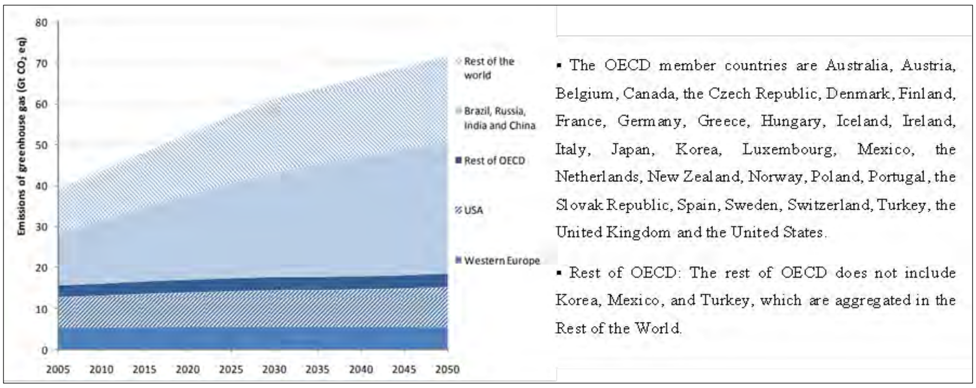


**Figure 3. 1.** Evolution of GHG worldwide over the coming decades (Source: OECD, 2008, Modified)

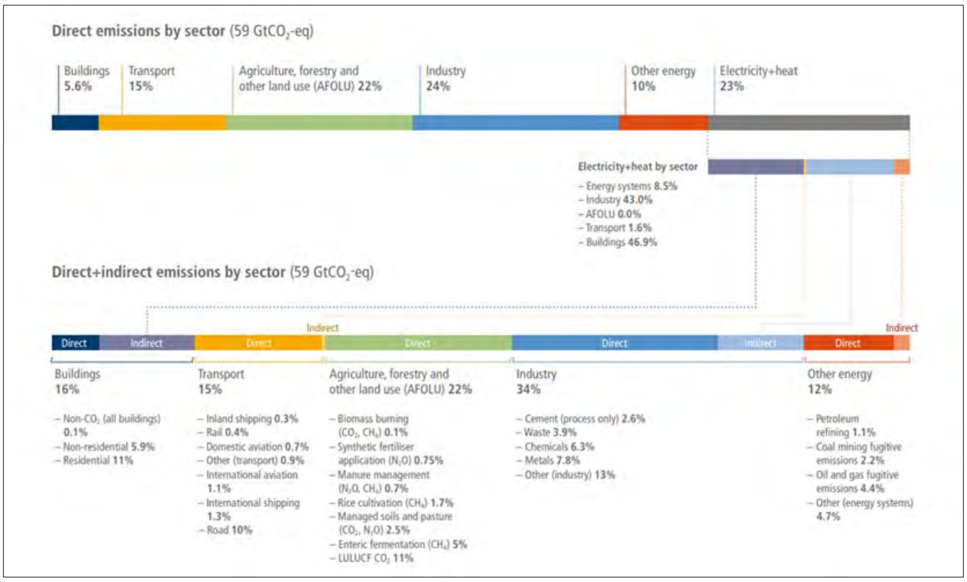


**Figure 3.2.** Direct and indirect GHG emissions (in $GtCO_2$-eq) by sector and subsector in 2019 (Source: IPCC 2022)

### 3.2.2 Impacts of climate change on basin hydrology and water resources

The majority of climate change impacts are related to water. It is simple to see how every step of the water cycle is impacted by climate change when we look at the water cycle diagram in Figure 3.4 a. Climate change is connected to water through different formations, such as evaporation, precipitation, surface runoff, and stream flow, oceans, snowpack, clouds, changes in water demand, water stress, and floods. The water cycle of Figure 3.4 b, showed a balance of rainfall, evaporation, and the other components on both sides (hotter/drier condition; left side, and hotter/wetter conditions; right side). This happens when the rate at which water evaporates into the atmosphere accelerates with rising temperatures, increasing the atmosphere's ability to "hold" water (USGCRP 2014). Increased evaporation could cause some locations to become drier and more precipitation to fall in other regions. Climate change is also affecting water quality, with heavy rainfall increasing the quantity of sediments and pollutants washed into rivers due to runoff. This also makes water unusable and necessitates the need for water treatment (CSP 2008). Also, when the sea level rises, saltwater infiltrates freshwater regions, causing the need for removal of salt from water, and can extend to infiltrate groundwater that it is used for drinking (CSP 2008). The effects of climate change also extend to groundwater by reducing recharge processes, leading to lower piezometric levels between adjacent aquifers. (Tixier et al., 2009; Sayed et al., 2020; Jannis et al., 2021; Gona et al., 2022). Depletion of groundwater has occurred in many countries, such as Pakistan, Oman, Tunisia, China, India, and Egypt (Mustafa and Qazi, 2008; Remmington, 2018; Mokadem et al., 2018; Yin et al., 2011; Das et al., 2020; Brückner et al., 2021; Freeg et al., 2023). In many regions of the world, river flows are also changing, frequently as a result of variations in precipitation, although direct human impacts are also significant. River flows often increase in high latitudes while decreasing in mid- and low latitudes, as shown in Figure 3.5.

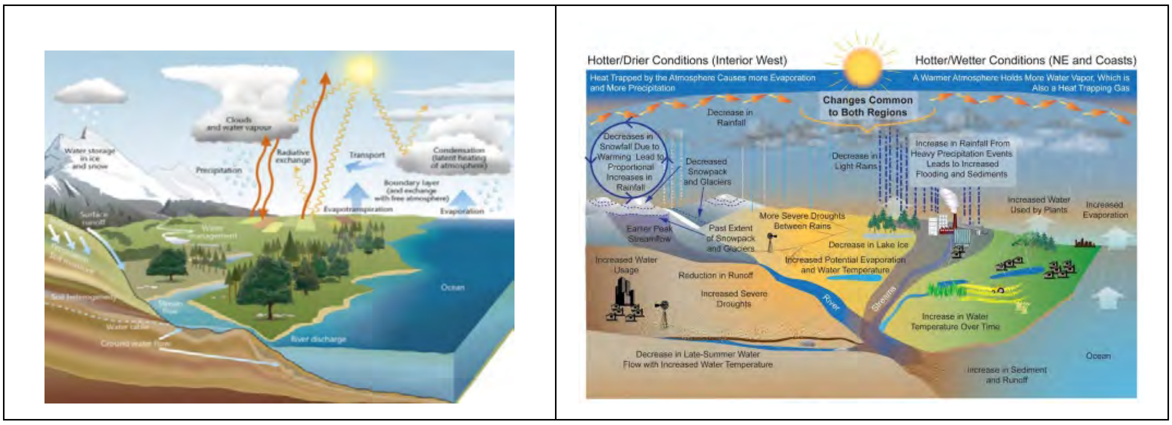


**Figure 3.3.** Impact of climate change on water resources; a) Water cycle (Source: Fecht 2019); b) Projected changes in the water cycle (source: USGCRP 2009)

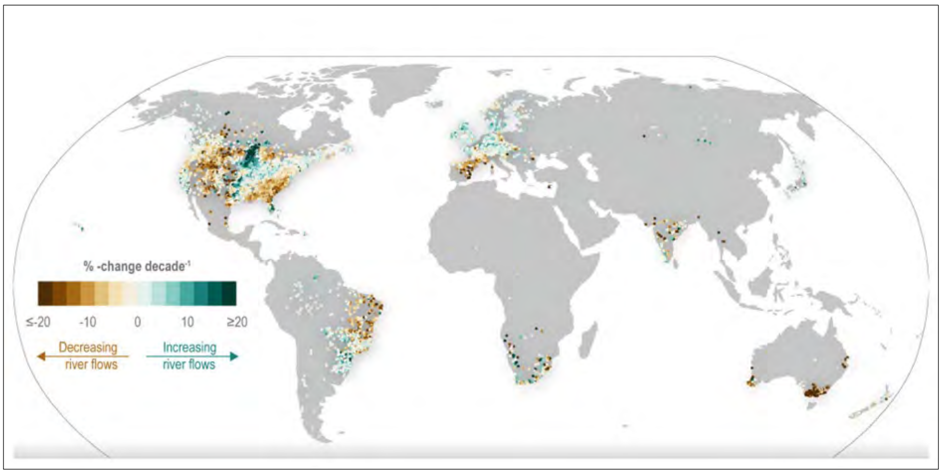


**Figure 3.4**. Observed changes in mean river flows from 1971 to 2010 (Caretta 2022).

### 3.2.3 Case studies on climate change impacts on agricultural water management

With each degree of global warming, it is anticipated that climate change will have an increasing impact on water availability, as shown in Figure 3.6. According to the World Economic Forum (2021), water risks are considered among the top 5 risks caused by climate change, as shown in Figure 3.7. When unexpected changes in the natural condition related to water availability either drought or flood occurred, it directly influences the way of agricultural water management. Recently, several heavy precipitation events and drought have occurred around the world, as shown in Table 3.1. The studies were selected based on some scientific literature with impacts on agricultural water management (flood and drought). This is not a thorough analysis of the physical science results of event attribution findings. For more information see *World Food Program-USA and Chapter 4 of the Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*

In conclusion, there have been significant geographical variations in the frequency and size of river floods over the past few decades. The likelihood of extreme precipitation events has grown due to human-caused climate change, as have the frequency and size of accompanying river floods. High confidence exists that the warming in the previous 40–60 years has caused changes in the frequency and severity of snowmelt floods, variations in timing and amplitude of ice-jam floods, and a maximum of 10 days earlier spring floods per decade (Caretta et al., 2022). As a result, a severe impact on agricultural production has occurred, with climate change being singled out as a key cause of food poverty, as explained in Table 3.1. Under a scenario of rapid global warming, agricultural yields could be reduced by 3-12% by the middle of the century ($21^{st}$) and by 11-25% by the end (Wing et al., 2021). Between 1980 and 2018, excessive soil moisture affected yields of rice, maize, soybeans, and wheat over the world by 7 to 12% (Borgomeo et al., 2020). By 2050, it is predicted that 11% ( 5%) of croplands worldwide will be vulnerable to anticipated climate-driven water scarcity (Fitton et al., 2019). Crop yields and cropping patterns were significantly impacted by changes in groundwater availability and storage, which are influenced by how intensively irrigated agriculture is practiced. Concurrently, it is anticipated that groundwater depletion will rise from roughly 204 (± 30) $km^3$ $year^{-1}$ in 2000 to 427 (±56) $km^3$ $year^{-1}$ by 2099 (Wada 2016).

**Table 3.1.** Selected major floods and drought events that impacted agricultural water management

| Country | Water risk type | Impact |
|---|---|---|
| *In 2023, South Sudan (U.N.WFP 2023).* | • Extreme weather events including four consecutive years of flooding. | • Extreme food scarcity forced some families to depend on wild foods like water lilies to cope<br>• Invasive hyacinth weed – an invasive plant that blocks waterways and emits a large amount of methane when it decomposes. |
| *In 2022, Madagascar (U.N.WFP 2023).* | • It was hit by four tropical cyclones: Emnati, Dumako, Batsirai and Ana. | • Decimated rice crops just weeks away from harvest and left over 270,000 people in urgent need of food assistance. |
| *In 2022, Pakistan (U.N.WFP 2023).* | • Heavy rainfall caused flooding and landslides at a rate nearly ten times the national 30-year average. | • Damaged 4.4 million acres (about twice the area of Connectict) of agricultural land.<br>• killed 800,000 livestock. |
| *In 2022, Sudan (U.N.WFP 2023).* | • Devastating floods. | • Disrupted the planting season. |
| *For the past five, Somalia, (U.N.WFP 2023).* | • Rainfall has been below adequate levels for harvesting and keeping livestock. | • Total crop failure and a lack of rural employment opportunities. |
| *In 2022, Chad (U.N.WFP 2023).* | • Worst flooding in 30 years. | • More than 1 million people were affected.<br>• 1,149,114 acres of farmland were devastated. |
| *Last years, Burkina Faso, Niger and Mali (U.N.WFP 2023).* | • Increasing temperatures and unpredictable rainfall patterns that have resulted in more frequent and severe droughts. | • These shocks are exacerbating existing challenges including hunger and poverty. |
| *Last years, The Dry Corridor, region in Central America (U.N.WFP 2023).* | • Devastating effects of the climate crisis.<br>• Droughts, heatwaves, and unpredictable rainfall patterns. | • Led to crop failures and forced migration.<br>• The situation is particularly dire for small-scale farmers. |
| *In 2021, Afghanistan (AAN 2021).* | • One of the worst droughts of the last two decades. | • Water resources in these regions are severely reduced.<br>• Crisis levels of food insecurity and poverty. |
| *In 2017, North-East Bangladesh (Rimi et al. 2019; IPCC 2022).* | • Flash flood. | • 220,000 ha of nearly harvestable Boro rice damaged.<br>• Crop failure contributed to a record 30% rice price hike compared to the previous year. |
| *In 2017, China (Sun et al. 2019; IPCC 2022).* | • Heavy rainfall. | • 605,000 hectares of crops were affected.<br>• 116,000 hectares without harvest. |

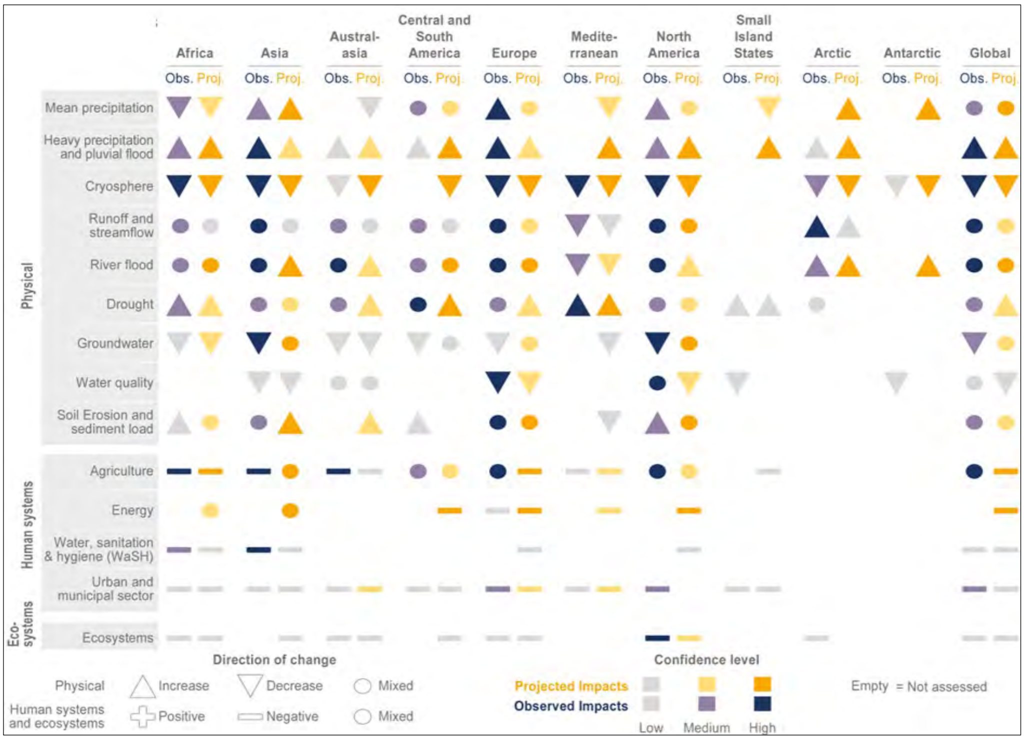


**Figure 3.5.** Regional synthesis of changes in water and consequent impacts (Source: Caretta 2022)


**Figure 3.6**. Global risk by impact (Source: World Economic Forum Global Risks Report 2021)

## 3.3 Adaptation to changing climate in agricultural water management

### 3.3.1 Adaptation in agricultural production and farming system

Examples of ways to reduce agricultural emissions are provided in Table 3.2. For a more thorough list of alternatives and an in-depth analysis of how each alternative impacts various gases, see *Chapter 7 of the Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, United States Environmental Protection Agency (EPA)- Sources of Greenhouse Gas Emissions, and Climate Smart Agriculture Report of FAO.*

**Table 3.2.** Examples of reduction opportunities for the agriculture sector (Source: FAO 2011, EPA 2021; IPCC 2022; Modified).

| Type | GHG reduction approaches in agriculture |
|---|---|
| Agroecology; *Holistic and integrated approach that simultaneously applies ecological and social concepts and principles to the design and management of sustainable agriculture and food systems (FAO 2023).* | • Minimal amounts of synthetic fertilizer.<br>• Increased nitrogen use efficiency (Improve soil quality, which encourages nutrient cycling). |
| Conservation Agriculture; *Farming system that promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species (FAO 2022).* | • Reduce the use of machines.<br>• Lower oxidation of soil organic materials.<br>• Improve soil quality, nitrogen cycling, and the use of cover crops. |
| Integrated Production Systems; *In integrated production systems the products, by-products, or services of one component of the system serve as a resource for the other production component (FAO 2023).* | • Reduce fertilizer application.<br>• Improved Nitrogen use efficiency.<br>• Improved livestock diets.<br>• Reduce deforestation. |
| Organic Farming; *It is a system that begins to consider potential environmental and social impacts by eliminating the use of synthetic inputs, such as synthetic fertilizers and pesticides, veterinary drugs, genetically modified seeds and breeds, preservatives, additives, and irradiation (FAO 2023).* | • Soil inputs include crop residue, livestock manure, green manure, and compost.<br>• No use of synthetic Nitrogen fertilizers.<br>• lower livestock stocking rates, reliance on biological Nitrogen fixation, and use of cover/catch crop. |
| Integrated food-energy systems; *Producing food and energy as a way to address the energy component of sustainable crop intensification (FAO 2011).* | • Manure application for crop production reduces greenhouse gas emissions that are associated with the manufacture, delivery, and use of synthetic fertilizers.<br>• Improved recycling of crop byproducts and wastes, as well as a reduction in emissions from feed production and their disposal. |
| Livestock management; *The exercise of efficient, productive, and moral care-taking of any agricultural-associated livestock (Goel 2022).* | • Increasing animal productivity by enhancing pasture quality can lower methane emissions per unit of animal product.<br>• New breeding practices can be used to promote increased output in animals.<br>• Adjusting feeding practices and other management techniques to reduce enteric fermentation's methane production. |

Approaches to farming systems can make a significant contribution to routes for adaptation and mitigation. Agroecology, conservation agriculture, integrated production systems, organic farming, and integrated food-energy systems are some of these connected and linked practices, as shown in Table 3.2. These approaches can significantly reduce emissions from on-farm practices such as crop cultivation, fertilizer and irrigation management, and chemical and organic fertilizers. Building a resilient agriculture system and yield mitigation can help with conservation agriculture, which is supported by enhancing agriculture and crop diversification (Powlson et al. 2016; Smith et al. 2017). The benefits of yield mitigation can be attained by improving fertilizer use and fossil fuels (Harvey et al. 2014; Cui et al. 2018). Agricultural practices can reduce $CO_2$ emissions on agricultural fields and adapt to climate change. Changes in the quantity of carbon stored in the soil can impact the global carbon cycle and change the atmospheric carbon dioxide concentrations, thus contributing to climate change. Carbon dioxide ($CO_2$) and nitrous dioxide ($N_2O$) are released in large amounts into the atmosphere when organic soils are drained because the underlying organic matter oxidizes and decomposes more quickly without water (Conchedda and Tubiello 2020). On the other hand, irrigation practices management can also impact climate change. A newly published study (Mathur and AchutaRao 2019) uses a global atmospheric circulation model CESM1.2 (*Community Earth System Model*) which was conducted to analyze the climate effects of irrigation in India. The study showed that during the peak irrigation months of April, May, and June (pre-monsoon), irrigation reduces the regional land surface maximum and minimum temperatures by about 3°C and 4°C, respectively. This explains that irrigation is partly masking the otherwise rising temperatures. In turn, the surface cooling causes a reduction in the land-sea temperature contrast in the months prior to the monsoon, which could postpone the start of the monsoon and also lessen the intensity of rainfall (Bajaj 2020). There are trade-offs with some farming methods that are deemed sustainable, and their application may harm ecosystem services or adaptation. For example, the growth of nitrogen-fixing crops (legume crops family), despite its importance economically and even on health, leads to increased availability of nitrogen in the soil and results in emissions of nitrous oxide ($N_2O$) (EPA 2021; Mahmud et al., 2020). Although fast-growing tree monocultures and biofuel crops (agroforestry) may increase carbon stocks, they can limit the amount of agricultural land that is available and downstream water availability (Schrobback et al. 2011; Windham-Myers et al. 2018; Kuwae and Hori 2019).

Eventually, it is also important to understand that the implementation of farming system concepts for climate mitigation is complicated by a number of obstacles. According to (IPCC 2022), the barriers to farm system mitigation include; ***i)*** Design and coverage of financing mechanisms, ***ii)*** In order to reduce risk and uncertainty, particularly in agriculture, new or innovative technologies that demand major time or money investments are needed, ***iii)*** Poverty, where adaptation and mitigation strategies can have significant effects on vulnerable individuals and communities, such as raising the cost of food and fiber internationally, ***iv)*** Cultural values and social acceptance to the new technologies and practices in agriculture, ***V)*** Institutional barriers, such as Transparent and accountable governance, clear land tenure and land-use rights, and lack of institutional capacity, ***VI)*** Ecological barriers, such as availability of land and water and adaptation benefits and biodiversity conservation, and ***VII)*** Technological barriers, such as monitoring, reporting, and verification of new technologies.

### 3.3.2 Water-related adaptation response

Keeping global warming to 1.5°C would limit the rise in hazards in associated water use sectors, on the other hand, many adaptation strategies may have an impact on future water security. At the same time, adaptation techniques have to be made and considered in the appropriate location and environmental conditions, for example, afforestation and reforestation if adopted in inappropriate locations will impact the water footprint (Canadell et al., 2021). Therefore, water security adaptation requires an integrated system that considers the various impacts on water resources. There are many techniques that are considered when water-related hazards occur, such as; ***i)*** Establishing national disaster adaptation and management of water infrastructure (irrigation and drainage), ***ii)*** Designing efficient watershed management systems, ***iii)*** Harvesting rainwater during the rainy season, ***iv)*** Building small water conservation ponds, ***V)*** Building groundwater recharge schemes (Artificial discharge), ***VI)*** Adopting new irrigation techniques, such as surface irrigation (Furrow, basin, and border irrigation), drip, and sprinkler irrigation, ***VII)*** Crop diversity and biodiversity, growing different types of crops can increase revenue per unit of irrigation water and growing the variety of animals, plants, fungi, and even microorganisms like bacteria, ***VIII)*** Constructing and restoring flood protection walls and groundwater channels (large-scale level), ***IX)*** Supporting the ecosystem by the 'nexus' between energy (wind and solar), water, and land, ***X)*** Climate-smart agriculture to increase water productivity and manage cropland, livestock, and forests, ***XI)*** Water and soil conservation measures (e.g., reduced tillage, contour ridges or mulching), ***XII)*** Changes in cropping patterns, the timing of sowing and harvesting, crop diversification, ***XIII)*** The use of non-conventional water sources (e.g., desalinated and treated wastewater), and ***XIV)*** Policies, institutions, and capacity building. These techniques are crucial for building resilient irrigation and drainage systems capable of withstanding unexpected climate impacts. Some examples include the use of these techniques are shown below in Table 3.3. Collectively, these measures help manage rainwater, drought and reduce flood risks and ensure that water reaches stores areas where it can be most utilized.

**Table 3.3.** Examples of water-related adaptation responses (Source: Authors)

| Type | Water-related adaptation responses | Examples of adaptation response |
|---|---|---|
| *Disaster adaptation and water infrastructure.* | • Build water systems with transit and telecommunications systems.<br>• Craft power systems that can endure the effects of a flood or other severe disaster.<br>• Green infrastructure. | • The American Red; Japan Seawall; Scheveningen Boulevard Coastal Barrier, The Hague Netherlands; The Big U, New York City; The Sunset Harbor Street Program, Miami Beach; Saemangeum Seawall, Gunsan, South Korea; The MOSE Project, Venice; Louisiana Coastal Protection and Restoration Authority's Comprehensive Plan for a Sustainable Coast, Louisiana. |
| *Watershed management systems.* | • Diversion drains.<br>• Farm ponds and percolation ponds.<br>• Land levelling.<br>• Diversion streams. | • Mississippi watershed, in the United States. |
| *Rainwater harvesting.* | • Gully and cement plugs.<br>• Gabion structure.<br>• Contour bund.<br>• Dugwell recharge.<br>• Recharge shaft. | • There are many countries with good Rainwater Harvesting mechanisms, such as Brazil, Japan, New Zealand, China, India, and other countries are giving great examples. |
| *Artificial recharge.* | • Infiltration basins and canals.<br>• Water traps and cutwaters.<br>• Surface runoff drainage wells.<br>• Diversion of excess flows from irrigation canals into sinkholes. | • There are several artificial recharge techniques in use in Latin America and the Caribbean. |
| *Modern irrigation techniques.* | • Surface irrigation (Furrow, basin, and border irrigation), drip irrigation, sprinkler irrigation, and subsurface irrigation. | • There are many countries that are giving great examples, such as the United States, Japan, and Australia. |
| *Crop diversity and biodiversity.* | • Intercropping systems, such as corn and soybean, wheat and chickpea, sorghum and legumes.<br>• Multiple cropping and growing crops in rotation, such as oats, wheat, barley, soybean, sorghum, alfalfa, and numerous clovers and grasses. | • India is famous for its intercropping system, especially sorghum and legumes, maize and potato. |
| *Constructing flood protection walls and groundwater channels.* | • Flood control by constructing dikes and flood walls.<br>• Flood control by construction of storage tanks and reservoirs.<br>• Flood control by construction of diversion channels.<br>• Flood control by construction of terraces.<br>• Flood control by soil conservation methods. | • Netherlands has one of the best flood control systems in the world. |
| *Climate-Smart Agriculture (CSA).* | • Sensors for soil scanning and water, light, humidity, and temperature management.<br>• Telecommunications technologies such as GPS network.<br>• Hardware and software for enabling IoT-based solutions (Internet of Things), robotics, and automation, as well as for use in specialized applications.<br>• Transmission mechanisms for decisions and directives. | • Recently, the World Bank developed CSA investment plans in Bangladesh, Zimbabwe, Zambia, Lesotho, Mali, Cote D'Ivoire (World Bank 2021). |
| *Water and soil conservation measures.* | • On-farm water and soil conservation.<br>• Crop rotation, reduced tillage, mulching, cover cropping. | • Several studies discussed the impact of water and soil conservation measures on water saving and improving soil quality, such as Vicente and Wu 2019; Niacsu et al., 2022; Reicosky et al., 2023). |

| Type | Water-related adaptation responses | Examples of adaptation response |
| --- | --- | --- |
| *'Nexus' between energy (wind and solar), water, and land.* | • The ability of wastewater treatment facilities to generate energy from biogas and provide purified water for environmental or agricultural purposes.<br>• Employing desalination units powered by renewable energy and putting floating solar panels on reservoirs.<br>• Using non-traditional energy sources, such as solar, wind, geothermal, hydropower, ocean, and bioenergy. | • There are many countries that are giving great examples, such as Denmark, where the solar and wind power energy share is 51%. In Uruguay, solar and wind power account for 46.7% share of total energy power, and other countries are giving great examples (Climate Council 2022). |
| *Changes in cropping patterns and crop systems.* | • Introducing new crops.<br>• Crop diversification towards cash crops.<br>• Improving crop cultivars. | • Recommendations for new crops that can be used as an adaption for climate change have been suggested by several studies, such as Reijers 2014; Kakumanu et al., 2019; Makate et al., 2019). |
| *Use of non-conventional water sources* | • Agricultural drainage water.<br>• Brackish groundwater and/or seawater.<br>• Treated municipal wastewater. | • The use of non-conventional water sources is emerging as an important component of increasing water availability for agriculture (Morote et al., 2019; Hussain et al., 2019; Qadir et al., 2022). |
| *Policies, institutions, and capacity building.* | • Crafting rules.<br>• Incentives instruments.<br>• Appropriating of finance.<br>• Establishing water community-based.<br>• Training and capacity building. | • Participation, collaboration, and bottom-up involvement are essential for adaptation and have been documented in many research McCracken, Meyer (2018; Ferrero et al., 2019; Farig et al., 2021; Frenova 2021). |

## 3.4 Adaptation with irrigation and drainage management

Most farmers rely on canal water from dams for irrigation, but a significant amount of water seeps a few meters downstream from the dam embankment. Despite studies indicating this seepage water is saline, it is often diverted for irrigation due to canal water scarcity. In arid and semi-arid regions, the increasing demand and unreliability of canal water force farmers to use poor-quality water, either alone or mixed with canal water. More equitable water distribution schemes have helped farmers know their irrigation schedule, leading to increased production. However, ensuring adequacy and equity in water-scarce areas is challenging without coordinated efforts and enforcement of irrigation rotations and rules. This necessitates organizational and management skills within farmers' organizations, which require capacity building in technical and institutional areas to sustain irrigation systems. Urgent action is needed to improve water allocation and distribution at the scheme level by enhancing technical capabilities and strengthening farmers' organizations.

Typically, farmers irrigate common crops such as maize and onion every 2 to 3 weeks, while cereals (barley, sorghum, teff) and legumes (vetch, chickpea) are irrigated every 3 to 4 weeks. The amount of water used in each irrigation is based on individual farmers' judgment rather than crop water requirements (CWR). Consequently, poor land leveling leads to water pooling in fields and runoff to adjacent plots due to over-irrigation. Poor irrigation water management is a common issue in developing countries. Researchers agree that inappropriate irrigation scheduling, not based on CWR and soil type, is a major cause of poor performance in irrigation schemes. Other problems include the lack of locally adapted crop manuals, limited knowledge, and insufficient skills among farmers and development agents (Fissahaye et al., 2023).

## 3.5 Countermeasures to climate change damages

Continuous improvement of early warning systems and enhanced deployment and coordination of pre-disaster prevention measures can significantly boost the effectiveness of adaptation actions in reducing loss and damage caused by extreme weather events linked to climate change (IPCC, 2022). However, current international climate governance tends to prioritize mitigation over adaptation, thereby weakening support for adaptation efforts in pre-disaster prevention and preparedness planning. However, this shift diminishes developing countries' opportunities to gain practical experience and capacity to prevent extreme disasters. Developing countries should establish a framework and assessment methodology for pre-disaster preparedness systems to address loss and damage. This should involve referencing the early warning systems and adaptation action goals outlined in the Convention's reports. Key focus areas include measuring the costs, overall objectives, and future needs of preparedness systems in these countries. Financial allocation should be refined based on existing adaptation priorities related to loss and damage, such as agriculture, food security, water resources, coastal zone management, and human health, and aligned with national development plans. Clusters of demonstration projects with strong disaster prevention capabilities at national, regional, and global levels could help build a climate governance and defense network. This network would synergize adaptation with loss and damage strategies and offer guidance for defending against climate hazards of varying types, times, and regions (Liu et al., 2024).

### 3.6 The role of government policies and regulations in facilitating adaptation in agricultural water management

Agricultural water management encompasses all activities related to the storage, distribution, consumption, and drainage of water for crop production, fisheries, and livestock which have varying management systems (Seijger and Hellegers 2023), as shown in Figure 3.8. Agriculture has a significant influence on water worldwide as it accounts for 72% of all water withdrawals and contributes an estimated 56% of total polluted effluent (FAO 2021). Globally, societies face varied priorities related to climate change adaptation and mitigation (IPCC 2022), environmental conservation (IPBES 2019), and renewed attention to food security which in turn influence shifts in societal priorities and changes in agricultural water management (Hellegers 2022). Policies and regulatory frameworks function to oversee and govern these shifts in societal priorities and assess them against relevant reforms needed in agricultural water management and accommodate the various competing demands for water resources.

Newly dominant societal priorities have driven reforms of agricultural water management i.e., reorientation. Seijger (2023) explored the diversity and dynamics of reorientations around the world as seen in 21 case studies below. These examples highlight how societal priorities can serve as a starting point for changes in agricultural water management, for which government policies and regulations are central to achieving targeted objectives and balancing competing demands. A reorientation can start locally, for instance, with an informal adaptation to a new climate reality which then influences larger-scale policies and plans (Lee et al., 2014). Or, a reorientation may be centrally steered, starting with the formulation of plans and policies to influence farmers and other water users Seijger et al., (2019).

Long-term decision-making and strategic planning by governments are important vehicles for agricultural water management reform (Banihabib et al., 2017; Seijger et al., 2019). To achieve this, governments should clearly allocate and distinguish roles and responsibilities, operational management and promote cross-sectoral coordination among the responsible authorities. As these authorities would engage at different scales, considerations should be made for regional policy coherence, particularly for transboundary water systems that cover more than two countries. Across all national and regional levels, it is important to update and share timely water- related data and information and use it to assess changes/ trends, forecast planning and improve overall water policy.

As government policies and regulations oversee not only agriculture but other sectors, it is the duty of the government to mainstream integrity and transparency across water institutions and related governance frameworks for enhanced accountability. This creates a solid foundation to build stakeholder awareness campaigns on the importance of sustainable agricultural water management, encourage dialogue among stakeholders and promote cross-sectoral coordination among relevant water authorities. integrity and transparency from the government could promote community policing to improve watershed protection and adoption of community-based solutions.


**Figure 3.7.** Examples of 21 reorientations that drive reform of agricultural water management (Seijger 2023)

## 3.7 International agreements and frameworks related to water and climate change in the agriculture context

Making the transition to sustainable agriculture demands strong political commitments, and cross-setoral coordination among the various sectors dealing with climate change, agricultural development, and food security. Two major international agreements were reached in 2015 that influenced policies, strategies, and actions at the global level: the 2030 Agenda for Sustainable Development, and the Paris Agreement on climate change. A third global framework that guides national sustainable development activities is the Sendai Framework for Disaster Risk Reduction (SFDRR) 2015-2030, which was adopted at the Third World Conference on Disaster Risk Reduction in Sendai, Japan in March 2015.

The 2030 Agenda and Sustainable Development Goals: The 2030 Agenda for Sustainable Development, including the 17 SDGs articulate global objectives that were agreed by United Nation Member States and represent the follow-up to the Millennium Development Goals. The SDGs will shape national development plans. At the core of the 2030 Agenda is the agriculture sectors. To make progress toward reaching the targets laid out in the SDGs, it is imperative to make agriculture and food systems more sustainable through improved management practices in crop and livestock production, forestry and fisheries and aquaculture. A key aspect in the implementation of Agenda 2030 is establishing a country-driven and country-owned development process, which can be achieved by adopting a system-wide and integrated approach to capacity development.

The Paris Agreement: The Paris Agreement – an outcome of the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) – provides opportunities for adaptation and mitigation actions in agriculture. Among other things, it establishes the global goal of enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change, with a view to contributing to sustainable development and ensuring an adequate adaptation response (IPCC 2014). The foundation of the Paris Agreement lies in the Intended Nationally Determined Contributions (INDCs), which are renewed every five years. A FAO analysis of the INDCs shows that countries have accorded the agriculture sectors a prominent role in their climate change actions. The targets and objectives outlined in INDCs need to be translated into actions on the ground, of which policy coherence within and across all the agriculture sectors is of high importance. Countries can deliver their determined adaptation and mitigation contributions: National Adaptation Programmes of Action (NAPAs), National Adaptation Plans (NAPs) and Nationally Appropriate Mitigation Actions (NAMAs).

The Sendai Framework for Disaster Risk Reduction (SFDRR): This framework recognizes that disaster risk reduction is an integral part of efforts to achieve sustainable development and address climate change. The actions at the national and global levels that are promoted by the SFDRR fall into four priority areas; gaining a better understanding of risk; strengthening risk governance; investing in resilience; and improving preparedness, response, and recovery.

There is a need for a more robust alignment between global agendas at the national level, and the agriculture sector offers significant potential and opportunities to create synergies and complementarities between activities to address climate change, promote sustainable development and reduce the risk of disasters.

## 3.8 Policy changes or improvements to support agricultural adaptation efforts

Government stakeholders should consider and account for the fast and slow changes emanating from shifts in societal priorities that subsequently influence farming practices in land and water systems at local and national levels. It is important to note that the connection between societal priorities, change in weather patterns and change in agricultural water management may be long term and indirect, hence the need for extensive consultations with all relevant stakeholders in the short-and long-term water allocation processes.

Farmers and local stakeholder-led (including smallholder farmers) national policy dialogues are essential to provide evidence-based analysis of climate change influences on agricultural production and where adjustments need to be in the future for adaptation. Such stakeholder-driven dialogues tailored to countries' needs have been done in several counties (Akhmouch and Correia 2016) and can support sound policy development for sustainable agriculture. As noted in FAO (2008), “the policy environment must be supportive of smallholder production, consumption, and marketing of agricultural products.”

Public policies for sustainable water management should be strategized focusing on promoting water-use efficiency, adoption of sustainable water management technologies, re-oriented policy incentives with minimal environmental consequences and watershed management approach. For example, the World Bank project titled ‘Paani Bacho, Paise Kamao’ (save water, earn money) shows practical insights into future public policies designed to promote efficient water use through Participatory Irrigation Management (PIM) (World Bank 2022). Multiple policy responses at different levels, each adapted to specific water resource systems are essential to increase the overall efficiency of water use by the agricultural sector, reduce the sector’s impact on freshwater resources, and improve its resilience to water risks.
Analyses

National governments and academia should engage to develop country-specific indicators and analyses methodologies that will contribute to formulate policy responses, define pathways to make policy changes and facilitate their implementation toward sustainable agriculture water management. Such indicators and analyses methodologies enable regular monitoring and evaluation of agricultural water management policies and allow for planning on where to adjust when needed.

Agricultural water management governance policies and regulations need to address gender issues and provide women with technical training on water management. According to FAO women account for an average of 43 percent of the agricultural labor force in developing countries but still, water policies related to agriculture continue to marginalize women (FAO 2011). The State of Food and Agriculture 2010-2011 by FAO, suggests that bridging the gender gap in agriculture could increase agricultural yields to potentially reduce the number of hungry people by 100 to 150 million. It is essential that gender issues are mainstreamed in all governance processes related to agriculture water resource management.

## 3.9 Conclusions

Weather patterns are changing as a result of climate change, and this leads to extreme weather events, uncertain water availability, a worsening of water scarcity, and damaging water sources. Consequently, water-related hazards in the agricultural sector have increased. This chapter will explore how climate-resilient water and farming systems can promote sustainable agriculture and enhance rural livelihoods. Examples of effective climate-proofed initiatives and inclusive water management strategies that increase resilience to extreme climate events while emphasizing sustainability are provided.

This chapter shows that greenhouse gas emissions over the last decades have reached their greatest points in recorded human history, and warming is projected to exceed 1.5°C. Hence, the water hydrological cycle is greatly affected due to the high exchange of water between the Earth's surface and the atmosphere. This has caused the annual mean precipitation range to vary between increasing and decreasing over many regions. The evapotranspiration (ET), soil moisture, and groundwater were influenced by the changes in precipitation following the same pattern. From drought to floods, more people are pushed into extreme hunger and poverty. The agriculture sector has been greatly affected by these extreme events in many countries, and agriculture has been devastated. The vulnerability of food production systems to climate change has been observed and documented in local, regional, and global evidence. The effectiveness of some adaptation reactions was demonstrated by a large range of available hard and soft adaptation alternatives for water-related adaptation in the agriculture sector.

Farming system approaches (e.g., agroecology, conservation agriculture, integrated production systems, organic farming, integrated food-energy systems, and further livestock management) have shown a wide range of co-benefits in saving water, improving soil quality, and farmers' yield, besides, building resilient systems to climate change, and therefore build adaptation actions against the environmental constraints. Further, water-related adaptation has shown a wide positive response toward sustainable irrigation. Techniques for conserving water and soil, including mulching, contour ridges, and reduced tillage, are an example of an adaptation response. These techniques are among the most widely used adaptation responses in rain-fed agriculture and showed potential efficacy in reducing impacts a 1.5°C. In Africa, among the most common adaptation strategies adopted by farmers are changes in cropping patterns, crop diversification towards cash crops, and the development of cultivars that are tolerant to floods and drought. Employing technologies in agriculture such as smart agriculture has proved its influence to increase water productivity and reduce vulnerability to drought, pests, diseases, and other climate-related risks, besides lower emissions for each unit of food produced. On the other hand, the utilization of non-conventional water sources (desalinated, treated wastewater) is becoming increasingly crucial under water stress in arid coastal areas and arid regions with water scarcity. The 'nexus' of energy, water, and land is a crucial factor in sustaining and regulating the environment. Diversifying energy, such as wind and solar is an effective approach to reduce water-related impacts on the energy sector and is considered an effective adaptation and mitigation strategy. In order to ensure effective adaptation in agriculture and water management and to increase food security, policies, institutions, and capacity building are crucial adaptation measures in agriculture. This is mainly because climate change is always linked with new strategies that have not been before, and farmers are finding it hard to plan and manage their farm system (water and production). Eventually, the world continues to change, and adaptation to these new situations is needed. These options can also reduce the risks when combined or integrated.

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# CHAPTER IV
# Smart Water Management Against the Climate Change

Takanori Nagano[1], Jih-Shun Liu[2]

## 4.1 Introduction

Smart water management can be carried out at on-farm scale or at a larger scale such as district level, basin level etc. The term "smart" in general means "adaptive" in contrast to "normative". Holling (1978) defined adaptive management as a structured, iterative process of robust decision making in the face of uncertainty, with an aim to reduce uncertainty over time via system monitoring. Today advancing information and communication technologies facilitates real-time monitoring and adaptive operations based on quicker computation.

The term "smart agriculture" covers wide spectrum of technologies today. "Smart water management" can be considered as one domain of "smart agriculture" in the narrow definition. However, when it comes to irrigation district management or basin hydrological management, then their concept may protrude "smart agriculture". In this chapter, definition of "smart agriculture" and "climate smart agriculture" are explained first. Then different forms of "smart water management" are explained. Finally, the question whether "smart water management" can mitigate impact of climate change has been discussed.

## 4.2 Smart agriculture

Smart agriculture realizes adaptive management in agriculture. Smart agriculture is also known as precision agriculture or digital agriculture today. It is an innovative approach to farming that utilizes sensors, communication and computations to optimize various aspects of agricultural production. The primary goal of smart agriculture is to increase the efficiency, productivity, and sustainability of farming practices while minimizing resources and environmental impacts.

The element of agriculture that influence growth of crops are nutrients, soil water, temperature, radiation, pest and diseases. Smart agriculture generally optimizes timing and amount of water, fertilizer and pesticide & herbicide application to maximize harvest in heterogeneous environment.

There are different sets of technologies realizing smart agriculture.

1. Data Analysis: Smart agriculture relies heavily on collecting and analyzing data from various sources, such as sensors, satellites, drones, and weather stations. This data is used to make informed decisions about crop management, irrigation, and livestock care.
2. Internet of Things (IoT): IoT devices like sensors and actuators are deployed in the field to monitor conditions such as soil moisture, temperature, humidity, and crop growth. These devices transmit real-time data to farmers or automated systems for analysis.
3. Remote Sensing: Satellite and drone technology is used to gather detailed information about fields and crops. This includes assessing crop health, identifying pest and disease outbreaks, and measuring soil properties.
4. Precision Farming: Smart agriculture enables precise management of resources such as water, fertilizer, and pesticides. Farmers can apply these inputs only where and when they are needed, reducing waste and costs.

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5. Automation: Farm equipment and machinery can be equipped with automation and GPS-guidance systems. This allows for precise planting, harvesting, and other operations, leading to increased efficiency and reduced labor requirements.
6. Weather Forecasting: Access to accurate weather forecasts helps farmers plan their activities, including planting and harvesting, to minimize weather-related risks.
7. Crop Management Software: Farmers use software applications to track crop growth, monitor yields, and optimize planting and harvesting schedules. These tools can also help with inventory management and supply chain optimization.
8. Livestock Monitoring: Smart agriculture extends to livestock farming as well. Sensors and tracking systems can be used to monitor the health and behavior of animals, ensuring their well-being and optimizing breeding and feeding practices.
9. Data Integration: One of the critical aspects of smart agriculture is integrating data from various sources to provide a comprehensive view of the farm. This allows farmers to make data-driven decisions.
10. Sustainability: Smart agriculture promotes sustainable farming practices by reducing resource waste, minimizing the environmental impact of agriculture, and supporting more efficient land use.

To summarize, smart agriculture conceptually comprises four layers.

1. Sensing layer: information collected by means of sensors installed on the ground, weather stations, sensors and actuators installed on agricultural machineries or drones and by remote sensing.
2. Communication layer: the main function of network layer is to transfer information from the source to the destination.
3. Computation layer: this system will integrate data from sensing layer and other computation layer (such as weather forecast) to create spatial data and process and analyze data to compute short-term forecast and optimized decisions on management.
4. Application layer: this layer visualizes data created by the computation layers and provide information and suggestions to end-users. In an automated system, devices change their state and operations to realize optimum management.

## 4.3 Climate-Smart Agriculture (FAO,2023)

FAO defines Climate-Smart Agriculture (CSA) an approach to help people who manage agricultural systems respond effectively to climate change. The CSA approach pursues the triple objectives of i) sustainably increasing productivity and incomes, ii) adapting to climate change and iii) reducing greenhouse gas emission. The CSA approach addresses deriving locally acceptable solutions and welfare of smallholders for achieving food security of the coming 20 years. The CSA approach is not to create universally applicable solutions but rather to involve different elements embedded in the local contexts. CSA relates to actions both on-farm and beyond the farm, and incorporates technologies, policies, institutions and investment.

The CSA targets different elements of agriculture as shown below (FAO, 2023).

1. Management of farms, crops, livestock, aquaculture and capture fisheries to balance near-term food security and livelihoods needs with priorities for adaptation and mitigation.
2. Ecosystem and landscape management to conserve ecosystem services that are important for food security, agricultural development, adaptation and mitigation.
3. Services for farmers and land managers to enable better management of climate risks/impacts and mitigation actions.

4. Changes in the wider food system including demand-side measures and value chain interventions that enhance the benefits of CSA.

The CSA action are characterized by

1. Expanding the evidence base: The evidence base is made up of the current and projected effects of climate change in a country, identifying key vulnerabilities in the agricultural sector and for food security, agriculture and the identification of effective adaptation options.
2. Supporting enabling policy frameworks: The approach supports the development of relevant policies, plans, investments and coordination across processes and institutions responsible for agriculture, climate change, food security and land use.
3. Strengthening national and local institutions: Strong local institutions to empower, enable and motivate farmers are essential.
4. Enhancing financing options: Innovative financing mechanisms that link and blend climate and agricultural finance and investments from public and private sectors are a key means of implementing CSA.
5. Implementing practices at field level: Adapting to CSA must be related to local farmers' knowledge, requirements and priorities. Local projects and institutions support farmers to identify suitable climate-smart options that can be easily adopted and implemented.

   CSA can be understood as a holistic approach to adapt to climate change. The time-scale of adaptive management is much slower than that of "smart agriculture" and its main notion is not technology-oriented.

### 4.3.1 Smart agricultural water management as an innovated technology – Overview

Drought is a kind of water stress (Niu et al., 1996; Shao et al., 2005) and has a direct impact on agriculture Morison et al., (2008), whereas global climate changes continue to worsen the current shortage situation and present unprecedented challenges to Taiwan's water system. During the drought period, some of the allocated agricultural water transferred to the domestic and industrial sector, resulting in a lack of irrigation water for farmers. Smart irrigation management plays an important role for effectively and efficiently use of water to enhance water use efficiency (WUE) under a limited water environment. WUE or water productivity (crop yield per unit of water used) emerged from the idea of drought tolerance and resistance Passioura et al., (2006), defined for the first time in agronomy in the 1860s Viets et al., (1962).

Enhancing water use efficiency (WUE), particularly that of agricultural water resources, to cope with climate change is a major concern worldwide. Simulation or optimization approaches are mostly used for water distribution system Yeh et al., (1985). Precision irrigation by using a smart simulation system is a possible approach of enhancing WUE and maintaining crop growth conditions to ensure productivity. Many simulation tools, take the system dynamic program VENSIM for example, it's a simulation approach, Sehlke et al., (2005) was used to establish many types of smart irrigation water management system and can be investigated the effect of water reduction in irrigation field.

System dynamics firstly developed by Jay W. Forrester, used to analyze the modeling system changes and dynamic behavior based on the linkage and response mechanism among models Forrester (1961), that was considered appropriate for modelling and simulation. It is a computer-aided approach to evaluating the interrelationships of components and activities within complex systems Sehlke et al., (2005). It is based on systematic thinking, an object-oriented simple tool which is very useful in management and planning. The stock-flow diagram in the system dynamics is the key to showing the problem structure and internal process of the system for making the transparent modeling process. Water resources system modeling, management and planning has been done recently and over the years the approach of system dynamics has been used as a productive and common method. For example, water resources management, planning, policy and sustainability analysis (winz et al., 2009; Simonovic et al., 1999; Xu et al., 2002), in environmental planning and management Guo et al., (2001), decision support systems for management of floods Ahmad et al., (2006), hydrological systems Khan et al., (2009), water accounting systems for water management Graham et al., (2009), and a decision support system for water management Jesus et al., (2009). Wu et al. applied the VENSIM model to a paddy rice field in Central Taiwan Wu et al., (2016). Elmahdi et al. presented a new approach for optimizing the irrigation demand management by composing systems dynamics model (VENSIM software, Ventana Systems, Inc, Salisbury, Wiltshire, UK) with optimization approaches Elmahdi et al., (2005). Luo et al. applied system dynamic model for time varying water balance in aerobic paddy fields Luo et al., (2009), which got the potential to be developed as smart irrigation system. Compared with other conventional methods, the smart system exhibited excellent performance with its reliable digital technology Sathish et al., (2015), due to the function for taking into account large number of components, feedback mechanism and behavioral response of water balance system, and has been shown to be an adequate tool to depict system dynamics (Miller et al., 2012; Yang et al., 2008).

## 4.4 Smart water management for adapting to the changing climate

### 4.4.1 System design

Smart water management system includes management platform with User Interface (UI) and field station. Nowadays, the most low-cost and reliable field transmission equipment is the Internet of Things (IoT) devices. The construction of an IoT architecture for water management involves various professional technologies and system integration. One crucial aspect is the local system part, which requires thorough field surveys and investigations to ensure the proper selection and placement of monitoring stations. During the field survey, specific attention is given reference as:

1. Determining the optimal locations for monitoring stations based on the physical range and accuracy requirements of the sensors.
2. Assessing the construction and measurement dimensions needed for installing the sensors at the selected sites.
3. Evaluating the lifespan of the sensors to plan for future maintenance and replacements.
4. Considering the impact of sensor installation on the current water supply channels and ponds.
5. Analyzing and planning the network, communication, and telecommunications requirements to ensure seamless data transmission from the monitoring stations to the central system.
6. Conducting a final review of the monitoring stations and their functionality.

Through these field investigations and analyses, the IoT architecture can be effectively designed and implemented, enabling efficient water management and data collection for decision-making processes. The integration of accurate sensor data and robust communication systems plays a vital role in optimizing water resource allocation and promoting sustainable agricultural practices.

The planning of field IoT station changes the traditional monitoring and measurement methods, and cooperate with the integrated system under the development of the new technology of the material network to achieve low power consumption, miniaturization, wireless, modularization and weather resistance of the monitoring and transmission components (with waterproof, shock resistant, etc.). The integrated structure of IoT Box can be shown as Figure 4.1 Chen et al., (2021).

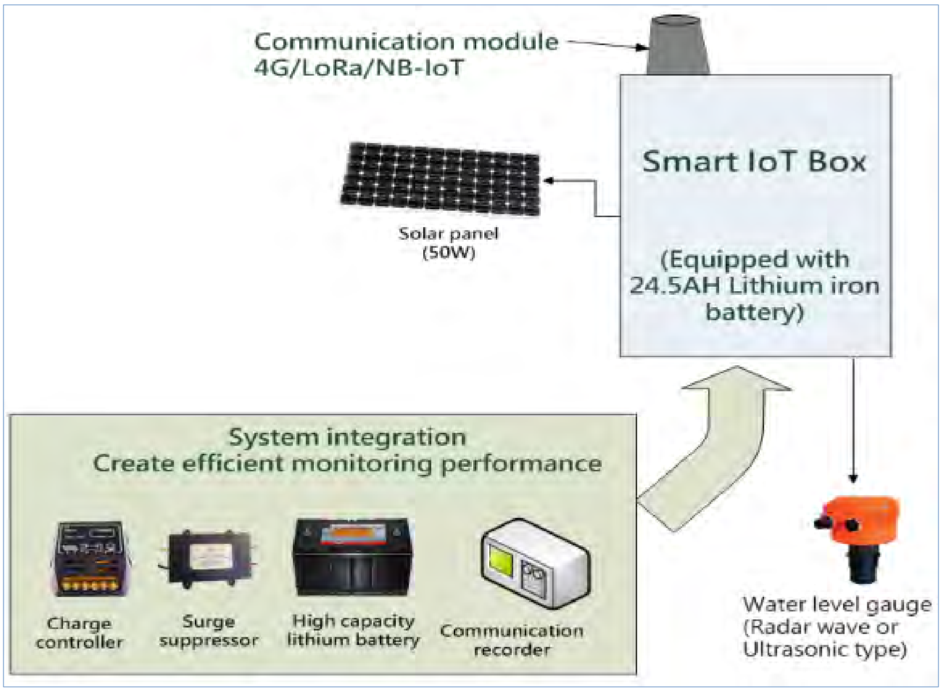


**Figure 4.1.** Integrated scheme of smart IoT box Chen et al., (2021).

### 4.4.2 Smart water management system construction

In order to safeguard farmers' water rights and enhance the sustainable use efficiency of water resources, under the pressure of water resources development and the need of agricultural water demand, a smart water management system aims at mastering the management and operation of the irrigation canals and storage ponds. In order to improve the effective use of water resources, grasp instant water quantity and quickly make water resources countermeasures, the system is suggested for using the mature and developed network communication and IoT technology, to handle the construction of whole system, the relevant work items are as follows:

1. Storage ponds water level sensing system construction;
2. Using interface of the Water Resources IoT System establishment;
3. Construction of the main canal water level sensing and prediction model;
4. Suggestion model construction for water storage allocation to ponds;
5. Monitoring of abnormality of water level in canals and ponds;

The establishment of the dashboard and workstation display system; the best UI is recommended as the popular social messaging software loke LINE.

The communication unit and flow chart are shown as Figure 4.2; all steps are described as follows. Through the IoT communication technology, collecting the water level data and transmit it to the Water Resources IoT become more convenient (Step 1~3). By combining Azure computing resources (Step 4~5), the relevant hydrological simulation calculations shown as Figure 4.3, can be carried out immediately to overcome the operation of the pond strategy, disaster prevention response, pond management recommendations, etc., and to build relevant web pages (Step 6), so that managers can view relevant analyzed outputs on mobile devices, desktop computers, and display systems of the conferences and workstations (Step 7~9). The relative software deployment architecture shown as Figure 4.4.

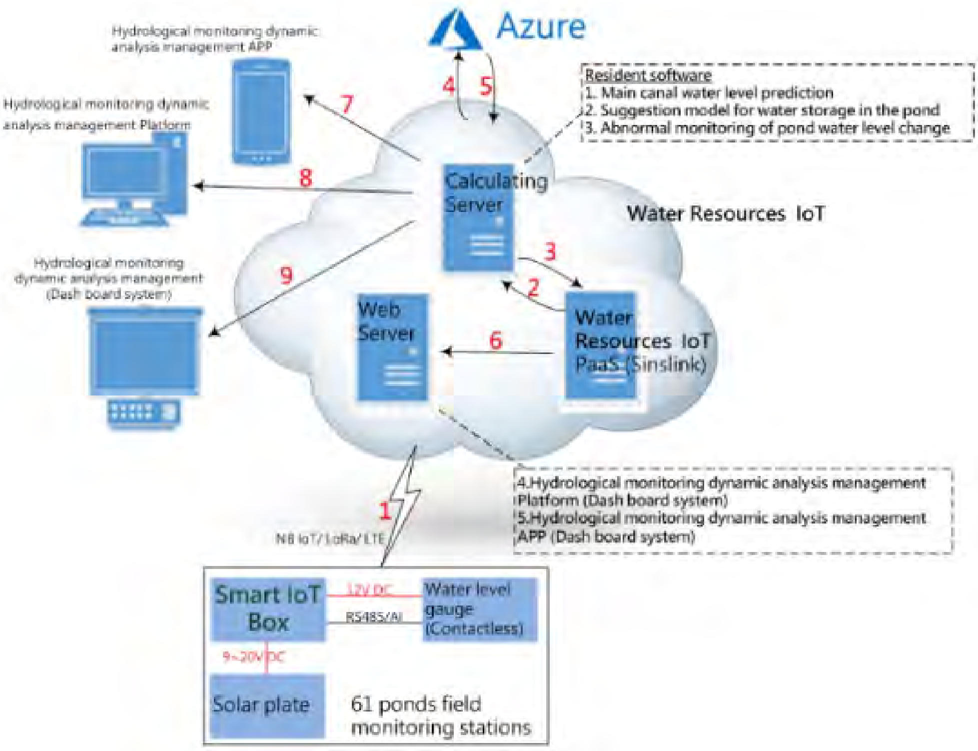


**Figure 4.2.** System communication flow chart

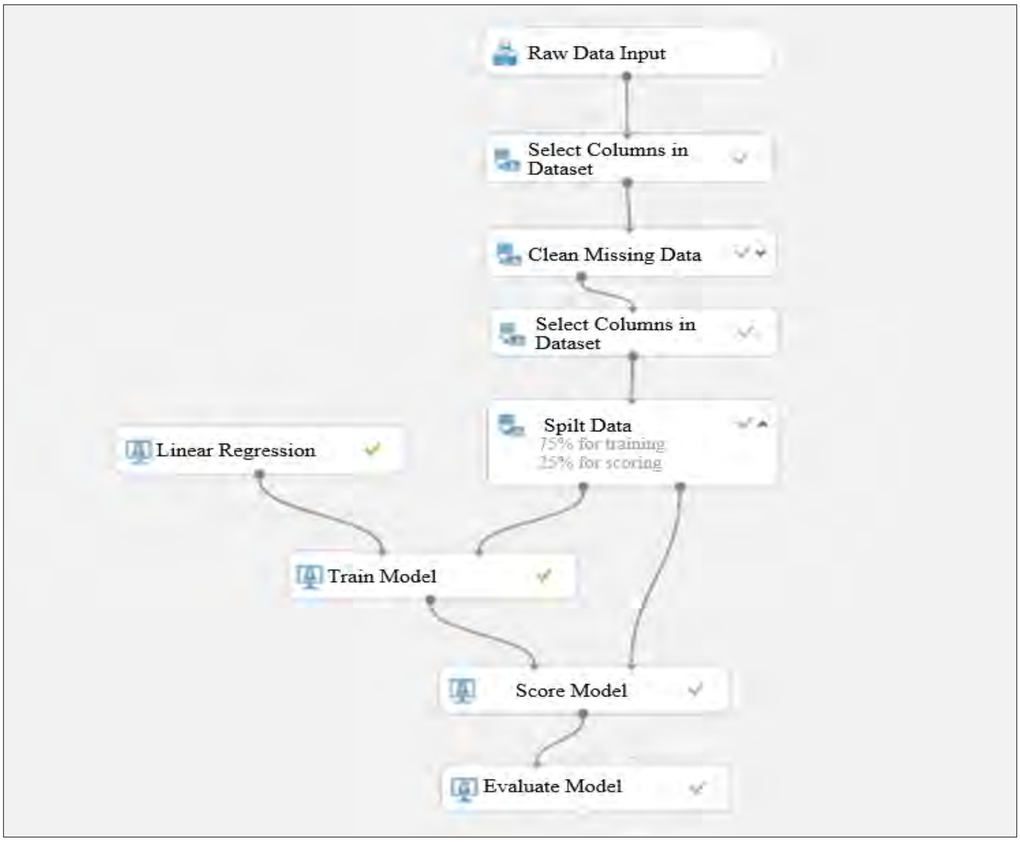


**Figure 4.3.** Schematic diagram of Azure calculation platform interface

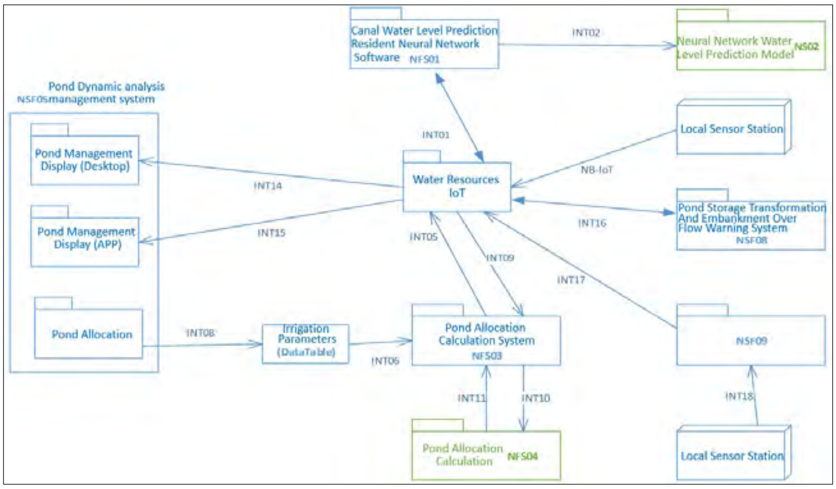


**Figure 4.4.** Software deployment architecture Chen et al., (2021)

## 4.5 Smart water management for mitigating the climate change and for sustainable production

In order to maintain farmer's water rights and improve water use efficiency, accurate water resource allocation is necessary, so as to efficient and accurate canal water level prediction model, a mart water management is suggested to be established including these two parts to allocate water storage more immediately which increases the water storage capacity in ponds for dry seasons. Through the established smart water management system and canal water level prediction model, its prediction results will be written back to the system platform, and the data can be read through the platform's Sensor Thing Application Programming Interface (API) to facilitate other programming languages such as R and Python, or other cloud data analysis platforms such as Azure and Tensor Flow are interlinked.

A smart water management system collects water level observation history data and can be provided to the manager through the Web service API or the linked LINE account. Through the water level real-time observation system and development information system, the website of smart water management system can display the instantaneous water level of whole canal, sub canal and storage capacity of each pond and the water storage capacity of each district and the whole assembly. The web system architecture taking the example from Taiwan Tao-Yuan Main Canal (TYMC) shown in Figure 4.5.

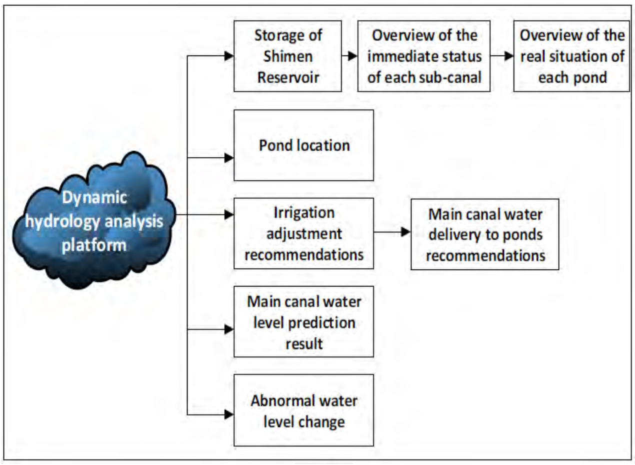


**Figure 4.5.** Architecture schema of smart water management system Chen et al., (2021)

## 4.6 Smart water management

### 4.6.1 On-farm smart water management

Smart water management can be considered as a part of smart agriculture if it is on-farm management. The basic concept of smart water management can be considered using a very simple example. A sprinkler irrigation system which starts irrigation for a given time when soil moisture sensor installed at a certain depth in the root zone measures a threshold soil moisture content. If this system uses multiple soil moisture sensors in the various spots and depths in the field, it can realize more efficient and reliable irrigation. Another example is a water inlet gate which operates with water level sensor in a paddy field. This system can reduce irrigation loss and keep water at a desired level. These cases realize simple feedback loop between irrigation and water management. They do not require telecommunication system. When multiple fields in the district are to be managed in a similar manner with control of pumps or water gates at a higher level, then telecommunication becomes necessary.

### 4.6.2 Smart water management of irrigation systems

When it comes to an irrigation district water management or basin water management, smart water management becomes more complicated. Also, the mode of management is completely different between flood management and drought management.

#### 4.6.2.1 Flood Management

Management needs to be fast adapting and precautionary in case of flood management. To avoid inundation damage downstream, water reservoirs have to release their stored water to reserve enough storing capacity before the onset of the storm. In low lying areas, drainage pumps have to operate before the onset of the storm to lower water level of the canal network. To realize such adaptive management, facility operators must have full access to reliable weather forecast. Runoff simulation models and reservoir operation curves must be prepared in advance to realize such management, too. Such system requires sensor layers, communication layers and computation layers.

#### 4.6.2.2 Smart water management in drought

Compared to flood management, drought management is a slower process which involves consensus-building among water users. In conventional drought management, uniform allocation reduction is declared in times of severe water scarcity, and irrigation rotations are usually introduced. Smarter water management without intervention of water authority is only possible where all water gates and intakes are equipped with flow measurement and flow control devices. Such system is already realized in Australia where water trading has been introduced (Wayne and Son, 2010). When water is scarce, water price goes up and ordinary crop producers sell and their water rights to the market and cattle producers or fruit producers who need to secure water for their sustained production buy these water rights. When irrigation system at all levels can respond to water trading, economically optimum allocation can be realized and impact of drought can be minimized. Such sophisticated system requires full involvement of four layers (sensor, communication, computation and application).

#### 4.6.2.3 Agricultural information system

Water demand at district level can be minimized by the introduction of agricultural information system. Agricultural information system is a user-oriented agricultural management expert system which suggest the best timing of irrigation for maximizing production. Agricultural information system is characterized by combination of high- resolution remote sensing, sensor networks, cloud computing and machine learning to suggest optimum operations to end-users. Machine learning approach finds optimum operations based on data inputs by the end-users through the two-way communication software. The system is aimed at maximizing production at given environment. Although adapting to extreme conditions is not the original design, the system saves water use and increase its capacity to adapt to abnormal conditions.

## 4.7 Can smart water management adapt to climate change?

Adaptive capacity of a smart water management system against extreme weather conditions depends on its original design. Therefore, system design and computations should take extreme climate scenarios into account. Even with that approach, technological sophistication of smart water management alone cannot correspond fully to climate change. Cost-benefit ratio of investment becomes worse if system design is intended to address more extreme scenarios. The CSA approach has a longer time perspective and it has more focus on institutional, cultural and economic aspect of management. Smart water management then becomes conceptually very similar to Integrated Water Resources Management and Integrated Disaster Risk Management in a long run.

Based on the risk assessment framework from previous studies, local and global risks to water resource systems are determined by evaluating vulnerability, exposure, and cost. The subsequent section details the risk factors affecting the water resource system. With the implementation of adaptive management strategies, the resilience of the water resource system significantly improved, achieving up to a 330% increase. Conversely, vulnerability and risk saw substantial reductions, with maximum decreases of 100% and 50%, respectively (Yang et al., 2023).

Historically, many cultures viewed disasters as acts of God, interpreting destruction and injuries as divine punishment for wrongdoing, which overlooked natural processes of global environmental change. Improved understanding of the physical Earth system shifted this perspective, equating disasters with natural hazards like floods and earthquakes. Advances in economic development and education fostered a more scientific and rational approach, prompting governments to respond more logically. Current knowledge shows hazards are not rare; many recur in specific locations, sparking a debate about classifying disasters as “unnatural,” as they result when humans fail to take necessary precautions. This is evident in urban flooding, where poor land use planning and inadequate drainage cause significant loss of life and infrastructure damage. Early civilizations like the Romans and Egyptians practiced flood risk management by situating infrastructure on elevated land and establishing warning systems. However, modern urban settings present more complex challenges. Research advocates shifting from traditional reactive disaster management to proactive disaster risk management. In 1987, the UN designated the 1990s as the “International Decade for Natural Disaster Reduction” to enhance preparedness and mitigate impacts. The 1994 Yokohama Strategy emphasized sustainable development for disaster reduction. The 2005 World Conference on Disaster Reduction established the Hyogo Framework for Action (HFA) to build community resilience, and the Sendai Framework for Disaster Risk Reduction (2015–2030) called for managing risk rather than disasters (Figure 4.6). The disaster management cycle has been a crucial tool for 30 years, outlining phases of prevention, mitigation, preparedness, response, and recovery. Despite criticisms and debates about its effectiveness, it remains in use for its robustness. Current research stresses integrating disaster risk reduction with climate change adaptation, as climate change triggers extreme events not fully accommodated by the current cycle. Alternatives like panarchy have been proposed, but the disaster management cycle continues to be widely used for its simplicity and reliability (Ahmad et al., 2021).

Conceptual explorations of transformation related to climate change mitigation and sustainability are increasingly focusing on cities, with city governments playing a key role in managing risks. These efforts are crucial for addressing urban disaster and climate change risks. Theories on urban low carbon transitions and urban sustainability transformations provide valuable insights for rethinking fundamental changes needed to tackle the root causes and drivers of urban risk. Building on this interdisciplinary approach, scholars should aim to integrate perspectives from various problem domains, academic disciplines, and societal actors to enhance disaster risk reduction and climate change adaptation (Filippi, 2022).

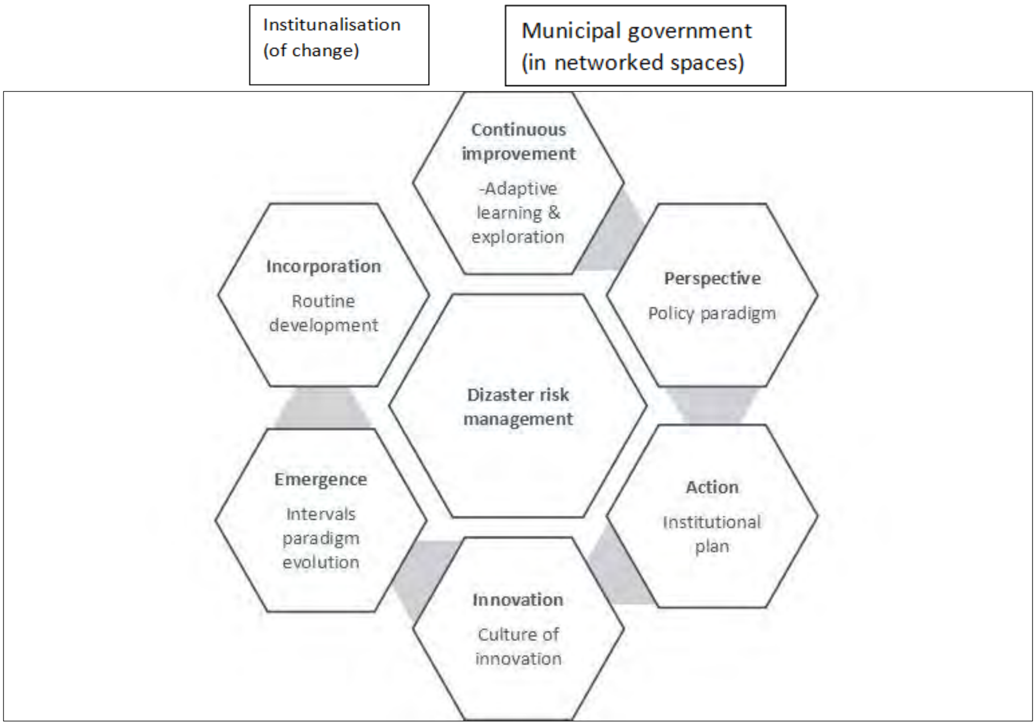


**Figure 4. 6.** Institutional disaster risk management (Filippi, 2022).

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# CHAPTER V
# Impacts of Climate Change on Agricultural Water Management and Adaptation - Case Studies in Northern Taiwan

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### Abstract

Under the threat of climate change, agricultural water usage is more vulnerable compared to other water usages in Taiwan due to the high risk of water shortage during droughts. because it accounts for 70% of all water usage and is always transferred to domestic water usage and industrial water usage. The past drought record can provide the vulnerability information but how much impact on agricultural water usage from the future climate change is still under discussion. The main purpose of this study is to use high-resolution General Circulation Model, GFDL-HiRAM, with RCP8.5 climate change scenario to explore the trend of changing rainfall in northern Taiwan and analyze the impact on agricultural water usage. In northern Taiwan region, the rainfall will slightly increase during the wet season and will decrease during the dry season. However, the flow discharge showed decreasing behavior during both periods under future climate change. The analysis indicated that there would be more water shortage in the dry season (spring and winter). Because domestic water takes priority in water supply, the risk of agricultural irrigation water being affected by climate change will be more significant. According to planned irrigation water demand as input, the maximum water shortage could 40% in spring. Future climate change will worsen the water shortage by increasing the ratio and extending the shortage period well into the late spring. The adaptation strategies related to agricultural water should be taken with a focus on spring impact.

## 5.1 Introduction

Climate change has led to the increasingly frequent occurrences of extreme weather events such as floods and droughts (IPCC, 2012), which pose a serious threat to human life, agriculture and property. Facing drought events, agricultural water usage has always been a controversial issue in Taiwan. This is because agricultural water usage accounts for 70% of all water usage and it is always transferred to domestic and industrial water usage to reduce the overall risk of water shortage during droughts. Under the threat of climate change, such problems may emerge in an endless stream.

The amount of agriculture water demand may change due to some issues. Li et al. (2017) indicated that agriculture water demand slightly decreased due to the reduction in farming areas. Such a reduction is not enough to compensate for the increased demand for domestic and industrial water usage. Agricultural water demand would be affected by the variation of meteorological factors such as rainfall under the conditions of climate change, and agricultural water usage which always be the major portion of the water consumption in Taiwan (Lee and Huang, 2014). Agricultural water accounts for about 60% to 70% of the total water consumption (domestic water, industrial water, and agricultural water) in Taiwan (Council of Agriculture, Executive Yuan, 2015), which is the highest sector of water usage. Some research results pointed out that Taiwan's agricultural water consumption will not change significantly in the future (Lee

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and Huang, 2017), but a large amount of agricultural water consumption still limits the allocation and dispatch of regional water resources (Li et.al., 2017). Under future climate change scenarios, both temperature and rainfall changes may have adverse effects on Taiwan's agricultural water environment. Research has pointed out that under future warming scenarios, an increase in average temperature may lead to increased evapotranspiration in rice fields, thereby increasing agricultural water consumption (Yu et.al., 2002). The study also pointed out the possible trend of future changes in rainfall patterns. The river flow in the rainy season increased significantly, while the river flow in the dry season decreased. This change will seriously affect the current agricultural production environment, especially the first phase of rice planting (between the beginning of January and the end of May) (Chiang & Liu, 2013). According to previous study results, it can be found that under such warming conditions that may lead to an increased in evapotranspiration, but rainfall may also increase in certain periods, resulting in more effective rainfall in the field. However, considering the above variables, the rainfall in the rainy season increases the benefit and will offset the increase in evapotranspiration. However, during the dry season, there is an increase in evapotranspiration while a negative trend in rainfall (Lee & Huang, 2014). Moreover, there is a peak in agricultural water usage during the dry season (November-April) which put extra stress on the system. Based on the above research results, Taiwan is likely to face a more severe challenge to agricultural water resources in the context of future warming scenarios.

In Taiwan, the water demand (agricultural, domestic and commercial) varies considerably between seasons and locations with a continuous annual increase. Droughts and water supply shortages generally occur in the winter and spring seasons. These shortages are caused by the decrease in rainfall patterns in the dry and wet seasons while there is a continuous increase in demand due to population growth, urbanization, and industrial development. These factors increased the challenges for the sustainable stable water supply to every sector of society. Additionally, the frequent occurrences of extreme weather events in recent years have made the water shortage and surplus situation even more extreme. Thus, the impact of climate change on agricultural water must be identified to determine whether current and planned "hardware" (i.e., facilities) and "software" (i.e., adaptation measures) solutions are adequate in response to the foreseeable impacts.

To assess the agricultural water shortage issue, it needs to take the whole water resources system to counts, such as the inflow, the reservoir, the supply to domestic and industrial water demand, and the supply to the irrigation system. Chiang and Liu (2013) used the System Dynamics Modeling software, VENSIM, to build up a water resources system to assess the impact of climate change on paddy field irrigation in southern Taiwan. The water resources system built up in VENSIM has considered the complex system from inflow and reservoir to the supply to domestic, industrial and agricultural consumption.

## 5.2. Study Area

To assess the climate change impact on agricultural water usage in Taoyuan, northern Taiwan, the Shihmen and Taoyuan irrigation district of Taoyuan city were chosen as a study area. Shihmen reservoir with the inflow of the Dahan River is the main source of water supply to the study site as shown in Figure 5.1. The total area of Taoyuan irrigation district and Shihmen irrigation district are 247.21km$^2$ and 120.85km$^2$, respectively. Most of the water demands by these two irrigation districts are for paddy irrigation. The planned irrigation water demands for two irrigation districts are shown in Figure 5.2. Taoyuan and Shihmen irrigation districts have only 62% and 88% Irrigation Satisfaction Rates (ISR, referring to actual water supply divided by planned water demand), respectively (Zheng, 2016). It means that there will be a huge water shortage if the Shihmen reservoir is going to fully supply the whole irrigation demands. The Shihmen irrigation district is supplied with Shihmen major ditch where the intake is located upstream of the Shihmen reservoir, while the Taoyuan irrigation district is supplied with Taoyuan major ditch where the intake is installed downstream of Shihmen reservoir.

The Shihmen reservoir has a total of 763 km$^2$ watershed area but needs four times refilling up in a year to supply water in the whole system. It not only supplies water for irrigation but also supplies water for domestic and industrial use. The intake of water for domestic and industry is from

Yuanshan weir, located downstream of Shihmen reservoir. The domestic and industrial water consumption is about 716× $10^3$ $m^3$/day and 545× $10^3$ $m^3$/day, respectively. Because of the small watershed of the reservoir and huge water demand in this area, the water supply system is extremely sensitive to the climate. If the precipitation is less in any season, the warning of water shortage might alarm, and agriculture might bear the brunt of water scarcity victims.

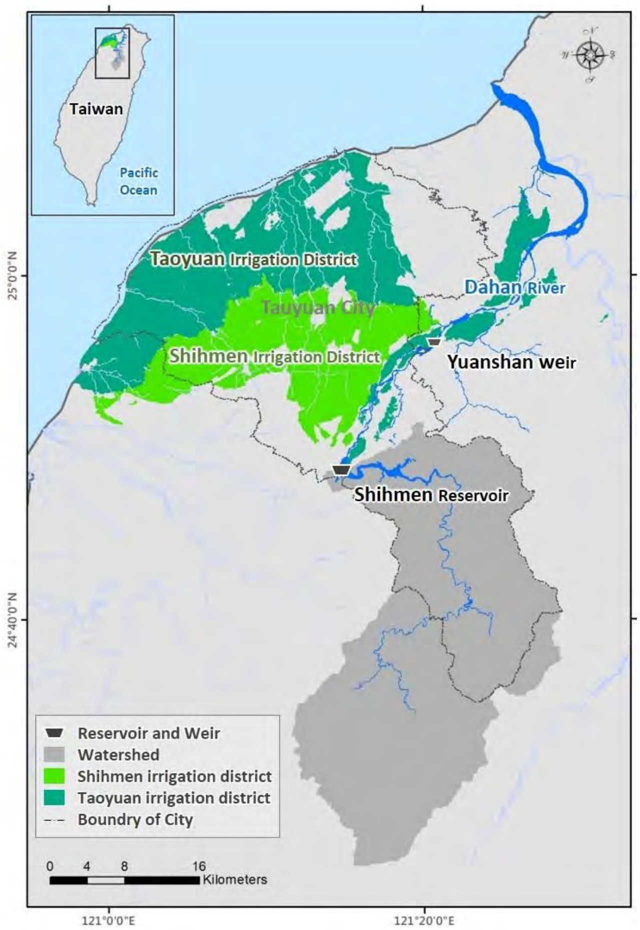


**Figure 5.1.** The location of the study area with one watershed, two irrigation districts and the main facilities of the water supply system

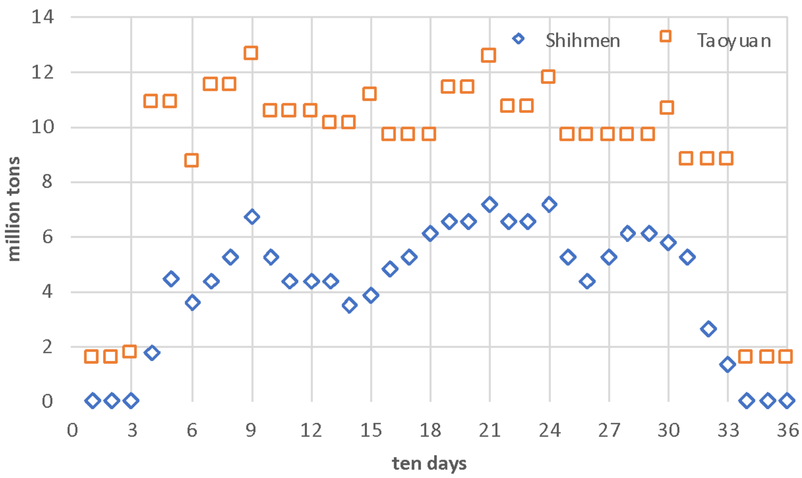


**Figure 5.2.** Water demand in average by two irrigation districts

## 5.3 Data and methodology

### a. General Circulation Model and Scenarios Description

The Geophysical Fluid Dynamics Laboratory-High Resolution Atmospheric Model (GFDL-HiRAM) with its ability in resolving severe weather systems such as tropical cyclones, has been proved powerful in assessing the impacts of climate change on extreme weather. The HiRAM GCM model was selected to simulate rainfall in the current climate and the projected rainfall in 2040-2060 under the RCP8.5 warming scenario.

### b. Bias Correction

Despite the good performance of HiRAM in simulating the characteristics of regional distribution of rainfall, it does not realistically simulate the detailed distribution of rainfall in Taiwan. Therefore, the simulated precipitation data in the current and future climate were subjected to bias correction. Bias correction has adjusted the simulated rainfall to exhibit realistic characteristics. The simulated spring rainfall (February to April) by HiRAM before bias correction shows maximum rainfall in eastern Taiwan (Figure 3(a)), while the observation rainfall exhibits the major rainfall area in northern Taiwan with maximum along the northern coast and over the western slopes of mountainous areas in Hsin-Chu, Miao-Li, and Nantou (Figure 3(c)) as indicated by the gridded rainfall data provided by the Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP). Bias correction was applied to the HiRAM rainfall to adjust the model biases. Bias-corrected spring rainfall shown in Figure 3(b) properly reproduce the detailed characteristics of observed rainfall. Note that bias correction was applied to model rainfall for all seasons and the results were all as realistic as the one shown in Figure 5.3.

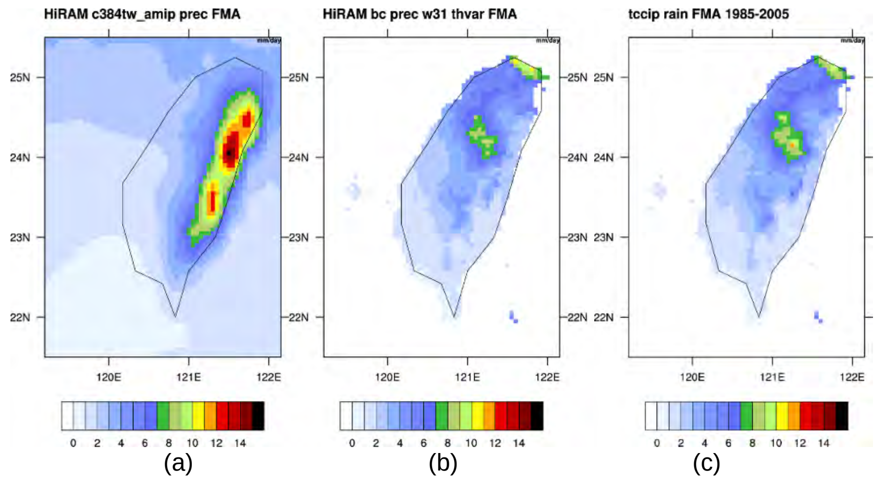


**Figure 5.3.** Precipitation of HiRAM before (a) and after (b) bias correction. (c) shows the observation of spatialized precipitation provided by TCCIP. All data is the average from February to April during 1985 - 2005

### c. Hydrological Model for Water Watersheds

This study used the water flow sub-model in the Generalized Watershed Loading Function (GWLF) and a pollution transmission model developed by Cornell University for water watersheds (Hath et al., 1992) to simulate the water flow of watersheds. GWLF simulates water flow by determining the hydrological variables (and their equilibria) of water watersheds. In the simulations, the total water flow consists of the surface runoff and underground water discharge. The water in water watersheds comes from precipitation, which either infiltrates into the soil or becomes surface runoff (and flows directly into water bodies) when it reaches the ground. Infiltrated precipitation replenishes the water content of unsaturated aquifers. Once unsaturated aquifers become saturated and the water within exceeds field capacity, the excess water, pulled by gravity, leaks further downward to shallow aquifer layers. When shallow aquifer layers become saturated, the water is discharged as underground water. Surface runoff and underground water discharge combine to form the overall water flow of a water watershed.

### d. Water Resource System Dynamic Model

This study used the system dynamics model, VENSIM, to model the water resource systems of study area. The system dynamic models of the water resource system to Northern Taiwan was validated (Tung et al., 2014) and added on new facilities to simulate in this study. TaiWAP (Liu et. al, 2009), climate change integrated assessment model was used to simulate future variations in river flows, generate water-demand time series data, and integrate the simulation results obtained by the water resource system dynamic model to simulate and investigate the water supplies in the study area.

## 5.4 Hydrology and Water Supply Analyses

To examine the impact of climate change on agricultural water, we used the outputs of HiRAM to obtain temperature and precipitation data in the Shihmen watershed from 1986 to 2005 and from 2040 to 2060. Subsequently, the data were substituted into the GWLF hydrological model to simulate the inflow discharge of Shihmen reservoirs. Next, the water supply and demand data for northern Taiwan were entered into Vensim to develop the water resource system dynamics model for simulating the conditions in northern Taiwan. The planned development of water supply and demand have given social and economic development up until 2031 and climate change between 2040 and 2060 were also considered.

### a. Variation Analysis on the Current and Future Hydrology

Accordingly, for the hydrological impact assessment, this study analyzed the rivers supplying water to the Shihmen Reservoir (i.e., the Dahan river). Figure 5.4 shows precipitation changes for the future on the watershed in 1986–2005 and 2040–2060. The watershed exhibited the trend with precipitation increasing in the wet season (May to October) by 4% and decreasing in the dry season (November to April) by 24% on average. Annual total precipitation thus exhibited a decreasing trend of 5%.

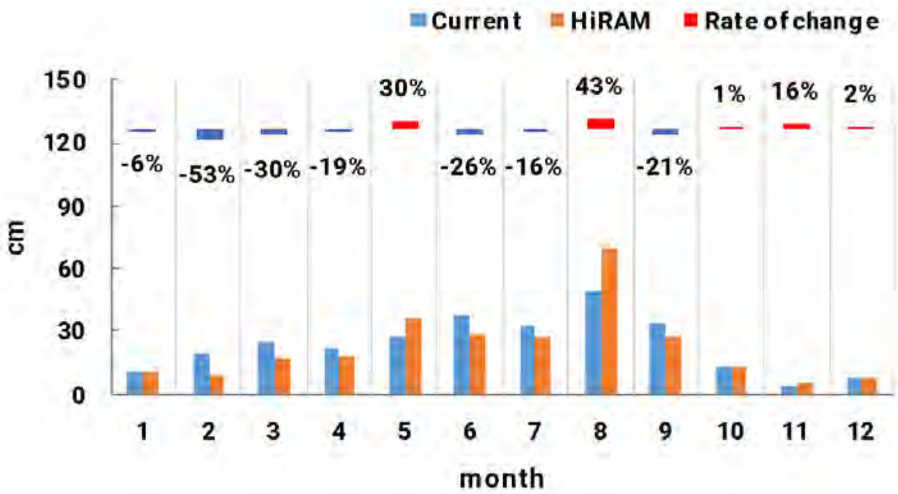


**Figure 5.4.** Current and future precipitation analyses in Dahan River watershed

Figure 5.5 shows the changing rate of discharge of the Dahan River watershed that supply water to Shihmen reservoir in northern Taiwan from 1986 to 2005 and from 2040 to 2060. The result exhibited that water flow decreased in the rainy season by 5% and also decreased in the dry season by 44% on average. Annual total water flow thus exhibited a decreasing trend of 16%.

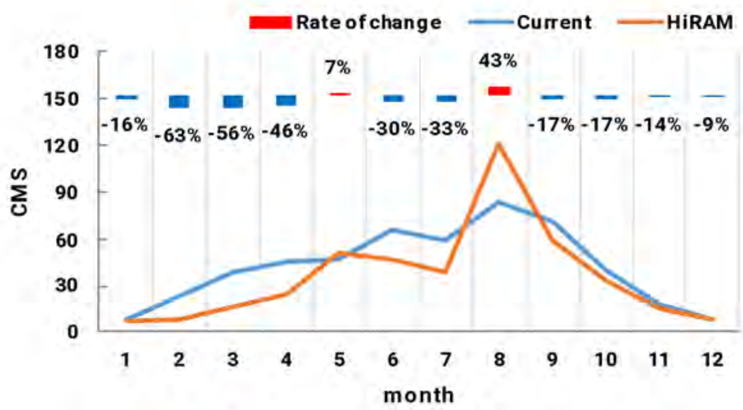


**Figure 5.5.** Current and future flow discharge analyses in Dahan River watershed

### b. Analyses of the Current and Future Agricultural Water Shortage

This study selected the Shihmen and Taoyuan irrigation districts as case study to analyze the climate change impact on agricultural water in Taiwan. Both irrigation districts receive most of their water from the Shihmen Reservoir, which allowed this study to examine the effects of implementing water resource projects on the risk of agricultural water shortage. The simulation results (Figure 5.6 and Figure 5.7) revealed that the irrigation in the first crop period, which began in the spring, increased the water shortage ratio because it used water during a period when the irrigation demand was high and the water supply was insufficient. The water shortage could be higher than 40% in spring. Future climate change will worsen the water shortage by increasing the ratio and extending the shortage period well into the late spring.

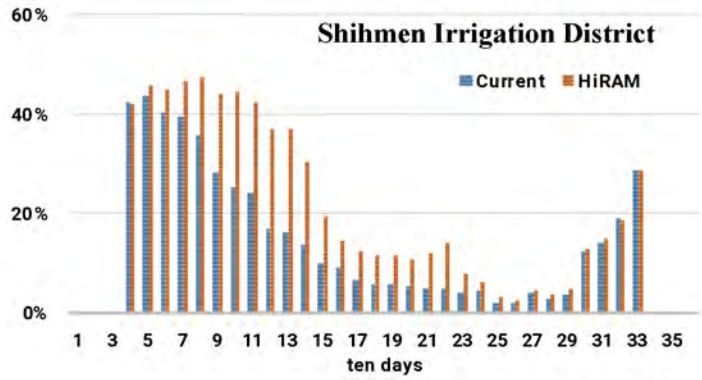


**Figure 5.6.** Agriculture water shortage rate to current and future climate change situation in Shihmen irrigation district

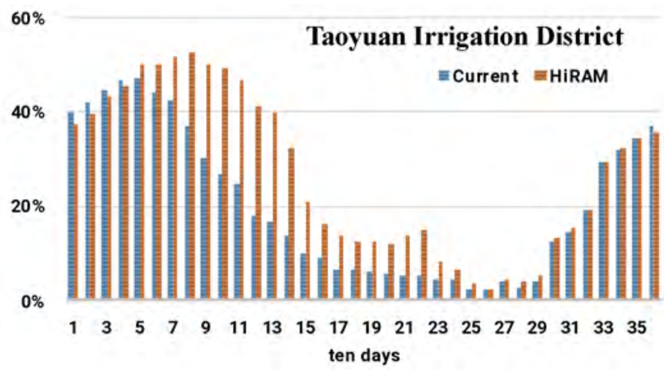


**Figure 5.7.** Agriculture water shortage rate to current and future climate change situation in Taoyuan irrigation district

In the simulations, the planned irrigation water was set depending on the level of water demand. Because the simulated water demand was higher than the actual water demand, which varied according to the implemented irrigation projects, the actual water shortage ratios were lower than those obtained from the simulations. However, the risk of agricultural water shortage is considerably higher than that of public water shortage because future water resource projects mostly take domestic water consumption as a priority. Thus, the effect of climate change on the agricultural water shortage rate is anticipated to be higher than that of the public water shortage rate.

Using the average water shortage rate of each ten days and the planned water demand to estimate the annual water shortage, the Shihmen irrigation district, Taoyuan irrigation district and the total annual agricultural water shortage can be obtained as shown in Figure 5.8. The annual agricultural water shortage in the simulation of the current situation is 20 million tons and 56 million tons in Shihmen and Taoyuan irrigation district respectively. Under the impact of climate change, the annual agricultural water shortage increased to 71 million tons and 81 million tons in Shihmen and Taoyuan irrigation district respectively. The total annual agricultural water shortage under climate change impact reaches 153 million tons, which is equivalent to 0.78 times the storage of Shihmen reservoirs (197 million tons). Compared with the current situation, climate change will double the water shortage for agricultural water in total. Such a water shortage is equivalent to an increase of 420,000 tons of water supply per day to meet.

These facts and Figures above represent the water shortage that may be caused if all the planned water consumption of agriculture is to be supplied. However, the number of actual Irrigation Satisfaction Rate (ISR) reveals that the Shimen reservoir cannot fully supply all the water under the conditions of preferentially meeting domestic and industrial water. The simulated ISR which is annual irrigation water supply divided by annual irrigation water demand as shown in Figure 5.9. The actual Irrigation Satisfaction Rate of Taoyuan and Shihmen irrigation districts are 62% and 88% respectively, which can be totalled as 70% after calculation. The value of a total 84% in the simulation result is higher than the actual Irrigation Satisfaction Rate in the study area. This is because the actual amount of water supply for irrigation is based on the water supply conditions at the time. The fallow method allows the reservoir to have enough water to meet the water demand in each period. The operation process is based on extreme drought conditions to determine the amount of fallow. Therefore, compared to the reduction in the actual water shortage reflected in the model simulation, the actual fallow water amount will be much greater than the simulated water shortage. From the simulation results of the total ISR of the two irrigation districts, it can be seen that under the influence of climate change, the ISR will be reduced by 16% in the future, which means that the rice field under Shihmen Reservoir must have more fallow in the future to meet the needs of the entire region. Unless there are adaptation strategies and methods that can increase water supply in this area.

## 5.5 Adaptation Case in Taiwan - Direct Seeded Rice on Dry Field

The frequent water shortage for agriculture use has an impact on the rice first crop season in Taiwan. According to the announcement from the Ministry of Agriculture, there have been 7 times of water shortage from 2002 to 2018. In 2004, a total of 65,385 hectares of farmland in five irrigation areas, including Taoyuan, Hsinchu, Miaoli, Chiayi, and Tainan, were fallowed due to water shortages. In 2015, five irrigation areas, namely Taoyuan, Hsinchu, Miaoli, Taichung, and Chiayi, experienced fallowing due to water shortages, with a total fallowed area of 43,659 hectares. The fields of Xinfeng Township in Hsinchu County were irrigated by Shihmen reservoir, and it located at the edge of irrigation area. The demand for irrigation water in the first crop season might be even tighter. It could turn into an agricultural water shortage in Shimen Irrigation District. Therefore, TCCIP project team implemented the demonstration case of direct seeding technology in this region.

Direct seeding is to sow seeds directly into the field without nursing seedlings. It can be used as a method to replace transplanting or to complement with each other. Its advantages are that the root system will be more complete, more tolerant to stress, and lower cost. Although dry field direct seeding requires more precautions in the early stage, such as soil texture, cultivation technique, weed management, etc., as it grows to about 3-leaf stage, the method follows the conventional way of cultivation and management methods, and can achieve this case to avoid water use during dry seasons. While the direct seeding also could reduce the labours during nursery seedling, this study cooperates with experimental producer with direct seeding to meets producer requirements.

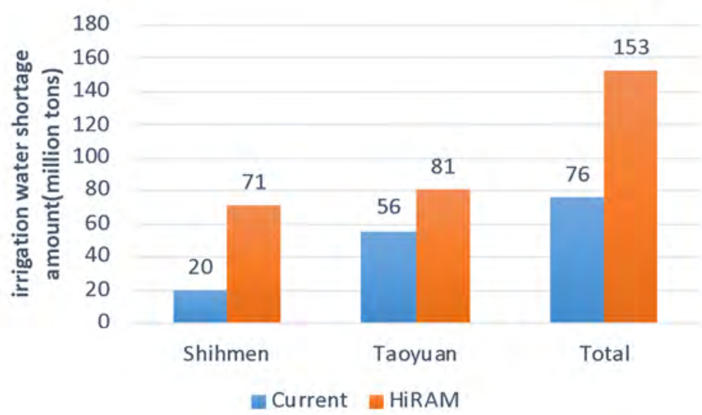


**Figure 5.8.** Irrigation water shortage amounts of two irrigation districts and total summation

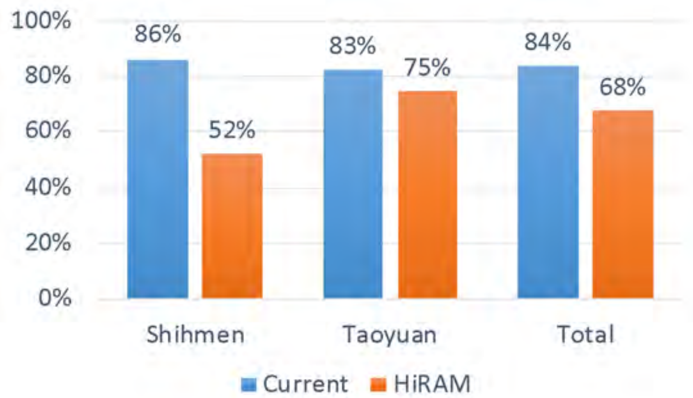


**Figure 5. 9.** Irrigation Satisfaction Rate of two irrigation districts and total summation

This study used the rice variety Tainan 11 (TN11) to conduct the direct seeding on dry field, which planted during late December in 2018 and 2019 in Xinfeng Township of Hsinchu County. The plow sole of rice field was broken by the deep-plowing machine, and the machine drill pre-treatment seed into the field. The conventional way was planted during mid-February.

In order to cooperate with the implementation of scientific research in stakeholders, discussions with experts, interviews with local producers. Therefore, suitable adaptation options are listed to reduce the amount of irrigation water used in the early period. Also following the crop transfer policy and adjusting the planting time, we would like to plant forage corn in the second crop season and present this cropping system as a demonstration (Figure 5.10).

Here is the summary of the adaptation case of Direct Seeded Rice on Dry Field in Taiwan:

1. Taking 2019 as an example, after direct seeding of rice was sown on December 23, 2018, it gradually germinated from the field around the beginning of January. In the conventional method field, the date of transplanting was on February 16, 2019.

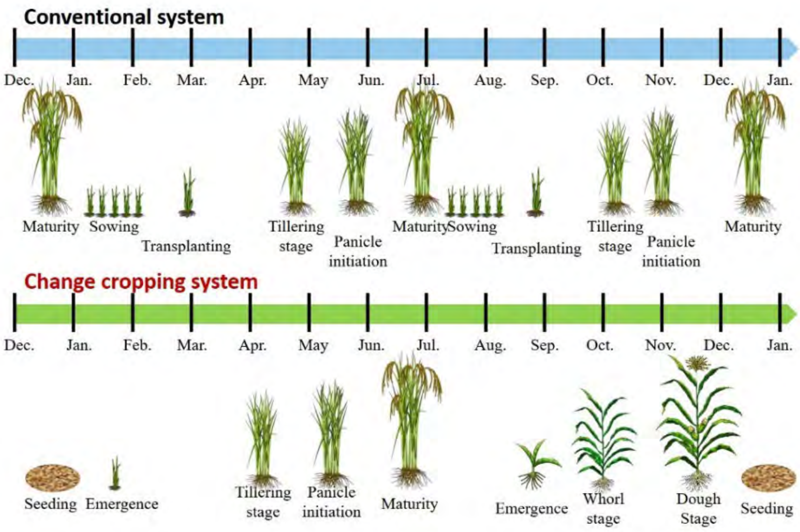


**Figure 5.10.** Schematic diagram of the conventional and new cropping system.

2. Due to the physical damage to the root system after transplanting, the growth period of transplanted rice is 7-10 days later than that of direct seeding rice. However, when the transplanted rice has passed the live period, the growth rate is equivalent to that of direct seeding rice until the harvest period, so the growth stage of transplanting is about one stage slower.
3. The treatment of direct seeding took to later growth stage at the same date due to early sowing. Compare the two treatments, the yield of direct seeding method was about 8.1% less than the transplanting one. The grain quality characters of direct seeding treatment have no significantly difference.
4. The rice seeds directly germinated and grown in the soil, which mainly relies on the rainfall and the management of the fertilizer are the same as conventional way, it might save about 383 metric tons of water per hectare during the land preparation. Compared with the transplanting way, the method, direct seeding on dry field, could save the seedling cost, as well as the irrigation and operation procedures.
5. In the study, the method could be regarded as one of the adaptation options in case of encountering unfavorable factors of unstable irrigation water supply, lack of labor force, and impact of climate change.

## 5.4 Conclusion

The main purpose of this project is to use the results simulated by the GFDL-HiRAM to explore the impact of climate change on agricultural water in northern Taiwan through the hydrological model and water supply system dynamics model. We conducted the hydrological impact assessment and the water supply simulation of Shihmen reservoir water supply system and evaluated the water shortage risk under the current and future climate change situations.

The results of the precipitation analysis under HiRAM_RCP8.5, scenario (baseline: 1986–2005) and (mid-century: 2040–2060), showed that rainfall will increase slightly in the wet period and decrease in the dry period. The inflow discharge of the reservoir has a different changing trend for the future. It will decrease in the wet as well as dry period. It is obvious that climate change will impact the water resources due to less inflow in both wet and dry season. Through the water supply system dynamics modeling, it is more clear how climate change will impact agricultural irrigation water. In the study area of Taoyuan and Shihmen irrigation districts, the current Irrigation Satisfaction Rates are only 62% and 88% respectively. Through the model simulation, the irrigation shortage rate as high as 40% in spring can get with taking all the planned irrigation water as the simulation demand condition. The irrigation water shortage rate will be higher in spring due to climate change impact in the future. The total irrigation water shortage will be double under climate change in the future. The Irrigation Satisfaction Rate will be reduced by 16% in the future, which means that the rice field under the Shihmen reservoir supply system must have more fallow in the future to meet the needs of the entire region. Under the result of the simulation, the adaptation strategy should better be a focus on the spring impact.

## Acknowledgement

This study is supported by the Academia Sinica and Ministry of Science of Taiwan under Contract No. AS-105/106-SS-A02 and by the Ministry of Science and Technology of Taiwan under Contract No. MOST 109-2621-M-865-001 for the project of “Taiwan Drought Study: Change, Water Resource Impacts, and Risk Perception and Communication” and “Taiwan Climate Change Projection Information and Adaptation Knowledge Platform”, respectively.

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# CHAPTER VI
# Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Pakistan

Fiaz Hussain[10], and Ray-Shyan Wu[11]

**ABSTRACT**

Climate change is now an undeniable reality. It is vital for all of us to work together to tackle this issue. The analysis of meteorological data presented in this study indicates clearly that the climate of Pakistan is getting warmer, with some regions facing a faster increase in average annual temperature. The rate of change is 0.74°C for the period 1961–2018 with highest increase in southern part (+0.32°C to +0.50°C per decade) than northern part (+0.02°C to + 0.10°C per decade). Since 1961, average annual rainfall has increased (19%); but for the most part, that increase occurred in 1961–89, while the years after 1990 generally showed a decline in rainfall. There is a decreasing trend (-0.54 mm/day) in annual precipitation under RCP4.5 while increasing trend (0.9 mm/day) in precipitation under RCP8.5 for 2011 to 2100. A 1°C average increase in temperature increases agricultural water requirements by about 5% by 2050, while a 3+°C change in temperature increases crop demand by 6% by 2025 and 12–15% by 2050. It is important to note that central and southwest region (Punjab Balochistan) showed decreasing trend in evapotranspiration. The research findings emphasis that the scope of policy related to climate change adaptation should focus on the strategies at community and farm level for significant development outcomes. While analysis has identified some of the broad changes underway in Pakistan's climate, the findings also point to the critical need to take into account regional and local trends.

***Keywords***: Observed Climate Changes, Future Projections, Temperature, Rainfall, Flow, ET, Adaptation

## 6.1. Introduction

Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2018) and the outlook for Asia is particularly troubling. Pakistan is a "water-stressed" country and its water resources are considerably vulnerable to climate change. Precipitation trends over the country have increased significantly (25 percent, or 63 mm) over the country during the 20$^{th}$ century while temperature trends also showed pattern of warming (+0.6°C) (Sheikh et al. 2009). Annual historical inflows on the Indus have been declining over the period of 1937-2011 (Yu et al., 2013). Studies show that crop yield declines with the rise in temperature. For example, a 1ºC rise in temperature would result in wheat yield declines of 5%-7% (Aggarwal and Sivakumar 2011). In semi-arid regions of Pakistan, the rice yield could decline by 15% from 2012 to 2039, 25% from 2040 to 2069 and 36% from 2070 to 2099 if the rise in temperature continues (Ahmad et al. 2013). The increase in temperature along with decreasing rainfall affects crop production. If rainfall decreases by 6%, net irrigation water requirements in Pakistan could increase by almost 29% (Spijkers, 2010).

The climate scenario assessment approach can be used for climate impact assessment. A modest amount of climate modelling using multiple model ensembles under different scenarios has been undertaken at the regional level to inform analysis of how Pakistan's climate will change in the future; subnational-level projections are largely absent (Salik et al., 2015). Generally, the model outcomes suggest that the observed trend of rising temperatures will continue over the remainder of this century. Pakistan's mean annual temperature is projected to rise by 3.8°C

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(within a range of 2.1°C to 5.1°C) by 2100 (Climate Service Center, 2013). Other studies suggest an increase of 1.4°C to 3.7°C by the 2060s, and a potential increase to 6.0°C by the 2090s (GFDRR, 2014). This increase will not occur uniformly across the country or on a seasonal basis, with greater warming expected in northern regions and during the winter (GFDRR 2011; World Bank, 2015).

Therefore, to minimize adverse impacts of climate change on water resources of Pakistan, it is imperative to implement two approaches of adaptation and mitigation, simultaneously. Salient features are integrated management water resources management, watershed management, water conservation, efficient design of water storage and distributions & supply system. This study overviews recent advances in understanding the impact of climate change on agricultural water management and water resources of Pakistan, and presents certain agricultural adaptation strategies that are determined in the literature studies.

## 6.2. Methodology

### *6.2.1* Study area

Pakistan is situated on the western edge of the monsoon region in South Asia. Its major topographical regions include (a) the western offshoots of the Himalayas, which cover its northern and northwestern parts and in which the highest peak, K-2, rises to 8,611 meters above sea level; (b) the Balochistan plateau in the southwest of the country; (c) the Indus Plain, stretching across most of the eastern and central part of the country; and (d) the Potohar Plateau and Salt Range, situated between the Indus and Jhelum rivers in northern Punjab. The climate varies from arid to semiarid. Rainfall occurrence is due to monsoon disturbance in July to September and western disturbances system in January to March that shows large temporal and spatial variability. In most parts of the country, normal annual rainfall is less than 400 millimeters (mm). However, the southern slopes of the Himalayas, sub-mountainous northern region of AJK, northern Punjab, and parts of northern KP typically receive 800–1,800 mm of rainfall every year. The annual normal mean temperature ranges from 8°C in the north of the country to 28°C in the southernmost areas.

### *6.2.2* Data acquisition and methods

In this study, we have utilized long-term data generated at 55 observing stations in Pakistan for multiple climate parameters to assess changes in the country's climate over the period 1961–2018. The yearly data of rainfall and mean temperature was acquired from Pakistan Meteorological Department (PMD). Key climate change trends (temporal and spatial) are identified at the national level. The spatial patterns were plotted using IDW interpolation method in GIS environment. We use 30-year averages, computed for the period 1961–90, termed "reference normal," as the benchmark for observed climate change assessment (WMO 2017). The river inflows data of five major rivers (Indus, Jhelum, Chenab, Ravi and Sutlej) was acquired from Surface Water Hydrology Project-Water and Power Development Authority (SWHP- WAPDA) for 1961-2016 on yearly basis. The linear trend analysis was adopted to identify the increasing or decreasing trends of river inflows. The spatial patterns and trend analysis of potential evapotranspiration (ETp) over Pakistan was done using the gauge-based gridded ETp data of Climatic Research Unit (CRU). The spatial patterns of the changes in ETp on annual basis are investigated for the period 1967–2016. The CRU data was used because it offer longer temporal span that can be used easily to find change in ETp. Previous studies testified performance of CRU data compared with other gridded data over Pakistan (Iqbal et al., 2019; Khan et al., 2018). Afzaal et al. (2009) showed correlation coefficients above 0.9 between PMD and CRU data for the period 1960–2000.

For the future projections of temperature, rainfall, river flows and evapotranspiration, this paper is primarily based on literature studies (Bokhari et al., 2017; Chaudhry, 2017; GOP, 2013; Parry, 2016; Amir and Habib, 2015; Yu et al., 2013; Khan, 2011). Due to the nature of research, the emphasis and reliance was given to the secondary sources. The documents and reports were obtained from Ministry of Environment and Climate Change; PMD (Pakistan Meteorological

Department); WAPDA (Water and Power Development Authority) and Pakistan Agriculture Research Council. In addition, the reports, documents, policy briefs obtained different NGOs working in Pakistan. The literature cited was selected based on a critical review of publications of greatest relevance to Pakistan using Google Scholar, Web of Science, Scopus, and Science Direct (Hussain et al., 2020).

## 6.3. Results and Discussion

### 6.3.1 Present Climate and Observed Changes

#### *a. Spatio-temporal trends of temperature*

Figure 1 indicating warming trends since 1960s. The rate of change is 0.74°C for the period 1961–2018. The rise in the latter half of this period is very prominent (0.67°C). The highest increase is seen in the southern cities of Quetta (in Balochistan), at +0.50°C per decade, followed by Karachi (in Sindh), where the annual mean temperature has risen by +0.32°C per decade. The northernmost cities, Muzaffarabad (in AJK) and Gilgit (in GB), have experienced the least increase at +0.02°C per decade and+ 0.10°C per decade, respectively. Figure 6.1-2 shows the spatial pattern of mean annual temperature changes. Warming is apparent over almost the entire country, and it is greater over major parts of Balochistan, in southeastern and southwestern Sindh, and in eastern parts of Punjab.

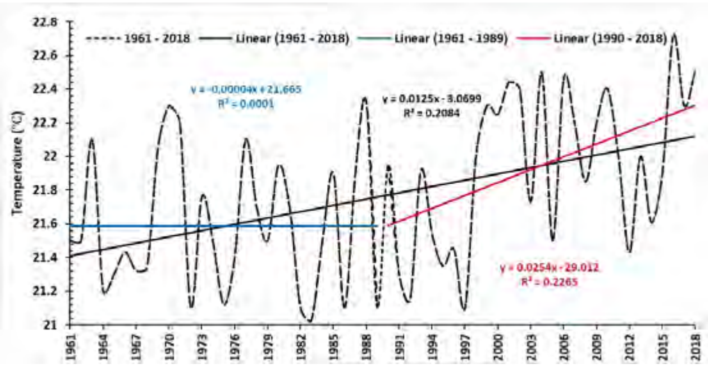



**Figure 6.1.** Annual temperature trends in Pakistan, 1961–2018, 1961–89, and 1990–2018

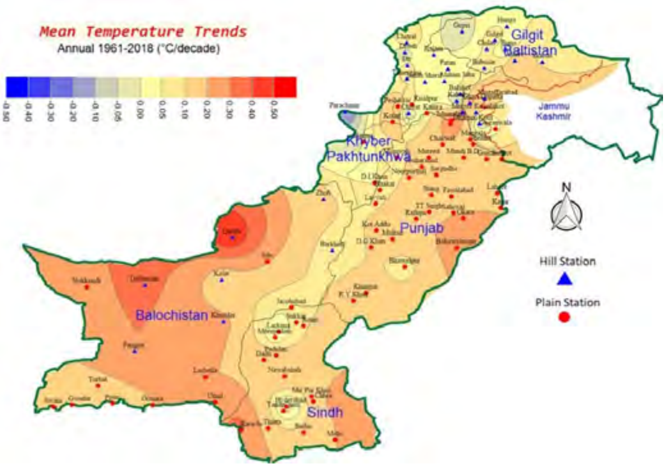



**Figure 6.2.** Spatial distribution of mean annual temperature trends, 1961 to 2018 (°C/decade)

### *b. Spatial-temporal trend of rainfall*

For the country as a whole, average annual rainfall shows an increase of 19% over the period 1961–2018. Average annual rainfall increased in the earlier period but shows a decreasing trend in the latter half (Figure 6.3). The tendency of rainfall on regional level is somewhat mixed. Annual total rainfall has increased the most in Peshawar (+39 mm/decade), followed by Islamabad (+37 mm/decade) and Lahore (+26 mm/decade), while it has decreased in Muzaffarabad (–19 mm/decade) and Karachi (–17 mm/decade). Figure 6.4 illustrates the spatial distribution of annual rainfall trends and shows that in most parts of the country, there is either no change in average annual rainfall or a slight increase. However, a decrease in annual rainfall is evident in the southernmost parts of the country and also in the northeastern region of AJK and adjoining areas.

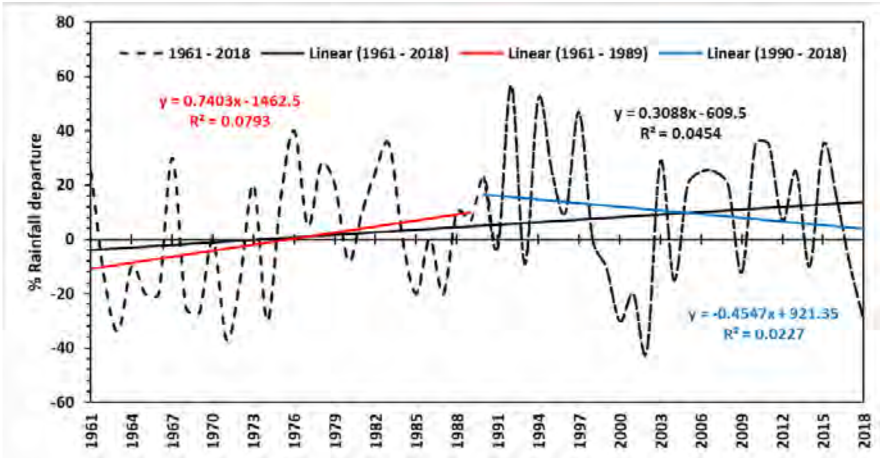



**Figure 6.3.** Annual precipitation trends in Pakistan, 1961–2018, 1961–89, and 1990–2018

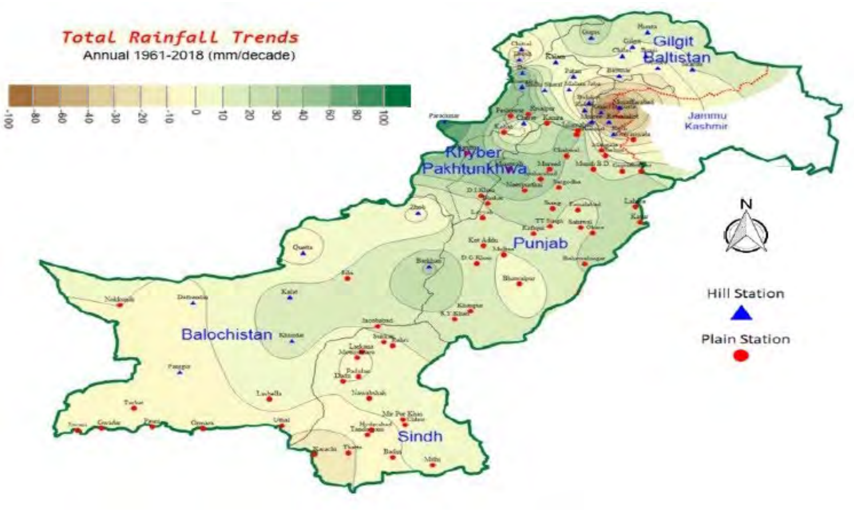



**Figure 6.4.** Spatial distribution of mean annual rainfall trends, 1961 to 2018 (mm/decade)

### *c. Temporal trends of major river flows*

Stream flow is the major source of irrigation. A plot of annual inflows from the Indus main stem indicates a significant decline over the period of record (Figure 6.5). The Jhelum yields an average of about 23 MAF per year while Chenab delivers about 25 MAF per year at the Marala Headworks. Figure 6.6 indicates the rapidly declining rate of discharge on the Ravi and Sutlej. Ravi inflows at Balloki Barrage display a step function beginning at roughly eight MAF per year in the 1970s, dropping to four or five MAF until 1999, and less than two MAF thereafter. Sutlej River inflows at Sulemanki Barrage also declined dramatically in the 1970s, though with a different pattern than occurred on the Ravi. The Sutlej displays much higher variability than the Ravi. Overall, annual inflows appear relatively stable over the period of record. In contrast with the other two rivers, the Chenab's recent decade of flows are most often below the mean, which raises water concerns downstream.

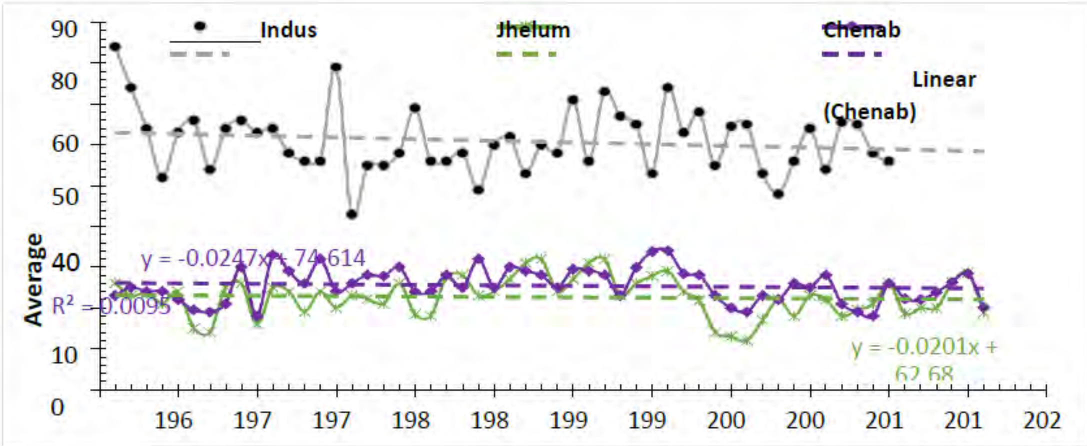



**Figure 6.5.** Annual inflows: Indus, Jhelum, and Chenab Rivers. Plotted from WAPDA data.

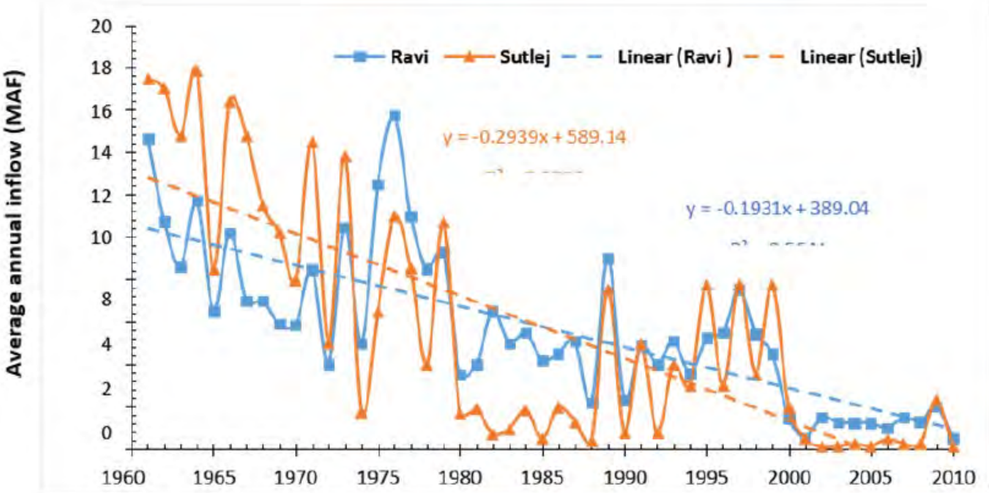



**Figure 6.6.** Annual inflows: Ravi and Sutlej Rivers. Plotted from WAPDA data.

### *d. Potential Evapotranspiration (ETp)*

The spatial patterns of mean annual ETp from 1967 to 2016 indicating 657 mm in the north to 2540 mm in the southwest (Figure 6.7). The southern region has ETp between 1610 and 1910 mm while central region of the country has ETp between 1290 and 1600 mm. The southwest and the southeast has ETp between 1920 and 2230 mm, respectively. Southwest corner showed highest ETp (2240 – 2540 mm), while lowest (657-971 mm) in north. The spatial patterns in trends of ETp show changes between 1.65 and − 1.59 mm/year (Figure 6.8). The southern, southwest and southeast and extreme north regions showed increasing trend ranging from 0.01 to 1.65 mm/year while most of the area (central and extreme southwest region) has negative values ranging from − 0.19 to − 1.59 mm/year. It is important to note that ETp of central and southwest region (Punjab, Balochistan) showed is decreasing.

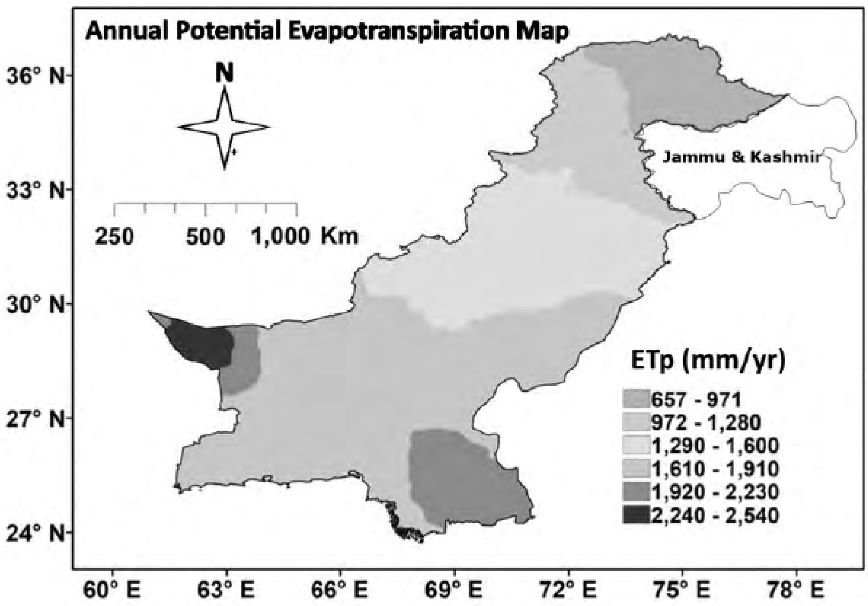



**Figure 6.7.** Spatial patterns of mean annual potential evapotranspiration of Pakistan during 1967 to 2016

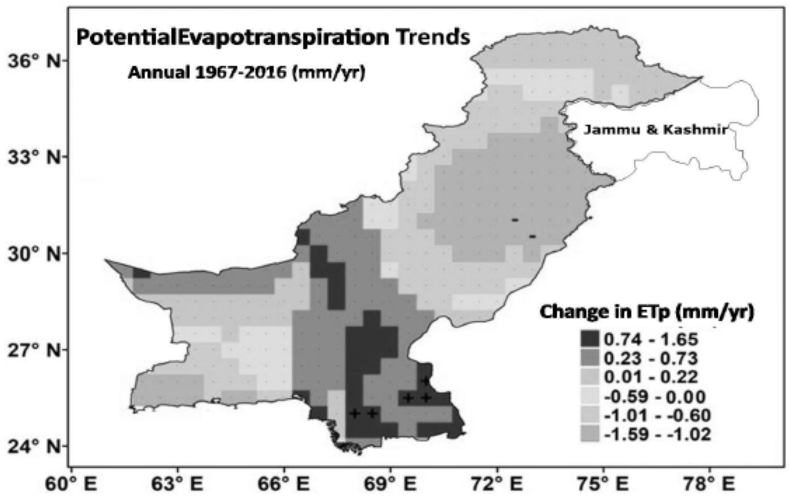



**Figure 6.8.** Spatial patterns of the changes in annual ETp of Pakistan

### 6.3.2 Future Climate Projections in Pakistan

#### *a. Future Trends of Temperature and Precipitation under RCPs Scenarios*

According to Pakistan Meteorological Department (PMD) data for the four different General Circulation Models, using the World Climate Research Program-Coupled Model Inter Comparison Project Phase-5 (CMIP5), there is a significant positive trend in annual mean temperature of 3°C to 3.5°C for the period 2011-2100 under RCP4.5 while under the RCP8.5 scenario, the increase in annual mean temperature is 8.3°C. There is a decreasing trend (-0.54 mm/day) in annual precipitation under RCP4.5 while increasing trend (0.9 mm/day) in precipitation under RCP8.5 (Figure 6.9). The rainfall is highly variable in both spatial and temporal domains.

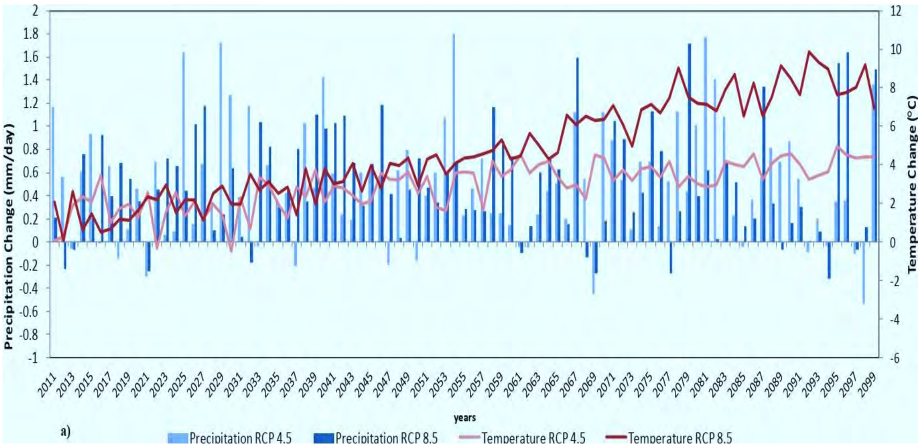
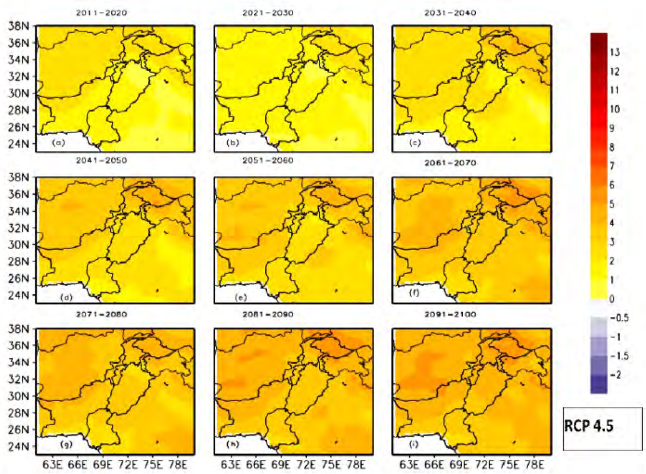


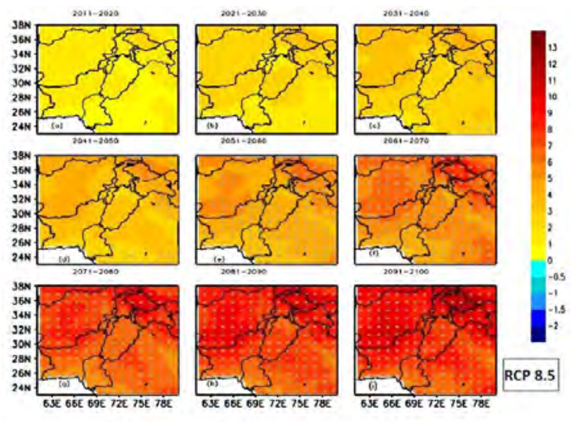

**Figure 6.9.** Pakistan's Mean Annual Temperature and Precipitation Deviation Projections during the 21st Century Using Two Different Emission Scenarios

According to the model, spatial patterns of temperature and precipitation have similar behavior. RCP 4.5 shows an overall effect of higher warming ranging 3°C to 4°C over the northern areas including GB, Kashmir and Northern part of KPK as compared to southern parts of the county. The southern parts show warming of 2°C to 3°C with a slightly higher rate over Balochistan (Figure 6.10a). In RCP 8.5 however, the warming effects are more enhanced with an increase of 3°C to 8°C over the northern areas during the first half of the 21st century and up to 11°C by the end of the 21st century. Southern parts of the country also show higher rates of warming under this scenario ranging 5°C to 7°C by the end of the century (Figure 6.10b)

The changes in annual mean precipitation under both RCP scenarios show an overall increase in precipitation of 2 mm/day to 3 mm/day over the domain. Regions showing a greater change in temperature also show an increase in precipitation. RCP4.5 shows an increase of 4 mm/day in annual mean precipitation with a shift in maxima toward the northeastern part of the country until 2050. After 2050, the precipitation pattern shifts toward northwest until the end of the 21st century with the same magnitude and wet situation in the southern region. A similar pattern is seen in the RCP8.5 scenario but with less magnitude of up to 2– 3 mm/day and more spatial spread (Figure 6.11a and 6.11b).

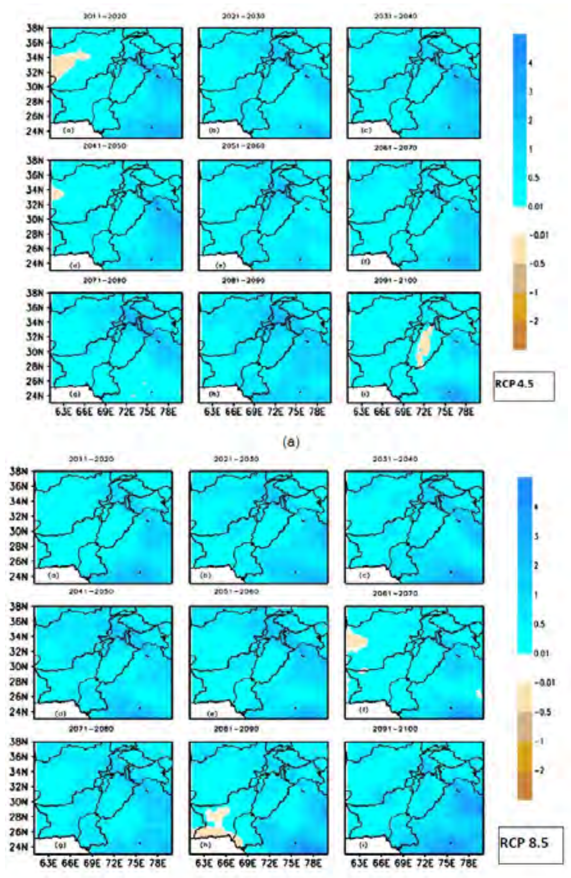



(a)




(b)

**Figure 6.10.** Coupled Model Intercomparison Project Phase-5 Projections of Annual Average Temperature Changes (°C) for 2011–2100 under Representative Concentration Pathways 4.5 (a), and 8.5 Relative to 1975– 2005 APHRODITE Baseline (b)



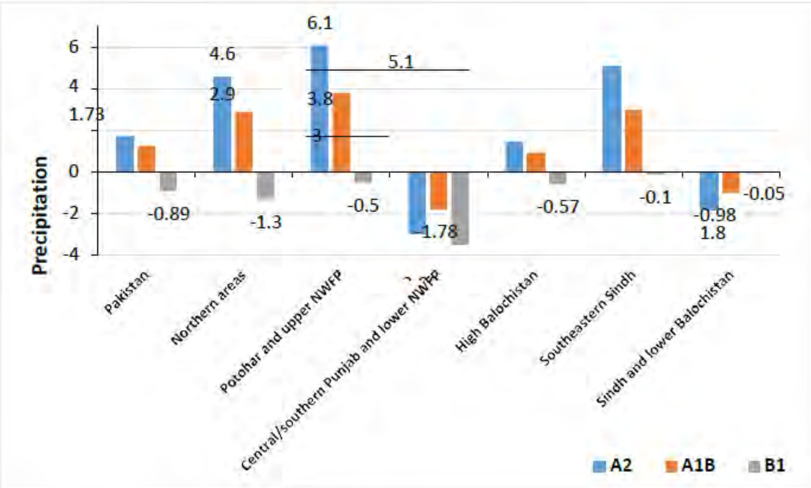

(b)

**Figure 6.11.** CMIP5 Projections of Changes in Annual Mean Precipitation (mm/day) for 2011-2100 Under RCP4.5 (a), and RCP8.5 Relative to 1975–2005 APHRODITE Baseline (b)

**Notes:** RCP4.5 is a stabilization scenario where greenhouse gas emissions stabilize by 2100. In RCP 8.5, radiative forcing does not peak by year 2100. APHRODITE = a climate model. Hatching show changes exceeding 90% significance level. Source: Pakistan Meteorological Department. 2015. High Resolution Climate Scenarios. http://www.pmd.gov.pk/rnd/rndweb/rnd_new/climchange_ar5.php

### *b. Future Trends of Temperature and Precipitation under SRES scenarios*

The PMD conducted another significant study that computed temperature and precipitation change for different regions of Pakistan from 2011 to 2050 under climate change scenarios (A2, A1B and B1) based on IPCC Special Report Emission Scenarios (SRES). The climate models show a maximum rise in the northern areas of Pakistan (0.39 to 0.76 ℃/decade), central and south Punjab and lower parts of Khyber Pakhtunkhwa Province (0.63 to 0.71 ℃/decade). However, mixed trends are projected for precipitation over different regions of Pakistan (Figure 6.12).



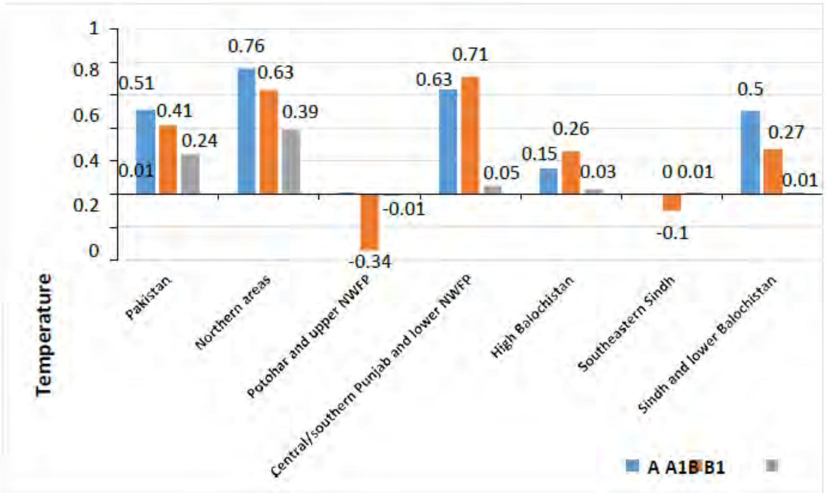




**Figure 6.12.** Region wise Climate Projections for Pakistan for Alternative Scenarios, 2011–2050. Projected regional precipitation and temperature change in Pakistan with three prospective scenarios (2011–2050). Source: (ADB 2017; Chaudhry et al. 2009). A2 signifies business as usual scenario; A1B signifies balanced scenario; B1 signifies ideal world scenario (SRES Report IPCC 2001). NWFP = Northwest Frontier Province and current Khyber Pakhtunkhwa.

According to Iqbal and Zahid, (2014) the temperature rise in the northern areas by 2020 is projected to be 1.4+/-; it is projected to be 2.7+/- by 2050. Likewise, for southern areas the temperature rise is projected to be 2.7 +/- degrees by 2020 and 2.4 degrees by 2050 (Table 6.1). Similarly, precipitation increases in northern areas and rising temperature trends will affect all sectors: in particular, agriculture.

**Table 6.1.** Ensemble mean of climate change projections based on IPCC AR4 using 17 GCMs and the A2 SRES and the A1B SRES (Amir and Habib, 2015)

| | A2 | | | A1B | | |
|---|---|---|---|---|---|---|
| Scenario/area | 2020s | 2050s | 2080s | 2020s | 2050s | 2080s |
| Temperature change (°C) | | | | | | |
| Northern Pakistan | 1.4 ± 0.1 | 2.7 ± 0.2 | 4.7 ± 0.2 | 1.6 ± 0.1 | 3.0 ± 0.2 | 4.1 ± 0.2 |
| Southern Pakistan | 1.3 ± 0.1 | 2.4 ± 0.1 | 4.2 ± 0.2 | 1.4 ± 0.1 | 2.6 ± 0.1 | 3.7 ± 0.2 |
| Precipitation changes (%) | | | | | | |
| Northern Pakistan | 2.2 ± 2.3 | 3.6 ± 3.2 | 1.1 ± 4.0 | –0.7 ± 1.5 | –1.8 ± 2.2 | –0.7 ± 3.1 |
| Southern Pakistan | 3.1 ± 5.1 | 6.4 ± 7.5 | 4.3 ± 9.4 | –3.2 ± 4.3 | –0.3 ± 5.5 | –0.9 ± 7.9 |

### c. *Runoff and river flows*

The impact of climate change on river flows was assessed from previous research studies published during 2015 to 2020. Most of these studies were conducted in the sub catchments of Upper Indus Basin (UIB) and future climate impact were assessed using hydrological models (SWAT, SRM, UBC model and HBV) under RCP 4.5 and RCP8.5 scenarios for 2011-2040, 2041-2070 and 2071-2100 periods (Shah et al., 2020; Haider et al., 2020; Anjum et al, 2019; Nauman et al., 2019; Hayat et al., 2019; Ali et al., 2018; Adnan et al., 2017; Garee et al., 2017; Lutz et al., 2016; Ali et al., 2015). The brief analysis and findings of these studies is summarized in Figure 6.13. According to literature studies, it is anticipated that total water flows in the Indus Basin in the near-term (i.e. before 2050) will remain relatively stable, although there could be an increase in flows due to higher run-off as temperatures warm and a shift in the timing of peak water flow to earlier in the year (Immerzeel et al., 2009). Results depicted an overall increase in average annual flows under RCP 4.5 and RCP 8.5 up until 2100. Mean annual discharge was projected to increase 30.43% (RCP 4.5) and 41.87% (RCP 8.5) and 35.79% (RCP 4.5) and 50.15% (RCP 8.5) for (2011-2040) and (2041-2070), respectively. For 2071-2100 period, the increase in flow is 42.03% and 66.47% during RCP4.5 and RCP 8.5, respectively. Likewise, the anticipated changes in precipitation ranges from 1.2% to 2.5% for RCP4.5 and 3.1% to 6% under RCP8.5 (from mid-century to late century).

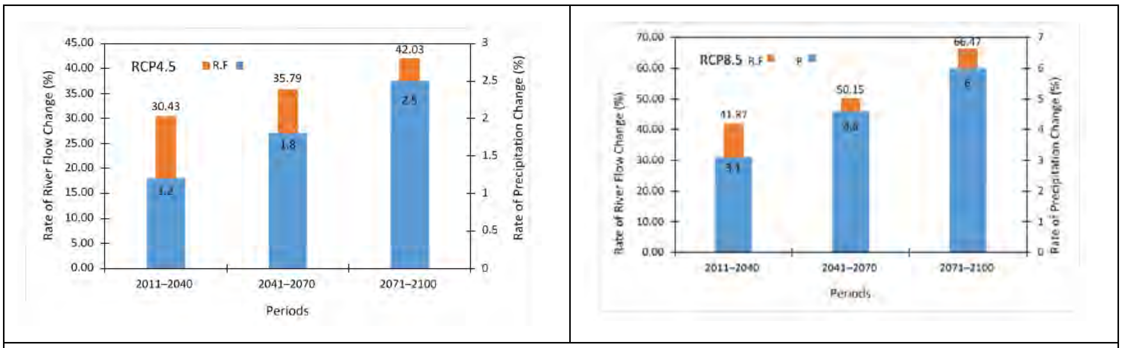



**Figure 6.13.** Changes in precipitation (P) and river flow (R.F) in the Upper Indus Basin of Pakistan under RCP scenarios

### d. *ET and Groundwater*

Agricultural water demand estimates for Pakistan have been summarized in several documents; most projections are based on linear trends. A recent report (Engro Polymer and Chemicals, 2015) summarizes and documents demand for agriculture in 2015 as 111 MAF; in 2020 as 115 MAF;

and in 2025 as 119 MAF. Thus by 2025, 8 MAF more than current 2015 estimates is required. In the case of environmental requirements, the 2015 water demand is estimated at 1.54 MAF; this will rise to 1.62 by 2020, and to 1.70 by 2025 – with an additional requirement of 0.16 MAF from the base year of 2015. This study also notes that due to the expanding population in Pakistan per capita water availability, which was 1,500 cubic meter per annum in 2010, will decline to 1,000 cubic meters per annum in 2025 and to 900 cubic meters in 2050. This clearly shows the water challenge Pakistan faces. Rasul et al. (2011) note that for every 1, 2 and 3 degree rise in temperature crop water requirements will increase by 11%, 19% and 29%, respectively, implying that at 2 degree rise, crop water requirements will almost double water needs in the northern areas. Water demand for 1 and 3 degree Celsius increases under A2 in temperature are estimated in Figure 6.14. A 1 degree average increase in temperature increases agricultural water requirements (crops and livestock) by about 5% by 2050, while a 3+ degrees change in temperature increases crop demand by 6% by 2025 and 12–15% by 2050.

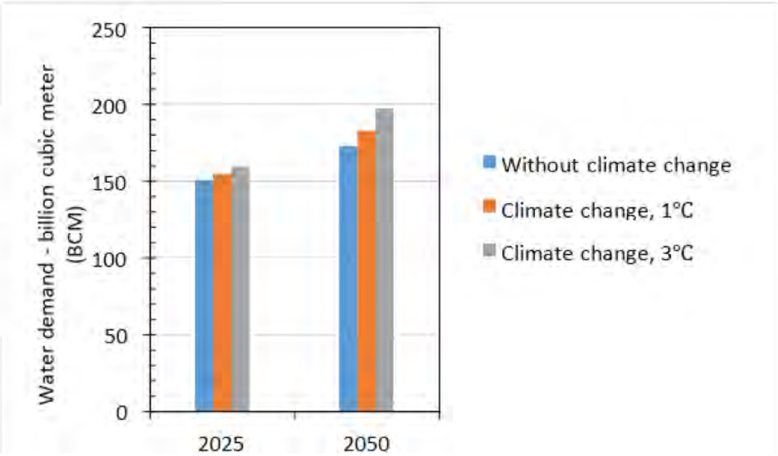



**Figure 6.14.** Climate change impact on agriculture water demand – years 2025 and 2050 (Amir and Habib, 2015)

Rising temperature and changing precipitation pattern will directly affect groundwater recharge, discharge, level and storage. Groundwater plays a major role in irrigated agriculture in Pakistan (Qureshi et al 2004). With increasing trend of irrigated cropping area and crop yield to provide food to increasing population implies that more water will be required and without careful planning and building of new dams, this will inevitably mean using more groundwater. Globally, Pakistan is the fourth biggest user of the groundwater, according to a recent report by the National Groundwater Association of United States of America (Amir and Habib, 2015). Irrigation is the largest consumer of water in the Indus basin that is using both surface (113 $km^3$ or 434mm) and groundwater (68 $km^3$ or 262 mm) to meet the crop water requirements (Cheema et al., 2013). The few estimates of the total volume of usable groundwater suggest that the increased rate of groundwater use could exhaust the best quality groundwater in as little as 50 years (Figure 6.15). The groundwater requirement shows the probable increasing requirement in the absence of alternative policies and adaptations.

### *e. Agriculture Yield*

Climate change will disproportionally affect agricultural production across the country. It has been projected that a 4°C increase in temperatures and 3 percent rise in precipitation by 2080 could result in a loss in agricultural productivity of up to 13 percent in Punjab and Sindh provinces (Dehlavi et al., 2014). More positively, in Pakistan's northern foothills, wheat, maize and rice yields could increase due to longer and hotter summer seasons (Rasul & Ahmed, 2012). It has been projected that a 1°C rise in temperature during the vegetative and flowering stages of cotton growth would reduce yield by 24.14 percent and 8 percent, respectively in Sindh (Raza & Ahmed, 2015). According to data of World Bank on projected changes in wheat, rice and maize yield (2030-2080) under A2 scenario, the wheat yield may decrease 3.2 to 27 %, the rice yield may decrease 0.8-1.9% and maize yield may reduce 2.4 to 4.3 % (Figure 6.16). With these facts, there is more stress on wheat crop, so the population should have to reduce dependence on wheat and shift to use coarse grains such as barley, sorghum, millet, oat and coarse rice. The decline in water availability also suggests the shifts in crop rotations and alter sowing and harvesting patterns in coming two or three decades.

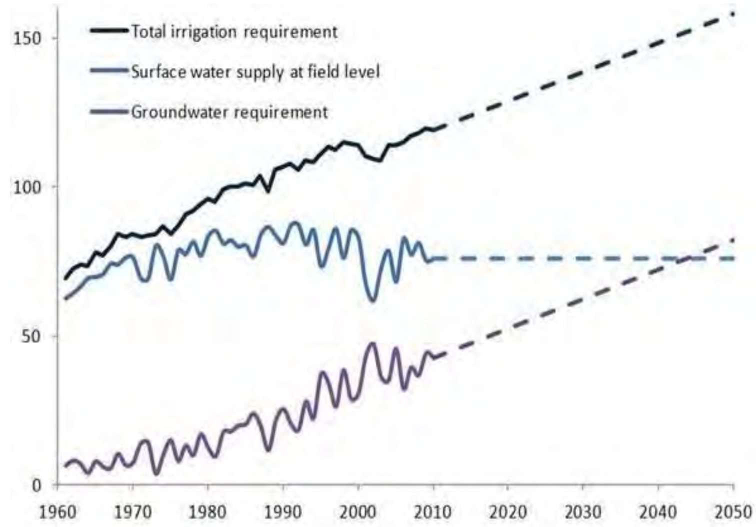



**Figure 6. 15.** Historical (to 2013) and projected (2013 to 2050) total irrigation requirement, surface water supply to the field, and groundwater requirement, in billion cubic meters (BCM). (Source: CSIRO, 2019)

Overall, available research suggests the potential for water-intensive crops to be most affected by climate change, resulting in significant reductions in crop yields. Current climate-induced changes are affecting the cropping system of Pakistan in diverse ways:

- A change in temperature has increased the annual evapotranspiration, which is not uniform over the critical crop growth periods and across various agro-climatic zones.
- A weather shift (still not fully understood) impacts the water stress periods and gross crop yields.
- Extreme events can cause large-scale crop damage.

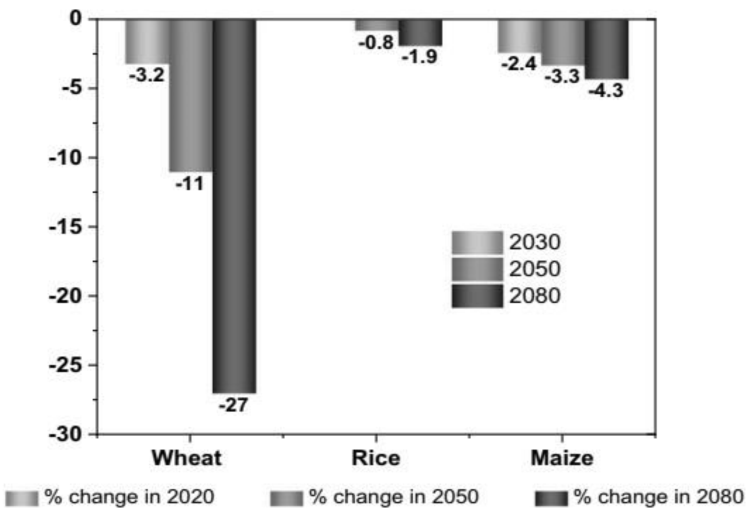



**Figure 6.16.** Comparison of estimated change in crop yield (2020–2080) with standard crop yield (1961–1990) by A2 Scenario. Source: (World Bank, climate change portal).

## 6.4. Pakistan's options for climate change mitigation and adaptation

The present share of water use for agriculture (the most dominant sector) is 111.21 MAF; this accounts for around 92% of total water use. This share is likely to decline as water availability is reduced due to climate change. Based on current temperature and precipitation projections Pakistan must face water shortages and increased demand for water to grow crops and to sustain its agriculture. The projected demand for agricultural water in 2025 is 119.85 MAF; for 2050 it is 135.76 MAF. The gap between present water availability and future availability has clear implications for agriculture in terms of cropping patterns, rotations and water needs under different systems of irrigation like drip, bubbler, and sprinkler and raised bed farming. Without marked investment in irrigation efficiency improvement and water conservation technologies, continuing with the present-day level of agriculture will be difficult (Ali, 2009).

There are two approaches available to for tackling climate change: (upstream) mitigation or abatement, and (downstream) adaptation. Farmers in Pakistan are using a variety of adaptation practices to counter the adverse impacts of climate change. Ali and Erenstein, (2016) conducted a study related to farmer use of climate change adaptation practices in Pakistan using regression models based on structured questionnaire. The data relating to the farmers' experience of climate changes, various adaptation practices adopted and their impact on crop yields was collected. Most (87%) of the respondents reported observing changes in climatic conditions, which suggests that climate change has been experienced by most of the surveyed rural society. Similarly, majority noted a change in rainfall (timing and amount), monsoon onset and temperature during last ten years. Farmers typically adjusted the sowing time of their crops (22%) to the changing conditions, while 15% of the farmers adopted heat/stress tolerant varieties. A quarter shifted to new crops due to changing weather conditions. Adjustment in sowing time (22% households), use of drought tolerant varieties (15%) and shifting to new crops (25%) were the three major adaptation practices used by farmers in the study area. Farmers adopting more adaptation practices had higher food security levels (8-13%) than those who did not, and experienced lower levels of poverty (3-6%).

The research studies emphasis that the scope of policy related to climate change adaptation should focus on the strategies at community and farm level for significant development outcomes. An integrated approach is required to optimally use the available water resources because water availability shortage that was 11% in 2004 will increase to 31% by 2025. There are two options to overcome this shortage, (1) hard path i.e. construct small and large dams where possible, improve the surface water governance with proper pricing, legislate and restrict indiscriminate groundwater abstraction, control increase in population. This path involves huge investment, requires appropriate sites, requires considerable time for (feasibility study, completion of the project, re-settlement issues, and environmental issues) and needs national consensus. The other path is called soft path i.e. improving conveyance and application efficiencies (canal and watercourse improvement/maintenance, improving farm layout, leveling of fields), using high efficiency irrigation systems (bed and furrow methods of irrigation, sprinkler/drip irrigation system), changing the existing cropping patterns (adopting low delta crops), adopting proper irrigation scheduling (when to apply and how much to apply water?), using saline groundwater, in conjunction with canal water, or independently with salt tolerant crops and use of improved agronomic practices. The adaptation of soft path at farm level is an integrated approach, some case studies have been conducted in University of Agriculture Faisalabad and Pakistan Council for Research in Water Resources (PCRWR), and results are shown in Table 6.2.

Intercropping is also a well-known technique to improve water productivity for example the case study results of intercropping of sugarcane in wheat indicated is equivalent to 3 irrigations compared to sowing of sugarcane with traditional method. Another potential option is rainwater harvesting and according to PCRWR study, there is a great rainwater harvesting potential in Pakistan such as from rainfed areas (6.0MAF), deserts areas (0.34 MAF), coastal areas (0.53 MAF) and hill torrents (18.0 MAF).

**Table 6.2.** Potential of adopting Bed Plating technology at national level

| Description | Wheat | Cotton | Maize | Rice |
|---|---|---|---|---|
| Area under crop (Mha) | 8.41 | 3.05 | 1.02 | 2.52 |
| Average production (000 bales/000 tons) | 21749 | 11655 | 3313 | 5563 |
| Average yield increase (%) | 17 | 12 | 27 | 25 |
| Increase in national production (000 bales/000 tons) | 3654 | 1364 | 885 | 1396 |
| Average water saving (%) | 46 | 43 | 42 | 30 |
| Potential of increasing area under crop (Mha) | 3.83 | 1.31 | 0.43 | 0.76 |

Agriculture has a significant role to play in adapting and mitigating the impacts of climate change. There are some recommendations for protecting water resources and improving agricultural yield for climate change adaptation (Alvi and Khayyam, 2020; Iqbal and Khan, 2018; CIAT, 2017; Abbass, 2009; Khan, 2008).

- Assess the vulnerability of water sector and estimate the changes in the water availability due to climate change.
- Re-model and up-grade irrigation infrastructures to the projected range of expected extreme weather events.
- Introduce water harvesting and conservation schemes in rural and urban areas
- Improve irrigation technology and promote compost organic fertilizers to reduce water requirements in agriculture
- Construct small and medium-sized reservoir dams to capture water from flash floods
- Promote forestation and reforestation programs to increase water catchments
- Promote judicious use of water by increasing consumer awareness and by applying water metering and budgeting systems
- Establish systems to monitor ground and surface water resources
- Bring crop patterns (planting) in line with shifting weather patterns and adopt farming practices suited to the climate
- Introduce drought and heat resistant crop varieties and reduce dependency on traditional agricultural staples
- Introduce new varieties of crops which are high yielding and less water intensive
- Employ integrated nutrient management techniques to reduce emissions on-site by reducing leaching and volatile losses
- Improve agro-forestry systems by establishing shelter belts and riparian zones/ buffer strips with woody species
- Up-scale land leveling, which enables 30 percent water saving with corresponding increases in productivity
- Modify the local market to absorb the change in cropping patterns in rainfed areas due to climate change
- Establish climate change units or centers at agriculture research organizations to setup agricultural production surveillance system in vulnerable areas to categorize according to extreme climate events and vulnerability
- Awareness raising and capacity building of local level organizations in using sustainable farming techniques, water efficiency and climate

- Enhance capacity of academia and private sector to develop indigenously low cost agricultural water management techniques
- Undertake extensive review of existing research about mitigation options and prepare digital simulation models of climate change impacts on agricultural water to assess the value of investment in this program.

## 6.5. Conclusions

The analysis of meteorological data presented in this study indicates clearly that the climate of Pakistan is getting warmer, with some regions facing a faster increase in average annual temperature. The rate of change is 0.74°C for the period 1961–2018 with highest increase in southern part (+0.32°C to +0.50°C per decade) than northern part (+0.02°C to + 0.10°C per decade). Since 1961, average annual rainfall has increased (19%); but for the most part, that increase occurred in 1961–89, while the years after 1990 generally show a decline in rainfall. The tendency of rainfall on regional level is somewhat mixed. Annual total rainfall has increased the most in Peshawar (+39 mm/decade), followed by Islamabad (+37 mm/decade) and Lahore (+26 mm/decade), while it has declined in Muzaffarabad (–19 mm/decade) and Karachi (–17 mm/decade). The plotting of river inflows indicating declining rate of discharge on Indus, Jhelum, Chennab, Ravi, and Sutlej over the period 1961-2016. The spatial patterns in trends of mean annual ETp show changes between 1.65 and − 1.59 mm/year from southern to central region of Pakistan. It is important to note that ETp of central and southwest region (Punjab Balochistan) showed evapotranspiration paradoxical behavior i.e. the temperature is increasing while the ETp is decreasing. According to CMIP5 model, there is a significant positive trend in annual mean temperature of 3°C to 3.5°C for the period 2011-2100 under RCP4.5 while under the RCP8.5 scenario, the increase in annual mean temperature is 8.3°C. There is a decreasing trend (-0.54 mm/day) in annual precipitation under RCP4.5 while increasing trend (0.9 mm/day) in precipitation under RCP8.5. RCP 4.5 shows an overall effect of higher warming ranging 3°C to 4°C over the northern areas including GB, Kashmir and Northern part of KPK as compared to southern parts of the county. The southern parts show warming of 2°C to 3°C with a slightly higher rate over Balochistan. The changes in annual mean precipitation under both RCPs scenarios show an overall increase in precipitation of 2 mm/day to 3 mm/day over the domain. Regions showing a greater change in temperature also show an increase in precipitation. Results depicted an overall increase in average annual flows under RCP 4.5 and RCP 8.5 up until 2100. Mean annual discharge was projected to increase 30.43% (RCP 4.5) and 41.87% (RCP 8.5) and 35.79% (RCP 4.5) and 50.15% (RCP 8.5) for (2011-2040) and (2041-2070), respectively. A 1°C average increase in temperature increases agricultural water requirements by about 5% by 2050, while a 3+ °C change in temperature increases crop demand by 6% by 2025 and 12–15% by 2050. The groundwater requirement shows the probable increasing requirement in the absence of alternative policies and adaptations. According to data of World Bank on projected changes in wheat, rice and maize yield (2030-2080) under A2 scenario, the wheat yield may decrease 3.2 to 27 %, the rice yield may decrease 0.8- 1.9% and maize yield may reduce 2.4 to 4.3 %. The research studies emphasis that the scope of policy related to climate change adaptation should focus on the strategies at community and farm level for significant development outcomes. While this analysis has identified some of the broad changes underway in Pakistan’s climate, its findings also point to the critical need to take into account regional and local trends, which may diverge greatly from country-level trends. Pakistan needs to develop policies and programs that promote an economy and society resilient to a range of shocks and stresses, including those induced directly and indirectly by climate change.

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# CHAPTER VII
# Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Nepal

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**Abstract**

Water resources and agriculture serve as vital pillars of livelihood and socio-economic development for a significant portion of the Nepalese population and the nation as a whole. Nepal's vulnerability to climate change is widely recognized given its geographical, social and economic realities. In recent years, climate change has notably affected water resources, posing challenges to their effective development and utilization. This impact has far-reaching consequences on various aspects of socioeconomic development. Irrigation emerges as a multifaceted solution, supporting agricultural growth, ensuring food security, and aiding in climate change mitigation by supplying water during dry periods. However, the allocation of water resources for irrigation development faces constraints. This review delves into the diverse facets of climate change's influence on Nepal's water resources and irrigated agriculture, analyzing its socio-economic, financial, and economic dimensions. Finally, the existing policies and priorities in addressing climate change impact on water resources and irrigation are discussed and suggested some measures for future action plan.

**Keywords:** Water resources; agriculture; Irrigation; Climate change; food security.

## 7.1 Introduction

Climate change is one of the top global issues of current time whose impact is felt across diverse sectors of social, economic, environmental systems in almost every nation. The sixth assessment report (AR6) of inter-governmental panel on climate change (IPCC) indicate that approximately 3.3 to 3.6 billion people reside in circumstances that are highly vulnerable to climate change. Among them, region and people with limited development capacity are at higher vulnerability to climatic hazards (Calvin et al., 2023). The report raises concern regarding the increased frequency of extreme weather and climate events, which have left millions of individuals vulnerable to severe food shortages and diminished access to clean water. These adverse effects are particularly pronounced in numerous regions and communities across Africa, Asia, Central and South America, as well as in least developed countries (LDCs). Water resources and the global climate change crisis is inextricably linked (UN-Water, 2019). Anticipated climate change impacts are likely to worsen water shortages and scarcity, while also having a detrimental impact on agricultural output (FAO, 2020). In this context, food security lies at the core of every nation's policies, planning and sustainable future, given the underlying vulnerability of increasing population, climate risks, pandemic, war and global geo-politics among others. The sustainable development goals (SDGs) which are also centered on alleviating poverty and ending hunger also requires ensuring food security. It is estimated that the food production needs to be increased by 70% to meet the global demand by 2050(FAO, 2009). The irrigated agriculture contributes about 40% of global production in 20% of the agriculture land (van Dijk et al., 2021; World Bank, 2022). Enhancing agricultural production and productivity requires several inputs; irrigation, fertilizers, seeds, agriculture extension service, energy, transportation, etc. Providing sufficient water through irrigation in a timely and reliable manner is critical to crop growth and hence the production. Irrigation systems are developed to assure water to crops and hence reduce the uncertainty associated with rainfall dependent agriculture. In this regard, any challenges to sustainable development and management of irrigation systems will sure to have an impact on the agricultural development. Irrigation and agriculture sector is already inflicted by several natural

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and anthropogenic factors. Not only the future development of irrigation needs to be climate resilient but also the existing irrigation systems should be managed in a way that is adapted to the uncertainty of climate change. To address the challenges of climate change on irrigation and agriculture, first a review of the current status and the challenges pertaining to climate change on the irrigated agriculture needs to be understood. The adaptation strategies, climate resiliency, mitigation measures, etc. needed for the sustainability of irrigated agriculture can only be formulated and implemented after understanding the impending impacts of climate change.

The impact of climate change on water availability, streamflow, snowmelt, agricultural yield, temperature, etc. has been studied by many researchers (Abbaspour et al., 2009; Gurung et al., 2013, 2015; Shrestha & Aryal, 2011; Speaker & Kim, 2017; S & Joseph, 2023). The impact assessment of climate change in water resources is crucial for efficient, effective and sustainable planning and development of water resources. However, the potential impact across irrigation sector has not been covered in detail in most of the previous studies (Elnashar & Elyamany, 2023; Fischer et al., 2007; McDonald & Girvetz, 2013; Woznicki et al., 2015). Impact of climate change on the performance of existing irrigation systems, water availability under climate change, future irrigation development, etc. could be vital in aligning irrigation development with climate change impacts. In this context, the objective of this chapter is to briefly review and identify the challenges of climate change that affect the sustainable development and management of irrigation. And finally, propose potential adaptation and mitigation measures to the impact of climate change in irrigation.

## 7.2 Climate change and water resources in Nepal

Nepal is characterized by diverse geography that consists of Terai plains, hills, and high mountains. Elevation vary as low as 60m in the plains to the high of 8848m above mean sea level within a span of less than 200km (Karki et al., 2023). As a result, diverse climatic conditions are inherent to different regions. Climatic variables like precipitation, temperature, evapotranspiration display significant spatial and temporal variation. Nepal receives in average about 1500mm of precipitation annually, over two-third of which occurs in the month of June to September (Water and Energy Commission Secretariat (WECS), 2011). About 42% of the area of Nepal is covered by forest while agricultural land makes up nearly 26% (Forest Research and Training Centre, 2022). Nepal possesses abundant natural resources, primarily in the form of water and forests. Freshwater, sourced from glaciers, snowmelt, and rainfall, constitutes approximately 2.27% of the world's total supply (World Bank, 2021). Nepal consists of more than 6000 rivers of different sizes that contributes about 225 billion cubic meters (BCM) of surface water as depicted in Figure 7.1. Less than 10% of this water is currently in use (Water and Energy Commission Secretariat (WECS), 2011). In addition, about 13 BCM of rechargeable groundwater is also available. Water resources is recognized as the key sector whose sustainable development and management can significantly contribute towards the socio-economic growth and the prosperity of the country (Water and Energy Commission Secretariat, 2002). However, the availability of water across different rivers and regions is not consistent throughout the year which is characterized by spatio-temporal variability. Furthermore, the climate change has posed a challenge on the sustainability of water resources and hence their utilization.

Rivers originate at different physiographic regions in Mountains, Hills and Chure-Terai and are characterized as snowfed, springfed, rainfed, etc. The large and the major river basins Koshi, Gandaki (Narayani), Karnali and Mahakali originate from the Himalayas and are all dominantly snowfed. Medium size river basins like Kankai, Kamala, Bagmati, West Rapti, Babai, etc. originate in the mid-hills and are combination of springfed and rainfed. In addition, several small rivers originate in the Chure-Terai region which are intermittent to ephemeral in nature. River flow fluctuates between the seasons as affected by the temporal climatic variability. The mean monthly flow of large-size Himalayan rivers and medium-size rivers are shown in Figure 7.2 (a & b).

River flows are utilized at the community/household scale locally to regional and national scale. Irrigation, hydropower, water-supply, industrial use, religious uses are some of the sectors of water uses in Nepal. Projects on irrigation, hydropower in Nepal have been developed mostly in the medium-sized river basins and tributaries of major river basins. Hydropower and irrigation projects that are designed on the basis of long-term available dependable flows are affected by the change in magnitude and timing of river flows due to climate change. Irrigation/agriculture sector accounts for nearly 96% of the total water use in Nepal (Water and Energy Commission Secretariat (WECS), 2011). Not only the existing water resources projects under operation are affected, the development potential of the available water resources could be restricted by the impact of climate change in the long-term.

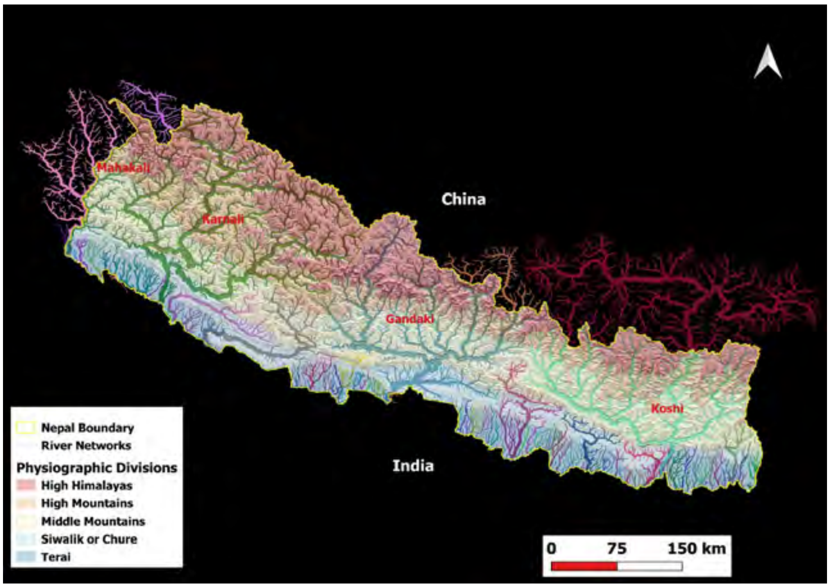


**Figure 7.1.** Physiographic divisions and river of Nepal

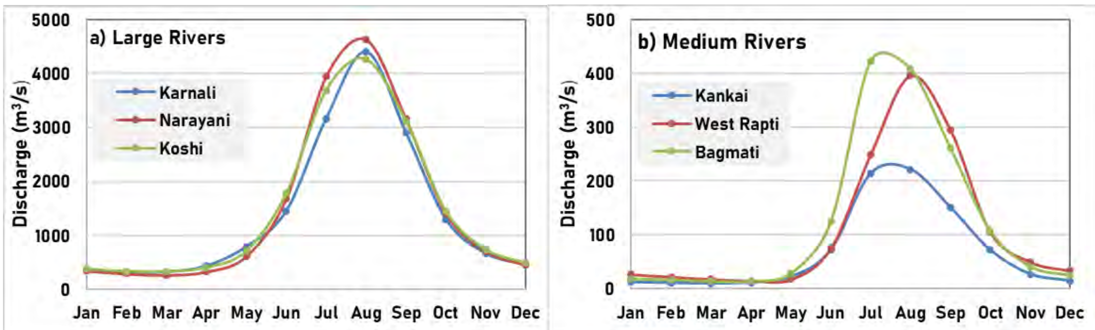


**Figure 7.2.** Typical flow pattern of Nepalese rivers

Several studies have been conducted to analyze the impact of climate change on water resources of Nepal (Bharati et al., 2014; Chaulagain, 2009; ICIMOD, 2009). Climate change has increased the risk of GLOF, timing and magnitude of snowmelt, reduced soil moisture due to increased evaporation, hydrological drought, etc. Food security and water security have been adversely affected due to climate change hindering the efforts to meet SDGs. Climatic and non-climatic driver have resulted in nearly half of the world's population experiencing severe water scarcity for at least part of the year. The agricultural growth has also slowed due to climate change. Additionally, substantial damages with irreversible losses in terrestrial and freshwater systems, hydrological changes resulting from the retreat of glaciers, climate hazards, are the notable impacts of climate change on water resources (Calvin et al., 2023).

The major effect of climate change on Nepalese water resources can be divided into three broad aspects; change in snowmelt and retreat of glaciers, increased climate extremes and the shifting of climatic patterns. The change in magnitude and timing of snowmelt runoff affects the flow availability across seasons, water reserve in the form of snow while the retreat of glacier increases the risk of glacier lake outburst floods (GLOFs) and the impact to downstream communities and projects. Similarly, increased climate extremes like cloud outburst, high intensity rainfall could result in substantial socio-economic damages due to flood and landslide hazards while the long spell of drought could lead to losses in agriculture outputs. Shifting climatic patterns in the form of change in average temperature, rainfall, and climatic zones will have effect on the livelihood, agricultural production, shift in hydrological regime of rivers, reduced potential of water resources projects, etc.

## 7.3 Irrigated agriculture in Nepal

Agriculture is a key primary sector of Nepalese economy that contributes about one-quarter to the national GDP while nearly two-thirds of population are associated to agriculture sector in different forms. Out of the total 14.779 million hectares of land area of Nepal, 3.557 million hectares (24%) area is cultivable in the form of level terrace, sloping terraces, valley, tar and plains of the Terai (Department of Water resources and Irrigation, 2019). Of the cultivable land, 2.536 million hectares (71% approximately) is classified as suitable for irrigation of some types as per the recent draft of Irrigation master plan of Nepal, 2018 published by the Department of Water resources and Irrigation, Nepal. But there are inconsistencies in data as some studies suggest total cultivable land to be around 29% of the area of Nepal. Currently about 1.53 million hectares of land are equipped with some forms of irrigation service. 1.01 million hectares are covered by surface irrigation schemes while groundwater sources provide irrigation water to the remaining 0.51 million hectares.

The cropping season in Nepal can be broadly divided into three groups; 1) Main or monsoon season (July-October), 2) Winter season (November-February) and 3) Summer season (March-June) (CIAT et al., 2017).

**Table 7.1.** Major food crops (cereal and pulses crops) with their production (Ministry of Agriculture & Livestock Development, 2022)

| A | Cereal crop | Area (Hectares) | Production (m/t) |
|---|---|---|---|
| 1 | Paddy | 1,473,474 | 5,621,710 |
| 2 | Maize | 979,776 | 2,997,733 |
| 3 | Wheat | 711,067 | 2,127,276 |
| 4 | Millet | 265,401 | 326,443 |
| 5 | Buckwheat | 13,875 | 15,917 |
| 6 | Barley | 21,862 | 29,433 |
| | Total | 3,465,455 | 11,118,512 |
| B | Pulses | Area (Hectares) | Production (m/t) |
| 1 | Lentil | 202,416 | 246,092 |
| 2 | Chickpea | 9,840 | 11,065 |
| 3 | Pigeon Pea | 16,591 | 16,649 |
| 4 | Black Gram | 24,500 | 21,633 |
| 5 | Grass Gram | 10,456 | 11,965 |
| 6 | Horse Gram | 13,311 | 15,453 |
| 7 | Soyabean | 25,758 | 32,178 |
| 8 | Others | 32,262 | 39,320 |
| | Total | 335,143 | 394,355 |

**Table 7.2.** Major cash and other crops with their production

| A | Cash Crops | Area (Hectares) | Production (m/t) |
|---|---|---|---|
| 1 | Oilseeds | 259,101 | 287,038 |
| 2 | Potato | 198,788 | 3,325,231 |
| 3 | Sugarcane | 64,354 | 3,183,943 |
| 4 | Jute | 7,415 | 10,451 |
| 5 | Cotton | 142 | 147 |
| | Total | 529,800 | 6,806,810 |
| B | Other Crops | Area (Hectares) | Production (m/t) |
| 1 | Fruits (productive area) | 128,733 | 1,356,218 |
| 2 | Vegetables | 284,121 | 3,993,167 |
| 3 | Tea | 16,917 | 23,745 |
| 4 | Coffee | 3,052 | 315 |
| 5 | Large Cardamom (Productive area) | 15,668 | 8,289 |
| 6 | Ginger | 21,912 | 279,206 |
| 7 | Garlic | 9,784 | 72,490 |
| 8 | Turmeric | 10,340 | 105,719 |
| 9 | Dry Chili | 12,525 | 87,731 |
| | Total | 503,052 | 5,926,880 |

Rice, maize and wheat are the major food crops that occupies about 31%, 20% and 15% of the total cultivated area in Nepal (Ministry of Agriculture & Livestock Development, 2022). The details on different types of crops along with their cultivated area and production for the year 2020/21 is given in Table 7.1 and 7.2. Oilseeds, potato, sugarcane are major cash crops while vegetables, cardamom, tea are high value crops in terms of market value. The agricultural productivity is well below the regional and global averages. Lack of timely availability of good quality seeds, fertilizers, market uncertainty and low return, farmer's friendly policy, low commercialization, traditional subsistence agriculture with lack of technological adoption, etc. are some of the constraints to the sustainable growth of agriculture sector in Nepal. Apart from these, the high dependence on monsoon rainfall due to the lack of sufficient irrigation water/services is a major concern. Both during the main cropping season and winter cropping season, timely and sufficient rainfall has direct impact on the agricultural production.

In this context, the role of irrigation as a key input for enhancing production and productivity cannot be overlooked. Irrigation has played a crucial role in supporting the agriculture in large areas of Terai plains as well as in the hills of Nepal. Figure 7.3 depicts the distribution of irrigated command areas across Nepal. As it can be seen that the large command areas lie in the lower plains whereas the small command areas lie in the hills. Medium to small irrigation schemes in Hills and Terai, fully developed and managed by the farmers, are known as Farmer Managed irrigation systems (FMIS) which account for over 50% of the total irrigated areas. The larger schemes in the plains are agency managed (Agency Managed Irrigation Systems, AMIS) or jointly managed by the agency and Water Users' Association (JMIS). The prevailing challenges to the irrigated agriculture in Nepal are as follows;

- Reduced water availability in run-of-the river irrigation schemes in dry season
- No storage projects
- Low water use efficiency resulting in weak performance of the system.
- Ageing infrastructure and lack of proper management, operation and maintenance due to the financial, human resources, technological constraints

- Climate related hazards like floods, landslides causing damage to irrigation infrastructures.
- Low capacity of water users' association as well as the local level government in irrigation system management.
- Several policy and legal issues (land acquisition, use of forest areas, land use change, etc.) hindering the timely and smooth irrigation system development.
- Lack of coordination between related stakeholders of irrigation and agriculture sector.
- Lack of institutional and human resources capacity development of irrigation sector.

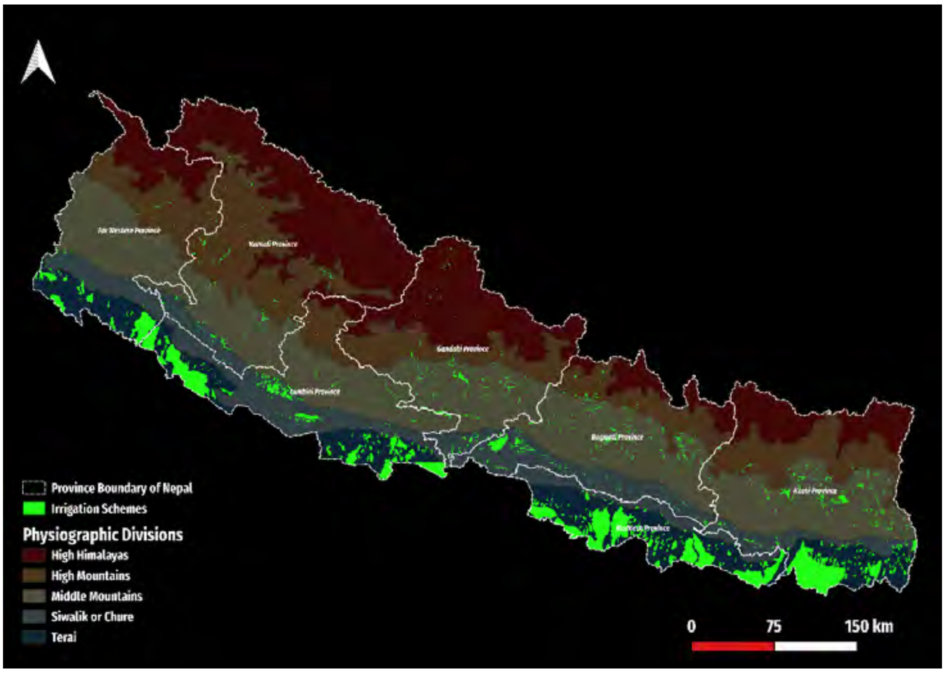


**Figure 7.3.** Distribution of irrigation schemes across Nepal

## 7.4 Irrigation challenges due to climate change

Irrigation sector which is already encircled by multifold problems is further grappled by the impact of climate change. The domain of irrigation is not limited to a mere water delivery but encompasses an interconnected aspects of socio-economic, hydrologic, institutional, agricultural and financial systems. The impact of climate change should be viewed from a broad perspective of interconnected areas. The impact on one aspect will likely have an effect on other areas too. Climate change challenges to irrigation across several aspects is dealt below:

### 7.4.1 Socio-economic

The socio-economic structure of Nepalese community and the livelihoods of its people are very much dependent on climate. Agriculture and water resources are the key means of livelihood. Climate change can disrupt the socio-economic balance thus leading to livelihood insecurity. Climate induced migration, food and water insecurity, unequal access to resources will widen social inequality. For years, communities have played a significant role in managing irrigation system. Climate change can decline the capacity of the communities due to multiple impacts on the socio-economic status. Consequently, the indigenous and traditional knowledge on the management of water resources will slowly disappear. Enhancing a strong and resilient socio-economic system is urgent for adapting to climate change and ensuring the sustainability of vulnerable communities.

### 7.4.2 Hydrological

The hydrological impact of climate change is reflected on water availability, flood and drought events, snowmelt runoff timing and magnitude, and the hydrological cycle as a whole. Reduced flows during dry season in run-of-the-river irrigation systems is a major existing challenge to meeting irrigation water demand which can worsen in the future. Not only the effective operation and management (O & M) of irrigation systems will be challenged but the O & M cost will increase due to infrastructural damages as a result of increasing climate hazards like floods, erosion, deposition of sediments and landslides.

### 7.4.3 Agricultural

Agriculture is highly sensitive to weather and climate. Various elements of agriculture are being adversely affected by the increase in average temperature, reduced river flows, floods and inundation, shifting climate patterns, unpredictability of rainfall which are all attributed to climate change. Such climatic behavior will result in unfavorable environment for agriculture development and production. Change in the crop growing period, change in zones of certain crops to further higher elevations and reduced yields are some of the notable climate change impacts on agriculture.

### 7.4.4 Institutional

Addressing climate change requires coordinated and strengthened framework of institutions, policies and governance. Nepal's governance systems and institutions face challenges in efficiently coordinating and executing policies and measures related to climate change. Strengthening institutional capacity, technology, considering climate change in current programs, practices, design, etc. are vital to mitigating climate change impacts and making resilient systems, infrastructure, and adaptation measures. Institutions that primarily work in the sector of water resources, agriculture, and environment will need to re-orient its structure and build capacity of the personnel to effectively formulate and implement climate change actions plans and programs.

### 7.4.5 Financial

Erratic rainfall, increased climate extremes, droughts, reduced crop yield, disaster, infrastructure damage, social inequality, etc. will have financial implication. Climate change is causing more intense and frequent weather extremes. Floods and landslide events will increase the likelihood of damage to the irrigation infrastructure limiting the smooth operation of the irrigation system. Dominantly floods and landslides will increase the operation and maintenance cost. Untimely rainfall in rainfed agriculture and reduced low flows will lead to reduced crop yield as well as losses during the harvesting season.

**Existing policies and priorities for mitigating climate change impact in irrigated agriculture**

As one of the most vulnerable countries to climate change, Nepal became a party to the United Nations Framework on Convention of Climate Change (UNFCCC) and have ratified the Paris Agreement whose objective is to limit the temperature rise to 1.50C and mitigate the impacts of climate change. Accordingly, Nepal has adopted several policies, plans, programs and actions across legal, institutional, socio-economic and infrastructural dimensions of the country. Sustainable Development Goals, SDGs indicators across several goals have also incorporated the issues of agricultural productivity, food security, integrated water resources management, climate change mitigation and adaptation, water use efficiency, annual irrigation, etc. with priority. In this section, we discuss policies and priorities that primarily relates to irrigation and irrigated agriculture in brief.

### 7.4.6 Climate change policy and National Adaptation plan

The climate change policy's (2011) has been formulated with a mission to address the adverse impacts of climate change and utilize the opportunities created from it to improve livelihoods and achieve climate-friendly physical, social and economic development. It sets out policies across different dimensions of climate change that include climate adaptation and disaster risk reduction, low carbon emission and climate resilience, capacity building and people's participation, study and research, climate-friendly natural resources management, technology development and transfer, etc. The objectives of climate change policy should be reflected in the actions and planning of irrigation, agriculture and water resources sector for maximizing the effectiveness of climate change policy.

Nepal National Adaptation Plan, NAP (2021-2050) has identified ten thematic sectors and set the priority programs for climate change mitigation and adaptation in the short (2025), medium (2030) and long-term (2050). Agriculture and food security, forest, biodiversity and watershed conservation, water resources and energy, disaster risk reduction and management, national capacity building and climate awareness raising are some of the thematic sectors where different action programs have been proposed. These mentioned sectors are closely related to agriculture and irrigation aspects.

### 7.4.7 Agriculture

Self-reliance and sustainability are the two major elements of Agriculture development strategy, ADS (2015-2035) formulated for the overall development of agriculture sector in Nepal. Self-reliance in the food and agricultural products and sustainability in the socio-economic and environmental dimensions of agricultural system is the target of ADS. It highlights that the sustainable modernization of agriculture must ensure resilience of agriculture to climate resilience. Efficient management of irrigation water, innovative irrigation technology, inter-basin transfer, groundwater development, watershed management, research, gender equality, capacity development, etc. are proposed for improving agricultural productivity and ensuring sustainability of irrigated agriculture.

### 7.4.8 Irrigation

In irrigation sector, Water resources strategy (2002), National Water plan (2005), Water resources policy (2020), Irrigation Policy (2023), Irrigation Master plan (2019), River and Water induced disaster management policy (2023), Periodic Plan, etc. have all recognized, directly or indirectly, the importance of climate change impact management and mitigation for the sustainability of water resources, water induced disaster management, irrigation and agriculture.

WRS laid down integrated water resources management (IWRM) approach to water resources planning, development and management which basically relies on social and economic development and environmental sustainability principles. Although, it didn't directly mention the impact of climate change, the approach, principles and outputs contribute towards climate change impact mitigation and adaptation which are equally relevant at the present time.

Realizing the inefficient use, under development, haphazard management, over-exploitation, climate change impact, etc. in the water resources sector, water resources policy (2020) has been formulated as an integrated umbrella policy of water resources aligning with the new constitution and governance structure of Nepal. River basin planning, IWRM, people's participation, institutional capacity development, research, coordination, disaster management, minimizing socio-environmental impacts, etc. are some of the strategies of the policy. Different forms and technology in irrigation practices, inter-basin water transfer, reservoir projects, groundwater, water sources conservation, conjunctive use, rainwater harvesting, watershed management, climate resilient and adaptive programs and projects, drought management, glaciers lakes management, etc. are some of the action plans towards sustainable water resources management that can be related to irrigation sector.

One of the five objectives of the recent Irrigation policy (2023) is to develop and manage irrigation systems in such a way that they are resilient to the impact of climate change and are able to adapt to the effect of climate change. Based on this objective, priorities that encompass institutional, technical, social dimensions of sustainable irrigation development and management are included in the policy.

River and Water induced disaster management policy (2023) has prioritized the adoption of appropriate technology for the mitigation of climate change impact on river and water induced disaster. One of its strategies is to apply environment friendly and climate resilient measures in water induced disaster mitigation.

Similarly, IMP (2020) has adopted two main strategies; 1) inter-basin water transfer from surplus to deficit basins and 2) groundwater irrigation development along with conjunctive use for ensuring year-round supply of irrigation. Modernization, management and rehabilitation of existing systems are also equally prioritized. These strategies ultimately help to tackle the water scarcity problems that can arise due to climate change and ensure achieving future food security. In this context, Department of Water resources and irrigation (DWRI) are carrying out several programs and projects on inter-basin water transfer, conjunctive irrigation, solar lift irrigation, groundwater development, integrated watershed conservation, river management programs for enhancing irrigation service. However, the impact of climate change on these projects are not properly researched. Also, to what extent will these programs and projects support climate change impact mitigation and adaptation are not analyzed in detail.

Current periodic plan (2019/20 – 2023/24) has also set the goal to contribute towards the development of sustainable society through the enhancement of adaptation capacity and mitigation of adverse impact of the climate change. It has also recognized the importance of climate resilient and environment-friendly agricultural systems for minimizing climate change impacts on agriculture and hence proposed several actions and strategies. It has also highlighted impending water security problems in irrigation sector resulting from climate change. Appropriate and innovative technology, indigenous knowledge, inter-basin water transfer, reservoir, groundwater development, non-conventional irrigation like drip, sprinkler, rainwater harvesting, small ponds, etc. are proposed strategies for ensuring sustainability of irrigated agriculture in the context of climate change. All of these policies have also iterated the importance of research and development in understanding and effective implementation of and achievement of the policies objectives.

## 7.5 Conclusions

We briefly discussed multiple dimensions of water resources, irrigation, irrigated agriculture, and climate change impact in Nepal. Nepal's vulnerability to climate change is widely recognized given its geographical, social and economic realities. Nepal's growth, achievement of SDGs, water resources development, socio-economic stability and environmental sustainability all hinge on effectively managing, mitigating, and adapting climate change. Reducing poverty and ending hunger requires enhancing food production to meet future food demand of increasing population. But climate change will be a major hurdle among others to achieving food security and sustainability in the country. As climate change impact is felt across water resources, agriculture, disasters, etc., institutional, legal, political, economic and environmental effort and commitment should be concentrated to overcoming the challenge of climate change. There are ample institutional, policies, plans and programs formulated for addressing climate change issues in water resources, irrigation, and agriculture and disaster sector. However, a strong commitment is needed to translate policies and plans into action. Irrigation being the major areas of water use will face a significant challenge in the coming days. There is already a wide skepticism in Nepal over the appropriateness of investment in irrigation sector and this is likely to grow, if necessary, measures are not taken to minimize climate change impact in irrigation and agriculture. Because, it is the output of agricultural products that matters to the people and farmers. And if the investment of irrigation is not reflected in the agricultural produce, the future of irrigation becomes uncertain. Fiscal budget allocated in irrigation sector is in decreasing trend over the years and this will pose a challenge towards implementing actions on climate change impact mitigation and adaptation. Therefore, it is recommended that a comprehensive study and analysis on identifying and mitigating impending climate change impacts in irrigation sector is undertaken. Along with this, institutional strengthening or establishing a climate change section in DWRI, capacity building of irrigation professionals and farmers, coordination among federal, provincial and local levels, prioritizing local scale programs and upscaling them at the national level will be crucial in effectively dealing with climate change issues in water resources, irrigation and agriculture sector in Nepal.

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# CHAPTER VIII
# Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in India

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### Abstract

This study encompasses the multidimensional impact of climate change on agricultural water management and explores various adaptation strategies. It covers geographic diversity and different agricultural systems, shedding light on the challenges Indian farmers face. The articles delve into rainfall variability, prolonged drought, and extreme weather events affecting crop production and water availability regulation. Proposed water supply implementation plans, each tailored to address specific challenges arising from climate change. Notably, the case studies underscore the significance of community involvement and advocate for participatory methods in implementing effective reform strategies. This study's four major case studies are climate change, water availability, extreme events, and climate-smart technology. In this study, more attention is given to recent publications. Most studies indicate that temperatures will rise and rainwater availability will decline, leading to increased water demand for agriculture. This paper also presents the government's institutional structure and programs. It further discusses the challenges of adapting to a changing climate.

**Keywords:** Climate Change, Water availability, Extreme Events, Climate Smart Technology.

## 8.1. Introduction

Climate change affects water availability, quality, and demand, posing a significant challenge for agricultural water management. Rising temperatures and changing rainfall patterns have made it challenging for farmers to pursue sustainable agriculture. India possesses 4% of the world's land area, is home to 17.7% of the world's population, and has over 21% of the world's irrigated land. Between 1961 and 2016, India's irrigated areas grew from 58.8% to 60.4%(World Bank, 2017). From 2001 to 2015, the net irrigated area from various sources (canals, tanks, wells, tube wells, and others) increased to 68.38 Mha (MOSPI, 2018). Between 2000 and 2010, the amount of groundwater used for irrigation worldwide increased, with India accounting for 23% of this (Dalin et al., 2017). The global population will increase by up to 9.7 billion by 2050, and agriculture output will need to improve as much as 70%, so there is a need for agriculture water management and adaptation to changing climate, which makes this task more difficult (Pandey et al.,2021).

Irrigated agriculture is more appropriate in water-limited areas than rainfed agriculture (Cassman, 2016; Mueller et al., 2012). Even in places where there is an abundance of rain, poor management of water resources can increase reliance on groundwater because of the uneven distribution of rainfall (Rodell et al., 2009). India is dependent mainly on the Indian summer monsoon rainfall (ISMR), and as was the case in 2009, droughts can result from weaker summer monsoons (Goldin, 2016). When such dry spells occur, water extracted from groundwater lowers groundwater levels, making drought conditions worse (Van Loon et al., 2016; Dangar et al.,2021).

India's irrigation efficiency varies widely depending on the region and the type of irrigation used. The country's irrigation efficiency has improved in recent years, but it still faces significant challenges.

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This review shows a need to develop appropriate adaptation strategies to maintain agricultural water security in the face of climate change. Agriculture in India contributes 14% to the GDP and employs about 50% of the population (Ministry of Agriculture, 2013). Climate is one of the most critical factors affecting agricultural production in India, which significantly impacts food production and the economy (Shukla et al., 2002; Banerjee, 2015). Adaptation may also include regulations, programs, or solutions needed to mitigate the impacts of climate change on agricultural activities (Devkota et al., 2014; Dang et al., 2019; Esfandiari et al., 2020). According to the Sixth Intergovernmental Panel on Climate Change (IPCC) Assessment Report (A.R.), an estimated four billion people worldwide experience severe water scarcity for at least one month yearly. Comprehensive and inclusive mitigation strategies are needed to address the issues arising from a changing climate (Caretta et al., 2022; Kumar and Sazen, 2023). South-western rainfall is India's primary source of fresh water; Thus, the monsoon cycle is essential to meet the water needs of domestic users, industries, agriculture, the energy sector, and ecosystems. Approximately 80% of India's yearly precipitation falls between June and September during monsoon (Kumar et al., 2010). Thus, any alteration in the climate, especially during the Indian southwest monsoon, would have a significant effect on agricultural output, which is already under stress because of rapid population expansion and issues with the management of water resources (Mall et al., 2006; Kumar et al., 2017). The production of crops is strongly impacted by changing climate conditions such as temperature and rainfall. It has been observed that rising temperatures lower yields, but increasing precipitation is likely to neutralize or lessen the effects of rising temperatures (Adams et al., 1998; Malhi et al., 2021).

India's irrigation efficiency varies widely depending on the region and the type of irrigation used. The country's irrigation efficiency has improved in recent years, but it still faces significant challenges. According to a report by the Ministry of Water Resources, River Development, and Ganga Rejuvenation, the overall irrigation efficiency in India was 45% in 2015-16, a significant improvement from the 38% reported in 2002-03. However, many areas remain where efficiency remains low, particularly in small-scale irrigation projects.

One of the main challenges facing India's irrigation sector is the overreliance on groundwater, which has led to the depletion of aquifers in many parts of the country. This has made it more difficult to access water for irrigation and has lowered the efficiency of irrigation systems.

Another challenge is the use of outdated irrigation technologies and practices. Many farmers still rely on flood irrigation or other inefficient methods rather than adopting more modern approaches like drip irrigation or sprinkler systems. This lowers efficiency, wastes water, and can contribute to soil erosion and other environmental problems.

According to CWC (2013), India's Ultimate Irrigation Potential (UIP) is 140 Mha. The implementation of Inter Basin Water Transfer (IBWT) proposals may create an additional 35 Mha of potential, bringing UIP to 175 Mha, according to the Ministry's National Perspective Plan. In contrast, the gross irrigated area is only 93 Mha, while the nation's irrigation potential created (IPC) is 112 Mha. It is necessary to close the 19 Mha (16%) difference between irrigation potential utilized (IPU) and IPC (MoA&FW, 2016).

Of the 19 Mha gap, major and medium irrigation projects have estimated 13 Mha between IPC and IPU. The main reasons for this gap include inadequate field channel development for last-mile connectivity, poor maintenance of the canal system, a lack of participatory management, shifting land use patterns, and a divergence from the originally planned cropping pattern. Furthermore, the current rates of irrigation efficiency for surface and groundwater are roughly 30–40% and 55–60%, respectively. India can significantly increase the amount of water available by improving irrigation practices all around the country.

To address the aforementioned issues, several steps must be taken. The challenges of supply-side solutions include developing new channels for increasing supply, achieving equitable distribution, meeting sustainable development goals, and so on. The challenges of demand-side solutions include developing new technologies to reduce water demand, changing societal attitudes toward water use, initiating and enforcing water-related structural reforms, and so on.

The Ministry of Water Resources, River Development, and Ganga Rejuvenation (MoWR, RD, and G.R.) has implemented a multifaceted strategy to address the challenges of water resource development and management. These measures are divided into three categories: short-term, medium-term, and long-term, with completion dates set for 2020, 2025, and 2035.

## 8.2. Impact of climate change on agriculture water management

Climate change's impact on agricultural water management and adaptation is an essential task for decision-makers at national and regional or even gram panchayat level in India. Several articles are reviewed to find the impact of climate change on agriculture water management and its adaption can be done. During our analysis, one of the main exclusion criteria for literature was a traditional survey of areas with little to no impact of climate change on agricultural water management. Anwar et al. (2012) published a review paper showing the sequence of short-term, mid-term, and long-term initiatives, with each initiative interconnected. This sequencing approach helps us to eliminate many uncertainties associated with climate change, which ultimately helps us to better manage and adapt to climate change for agricultural water management. Wang et al. (2016), in their case study, suggest that alone water demand and water supply management are not enough to adapt to climate change, so they are given a combined approach that helps prepare the policies related to agricultural water management and adaption. Akinnagbe and Irohibe (2014) review the African farmer's strategies for counteracting the impact of climate change on agriculture. Farmers mainly used drought-resistant crops, improving soil moisture and irrigation, better tillage, agro-forestry, crop diversification, and changing in cropping to mitigate the impact of climate change on agricultural water management. Malhi et al. (2021) suggest several mitigation and adaptation strategies like micro irrigation, nutrient-smart practices, weather-smart activities, carbon-smart activities, and knowledge-smart activities.

### a. Review Questions

R.Q. 1- Climate change impact on agriculture.

R.Q. 2- Agricultural water demand and availability in view of climate change.

R.Q. 3- Climate extremes (heat waves, flood, and drought) due to changing climate and its impact on agriculture water management.

R.Q. 4- Climate-smart technology in agriculture for adaptation to changing climate.

### b. Exclusion Criteria

- Documents are written in languages other than English.
- Documents not related to the study topic.
- Documents not written well.
- Documents not published in well-reputed journals.

## 8.3. Case Studies

A review method is defined before conducting the case studies on adaptation to changing climate in agricultural water management. The case study is done in a well-known way (Kitchenham et al., 2009) and (Klompenburg et al., 2020). First, the research objectives are defined; then, different databases are selected to find the relevant studies. The databases chosen in this study are mainly Google Scholar, Science Direct, Springer, Scopus, and Willey Online. The publications taken for the study are selected based on research objectives, authors, year of publication, and type of publication. The studies on India are separated from the other studies. Some selected publications are given below tables.

**Table 8.1. Case Studies on Climate Change impact on agriculture**

| Paper | Objective | Study Area | Data Used | Methodology | Remarks |
|---|---|---|---|---|---|
| Bhutiyani et. al. 2009 | Study Precipitation variation due to climate change | North-Western Himalaya, India | Data on precipitation was gathered from the Indian Meteorological Department in Pune, the Indian Air Force Station in Leh, and the Manali Snow and Avalanche Study Establishment. | The study made use of the Standardized Temperature Index (STI) and Standardized Precipitation Index (SPI) series. | Decreasing winter snowfall causes a delay in winter, which results in the early spring season and reduced snowfall season. |
| Wassmann et. al. 2009 | Assesses spatial and temporal vulnerabilities of different rice production systems to climate change impacts in Asia. | Asian rice-producing regions, including India | Data collected from a review of previous studies | Review work | There is a need for developing more tolerant crop varieties and improving crop management is at the heart of adaptation measures. |
| Lobell et al. 2012 | Study of heat effects on wheat senescence in India | Indo-Gangetic Plains (IGP) in India. | The Global Summary of the Day (GSOD) data set from the National Climate Data Center and the high-resolution climatology maps found in the WorldClim database are combined to collect the daily minimum and maximum temperatures. | Regression and crop models are used to explore the possible effects of climate change on wheat green season length (GSL). | The findings suggest that wheat faces an even bigger challenge from warming than those suggested by earlier modeling studies and that crop sensitivity to extremely hot days will determine how well adaptations work. |
| Misra et al. 2014 | Development of efficient adaptation and mitigation policies and strategies to reduce the impact of climate change on water resources and irrigation, as well as easily and economically viable options to ensure food and water security under the changing climate. | India | Ministry of Water Resource (MOWR) Govt. of India | The significance and techniques of artificial groundwater recharge, as well as the use of wastewater in irrigation through the Soil Aquifer Treatment (SAT) method | Mitigating the effects of climate change on water resources and agricultural yield can be achieved through the use of artificial recharge structures for groundwater recharge and Soil Aquifer Treatment (SAT) systems that utilize wastewater to create an artificial lithology. |
| Saha et al.2014 | Climate change's effects on India's Summer Monsoon Rainfall (ISMR) | India | Data was collected from the Indian Institute of Tropical Meteorology, Pune, the National Centers for Environmental Prediction/National | Reliable projections of ISMR by general circulation models. | The research indicates two particular shortcomings: The Southern Indian Ocean (SIO) and the tropical Western Pacific Ocean |

| Paper | Objective | Study Area | Data Used | Methodology | Remarks |
|---|---|---|---|---|---|
| | | | Center for Atmospheric Research (NCEP/NCAR), and Global Precipitation Climatology. | | (WPO) are poorly represented by the Coupled Model Intercomparison Project Phase 5 (CMIP5) models. |
| Chevuturi et al. 2016 | A thorough analysis of climate patterns over the past few decades to understand the occurrence and impact of climate change over Leh, a representation of the Ladakh region | Leh (Ladakh), India | The three global reanalysis datasets (CRU, NCEP, and ERA-Interim), India Meteorological Department (IMD) | Several datasets were used to perform a statistical analysis of the climate over Leh. | According to this analysis, recent decades have seen a rapid rise in temperature and a variety of precipitation patterns, which signify a further changing climate and a higher likelihood of unexpected events over the Leh region in the years to come. |
| Pandey et al.2016 | This study looks at how agro-forestry can mitigate the effects of climate change at the local and smallholder household levels. | Tehri-Garhwal. Uttarakhand, India | Farmers field Data | To assess the historical effects of climate change on livelihoods, crop and tree productivity, and the role of agro-forestry in climate change adaptation, a semi-structured questionnaire was created. | Farm households that practice agro-forestry may be less affected by long-term climate change, which could have negative effects on food security and agricultural productivity. |
| Cotera et al.2023 | Provide stakeholder climate change adaptation process with evidence. | Seewinkel, Austria | Future climate projections from World Climate Research program EURO-CORDEX. Groundwater data from the Austrian water portal (eHYD.gov.at). Aquifer data from 70 measuring stations. | A novel hydrologic model based on system dynamics (S.D.) has been developed. Local observation data from lakes, aquifers, and precipitation data is used for calibration. | The result shows that the most effective way to adapt is to combine a change in irrigation method with a new crop rotation. |
| Kamdi et al.2023 | Developing Agro-adaptation strategies for sorghum because of climate change. | Semi-Arid regions of India. | Field Data collection. | Field Experiment and DSSAT-based Crop Environment Resource Synthesis (CERES) model. | The adverse effect of climate change on sorghum can be reduced by postponing the sowing season. Also, it has higher rainwater efficiency than flatbed broad bed furrow. |
| Thapliyal et | Examines the footprints left by glacier retreat and designated danger zones to the effects of | Satopanth (SPG) and Bhagirathi-Kharak (BKG) glaciers of the Mana basin in the | The Randolph Glacier Inventory, version 5 (RGI v5), and the topographic map of the Survey of | Using remote sensing data, the glacier retreat footprints and hazardous zones are identified in relation to the impacts | The volume of snow on the glacier is affected by excessive climatic variations, which leads to the |

| Paper | Objective | Study Area | Data Used | Methodology | Remarks |
|---|---|---|---|---|---|
| al.2023 | climate change in the Central Himalayan region. | Central Himalayan region of India | India (SoI). Various remote sensing datasets, such as Resourcesat-2 LISS IV, MODIS, and Sentinel-1A | of climate change over the central Himalayan region. | glacier drifting downward toward the ablation regions. |
| Verma et al.2023 | To address the various agricultural challenges that originated due to climate change and how Climate Smart Agriculture (CSA) and its pillars are necessary to overcome these challenges. | India | Field and farmer's level data. | Study of climate-smart agriculture (CSA) for reducing the impact of climate change in Indian Agriculture. | In the long run, appropriate strategies and regulations for climate change should be created and properly executed because climate change significantly impacts agriculture production. |

**Table 8.2. Case Studies on Water Availability**

| Paper | Objective | Study Area | Data Collected | Methodology | Remarks |
|---|---|---|---|---|---|
| Rosenzweig et al.2004 | For the reliability of irrigation, the implication of changing crop water demand and water availability is important | Major agricultural regions in Argentina, Brazil, China, Hungary, Romania, and the U.S. | Daily climate data from Dr. Roy Jenne of the National Center, Daily solar radiation was estimated using the WGEN weather generator, and soil was designated as medium silt loam 90 cm deep. | The WATBAL, CERES-Maize, SOY-GROW, CROPWAT, and WEAP models are used for the study. | Increasing water demand can be accommodated on time by improving water management institutions and irrigation facilities. |
| Rajeevan et al.2008 | Detailed analysis of the long-term trends and variability of extreme rainfall events over India using 104 years' worth of gridded daily rainfall data (1901–2004). | Central India | Indian Meteorological Department (IMD) | Correlation analysis is done. | Sea surface temperature (SST) variations over the tropical Indian Ocean impact the inter-annual and inter-decadal variability of extreme rain events in India. |
| Rodell et al.2009 | Satellite-based estimates of groundwater depletion. | India | GRACE (Gravity Recovery and Climate Experiment) satellite data. | Computed the uncertainty associated with the GRACE measurements. Removed GLDAS4 estimates of soil-water storage variations from the | The study demonstrated an increase in runoff and/or evapotranspiration, the majority of the groundwater that is subsequently withdrawn is lost from the area. |

| Paper | Objective | Study Area | Data Collected | Methodology | Remarks |
|---|---|---|---|---|---|
| | | | | GRACE TWS. | |
| Tiwari et al.2009 | Study on Dwindling groundwater resources in northern India from satellite gravity observations. | Northern India | GRACE (Gravity Recovery and Climate Experiment) satellite data. | Two of NASA's Global Land Data Assimilation System models, NOAH and Mosaic, are among the four hydrological models used in the study. | The analysis demonstrates the high demand for agricultural goods. The demand for groundwater is predicted to increase significantly in the upcoming years due to growing industrialization and agricultural growth. |
| Zaveri et al.2016 | Effects of climate change on agriculture and groundwater use. | India | Phase 5 of the Coupled Model Inter-comparison Project (CMIP5) of the World Climate Research Program, with the RCP 8.5 scenario. In this study, five different GCMs were employed. | Used Tobit and linear regression techniques to model areas that are irrigated. | The coupled model predicts that in the near future, support for sustainable groundwater management will become more and more necessary, regardless of the mechanism. |
| Malek et al.2017 | Climate change impact on irrigation losses. | Yakma River Basin, Washington State, USA | The data were obtained from reports, papers, and commercial catalogs. | Incorporation of a process-based irrigation module with VIC-CropSyst (coupled hydrologic/agricultural modeling framework) | Irrigation type and climate conditions have a large impact on irrigation losses. |
| Sunil et al. 2021 | Modeling future irrigation water demands in the context of climate change. | Jayakwadi command area, India. | Detailed reports of the Command Area Development Authority (CADA), Aurangabad, and Food and Agriculture Organization (FAO). India Meteorological Department (IMD). | The monthly crop water has been computed using the downscaled future climate data from the General Circulation Model (GCM), CanESM2. | The reference evapotranspiration values directly rise in response to temperature increases, increasing the water demand. |
| Cao et al.2023 | Virtual water flow (VWF) impacts regional water use and scarcity. | 31 Provinces of China. | Thirty-one provinces, autonomous regions, and municipalities (PAMs) with crop-related W.F., VWF, and water scarcity data were observed. | This study made use of the water footprint network (WFN) approach, a water stress index for regional water scarcity. | The study contends that managing water resources from the standpoint of crop cultivation is necessary to guarantee water security. |

**Table 8.3. Case Studies on Climate Extremes**

| Paper | Objective | Study Area | Data Collected | Methodology | Remarks |
|---|---|---|---|---|---|
| Prabhakar and Shaw,2008 | Climate change adaptation implications for drought risk mitigation. | 10 | Data Collected from Literature Review. | Review work | There is a need for region-specific climate scenarios, and uncertainties involved in future climate change must be identified for adaptation to climate change. |
| Bindi and Olesan,2010 | Responses of climate change on agriculture and its management, mitigation, and adaptation. | Europe | Literature | Review work | There is a trend of temperature increase and different precipitation patterns over Europe. Both autonomous and planned adjustments are needed to adapt to this condition. |
| Mandal,2014 | Explores crop diversification to mitigate the risk of floods on agriculture. | Assam Plains, India | Primary data was collected from four non-contiguous districts of the Brahmaputra and the Barak valleys of Assam with the help of multi-stage sampling. Farm survey data was also collected. | Allocation and regression-based models were used in this study. | The study shows that the farmers in the study area largely use the diversification of crops, which helps cultivate different crops during the flood-free season. |
| Panda, 2016 | Drought adaptation through climate change perceptions, rainfall trends, and perceived barriers. | Odisha, India | Household survey, Rainfall data from Indian Meteorological Department (IMD) Pune. | Trend and cross-verification of rainfall were analyzed using both parametric and non-parametric tests. Man-Kendall and linear coefficient method is used to find climate trends. | The barriers to adaptation are mainly a lack of information sharing and a lack of irrigation and water facilities. The study suggests planning at a local level for mitigating the effect of climate change. |
| Nath et al.2017 | Spatiotemporal characteristics of drought and its impact on agriculture. | Indo-Gangetic Plain, India. | The data used were a globally gridded SPEI v2.3 dataset, and GPCP data was used for rainfall. | The standardized Precipitation Evapotranspiration Index (SPEI), which is linked with soil moisture through correlation analysis, is used in this study. | The results show that higher temperatures increased the drying and evaporation, which ultimately increased in areas affected by drought in recent decades. |
| Kamruzzaman and Shaw, 2018 | The study aims to formulate a sustainable agriculture. | Haor Basin, Bangladesh | Data was collected from different manuals, reports, literature, and field-based studies. | Short-term, middle-term, and Long-term strategies were employed in the study. | The study results show three types of strategies for sustainable agriculture. |

| Paper | Objective | Study Area | Data Collected | Methodology | Remarks |
|---|---|---|---|---|---|
| Durodola,2019 | Review of climate extreme's impacts on agriculture and food security | Nigeria | Literature Review | Review work | Climate-smart agriculture, construction, and repair of drainage networks are needed to mitigate and adapt to climate extremes. |
| Zagaria et al.2022 | Spatiotemporal assessment of potential farm-based land and water management. | Mediterranean croplands. | Climate data from Literature and SPAM2010 dataset. | The study uses spatial multi-criteria analysis. | The results show a worsening effect of climate on agriculture, and there is a need for transformational adaptations. |
| Blasi et al.2023 | Effects of heatwaves and temperature on the agriculture sector. | Italy | Daily mean air temperature from Copernicus ERA5-land and occupation injuries in the agricultural sector from INAIL (Italian National Workers' Compensation Authority). | The study uses the distributed lag linear model. | Workers engaged in labor-intensive and outdoor activities are more prone to Climate change and need urgent adaptation studies. |
| Das et al.2024 | Comprehensive analysis of spatiotemporal variability of rainfall-based extremes and their implications on agriculture. | Upper Ganga Command Area, India | Rainfall data from Indian Meteorological Department (IMD) Pune. | Eight different extreme rainfall indices are used to assess spatiotemporal variations. | The study shows that negative and extreme rainfall significantly impacts agriculture. |

**Table 8.4. Case Studies on Climate Smart Technology**

| Paper | Objective | Study Area | Data Collected | Methodology | Remarks |
|---|---|---|---|---|---|
| Patle et al.2010 | Sustainable water uses through adaptive measures for improving rural livelihoods and increasing food production. | India | Literature | Review work | Efficient water use can be achieved through smart water technology to optimize agricultural productivity. Also, there is a need to transfer technology from developed countries to developing countries. |
| Chandra et al.2017 | Perspective and framing of climate-smart agriculture (CSA). | Global | Literature | Systematic review and qualitative analysis of data. | CSA needs to be implemented throughout the globe, and it needs to move beyond scientific approaches. |
| Partey et al.2018 | Development and promotion of climate-smart agriculture (CSA) with a focus on climate change and variability. | West Africa | Literature | Review work | The review found that agro-forestry and climate-smart information serve as effective methods for climate change and risk adaptation. |
| Mutenje et al.2019 | Cost Benefit Analysis of CSA. | Southern Africa | Examines data from Malawi, Mozambique, and Zambia. | A framework consisting of three models was developed to evaluate the economic efficiency of CSA interventions. | Cultural context, social relevance, and intra-household decision-making greatly impact small-household farmers. |
| Adesipo et al.2020 | Tries to develop a framework for smart village development. | Global | Literature | Analyze the framework for climate-smart agriculture. | Climate-smart technologies are fundamental for building smart villages. |
| Kurgat et al.2020 | Level of adaptation of technologies for climate-smart agriculture (CSA). | Tanzania | Data was collected from 821 farming households. | The multivariate probit (MVP) model is used to gain knowledge about farmers' decision-making regarding technologies. | Farm-based resources, female-controlled resources, and land ownership significantly influenced adaptation. |
| Habtewold, 2021 | Examining the impact of climate-smart technology. | Ethiopia | Data was collected from the Ethiopian Socioeconomic Survey (ESS). | Propensity score matching and endogenous switching regression methods are used. | The study shows that a decrease in multidimensional poverty can be done by increasing income via production by employing technologies. |

## 8.4. Current Policies, challenges, and future research directions

### a. The Climate Change Adaption Policy of India

The National Action Plan (NAPCC) of 2008 is a significant foundation of Indian climate policy. India's response to international demands was widely perceived as the NAPCC (Atteridge et al., 2012). India's NAPCC achieved a proper equilibrium between the Global community and the benefits of India's people, especially farmers. Many policies and programs have come into effect in India after that to help it adapt to the changing climate. India is mainly dependent on agriculture, and it is one of the sectors most badly affected by the changing climate. Figure 8.1 shows India's institutional structure and policies to adapt to changing climate. The Indian government also makes many other policies for adapting to changing climate, which are described below.

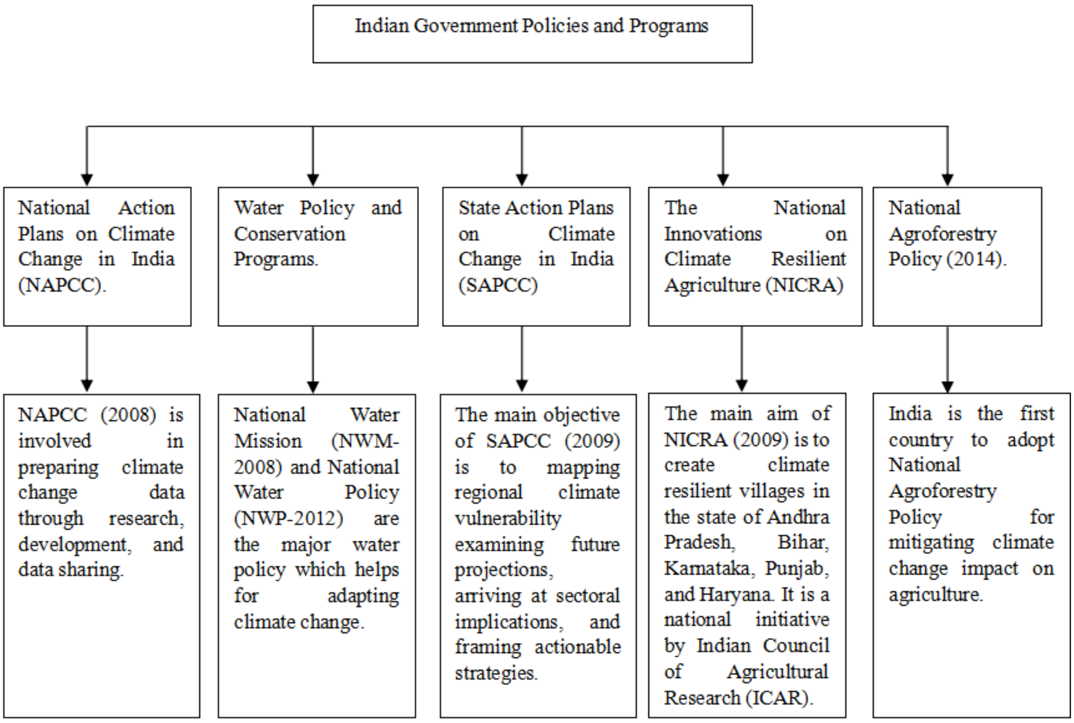


**Figure 8. 1.** Indian Government Policies and Programs

### b. Challenges to Adapt Climate Change

Adapting to climate change poses numerous demanding situations, including but no longer restricted to altered climate patterns, increased frequency of extreme activities, moving ecosystems, economic repercussions, and the desire for sustainable aid control. Overcoming these demanding situations calls for a complete and collaborative technique, integrating medical research, coverage tasks, and community engagement to construct resilience and mitigate the influences of a changing climate. In the Indian context, some of the challenges are described in the flow chart (Figure 8.2).

### c. Future research direction

Climate-smart agriculture will be essential for increasing climate resilience and adaptation in agricultural water management. Figure 8.3 shows the proposed climate-smart technologies and adaptation to the changing climate. Some of the climate-smart agriculture technologies are discussed, which can be extensively researched, especially in Indian conditions for water resource management and adaptation because of climate change. Laser land leveling smooths the soil surface, reducing irrigation use and increasing water efficiency. Water harvesting generally stores water in lakes, ponds, and storage tanks during the rainfall season, which is used for irrigation methods. It is a cost-effective method that is used to reduce the impact of climate change and improve water management. Due to the scarcity of water recently, municipal and industrial water is recycled and reused for agriculture. On the one hand, it helps conserve water and increase production. Partial root-zone drying irrigation with deficit and full irrigation gives a higher water use efficiency. The drip irrigation method can be employed to give water directly to the plant's root zone level, saving a lot of irrigation water. Cloud seeding is a method that can be employed in the area where water is scarce. Plastic mulching is the method of covering soil around the root zone with plastic, which reduces weed growth and conserves soil moisture. A liquid nutrient medium is provided in hydroponic systems, reducing water use and allowing aeroponic plants to grow in air and humid environments. Floating solar plants can be used to overcome water and energy crises.

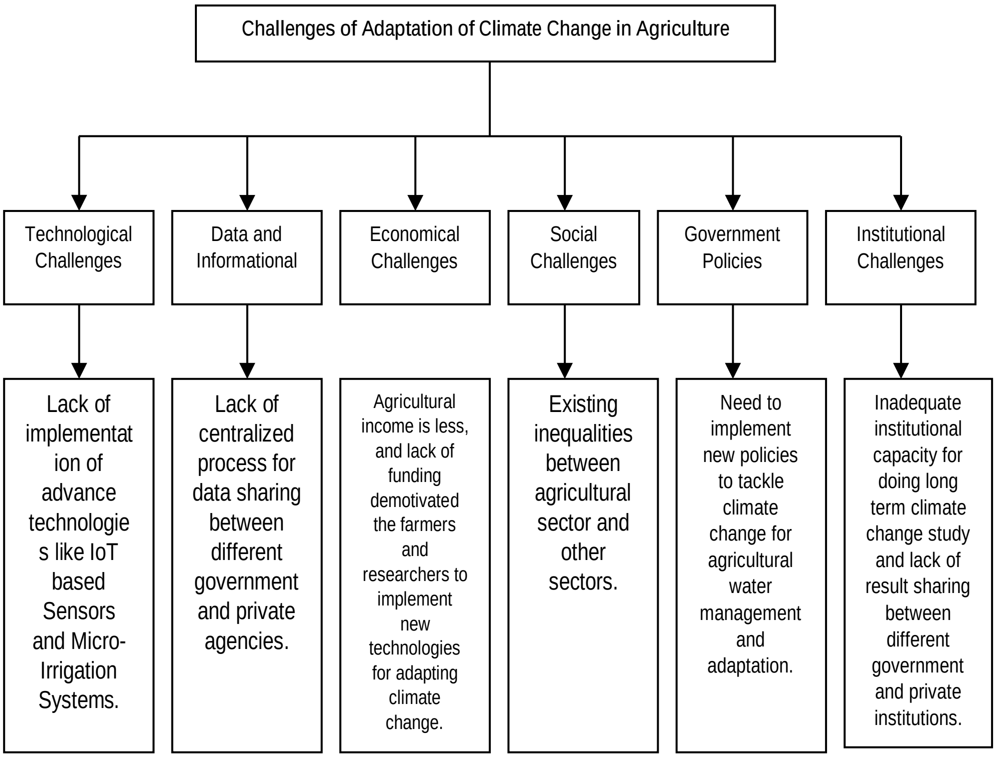


**Figure 8. 2.** Challenges of adaptation to climate change in agriculture

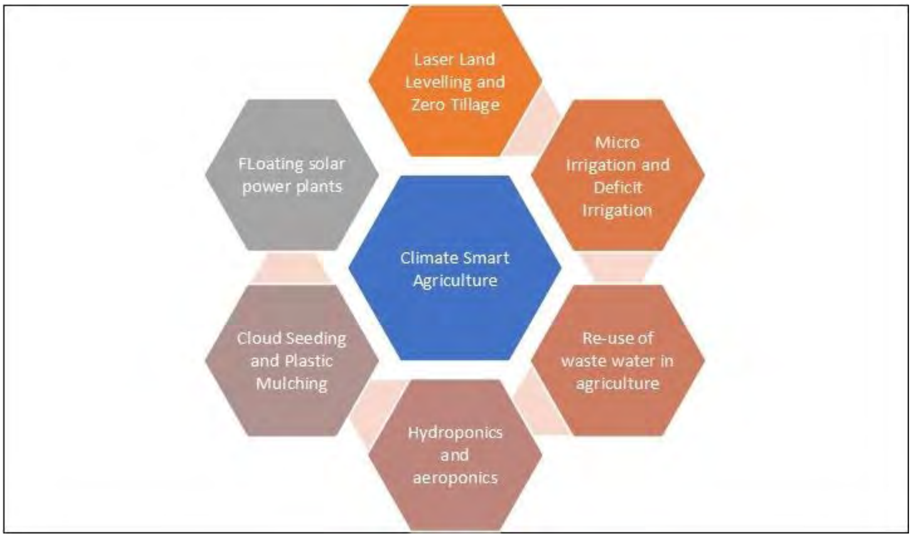


**Figure 8.3.** Climate Smart Agriculture

## 8.5. Conclusion

This case study reviews the literature, which is helpful for water resources management and adaptation in view of climate change. The government policy gaps and challenges are also pointed out through this study. To mitigate the harmful effects of climate change, it is necessary to improve water resources management, increase irrigation efficiency, and improve drainage networks. Preparing a comprehensive framework for water resource management for the agriculture sector is vital. Climate-smart agriculture is a more efficient way to counteract the effects of climate change without reducing production, even in most cases increasing productivity. There is also a lack of conceptual understanding of climate change among farmers, so there is a need to increase awareness. For proper adaptation and water resources, a multidimensional approach is needed.

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# CHAPTER IX
# Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in Iran

Nozar Ghahreman[1]

## 9.1. Introduction

One of the most serious environmental problems confronting the globe today is climate change. Climate change and global warming are currently the most serious environmental threats to the water supply. Freshwater resources may be severely impacted by climate change, with far-reaching implications for human societies and ecosystems. Depending on the different countries, geographical locations, and capacity to reduce or adapt to change, Climate change has immediate and long-term effects on water resources including floods, droughts, rising sea levels in estuaries, drying up of rivers, poor water quality on surface and groundwater systems, distortions of water vapor and precipitation patterns, improper distribution Ice snow and the amount of access and demand for water resources. Water resources in arid and semi-arid countries are becoming increasingly stressed as a result of poor management and increased human demand. This section provides an overview of climate change impacts on agricultural water management in Iran and Middle East North Africa (MENA) region.

## 9.2. Iran

### 9.2.1. Geography and Climate

Iran is located in the arid and semi-arid regions of the world. It is located between 25° and 40° north latitudes and 44°– 63° east longitudes in West Asia and borders the Caspian Sea, the Persian Gulf, and the Gulf of Oman. The total land area of Iran is 1.648 million km$^2$, including 1.636 million km$^2$ of land and 12,000 km$^2$ of the sea. Agricultural land accounts for almost 11.2 percent of the country's acreage, while woods, rangeland, deserts, and industrial/residential regions account for 8.7%, 52.1 percent, 19.7%, and 7.3 percent, respectively (Mousavi et al. 2020). For many centuries, the country's mountains have influenced both its political and economic history. From northwest to southeast, the Zagros Mountains halve the country. Many of the Zagros' peaks reach above 3,000 meters above sea level. The Caspian Sea is encircled by the Alborz Mountains, which are narrow but tall. The volcanic Mount Damavand (5,671 meters), Iran's highest mountain, is located in the middle of the Alborz. Iran's center portion is known as the Central Plateau. The eastern half of the plateau is covered by two salt deserts, the Dasht-e Kavir (Great Desert) and the Dasht-e Lut (Little Desert) (Barren Desert). These deserts are largely uninhabited, except for a few scattered oases, along the Iranian-Azerbaijani border, the Aras (also known as Araks) River flows (https://www.itto.org/iran/article/Iran-Geography/). The Aras River is the longest and one of the most important rivers in Iran, with a total length of 1072 kilometers. The Karun, with a length of 830 kilometers (520 miles), is the only Iranian river that flows into the water of other countries. Other major rivers include the Karkheh, spanning 700 kilometers (430 mi) and joining the Tigris; and the Zayandeh River, which is 300 kilometers (190 mi) long. Several other permanent rivers and streams also drain into the Persian Gulf, while several small rivers that originate in the northwestern Zagros or Alborz drain into the Caspian Sea. Iran has a temperature range of -20 to +50 °C (Environment 2010, Mousavi et al. 2020). The climate in Iran is changeable. Its altitude ranges from -40 m to 5670 m, which has a significant impact on climate diversity (Abbaspour et al. 2009). Winters in the Northwest are bitterly cold, with significant

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snowfall and below-freezing temperatures in December and January. Summers are dry and warm, although spring and fall are comparatively moderate. Winters in the south are warm, while summers are scorching, with average daily temperatures in July topping 38°C (100.4°F). The Khuzestan Plain experiences intense heat during the summer months along with heavy humidity. Iran has an arid climate, with the majority of the sparse annual average precipitation falling between October and April. In most parts of the country, annual precipitation is less than 250 millimeters (9.8 in). The higher Zagros mountain valleys and the Caspian coastal plain, where precipitation averages at least 500 (19.7 in) millimeters yearly, are the notable exceptions. Rainfall in the western section of the Caspian reaches 1,000 millimeters (39.4 in) per year and is evenly spread throughout the year. In contrast, some Central Plateau basins receive only 10 cm of precipitation or less (https://www.liquisearch.com/geography_of_iran/climate). Rainfall in central parts of Iran is less than 50 mm per year, while it can reach 1000 mm around the Caspian Sea coast. The average annual precipitation is around 240 mm, which is less than one-third of the global average (Narimisa and Narimisa 2018).

### 9.2.2. Climate change in Iran

During the last few years, Iran has experienced a decline in rainfall, drought, water scarcity, urban and industrial pollution, desertification, soil erosion, and biodiversity loss (Environment 2010). In recent years, Iran has seen some extreme precipitation events. ENSO has been found to have an impact on precipitation in Iran and other places in numerous research (Nazemosadat and Ghasemi 2004, Alizadeh-Choobari et al. 2018, Zhang et al. 2019, Dehghani et al. 2020, Ghasemifar et al. 2022, Jamshidi Khezeli et al. 2022). The pressure center of the western Mediterranean oscillation has impressed most of the precipitation in Iran, and the winter precipitation in Iran is primarily related to the Black Sea and the Mediterranean SLP (Ghasemi and Khalili 2008). According to studies by (Jamshidi Khezeli et al. 2022), there is a relationship between teleconnection indices (the El-Nino Southern Oscillation (ENSO), and North Atlantic Oscillation (NAO), and Madden–Julian Oscillation (MJO)) and extreme precipitation in the west of Iran. When ENSO was in a warm phase (El Niño conditions), heavy precipitation occurred, and it typically reached its peak in the spring, before reversing its intensity from weakening to strengthening before the commencement of extreme precipitation events. Due to easterly winds that travel a long distance over the northwest Indian Ocean to the Arabian Sea, an investigation of moisture fluxes found that the main humidity sources of the heavy precipitation were the Arabian Sea.

Atmospheric water vapor, which sources and transport pathways are primarily driven by different large-scale teleconnection processes, including the El Niño-Southern Oscillation (ENSO), generally controls regional climate variability. The warm (cold) phases of ENSO or the El Niño (La Nina) events effectively increase (decrease) the atmospheric water vapor over Iran during cold months, particularly both December and March. During the El Niño occurrences in December, precipitable stratocumulus and nimbostratus clouds were generally dominant across Iran, especially throughout the southern seas (Ghasemifar et al. 2022).

In 2100, the average number of warm spell days is expected to reach roughly 215 days, up from ten days in 1990. If global emissions fall swiftly, this will be restricted to around 50 days on average. (Organization 2015). Depending on the future scenario chosen, climate change will also influence thermal comfort in very diverse ways. As an example, future changes in cloudiness and wind speed will have a significant impact on thermal comfort in Tabriz city, northwest of Iran in the next decades. The expected overcast heating effect, as well as the reduced wind cooling potential, would have major consequences for heart-related ailments and various agricultural activities like animal husbandry in the region (Ghadaksaz and Saboohi 2020).

The results of (Zhang et al. 2022)'s study on the effects of climate change on river flow in 28 almost natural catchments in Iran showed that increasing temperature and the frequency of light rainfall events are the two main factors in reducing flow throughout the studied catchments. The expansion of arid and semi-arid climate-covered areas is one of the side effects of increasing greenhouse gas emissions and their implications for the globe due to climate change and global warming, especially for areas of the world that are located in warm and arid belts. By 2100, there is expected to be a progressive increase in the areas covered by warm and arid climates and a decrease in the amount of cold and temperate climates in Iran (Kiani and Kamangar 2022).

Iran (168.25 million tons of carbon), Saudi Arabia (147.65 million tons of carbon), and Turkey (88.21 million tons of carbon) are responsible for more than 65 percent of the region's fossil-fuel $CO_2$ emissions. In 2015, Iran's total carbon dioxide emissions were 630 million tons, or about 8.0 metric tons per capita (JG et al. 2015, Mousavi et al. 2020).

(Mansouri Daneshvar et al. 2019) stated that Iran is the first and seventh-most responsible for climate change in the Middle East and the world, respectively, due to its reliance on significant oil and gas production, as well as increasing urbanization and cumulative greenhouse gas (GHG) emissions approaching 616,741 million tons of $CO_2$.

## 9.3. Case Studies

### 9.3.1. Climate change impact on Water Resources and Agricultural Water Management of Iran

#### a. Climate change detection

According to the IPCC's Fourth Assessment Report, the Middle East will experience a temperature increase of up to 2 degrees Celsius in the next 15–20 years, and over 4 degrees Celsius by the end of the century, as well as a 20% decrease in precipitation.

Drought-related urban migration, lower agricultural production, and destruction of the environment have all been linked to climate change (Environment 2010). Frequent Droughts and decreased accessible water supplies have become more common in Iran as a result of climate change. Unanticipated droughts can be destructive to Iranian farmers (Mirzaei et al. 2022). According to recent studies, most parts of Iran would experience a temperature rise of roughly 4.5°C by the year 2100, with the central and southern regions being the most vulnerable to climate change due to their sensitivity (Borna et al. 2011, Darand et al. 2015, Mousavi et al. 2020). In Iran, the mean annual temperature is expected to rise by around 6.2°C on average between 1990 and 2100 under a high emissions scenario. If global emissions fall swiftly, the temperature rise would be restricted to roughly 1.7°C.

### 9.3.2. Climate change impacts on water resources and food security in Iran

Change in the time variation of weather patterns over a specific period of time could be the definition of climate change that change in the amount of precipitation, temperature, evaporation rate, and solar radiation received by the earth causes that. Climate change is predicted to have a net negative impact on water supplies and freshwater ecosystems in all parts of the world, with the strength and nature of the impact varying greatly from place to region. Rising temperatures, fluctuations in precipitation patterns, snow cover, and an increased chance of floods and droughts are the main effects of climate change on water supplies. Climate change may also have an impact on seasonal variations in river flow (Afshar and Fahmi 2019).

Climate change has caused yield fluctuations in many crops in Iran. In an study by (Ghamghami and Beiranvand 2021) it was found that except for few crops like potato and clover, the all other major food and forage yield will be reduced up to 80% as a result of climate change. Hence, policy-makers should adopt choices to mitigate climate change consequences and ensure sustainable food security.

Water scarcity and the effects of climate change pose a significant threat to the country's food security. At least half of the world's population is expected to endure water stress and scarcity by the year 2622. These conditions are worse for countries located in arid and semi-arid regions such as Iran.

### 9.3.3. Climate Change impacts on evapotranspiration and water use

Potential evapotranspiration (ETP) is one of the important elements of the hydrological cycle that plays an important role in water resources management projects, agricultural studies, irrigation network design, water structures, and climate research. Many case studies across Iran have been performed to project the impacts of climate change on evapotranspiration and crop water use. In general, it is predicted that in Iran, due to the significant increase in potential evapotranspiration in summer, the water requirement of the major warm season plants will increase significantly.

Mohammadrezaei and Ghahreman (2021), evaluated the possible impacts of climatic change on the virtual water content of wheat, barley, corn, potato, and tomato crops under RCP scenario in three regions namely Kerman, Bam, and Jiroft located in southern Iran. The findings of this study revealed that the quantity of virtual water estimated for all study crops would increase, with barley and wheat showing the highest increase in the future period.

Babolhekami et.al (2020) performed a study to identify the impact of climate change on reference evapotranspiration in Mazandaran province, north of Iran Climatic data of Gharakheil, Babolsar, Noshahr, and Ramsar weather stations were used during 1985-2005. Meteorological data for a future period (2006-2081) were estimated using the CanEMS2 model under RCP2.6, RCP4.5, and RCP8.5 scenarios and the reference evapotranspiration was calculated using climatic data for future periods. The results showed that the highest and lowest percentages of reference evapotranspiration changes would occur in October and March, respectively. Evaluation of the reference evapotranspiration at the selected stations shows that the percentage of evapotranspiration variations in different months varies between -16.1 to 25.7% and the highest increase and decrease in reference evapotranspiration will occur in Ramsar and Gharakheil stations, respectively.

### 9.3.4. Water Resources management and strategies in context of climate change

(Mousavi et al. 2020) in their research stated that Given the rising burden of diseases linked to climate variability in Iran, as well as the interdisciplinary nature of climate change and health issues, the Ministry of Health and Medical Education, as custodian of public health, needs to develop an integrated, multi-sectoral, and comprehensive approach for identifying, prioritizing, and implementing adaptation options to improve resiliency and adaption against adverse health effects of climate change.

Using less vulnerable species to climate change, such as medicinal plants, as a coping technique for climate change adaptation can be considered (Pourmeidani et al. 2020).

Estimates of water needs and studies of virtual water of plants in different parts of the country under new climate change scenarios are recommended to provide a suitable cultivation pattern and increase water productivity (Mohammadrezaei and Ghahreman 2021). Air temperature is a significant factor in estimating water needs and climatic change in climate and agricultural studies, particularly crop models. Despite the ease of measurement and a large number of recording stations, the creation of meteorological generators was necessitated by the need to fill statistical gaps and the requirement for future data. (Kamali et al. 2021) Used and evaluated the SHArP stochastic generator to simulate maximum and minimum temperatures on a daily scale. They concluded that this generator has a good ability to simulate air temperature data and can be used as a method to complete statistical gaps.

Early rainfall prediction is critical in agricultural water management because of inter-annual changes in rainfall and the occurrence of droughts. As a result, numerous scientists have attempted to forecast rainfall on various time scales. (Ghorbani et al. 2022) employed a stepwise M5 model tree to estimate annual rainfall in Hashem Abad station, north of Iran, utilizing observed data and 17 climate signals from 1985 to 2019. The results revealed that stepwise modeling is required due to the nature of rainfall changes and the greedy algorithm of the M5 model. Teleconnections' delayed impacts may be regarded as a useful feature for predicting next year's rainfall early and capturing inter-annual variance.

Evapotranspiration estimation on a regional scale is important for water resource management and agricultural water productivity, cropping pattern modification, as well as climate forecasting, and drought monitoring. For this purpose, (abdi et al. 2020) in their study analyzed and evaluated actual surface evapotranspiration data from the GLEAM model with evapotranspiration data from the water balance equation in the Karkheh basin. For all stations, the findings demonstrated that this model has satisfactory accuracy.

Iran is one of the arid and semi-arid countries in the world due to a lack of precipitation and inequitable distribution of time and space, therefore water resources must be handled properly. This purpose requires a more precise and scientific understanding of the components of water balance, notably precipitation, surface water, groundwater, and, most importantly, evapotranspiration. In the hydrological cycle, evaporation is a fundamental element. Estimating evaporation rates and analyzing the effects of climatic conditions are critical for both agricultural and water resource management (Solaimani and Bararkhanpour 2021).

From Rio 1992 to NY 2016, international climate change adoptions and agreements have been compiled. In 2015, Iran attended the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21) in Paris, which focused on countries' willingness to reduce carbon dioxide emissions, with signatory countries agreeing to change their industrial and economic development processes to reduce greenhouse gas emissions globally, with the goal of limiting global range temperature to 2 degrees Celsius, where it adopted its agreement on December 12, 2015, and signed its treaty on April 22, 2016, in New York. During COP21, Iran announced that it would voluntarily endeavor to decrease its greenhouse gas emissions by 4% until 2020, aiming for a total reduction of 12%, subject to a real lifting of unfair international sanctions and the receipt of necessary funds. Iran's national climate change strategy should concentrate on reducing GHG emissions in the energy sector. The Iranian energy agency has developed applications for renewable energy, such as solar panels, for this purpose. In this context, innovative approaches for exploring renewable energy applications and mitigating GHG emissions should be considered for future research and development in order to combat the growing risk of climate change effects. This goal should be supported by technological affairs and international participants (tv 2015, UNFCCC 2015, Mansouri Daneshvar et al. 2019, Mousavi et al. 2020). (Ghadaksaz and Saboohi 2020) stated that increasing the efficiency of fossil-fueled power plants to 46% by 2030, as well as reducing routine gas flaring, could easily cover Iran's unconditional and conditional energy sector pledges to reduce GHG emissions by 12% compared to business as usual. With technical and financial help, Iran may implement the Paris Agreement's Intended Nationally Determined Contributions (INDCs) in line with national objectives to reduce energy intensity.

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# CHAPTER X
# Impacts of Climate Change on Agricultural Water Management and Adaptation- Case Studies in China

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### Abstract

China, one of the most populous and rapidly growing economies worldwide, is increasingly facing challenges related to water scarcity and food security. With a population that has grown from 670 million in 1961 to 1.42 billion in 2020, the demand for food escalates, placing a strain on water resources. China will face great challenges in the future in terms of water availability, food security and climate change. Enhancing agricultural productivity through improved water use efficiency is vital for addressing water and food security issues in context of climate change. The research utilizes the Policy Dialogue Model Simulation (PODIUMSim) to analyze and simulate future irrigation water demand, crop yield, water productivity, and food surplus or deficit in China, considering hydrology, meteorology, water and land use, and crop planting data. It also employs General Circulation Models (GCMs) and statistical downscaling to predict climate changes and their effects on agricultural water demand in China. It also outlines the challenges and opportunities in adapting to climate change, emphasizing the need for efficient water use, water-saving practices, and investment in drought-resistant crops.

## 10.1 Introduction

As one of the most populated and rapidly growing economies of the world, China is increasingly facing water shortage and food security challenges. China's population has increased from 670 million in 1961 to 1.34 billion in 2010 and 1.42 billion in 2020 (excluding Hong Kong, Macao and Taiwan), accounting for 21% of the world's total population. Population growth increases food demand. With an improvement in people’s living standards, the dietary structure changes, including an increase in meat consumption, which requires several multiples of consumptive water to meet the same daily calorie needs. In China, irrigated agriculture is the foundation for rural economic development and the population, arable land, climate and water resources conditions have made it the most important part of China’s agricultural production. As might be expected, the challenge related to water in China is the problem of growing water shortages under increasing population pressure, exacerbated by advancing urbanization and increasing industrialization. Consequently, competition among different water uses has increased, resulting in the degradation of water quality and unabated environmental damage in catchment areas (Bandaragoda, 2006).

In fact, drought, flood and water pollution has become the three most serious water problems in China due to the uneven spatial distribution of land and water resources and rapid industrialization and urbanization. The arable land in the north of China accounts for three-fifths of the national total, but the water resources are only one-fifth of the total; and while the arable land in the south of China accounts for just two-fifths of the national total, the water resources make up four-fifths of the total. The per hectare water resources in the south are three times that in the north. With increasing competition for water from domestic and industrial sectors, it has become more and more difficult to increase the water supply to agricultural production. As a result, finding some

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sustainable and optimal water management options has become one of the most imperative issues for decision makers and natural resources managers.

Food security issues are not particularly pressing in China presently, but will heavily dominate the national political agenda in the next ten years as the population will reach its peak by 2030. Much will depend on local production, the global political and macroeconomic landscape and China's strategic positioning in the emerging world trade alliances. Local production will become a hostage to the variable hydrologic cycle, at least in the major food producing areas such as the North China plain and Yellow River basin. The great challenge for the coming decades in China will be the task of increasing food production with less water, particularly in basins with limited water resources such as the Yellow River basin. Increasing productivity in agriculture will play a vital role in easing competition for scarce resources, prevention of environmental degradation and provision of food security (Sharma, 2006). Boosting crop productivity by increasing water use efficiency will be the main pathway to addressing the water and food security issues.

China will face great challenges in the future in terms of water availability, food security and climate change. Therefore, great efforts should be made to promote efficient water use through adopting water-saving practices. In addition, increasing water productivity or importing food from other countries through virtual water trading is a better pathway to meet future food demand in China. Investing in drought resistant crops which use less water or adopting some non-structural water saving measures are possible options to mitigate the adverse impacts from climate change.

## 10.2 Methodology

**Analytical framework**

China was divided into nine major river basins in this research, including Songliao River basin, Haihe River basin, Huaihe River basin, Yellow River basin, Yangtze River basin, Pearl River basin, Southeast River basin, Southwest River basin and inland basin. Based on the data of hydrology, meteorology, water and land use, and crop planting in the current year 2010, the future (2030 and 2050) irrigation water demand, crop yield, water productivity and food surplus or deficit in China were analyzed and simulated using the Policy Dialogue Model Simulation (PODIUMSim) developed by the International Water Management Institute (IWMI).

General Circulation Models (GCMs) are powerful tools accounting for the complex set of processes which will produce future climate change (Karl et al, 2003). However, GCM projections are currently subject to significant uncertainties in the modelling process (Mearns et al., 2001; Allen et al, 2002; Forest et al., 2002), so that climate projections are not easy to incorporate into hydrological impact studies (Allen et al, 2002). Therefore, there is a wide range in results for the projection of both precipitation and temperature (the major factor that drive evapotranspiration) changes. In addition to this, there are also significant differences in the projections from different scenarios in the same GCMs. In particular, what is perplexing to gauge the reliability of results for precipitation changes is that some models predict increase under climate change while others predict decrease. So rather than use the outputs directly generated from one specific GCM, this research developed scenarios based on previous studies, by giving some increasing or decreasing percentages for P75 and ETp in PODIUMSim model, two major meteorological factors that drive irrigation water demand. ETp is average daily potential evapotranspiration for different month (mm/day) which can be used to calculate crop water requirement and P75 is monthly 75% exceedance probability rainfall (mm/month) which can be used to calculate seasonal effective precipitation.

**Statistical downscaling of GCMs**

It is widely accepted that present-day GCMs are able to simulate large-scale atmosphere state in a generally realistic manner, and it is believed that these models are the adequate tool to predict large-scale climate changes (Storch et al., 1993). However, although GCMs represent the main features of the global atmospheric circulation reasonably well, their performance in reproducing regional climatic details is rather poor (Sailor 2007). This is particularly true for variables such as precipitation and surface wind speed. With respect to the simulation of regional climates, GCMs suffer from several limitations, including lack of accurate surface condition data, inability of model parameterizations to model fine scales, and computational time required for high resolution runs. Hence, most GCMs are run at relatively coarse spatial resolutions generally greater than 2.0°for both latitude and longitude (>200km for middle latitudes). Therefore, direct use of outputs from the GCMs for climate change impact assessment is often limited by their incapability at representing local features and dynamics at spatial scales finer than the in-built GCM grid scale. The direct result of the poor spatial resolution of GCMs is a serious mismatch of scale between the available climate change scenarios and the scale of interest to climate data users. As a result, there is a need to convert GCM information to regional and local scales. Statistical or stochastic downscaling is a technique that is used to transfer the atmospheric information available from the GCMs to a smaller catchment scale. The transfer functions used to relate large-scale variables to surface parameters can be developed using any suitable technique, like multiple linear regressions, neural networks and classification & regression et al approaches.

The simulated effects for future climate changes are different from various GCMs, it has been proved by some scientists that the effects from the average of many models are better than that from one single model. Therefore, after interpolating and downscaling the simulated results from over 20 GCMs with different resolutions from the fourth IPCC report, the National Climate Centre of China integrated these into one resolution, and validated its simulated effects in East Asia. Integrating the multi-models with the Reliability Ensemble Averaging (REA) method, the National Climate Centre of China come up with a set monthly average data (precipitation and temperature two factors) between 1901 and 2100 for use by scientists conducting research on climate change impacts (17 modes for A1B and A2, and 16 models for A2) (Averaging) (Xu et al, 2009; Giorgi et al., 2002 and 2003). The resolution for these climate change projection products is 1°×1°. The Emission Scenarios of the IPCC Special Report on Emission Scenarios (SRES) are shown in the following:

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

However, since the grid size of the generated GCM outputs are relatively large, downscaling on the output data should be conducted when using the simulated results from GCMs. There are statistical and dynamical two downscaling methods. This research used the simple one, statistical downscaling, which include three statistical methods, i.e. transfer function, circulation based differentiation, and using weather producer. The commonly used method in transfer function is multiple linear regressions, such as stepwise regression, integrated PCA and multiple linear regression, integrated PCA and stepwise regression et al. In addition to this, it also includes some nonlinear methods, such as neural network. This research used BP neural network to conduct statistical downscaling **Figure 0.1**:Downscaling sketch map of GCM parameters. Firstly, building the relations between the observed precipitation in 1956-2010 and the predicted precipitation from GCMs in 1956-2010 with BP neural network, then predicting the precipitation in 2011-2050 based on the predicted precipitation from GCMs in 2011-2050 and the built BP neural network model. The temperature in the study area in 2011-2050 can also be predicted with the same method.

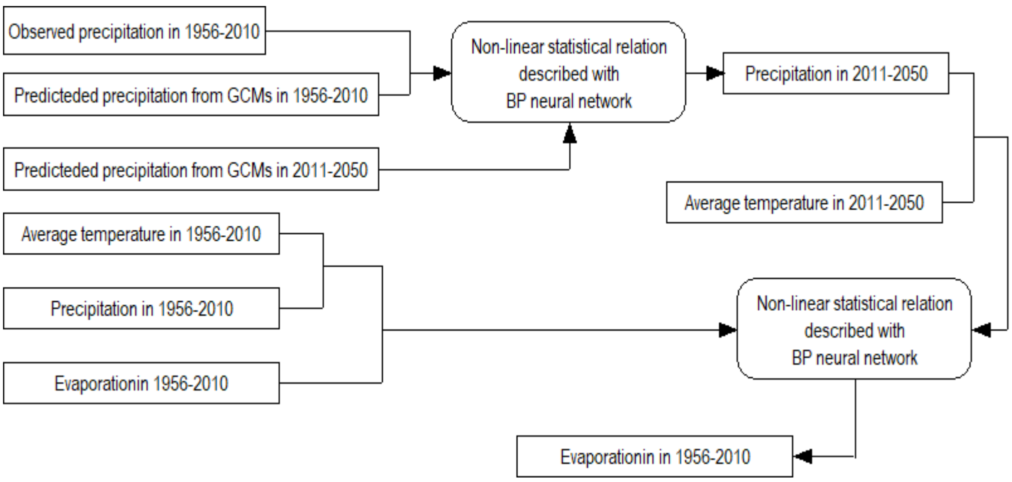


**Figure 10.2:** Downscaling sketch map of GCM parameters

**Projection of arable land area and water use efficiency**

According to the white paper *China's Food Security* issued by the Information Office of the State Council in December 2020, China will strictly abide by the red line of 120 million hectares of arable land area, and implement the policy of balance between occupation and compensation. Therefore, it is estimated that from 2030 to 2050, China's arable land area will be maintained at about 121 million hectares and 120 million hectares respectively, which will be reduced by 1 million hectares and 2 million hectares respectively compared with the current situation.

In order to ensure the national food security and the needs for new rural construction, it is estimated that the command irrigation area of farmland by 2030 will reach 930 million mu, 25 million mu more than the base year[1], and the per capita irrigation area will remain above 0.6 mu. The irrigation area of forestry, animal husbandry and fishery will reach 160 million mu, an increase of 80 million mu than the base year. It is estimated that the command irrigation area will reach 1.0 billion mu by 2050.

The projection of the irrigation area and rain-fed area of some main crops in China in different target years (2030 to 2050) mainly refer to the predicted values given by FAO Database (FAO). FAO mainly build three development scenarios, namely Sustainable Development scenario, Business as Usual scenario and Structured Societies scenario. The projection of arable land area under irrigation and rain-fed of some main crops in 2030, 2035, 2040 and 2050 under the three different scenarios are conducted first. The cropping area and cropping intensity of some main crops in different target years (2030 to 2050) also refer to the predicted values of three different development scenarios given by FAO Database (FAOSTAT). The prediction of cropping area and cropping intensity of some main crops in 2030, 2035, 2040 and 2050 under the three scenarios are also conducted.

China aims to establish a water management system combining total amount control and water use quota management. On the premise of ensuring economic and social development and improving the water use situation of ecological environment, the total amount of water use in China will be controlled within 700 billion $m^3$ by 2030. In the meantime, China will comprehensively promote the building of water-saving society, change the mode of water use, and increase the efficiency and benefits of water resources use.

By vigorously implementing efficient water-saving irrigation, the average irrigation water consumption per mu by 2030 will be controlled within 390$m^3$, a decrease of 73 $m^3$ compared with the base year, and the average irrigation water consumption per mu in medium drought years will be controlled within 430$m^3$, a decrease of 81 $m^3$ compared with the base year. The irrigation water use efficiency in China will increase from 0.50 in 2010 to 0.60 in 2030. The irrigation water use efficiency in large-scale irrigation area, medium-sized irrigation area, small-scale irrigation area and well irrigation area will reach 0.50-0.55, 0.55-0.65, 0.65-0.75 and 0.75-0.90 respectively. It is estimated that the irrigation water use efficiency will increase to 0.65 by 2050. In general, the irrigation water use quota will be strictly controlled, and the irrigation water use efficiency will reach a high level.

## 10.3 Water Challenges in the Context of Climate Change in China

### Climate change

With the increasing capacity of human beings to transform nature, the influence of human activities on the water cycle and water resources evolution process is becoming increasingly prominent. In addition to the influence of underlying surface changes and artificial water intake on water cycle, global warming is also an important factor in the spatial and temporal variation of water cycle. China is a developing country with large population, low level of economic development, coal-based energy structure and relatively weak ability to cope with climate change. With the acceleration of urbanization and industrialization and the continuous improvement of residents' energy consumption level, China is facing severe challenges in coping with climate

[1] Considering the difference between command irrigation area and actual irrigation area, 905 billion mu was used for the calculation of agricultural irrigation area in the base year 2010.

change. Climate change will pose a threat to China's natural ecosystem and social and economic development. For example, in the Yellow River Basin of China, the increase of irrigation water consumption caused by the construction of reservoirs and the decrease of precipitation caused by the global El Nino phenomenon in the past half century will lead to more water shortage.

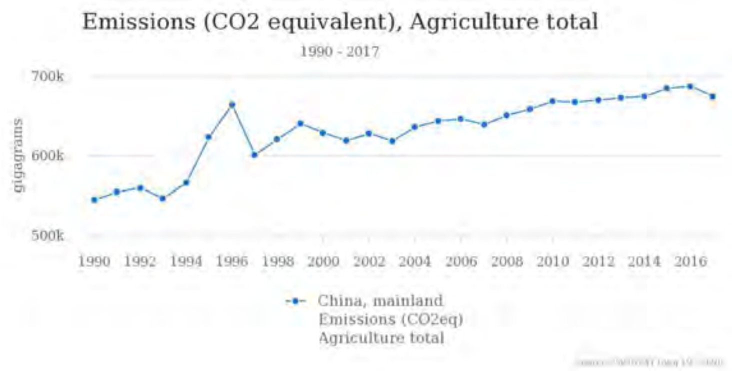


**Figure 10.2:** Total emissions from agriculture in China

Although there are some significant differences, there are still many similarities in climate change between China and the world. There is obvious evidence that the annual average temperature in China has increased by 1.1 °C in the past 50 years and increased by 0.5-0.8 °C in the past 100 years, which is slightly higher than the change of global average temperature in the same period. In the past 100 years, there has been no obvious change in the annual precipitation in China. However, the Yellow River basin and the North China plain have shown an obvious trend of drought, especially in Shandong Province. It is predicted that the temperature in northern China will rise by 1.0 °C by 2030 and 1.3-1.4 °C by 2050. Climate change will pose a great threat to the sustainable use of water resources in northern China. It is estimated that in the next 30 years, climate change will reduce the water availability of Haihe River basin and Luanhe River basin by 4.7% and 4-6% respectively. In addition, climate change will reduce the runoff of Haihe and Luanhe river basins by 12%. Therefore, climate change will have adverse impacts on water resources and their distribution, as well as the water availability, especially in northern China.

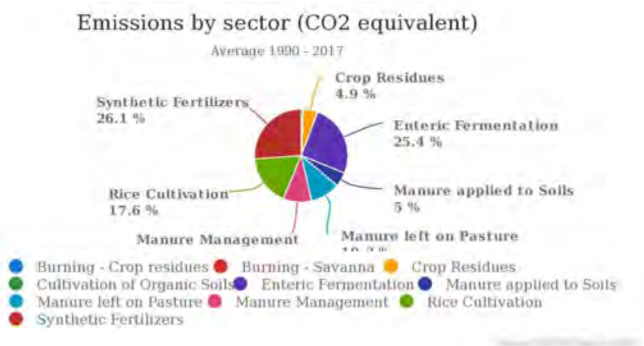


**Figure 10.3**: Emissions by sector in China

The existing studies also show that the impact of global warming on agricultural irrigation water is far greater than that on industrial water and domestic water, especially in areas where precipitation tends to decrease and/or evaporation increases more than precipitation increases.

**Water challenges**

By the end of 2015, China's irrigation area has reached 65.9 million hectares, accounting for 49% of China's cultivated land. 75% of the country's grain and 90% of the economic crops come from irrigated agriculture. Therefore, irrigation plays an important role in ensuring China's agricultural production, food security, economic and social stability, and raising 21% of the world's population with 6% renewable water resources and 9% arable land.

However, water shortage has always been a big problem for water safety in China. The average annual precipitation in China is 648 mm, which is 20% less than that of the world and 12% less than that of 740 mm in Asia. The overall distribution trend of annual precipitation in China is decreasing from southeast to northwest. In the southeast coastal areas of China and the southeast of China, the average annual precipitation is more than 2000 mm, and in the eastern region near the Sino Indian border, the average annual rainfall is more than 5000 mm. In China, 44% of the annual precipitation forms surface runoff, while the remaining 56% is evaporated or recharged to groundwater through surface water, plants and soil.

The average annual water resources in China is 2.8 trillion m3. However, the per capita water resources is only1980 m3, which is one fourth of the world average, making China one of the most water deficient countries in the world. In addition, the water resources in China is unevenly distributed spatially and temporally. In the north of China, the cultivated land accounts for three fifth of the total cultivated land area, while the total water resources account for only one fifth of the whole country; on the contrary, the cultivated land area in the south accounts for two fifth of the whole country, while the water resources account for four fifth of the whole country. The average water resources per area in the south is three times that in the north.

With the growth of population, the competition for water to meet the food demand will become increasingly fierce (Figure 10.2-10.4). The exploited water resources in China has increased from 100 billion m3 in 1949 to 560 billion m3 in 2000 and 602.2 billion m3 in 2010; the per capita water resources use has increased from 187 m3 in 1949 to 428 m3 in 2000 and 450 m3 in 2010; the exploited groundwater has increased from 57.2 billion m3 in 1970s to 74.8 billion m3 in 1980s, 107 billion m3 in 2000 and 110.8 billion m3 in 2010. The proportion of groundwater consumption to total water consumption increased from 14% in 1980 to 20% in 2000, and then decreased to 18.4% in 2010. The total water consumption in China in 2010 was 602.2 billion m3, including 369.2 billion m3 for agriculture.

Large population, small arable land, scare water resources, mismatched distribution of water and land resources, and long-term tight balance of agricultural products, especially grain supply et al national conditions make water the lifeblood of agriculture in China. Water plays an important role in ensuring China’s food security in agricultural production. China's agricultural development must take the road of irrigated (drainage) agriculture. In recent years, with the rapid increase of industrial and domestic water consumption, increasing agricultural irrigation water consumption has become more and more difficult. Therefore, how to reasonably arrange the limited water resources while meeting the national economic development, especially the national food demand, has become an important issue in the current water resources policy-making.

In recent years, China has taken a variety of water management measures, such as improving the water use efficiency and water productivity, South-to-North Water Transfer, sewage treatment and reuse, and water resources redistribution to solve the problem of water shortage and uneven spatial and temporal distribution, and great achievements have been made. It is clearly pointed out in the National Medium and Long-term Science and Technology Development Plan that the development goals of China's irrigated agriculture are: (1) increasing the command irrigation area from 55.9 million hectares to 60 million hectares, while the total agricultural water consumption remains unchanged at 400-420 billion m3; (2) increasing water use efficiency from 0.43 to 0.65, and increasing water productivity from 1 kg/m3 to 1.5 kg/m3. Therefore, in the case of water shortage and increasingly industrial and domestic water competition, the future development of irrigated agriculture will focus on water savings, so as to improve the water use efficiency and water productivity of available water resources.

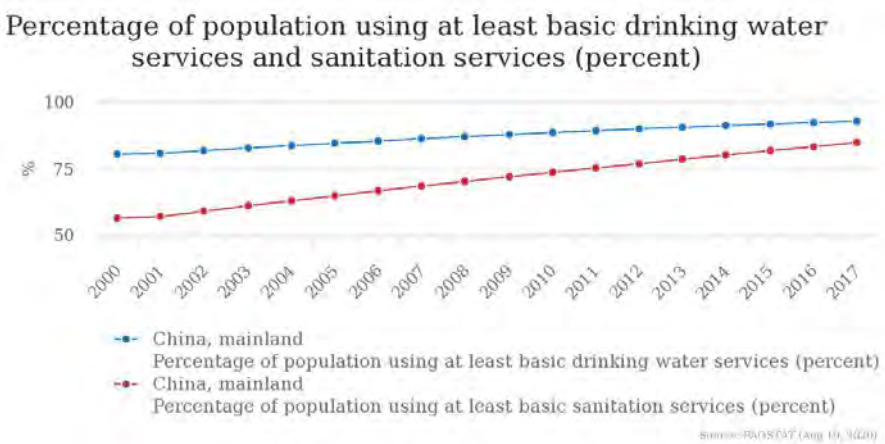


**Figure 10.4:** Percentage of population using at least basic drinking water services and sanitation services in China

## 10.4 Impact of climate change on future agricultural water demand in China

### Scenarios development for climate change

Climate change poses an important responsibility for national and international bodies to develop the means to mitigate, adapt and respond to this phenomenon (FAO, 2004). Unmanaged systems are likely to be the most vulnerable to climate change. With its complex climate and fragile eco-environment, China is vulnerable to the adverse impacts of climate change. And, as a developing country with a large population, a relatively low level of economic development, a coal-dominant energy mix and relatively low capacity to tackle climate change, China will surely face more severe challenges when coping with climate change alongside the acceleration of urbanization, industrialization and the increase of residential energy consumption. Climate change will threaten China's natural ecosystems and socio-economic development, including agriculture, livestock breeding, forestry, natural ecosystems, water resources and coastal zones. Some of the challenges that China is facing include (Zhang, 2008):

- 20 of the world's 30 most polluted cities are in China;
- Qinghai-Tibet plateau glaciers (47% of China's glacier cover) are shrinking by 7% a year;
- China has witnessed a sustained drop in precipitation since the 1950s;
- Coal will remain the backbone of energy supply and the culprit of major emissions – 70% of $CO_2$, 90% of $SO_x$, and 67% of $NO_x$ emissions; Cost of environmental damage from air and water pollution is made up of 5.8% of GDP (World Bank, 2007).

The climate change in China shows a considerable similarity to the global change, though there are still some significant differences between them. Warming was most noticeable across northern China. There has been a continuous drought in the North China Plain since the 1980s, while flooding disasters have happened frequently in southern China. This impact has been especially enhanced since the 1990s.

There are four ways to set future climate scenarios: arbitrary scenario, incremental scenario, analogy scenario and climate model-based scenario. Arbitrary scenario is based on the possible range of climate change in the future and any given change values of climate factors such as temperature and precipitation. For example, it is assumed that the annual average temperature increases by 1 ℃, 2 ℃, 3 ℃ and 4 ℃, and the annual precipitation increases or decreases by 5%, 10%, 15% and 20%. Incremental scenarios are simple adjustments to the baseline climate based on the predicted future changes. Because they include mandatory adjustments, they may not be true meteorologically. Analogical scenarios can be derived from past records or other regional analogies of changing climate, but may be difficult to identify and rarely used. Climate model-based scenario are mainly based on the predicted results of climate models as the future climate conditions. Because climate models contain the data of direct input of greenhouse effects, which can partly explain the physical mechanism of the current climate system, this method is most commonly used in the development of future climate scenarios.

The downscaled results of annual precipitation, temperature and evaporation with BP neural network under A1B, A2 and B1 three different emission scenarios are obtained. Table 10.1 showed the variation range of the predicted precipitation and temperature in the coming twenty (2010-2030) and forty years (2010-2050) compared to their historical annual averages (1956-2010).

**Table 10.1** Predicted climate results under different emission scenarios in the coming forty years

| Scenario | 2010 | | | 2010-2030 | | | 2010-2050 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Pre (mm) | Eva (mm) | Tem (℃) | Pre (mm) | Eva (mm) | Tem (℃) | Pre (mm) | Eva (mm) | Tem (℃) |
| A1B | 500.03 | 991.48 | 13.13 | 546.15 | 1027.7 | 13.53 | 547.76 | 1019.05 | 13.53 |
| A2 | 500.03 | 991.48 | 13.13 | 596.31 | 1010.17 | 13.87 | 542.56 | 1023.67 | 13.93 |
| B1 | 500.03 | 991.48 | 13.13 | 560.25 | 974.68 | 13.37 | 560.83 | 999.2 | 13.38 |

**Note:** Pre-Precipitation; Eva- Evaporation; Tem-Temperature

Comparison of the annual values between the historical average (1990-2008) and the future average: under the A1B emission scenario, the mean annual precipitation in the next 20 years (2010-2030) and 40 years (2010-2050) will increase by 9.22% and 9.55% respectively, the mean annual evaporation will increase by 3.65% and 2.78%, and the mean annual temperature will all increase by 0.4 ℃. Under A2 emission scenario, the mean annual precipitation in the next 20 years (2010-2030) and 40 years (2010-2050) will increase by 19.25% and 8.51% respectively, the mean annual evaporation will increase by 1.89% and 3.25%, and the mean annual temperature will increase by 0.74 ℃ and 0.80 ℃. Under B1 emission scenario, the mean annual precipitation in the next 20 years (2010-2030) and 40 years (2010-2050) will increase by 12.04% and 12.16% respectively, the mean annual evaporation will decrease by 1.69% and increase by 0.78%, and the average annual temperature will increase by 0.24 ℃ and 0.25 ℃. According to the average predicted results of the three emission scenarios, the annual precipitation will increase by 6.59%, the annual evaporation will increase by 1.28% and the annual temperature will increase by 0.46 ℃ in the next 20 years. Meanwhile, the annual precipitation will increase by 10.01%, the annual evaporation will increase by 2.27%, and the average annual temperature will increase by 0.48 ℃ In the next 40 years.

With the rationale mentioned above and the projections generated from many local and GCM models, eight scenarios were developed with P75 and ETP varying ±5% in the year 2030 and ±10% in the year 2050 respectively, on the basis of their values in 2010 in China. Scenario IV is the most favorable scenario, where P75 will increase by 5% and 10% respectively in 2030 and 2050 while ETP will decrease by 5% and 10% respectively in 2030 and 2050. Scenario VIII is the most unfavorable scenario, where P75 will decrease by 5% and 10% respectively in 2030 and 2050 and ETP will increase by 5% and 10% respectively in 2030 and 2050.

**Table 10.2** Scenario's development for climate change in China in the years 2030 and 2050

| Scenarios | 2030 | | 2050 | |
|---|---|---|---|---|
| | P75 | ETp | P75 | ETp |
| Scenario I | – | +5% | – | +10% |
| Scenario II | – | -5% | – | -10% |
| Scenario III | +5% | – | +10% | – |
| Scenario IV | +5% | -5% | +10% | -10% |
| Scenario V | +5% | +5% | +10% | +10% |
| Scenario VI | -5% | – | -10% | – |
| Scenario VII | -5% | -5% | -10% | -10% |
| Scenario VIII | -5% | +5% | -10% | +10% |

**Note:** "-" means zero change.

## 10.5 Impact of climate change on future agricultural water demand and water productivity

The eight scenarios for climate change shown in **Table 10.3** Scenario's development for climate change in China in the years 2030 and 2050 were applied to the PODIUMSim model to analyze the impact of climate change on future irrigation water demand and water productivity in China. **Table 10.4** Irrigation water demand in different climate change scenarios in 2030 and 2050, summarizes the simulated results of irrigation water demand, degree of development, depletion fraction, and the percentage of groundwater extraction to total groundwater availability under different climate change scenarios in 2030 and 2050.

It can be seen from **Table 10.5:** Irrigation water demand in different climate change scenarios in 2030 and 2050, that in scenario I where ETP increases by 5% and 10% in 2030 and 2050 respectively, and scenario VI where P75 decreases by 5% and 10% in 2030 and 2050 respectively, the irrigation water demand in scenario I will increase by 9% and 18% compared with the base year respectively, while in scenario VI it will increase by 4% and 8% respectively. It can be seen that the effects of increasing ETP on irrigation water demand are much greater than that of decreasing P75 in the same range. Table 10.4 and Table 10.5 show the water productivity under different climate change scenarios in 2030 and 2050, respectively.

In scenario II where ETP decreases by 5% and 10% in 2030 and 2050 respectively, and scenario III where P75 increases by 5% and 10% in 2030 and 2050 respectively, irrigation water demand in scenario II will reduce by 9% and 17% compared with the base year respectively, while in scenario III, it will reduce by 4% and 8% respectively. It can be seen that the effects of decreasing ETP on irrigation water demand are much greater than that of increasing P75 in the same range. Scenario V is the combination of the favorable effect of increasing P75 and the adverse effect of increasing ETP. Under this scenario, the irrigation water demand in 2030 and 2050 will increase by 5% and 10% respectively compared with the base year, which also shows that the effects of change in ETP on irrigation water demand is more significant. Scenario VII is a combination of the adverse effects of decreasing P75 and the favorable effects of decreasing ETP. Under this scenario, the irrigation water demand in 2030 and 2050 will be reduced by 5% and 9% respectively compared with the base year.

In the most favorable scenario, the irrigation water demand in 2030 and 2050 will decrease by 13% and 25% compared with the base year, reaching 387.8 billion $m^3$ and 310.1 billion $m^3$ respectively compared with the base year, and the total water demand will decrease by 7% and 12%, reaching 649.9 billion m3 and 590.7 billion $m^3$ respectively. The degree of development of water resources will decrease by 5% and 9% respectively. In the most unfavorable scenario, the irrigation water demand in 2030 and 2050 will increase by 13% and 26% respectively compared with the base year, reaching 456.0 billion m3 and 424.9 billion $m^3$ respectively, and the total water demand will increase by 7% and 13% respectively compared with the base year, reaching 752.9 billion $m^3$ and 763.0 billion $m^3$ respectively, which is much higher than the upper limit set in China's planning that the total annual exploitation and utilization of water resources should be maintained at about 700 billion $m^3$. The degree of development of water resources will increase by 5% and 10% respectively. Similarly, different climate change scenarios have significant effects on water productivity. As shown in Table 10.6: Water productivities in different climate change scenarios in 2030, and Table 10.7: Water productivities in different climate change scenarios in 2050, in scenario I where ETP increases by 5% and 10% in 2030 and 2050 respectively, and scenario VI, where P75 decreases by 5% and 10% in 2030 and 2050 respectively, the water productivity in scenario I is significantly lower than that in the base year. For example, the water productivity of paddy rice in 2030 is 0.03 lower than that in the base year, and in 2050 0.06 lower than that in the base year. The water productivity of irrigated wheat and Irrigated Maize will decrease by 0.12 and 0.06 respectively in 2030 and will decrease by 0.26 and 0.14 respectively in 2050. In scenario VI where P75 decreases by 5% and 10% in 2030 and 2050 respectively, the water productivity of irrigated crops is almost the same as that of the base year, but the water productivity of rain-fed crops is slightly higher than that of the base year.

In scenario II where ETP decreases by 5% and 10% in 2030 and 2050 respectively, and in scenario III where P75 increases by 5% and 10% in 2030 and 2050 respectively, the extent of increase of water productivity in scenario II is higher than that in scenario-III. For example, in scenario II, the water productivity of paddy rice, irrigated wheat, and irrigated maize in 2030 is 0.81, 3.35, and 1.68 respectively, while in scenario III, the values are 0.63, 2.60, and 1.33 respectively, which are significantly lower than those in scenario II.

In scenario V, where the favorable effects of increasing P75 are combined with the unfavorable effects of increasing ETP, the water productivity of irrigated and rainfed crops in 2030 and 2050 are lower than those in the base year. In scenario VII with the unfavorable effects of decreasing P75 combined with the favorable effects of decreasing ETP, the water productivity of irrigated and rainfed crops in 2030 and 2050 are significantly higher than those in the base year, which indicates that in the same range, the effects of decreasing ETP on water productivity is much greater than that of decreasing P75 on water productivity.

In the most favorable scenario, the water productivity of all the crops will reach the peak in 2030 and 2050. For example, the water productivity of paddy rice, irrigated wheat and irrigated maize will reach 0.67, 2.74 and 1.41 in 2030, and 0.82, 3.33 and 1.68 in 2050, respectively. In the most unfavorable scenario, the water productivity of all the crops will drop to the lowest values in 2030 and 2050. For example, the water productivity of paddy rice, irrigated wheat and irrigated maize will drop to 0.60, 2.46 and 1.25 in 2030, and 0.67, 2.78 and 1.38 in 2050, respectively.

**Table 10.8** Irrigation water demand in different climate change scenarios in 2030 and 2050

| Scenarios | 2030 | | | | | | | 2050 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P_{75}$ | $ET_p$ | Irrigation water demand ($10^9$ $m^3$) | Total water demand ($10^9$ $m^3$) | Degree of Development | Depletion fraction | GW abstraction - % of GW availability | $P_{75}$ | $ET_p$ | Irrigation water demand ($10^9$ $m^3$) | Total water demand ($10^9$ $m^3$) | Degree of Develop-ment | Depletion fraction | GW abstraction - % of GW availability |
| Benchmark | | | 404 | 700.9 | 68% | 89% | 149% | | | 336.8 | 674.8 | 69% | 91% | 192% |
| Scenario I | – | 5% | 439 | 736.3 | 62% | 86% | 109% | – | 10% | 396.4 | 734.4 | 76% | 91% | 192% |
| | | | 9% | 5% | | | | | | 18% | 9% | | | |
| Scenario II | – | -5% | 368.7 | 665.6 | 65% | 89% | 120% | – | -10% | 278 | 616.1 | 63% | 90% | 191% |
| | | | -9% | -5% | | | | | | -17% | -9% | | | |
| Scenario III | 5% | – | 387.8 | 684.8 | 67% | 89% | 149% | 10% | – | 310.1 | 648.2 | 66% | 91% | 191% |
| | | | -4% | -2% | | | | | | -8% | -4% | | | |
| Scenario IV | 5% | -5% | 353 | 649.9 | 63% | 88% | 150% | 10% | -10% | 252.6 | 590.7 | 60% | 90% | 191% |
| | | | -13% | -7% | | | | | | -25% | -12% | | | |
| Scenario V | 5% | 5% | 423.1 | 720.1 | 70% | 89% | 148% | 10% | 10% | 369.2 | 707.3 | 73% | 91% | 192% |
| | | | 5% | 3% | | | | | | 10% | 5% | | | |
| Scenario VI | -5% | – | 420.5 | 717.4 | 70% | 89% | 148% | -10% | – | 364.9 | 703 | 72% | 91% | 192% |
| | | | 4% | 2% | | | | | | 8% | 4% | | | |
| Scenario VII | -5% | -5% | 385.1 | 682 | 66% | 89% | 149% | -10% | -10% | 305.4 | 643.4 | 66% | 91% | 191% |
| | | | -5% | -3% | | | | | | -9% | -5% | | | |
| Scenario VIII | -5% | 5% | 456 | 752.9 | 73% | 89% | 147% | -10% | 10% | 424.9 | 763 | 79% | 91% | 192% |
| | | | 13% | 7% | | | | | | 26% | 13% | | | |

**Table 10.9** Water productivities in different climate change scenarios in 2030

| Scenarios | | Paddy | Wheat | Maize | Other Cereals | Pulses | Oil Crops | Vegetables | Roots & Tubers | Sugarcane | Fruits | Cotton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | Irrigated | 0.63 | 2.59 | 1.32 | 2.42 | 0.54 | 2.49 | 8.61 | 4.67 | 8.7 | 1.88 | 0.62 |
| | Rainfed | / | 4.14 | 1.67 | 1.02 | 0.59 | 3.23 | 7.93 | 7.59 | 16.1 | 4.11 | 0.71 |
| Scenario I | Irrigated | 0.60 | 2.47 | 1.26 | 2.30 | 0.52 | 2.39 | 8.11 | 4.40 | 8.20 | 1.77 | 0.58 |
| | Rainfed | / | 4.14 | 1.67 | 1.02 | 0.59 | 3.23 | 7.93 | 7.59 | 16.10 | 4.11 | 0.71 |
| Scenario II | Irrigated | 0.66 | 2.73 | 1.40 | 2.56 | 0.56 | 2.61 | 9.18 | 4.99 | 9.27 | 2.00 | 0.65 |
| | Rainfed | / | 4.14 | 1.67 | 1.02 | 0.59 | 3.23 | 7.93 | 7.59 | 16.10 | 4.11 | 0.71 |
| Scenario III | Irrigated | 0.63 | 2.60 | 1.33 | 2.43 | 0.53 | 2.48 | 8.69 | 4.73 | 8.78 | 1.90 | 0.62 |
| | Rainfed | / | 3.96 | 1.61 | 0.98 | 0.56 | 3.09 | 7.62 | 7.28 | 15.45 | 3.94 | 0.69 |
| Scenario IV | Irrigated | 0.67 | 2.74 | 1.41 | 2.56 | 0.55 | 2.57 | 9.27 | 5.05 | 9.36 | 2.01 | 0.65 |
| | Rainfed | / | 3.96 | 1.61 | 0.98 | 0.56 | 3.09 | 7.62 | 7.28 | 15.45 | 3.94 | 0.69 |
| Scenario V | Irrigated | 0.61 | 2.47 | 1.26 | 2.30 | 0.52 | 2.38 | 8.18 | 4.44 | 8.27 | 1.79 | 0.59 |
| | Rainfed | / | 3.96 | 1.61 | 0.98 | 0.56 | 3.09 | 7.62 | 7.28 | 15.45 | 3.94 | 0.69 |
| Scenario VI | Irrigated | 0.63 | 2.59 | 1.32 | 2.41 | 0.54 | 2.50 | 8.52 | 4.62 | 8.62 | 1.86 | 0.61 |
| | Rainfed | / | 4.33 | 1.74 | 1.07 | 0.61 | 3.38 | 8.28 | 7.92 | 16.82 | 4.29 | 0.74 |
| Scenario VII | Irrigated | 0.66 | 2.73 | 1.40 | 2.55 | 0.57 | 2.62 | 9.08 | 4.93 | 9.18 | 1.98 | 0.65 |
| | Rainfed | / | 4.33 | 1.74 | 1.07 | 0.61 | 3.38 | 8.28 | 7.92 | 16.82 | 4.29 | 0.74 |
| Scenario VIII | Irrigated | 0.60 | 2.46 | 1.25 | 2.29 | 0.52 | 2.39 | 8.03 | 4.35 | 8.13 | 1.75 | 0.58 |
| | Rainfed | / | 4.33 | 1.74 | 1.07 | 0.61 | 3.38 | 8.28 | 7.92 | 16.82 | 4.29 | 0.74 |

**Table 10.10** Water productivities in different climate change scenarios in 2050

| Scenarios | | Paddy | Wheat | Maize | Other Cereals | Pulses | Oil Crops | Vegetables | Roots & Tubers | Sugarcane | Fruits | Cotton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | Irrigated | 0.74 | 3.03 | 1.52 | 3.01 | 0.62 | 3.01 | 10.91 | 5.70 | 11.17 | 2.24 | 0.90 |
| | Rainfed | / | 3.99 | 1.77 | 1.09 | 0.66 | 3.72 | 9.01 | 8.56 | 17.18 | 4.59 | 0.91 |
| Scenario I | Irrigated | 0.68 | 2.77 | 1.38 | 2.73 | 0.58 | 2.79 | 9.79 | 5.11 | 10.03 | 2.01 | 0.81 |
| | Rainfed | / | 3.99 | 1.77 | 1.09 | 0.66 | 3.72 | 9.01 | 8.56 | 17.18 | 4.59 | 0.91 |
| Scenario II | Irrigated | 0.81 | 3.35 | 1.68 | 3.36 | 0.66 | 3.23 | 12.31 | 6.45 | 12.60 | 2.51 | 0.99 |
| | Rainfed | / | 3.99 | 1.77 | 1.09 | 0.66 | 3.72 | 9.01 | 8.56 | 17.18 | 4.59 | 0.91 |
| Scenario III | Irrigated | 0.74 | 3.02 | 1.51 | 3.02 | 0.60 | 2.94 | 11.03 | 5.78 | 11.29 | 2.26 | 0.89 |
| | Rainfed | / | 3.67 | 1.64 | 1.00 | 0.61 | 3.41 | 8.33 | 7.91 | 15.86 | 4.23 | 0.84 |
| Scenario IV | Irrigated | 0.82 | 3.33 | 1.68 | 3.37 | 0.63 | 3.07 | 12.42 | 6.50 | 12.76 | 2.52 | 0.96 |
| | Rainfed | / | 3.67 | 1.64 | 1.00 | 0.61 | 3.41 | 8.33 | 7.91 | 15.86 | 4.23 | 0.84 |
| Scenario V | Irrigated | 0.68 | 2.76 | 1.38 | 2.74 | 0.57 | 2.75 | 9.89 | 5.17 | 10.13 | 2.04 | 0.82 |
| | Rainfed | / | 3.67 | 1.64 | 1.00 | 0.61 | 3.41 | 8.33 | 7.91 | 15.86 | 4.23 | 0.84 |
| Scenario VI | Irrigated | 0.73 | 3.04 | 1.52 | 3.00 | 0.64 | 3.06 | 10.77 | 5.62 | 11.04 | 2.22 | 0.90 |
| | Rainfed | / | 4.38 | 1.94 | 1.19 | 0.72 | 4.10 | 9.84 | 9.36 | 18.81 | 5.03 | 1.00 |
| Scenario VII | Irrigated | 0.80 | 3.37 | 1.69 | 3.34 | 0.69 | 3.33 | 12.14 | 6.35 | 12.43 | 2.50 | 1.00 |
| | Rainfed | / | 4.38 | 1.94 | 1.19 | 0.72 | 4.10 | 9.84 | 9.36 | 18.81 | 5.03 | 1.00 |
| Scenario VIII | Irrigated | 0.67 | 2.78 | 1.38 | 2.72 | 0.58 | 2.83 | 9.68 | 5.04 | 9.93 | 1.99 | 0.81 |
| | Rainfed | / | 4.38 | 1.94 | 1.19 | 0.72 | 4.10 | 9.84 | 9.36 | 18.81 | 5.03 | 1.00 |

Based on the above analysis results, it can be seen that the effects of change in $ET_P$ on irrigation water demand and water productivity is much greater than that of change in P75 on irrigation water demand and water productivity.

## 10.4 Adaptation countermeasures to ensure agricultural water use in China

Water resources management has three major goals - to increase water availability, improve water quality and reduce water related risks. Maximizing the potentials of nature will help to achieve these three goals. It is necessary to create a favorable environment for change, including the establishment of an appropriate legal and regulatory framework, an appropriate financing mechanism and social recognition. The countermeasure to protect water security mainly include:

- Strictly control the total amount of water consumption and restrain the excessive depletion of water resources;
- Strictly implement water use quota management and increase water use efficiency and benefits;
- Strengthen the protection of ecological environment and realize the sustainable utilization of water resources;
- Rationally allocate water resources and improve the carrying capacity of regional water resources;
- Improve the water supply security system to ensure the sound and rapid development of economy and society;
- Implement the strictest water resources management system and comprehensively promote the social management ability;
- Build nature-based solutions for water.

Adaptation and mitigation measures to climate change in water resources

- ❖ Strengthening the protection of water resources and the control of soil erosion. Efforts should be made to strengthen the management of water function zones and the protection of water sources, reasonably determine the ecological water use standards of main rivers and lakes, and ensure reasonable ecological flow and water level. It needs to strengthen water environment monitoring and water ecology protection. On the basis of comprehensive planning, it is necessary to combine prevention, protection, supervision, control and restoration, take measures according to local conditions and disasters, optimize the allocation of engineering, biological and agricultural measures, and build a scientific and perfect comprehensive prevention and control system of soil erosion.

- ❖ Building the pattern of water resources allocation. Efforts should be made to build a water-saving society, construct various water storage, water diversion and water pumping schemes in line with local conditions, and improve key water source schemes and irrigation schemes. It needs to implement the strictest water resources management system, strictly implement the planning and management, water resources demonstration and water diversion permit system, and strengthen the total water consumption control and quota management. It needs to restrict the disorderly expansion of cities and the development of high water consumption industries in water shortage areas, reasonably exploit and utilize unconventional water resources such as rain flood, seawater, brackish water, reclaimed water and mine water.

Improving the flood control and drought relief system. Efforts should be made to speed up the construction of controlling hydro-junction projects in the main streams and tributaries of rivers, and strengthen the construction of embankments and river training for important rivers. It needs to adjust urban development and industrial layout, scientifically set up and rationally use flood storage and detention areas, strictly prohibit blind reclamation and barrier encroachment on river beaches and floodways, and strengthen flood risk management. It needs to improve flood control and drought relief command systems at all levels, improve emergency response mechanisms, and strengthen disaster monitoring, forecasting, and early warning.

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**Saroj Karki** is an accomplished water resources and irrigation engineer with over a decade of experience in the sector. Saroj earned his PhD degree in fluvial hydraulics from Kyoto University, Japan in 2019. He has published several research papers and articles in national and international journals and media. Currently, he is working as a senior divisional engineer at the Ministry of Water Supply, Irrigation, and Energy in Koshi Province, Nepal, focusing on developing and implementing water resources programs and policies at the local, regional, and national levels. His interest lies in the intersection of water science, policy, and community, and he has written extensively on local and national issues related to water resources management and development. He is a member of WG-Climate of ICID since 2024 representing Nepal National Committee on Irrigation and Drainage.

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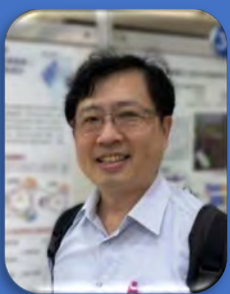

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