IMPACT OF CLIMATE CHANGE ON FOOD AND WATER RESOURCES IN PUNJAB, INDIA

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MSc Thesis in Environmental Systems Analysis

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Preface

Before you is the thesis titled impact of climate change on the food and water resources in Punjab, India. The basis for this thesis emerged from my interest to better understand the impact of climate change. As the impact of climate change is expected to be severe especially on developing countries, there is a need to better understand the impacts and to make mitigation plans in advance to reduce the severity of climate change on the food and water security.

First of all, I couldn’t have successfully completed my thesis without a string support system. I would like to sincerely thank my supervisor Dr Confidence Duku for his guidance during my thesis. I would also like extend my heartfelt gratitude to my parents and friends for their support and encouragement.

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Summary

The main aim of this study was to look at the impact of climate change based on the RCP (Representative Concentration Pathways) 4.5 and RCP 8.5 projections on the water resources as well as the impact on the agriculture sector in a selected watershed in Punjab, India. It further examined the impacts of changes in population according to the SSP1(Shared socio-economic pathway) and SSP3 narratives on the water use. In order to study the impact of climate changes on the watershed the SWAT (Soil Water Assessment Tool) model was used and for studying the impact of the population, the water use the scenarios developed by Hanasaki et al., (2013) was used. Based on the results, there is an increase in temperature (in °C) and precipitation (in mm) in the selected watershed area for both the RCP scenarios used in the study. A similar observation was made for the other parameters like evapotranspiration and potential evapotranspiration. The study also showed an increase in the yield for both rice and wheat for both the scenarios. The population increase projected for the study area for the selected socio-economic pathways was drastic and over 160% in all the scenarios considered for this study. Thus, even though the amounts of water consumed per capita do not increase in the selected pathways the water demand increases drastically because of the increase in population. This study area was selected as it was the epicentre of green revolution in India and hence heavily depended on agriculture. There has been study on the impacts of climate change in India but there is a need to look at the impacts on regional level to better adapt to changes. This helps policy makers to plan and develop more integrated policies to ensure that the impacts of the climate change are kept to a minimum. The selection of the scenarios was also based on the understanding based on the old adage hope for the best prepare for the worst. Knowing the worst can help better plan for the future to try and reduce the impacts to a minimum.

1.0. Introduction

With a population of 4.14 billion, Asia is responsible for feeding two-thirds of the population in the world. This region also accounts for 59% of the planet's water consumption (Rasul, 2014). Furthermore, South Asian countries have seen large-scale socio-economic development, but these countries are still facing the challenges of attaining food and nutritional security, ending hunger and poverty, and ensuring healthy lives for the rapidly increasing population (Rasul, 2016).

Climate change impacts on temperature and precipitation and has serious impacts on the hydrological cycle, irrigation water demand, water resource availability which in turn affects the agriculture productivity as well as production (Abeysingha, Singh, Islam, & Sehgal, 2016a). The World Bank estimates that 70-80% of the costs of climate change will be borne by the developing countries (Turral, Burke, Faures, & Faures, 2011). The future socio-economic projections modelled by IIASA (International Institute for Applied Sciences)show that the global, as well as the regional water requirements, may be affected by climate change and thus has its effects on agricultural water withdrawal (Hanjra & Ejaz Qureshi, 2010).

Several studies (eg. Abeysingha, Singh, Islam, & Sehgal, 2016b; Guiteras, 2009b; Hanjra & Ejaz Qureshi, 2010; Reinhard, Verhagen, Wolters, & Ruben, 2017; Tubiello & Fischer, 2006) have come to similar conclusions regarding the impact of climate change on agriculture and food availability. One main conclusion is that potential food shortage may be caused due to a decrease in agricultural productivity as a result of impeded access to water. But they also show that mitigation measures can have a positive impact on food security and agricultural productivity (Hanjra & Ejaz Qureshi, 2010).

Agriculture is one of the largest consumers of water and hence is likely to be the sector which would be severely affected by an increase in water scarcity (Hanjra & Ejaz Qureshi, 2010). The issues of water scarcity is exacerbated by degradation in ecosystem services, land degradation, water pollution along with increasing costs of developing new water sources (Hanjra & Ejaz Qureshi, 2010).

Indian agriculture is one of the largest consumers of the nation's available water resources. It accounts for consumption of around 80-85% of the available water(R. Kumar & Raj Gautam, 2014a). The water consumption for irrigation purposes has increased systematically over the years as agricultural intensification occurs in India. Groundwater and surface water has been used extensively for irrigation and this has helped in attaining self-sufficiency in food production especially in the past thirty years (R. Kumar & Raj Gautam, 2014a).

The issue of impact of climate change on food production and water resources has been addressed separately by several studies (eg.Damerau, Patt, & Van Vliet, 2016; Goswami, Sharma, & Bharati, 2015; Krishna Kumar, Rupa Kumar, Ashrit, Deshpande, & Hansen, 2004; N. Kumar et al., 2017; TERI, 2015) but the combined approach which considers the synergies, trade-offs and feedbacks between them has rarely been applied in India and the larger South-Asia region (FAO, 2014; Golam, Sharma, & Rasul, 2015).

A concept of nexus thinking was first introduced by the World Economic Forum in order to better promote and understand the linkages between food, water and energy and to ensure their sustainable use (Biggs et al., 2015a).

The United Nations identifies the food-water-energy nexus as one of the central concepts of sustainable development[1]. A nexus defines the interlinkages between the three facets, food,

[1] http://www.unwater.org/water-facts/water-food-and-energy/

water and energy (Reinhard et al., 2017). The demand for all three facets of the nexus is driven further by an increase in population, rapid urbanisation as well as economic development[2].

Water is an essential component of food production, water is also used for energy production and this energy is used for pumping water for irrigation purposes. This leads to a very complex cycle where overuse or imbalance of one can result in depletion in the others (Barik et al., 2016). Thus, creating a need for a combined thinking in order to better understand the situation.

As mentioned earlier, the concept of nexus is often closely associated with food security, water security and energy security. But this study only looks into the impact of climate change only on the food and water resources.

1.1. Literature review

The study by Lawford et al., (2013), suggests that the current trends in groundwater depletion need to be assessed immediately and the situation within India needs to be better understood through regional analysis and there is an immediate need in policy changes to ensure food-water and energy security. They also observed a lack of coherence in the policies within the various states of India thus making it as different as transboundary basins. The various experts that answered the survey for this study also ranked climate change and political and socio-economic changes as two of the top-ranked specific stresses on the basins (Lawford et al., 2013).

As mentioned earlier a nexus approach looks at the interlinkages between the different facets of a nexus. But as shown in the studies by Hoff (2011), very high extraction as well as consumption of natural resources can lead to a natural capital depletion without equitable benefits and increased climate risks (Hoff, 2011). This was observed in north-west India by Aggarwal et al., (2014) where government policies have acted as a strong driver for intensive agriculture in the area, in order to ensure food security at national level which has led to the degradation of ecosystems without further increasing levels of food security (Aggarwal, 2008; Biggs et al., 2015b). Punjab, the area considered in this study (detailed in Section 2.1), falls in the northwestern part of India where policies have resulted in the implementation of intensive agricultural practices where the current agricultural practices are turning more unsustainable. Hence making it of significance to better understand the impact of climate change on the agriculture and water resources and to take necessary adaptation measures.

Groundwater is a major source of water for agricultural production and the water-food-energy nexus in general. To assess how changes in groundwater affect the water-food-energy nexus, Barik et al., (2016) used remote sensing data from the gravity recovery and Climate Experiment (GRACE). They show that there is a decreasing trend in the groundwater storage in India during the last decade. They focused on the water-food-energy nexus based on the GRACE satellite data for the groundwater levels. This data was used as a proxy for evaluating the electricity consumption in the agriculture sector. This was used to understand the water-energy nexus and a similar analysis was done for the food production and groundwater consumption rates (Barik et al., 2016). They also concluded that the net per capita availability of food has decreased since the 1960s partly due to considerable increases in population. Furthermore, the decrease in food production in the years that coincided with the drought years have been recorded and there has been no significant drop since 2009. This was a result of the increased use of water for irrigation. This along with the energy subsidies put in place as part of the green revolution to ensure food security enables the farmers to use groundwater extensively for irrigation purposes. They also observed a very high negative correlation between food production and groundwater

[2] http://www.unwater.org/water-facts/water-food-and-energy/

storage in North-western Indian. The study also observed that despite heavy monsoons the dependency on groundwater did not decrease, which was concluded based on a correlation between rainfall and energy consumption. They finally indicated the need for a more local study in order to better understand how much area of Indian agriculture is rain-fed even though most of the reports suggest otherwise but this no longer holds true for India.

Kaur et al.,(2010) identified paddy-wheat cropping pattern in Punjab along with the urbanisation and rapid growth of industries in the area as the cause for rapid groundwater decline. The study also has identified the subsidies for the agricultural sector along with the technical feasibility (the ease of access to the technology) in Punjab, India also as a cause for the increase in the abstraction of groundwater levels in the region. The study also suggested a need for multi-tier approach including a change in the current crops being cultivated, along with strengthening of market infrastructure along with adoption of water saving agricultural practices (Kaur, Sidhu, & Vatta, 2010).

Climate change is also likely to affect the water-food-energy nexus. For example, Mishra et al. (2016) showed that climate change is likely to result in a decrease in streamflow across India. Even though groundwater is the major source of water for agricultural production, a decrease in streamflow can result in increased pressure on groundwater resources.

The study by Wiebe et al., (2015) analysed the impact of climate change on agriculture by 2050 based on socio-economic and emission scenarios (Wiebe et al., 2015). Based on the overall study they concluded that even though overall there was an increase in crop productivity with limitations brought on by lower temperatures, especially in the mountainous and high latitudes but observed a decrease elsewhere. The study also observed that the impacts of climate change was even more adverse for oilseed and rice and more moderate for wheat and coarse grains. They also observed that the changes with RCP (Representative Concentration Pathways) scenarios 4.5 and 6.0 were not very significant whereas the RCP 8.5 showed a drastic change. These scenarios are detailed further in Section 2.2.

1.2. Problem Statement

Climate change and changes in socio-economic development will put greater pressure on the water resources and agricultural production sectors (Narsimlu, Gosain, & Chahar, 2013). Yet, to date much of the research focus has been on the impact of climate change on crop yield responses whereas the underlying resource interactions that drive changes in crop yields have largely been neglected. Water is needed for agricultural production and an increase in the population and GDP leads to changes in the consumption patterns which has a direct impact on production patterns which affect water use. Even though there is industrial and economic growth in India, in order to attain and maintain food security there is a need to depend on the agricultural sector (Barik et al., 2016). The dependence on the agriculture sector affects the water resources being utilised for irrigation purposes. The drastically decreasing availability of fresh water affects the food security and hence the agriculture sector and putting more pressure on the groundwater source thus creating complex challenges in terms of food security, water security and energy security from extensive use for pumping groundwater (Barik et al., 2016). Although several studies (eg: (Lal, 2003),(Loo, Billa, & Singh, 2015)) have studied the variability of the monsoons in the Indian subcontinent and the South Asian regions, this study focuses on the variability of the monsoon within the state of Punjab and its possible impacts on agriculture.

Despite the progress made in understanding and quantifying the impacts of climate change on the water-food nexus, there still exist critical knowledge gaps at the local levels that must be filled in order to increase local adaptive capacity. Most of these studies are conducted at country level where input data and results are aggregated. This national approach has the tendency to overlook highly vulnerable subnational areas where limited resources need to be targeted to decrease their vulnerability.

Significance of the analysis:

Indian monsoons are the source of replenishment of the groundwater as well as surface water and the agricultural activities such as tilling sowing and harvesting are scheduled around the arrival of the monsoons (Barik et al., 2016). But recent years have shown that there is a considerable reduction in the Indian monsoons. Also, all the climate models predict extreme weather conditions like extreme drought or extreme rainfall in agricultural production areas (R. Kumar & Raj Gautam, 2014b). Thus an assessment of the seasonal variability and availability of the water resources both long-term as well as short-term is significant not only for the population of the region but also for proper planning by the local authorities as part of adaptation and mitigation (Kang, Khan, & Ma, 2009). Punjab was the face of green revolution of India and hence is one of the most agricultural dependant states in India, with extensive rice-wheat cultivation which are very water intensive. Hence it is necessary to understand the impacts of climate change on the water resources in terms of irrigation potential, groundwater recharge as well as agricultural yield to ensure continued productivity in the region.

1.3. Objectives and research questions

The main objective of this research is to analyse the impact of climate change on the food and water resources in the state of Punjab in India using the SWAT model. To achieve this objective, four research questions have been formulated.

1. How does climate change affect the following physical parameters in the selected watershed?
    a. Temperature
    b. Precipitation
    c. Potential evapotranspiration
    d. Evapotranspiration
2. How does climate change affect the groundwater resources in the selected watershed?
3. What is the impact of climate change on the yields of the crops (rice and wheat) in the selected watershed?
4. What is the impact of changes in population based on the SSP scenarios on the water use in the selected watershed?

In order to answer these questions, this study utilised the SWAT modelling software Based on the questions formulated in this study the required input data had to obtained from several sources. Hence section 2 of this report details from where the data was collected along with how the data was modified to suit the study area. This section also details the methodology followed by the various software used for the study as well as how the model was set up. This section also details how the model was calibrated and validated which is of significance for realistic modelling of the study area. Section 3 of the report details the results obtained as the model output as well as the results of the impacts of socio-economic changes. This section also gives details on how well the model rated on the performance parameters. Finally, section 4 discusses the results obtained and their implications on the food and water resources which is followed by the conclusions.

2.0. Methods

2.1. Study Area

The study area is the watershed in the state of Punjab in India. This area falls within the Indo-Gangetic Plain (IGP), with a net irrigated area ranging from 35% in West Bengal to 95% in Punjab according to the land statistics data of the Ministry of Agriculture in India (Panigrahy et al., 2011). The state of Punjab has been the centre of the green revolution in India making it primarily an agrarian community. The simulated impact of climate on agriculture in the state of Punjab has been shown to be negative (Hindering, 2011). The major crop rotation of Punjab is rice-wheat cropping rotation (Panigrahy et al., 2011). The main reason for following this cropping pattern in Punjab is the high subsidies and the guaranteed minimum prices set by the government (Rasul, 2016). The implementation of a high yielding variety of crops has resulted in using more water resources for growing these crops (Guiteras, 2009b). As of the data reported in 2013-14, approximately 73% of the area under cultivation is irrigated from wells or tube wells and only 27% of the irrigated area uses the water from the canals (Panigrahy et al., 2011). This indicates a heavy dependency on the groundwater resources in this area. The current status of the groundwater levels in most of the districts of Punjab are over-exploited, critical or semi-critical according to the government records (Gupta, 2011). This along with the fact that this state is the rice bowl of India puts both food security and water security at high risk. Hence it is essential to better under the impacts of climate change for better adaptation and mitigation.

Figure 1. Map of Punjab. Source: Google maps.

2.2. Climate change and socioeconomic pathways scenarios

Representative Concentration Pathways (RCP) Scenarios:

This study uses the Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5. This is because RCP 8.5 is the worst-case scenario thus enabling policy makers to develop adaptation plans accordingly in order reduce the impacts of climate change. Similarly RCP 4.5 is a medium stabilisation scenario. Both the scenarios do not lean toward a positive outcome thus showing the need for quick action from the policy makers. RCP scenarios were developed by the Intergovernmental Panel on Climate Change. Each (RCP) is defined by the levels of radiative forcing target levels to be reached by 2100 (van Vuuren et al., 2011). Radiative forcing is the aggregate of human GHG emissions and other forcing agents expressed in W/m^2. A sum total of four RCP scenarios were developed and all four uses the same historical emission data for initialisation of the model.

The four emission scenarios developed by the Intergovernmental Panel on Climate Change are:

- RCP 2.6 which includes a mitigation scenario leading to a low forcing level, with the radiative forcing reaching a peak of approximately 3 W/m^2 before 2100 and then declines. The concentration peaks at approximately at 490 ppm of CO_2 equivalent before 2100 and then declines. It represents a peak in greenhouse gas emissions by 2050 followed by a consistent decline throughout the rest of this century. It is the pathway needed to realize the targets set during the twenty-first Conference of Parties of the UN Framework Convention on Climate Change, i.e. keep mean global warming to within 2˚C above pre-industrial levels.

- RCP 4.5 represents a medium stabilisation scenario without overshoot pathway to a radiative forcing of 4.5 W/m^2 at stabilisation after 2100. The atmospheric concentration of reaches approximately 650 ppm CO_2 equivalent at stabilisation after 2100. As this is a stabilisation scenario, it assumes mitigation policies imposition (Thomson et al., 2011).

- RCP 6.0 also represent a high stabilisation scenario without overshoot pathway which has a radiative forcing of 6.0 W/m^2 at stabilisation after 2100. The concentration of reaches approximately 850 ppm CO_2 equivalent at stabilisation after 2100.

- RCP 8.5 has a rising pathway with increasing radiative forcing leading to 8 W/m^2 in 2100. Rising concentration of over 1370 ppm CO_2 equivalent in 2100. RCP 8.5 represents a baseline scenario which has no specific climate mitigation target. This scenario is based on the IPCC A2scenario meaning it develops on the demographic, socio-economic pathway, technological development and resource consumption of the A2 scenario (Riahi et al., 2011). It is representative of the business-as-usual scenario, i.e. a continued increase in greenhouse gas emissions.

Shared socio-economic pathways (SSPs):

The shared socioeconomic pathways provide a framework which describes plausible development scenarios in terms of society and economy without the inclusion of climate change or climate policies (Damerau et al., 2016). There are five SSP pathways that have been detailed by O'Neil et al., and each narrative describes very different socio-economic conditions (Hanasaki et al., 2013a).

SSP1 describes a sustainable world, SSP2 describes a middle of the road narrative, SSP3 describes a fragmentation narrative, SSP4 an unequal world and the SSP5 represents conventional development. In the sustainable world under the SSP1 narrative, it is easier for mitigation and adaptation where inequalities are lessened, there is rapid technological changes, and the technological changes are directed more towards environmentally friendly processes including for high productivity of the land. For the middle of the road narrative described by the SSP2 pathway describes an intermediate case between SSP1 and SSP2. The fragmentation narrative faces a high challenge for mitigation and adaptation. This scenario has high emissions due to a moderate increase in economic growth and a rapid increase in population, with slow technological changes. The unequal narrative of the SSP4 pathway describes high challenge for adaptation and low challenge for mitigation. This represents a mixed world with the rapid increase in technology in limited areas thus resulting in mitigating the changes in key areas. But in other regions inequality is high and development proceeds slowly leaving economies isolated and vulnerable to climate change. The conventional development narrative describes a high energy demand world with most of it coming from carbon-based fuels. This pathway faces a high challenge for mitigation and low challenge for adaptation. Investments in alternative energy are very low. Improved economic development which in itself is driven by high human capital investments. This along with the slower population growth leads to a world easy to adapt to (O'neill et al., 2014)(Hanasaki et al., 2013a).

This study uses SSP1 and SSP3 scenarios for understanding the impact of socio-economic changes. This choice was made on the basis of literature review where the scenarios most applicable to fast developing countries like India were found to be SSP1 and SSP3.

All the time periods used in the model have a duration of 25 years. This selection was based on the data availability for the baseline scenario. Also, as 25 years would provide sufficient data for an analysis on the impact of climate change. Hence for similar patterns of comparison all the timelines in this study were set in block of 25 years.

Baseline Scenario

For this study, the baseline scenario timeline was considered from 1980-2005. The reason for selection of this time frame again the availability of data. This study used the observed precipitation and temperature observations, from 1980-2005, obtained from the IMD (Indian Meteorological Department) was used for the baseline analysis and the calibrated values for this simulation. The calibration of the baseline scenario and the calibrated values are detailed in Section 2.5.

Future Scenario

The future scenario for this study was considered from 2025-2050. The temperature and precipitation simulated for the RCP 4.5 and RCP 8.5 scenarios were obtained from MarkSim (see Section 2.4.5).

The watershed characteristics all including land use, cropping pattern, agricultural management, soil properties, topography and anthropogenic effects are considered to be constant for both the future and the baseline scenarios. Thus, the results obtained are purely based on the changes in the climate.

2.3. SOIL-WATER-ASSESSMENT TOOL (SWAT)

The Soil-Water- Assessment Tool (SWAT) is a hydrological modelling tool that operates on a daily time step basis, for a watershed. It is a physically based computationally efficient hydrological model that is capable of simulating several physical as well as hydrological processes that occur within a watershed (Neitsch, Arnold, Kiniry, & Williams, 2011). SWAT is a physically based and thus requires specific input information about the weather, land management practices, topography, vegetation and soil properties in the watershed. These input data are directly used by SWAT for modelling the physical processes associated with the water movement, nutrient cycling, crop growth etc. The model divides the watersheds into sub-basins or sub-watersheds which are further organized into units called hydrological response units (HRUs). The HRUs are lumps of land areas that are characterised by the unique land cover, management and soil combinations within the sub-basins (Neitsch et al., 2011). The water balance equation on which the SWAT model is balanced is:

$$SW_t = SW_0 + \sum_{i=0}^{t} (R_{day} - Q_{surf} - ET_i - W_{seepi} - Q_{gw})$$

where SW_t is the water content of the soil (in mm), SW_0 is the initial amount (in mm) of water content in the soil on day i, t is the number of days, R_{day} is the amount (in mm) of the precipitation on the day i, Q_{surf} is the amount of surface runoff (in mm) on day i, ET_i is the amount (in mm)of evapotranspiration on day i, W_{seepi} is the amount of water seepage (in mm) into the vadose zone from the soil profile in day i, Q_{gw} is the amount of return flow (in mm) on day i. The SWAT model is projected on an ArcMap interface. The SWAT uses the Arc SWAT ArcGIS extension as the graphical interface for the model (Inchell, Rinivasan, & Uzio, 2010).

A review of SWAT model application in the Indian context

SWAT is a widely accepted model that has over 1000 peer-reviewed articles on the application of the model along with research and SWAT components (Gassman, Reyes, Green, & Arnold, 2007). It is a strong hydrological model and has been extensively applied in several regions of the world including USA, South Asia, Europe, China, Africa etc (Koch & Cherie, 2013). Several studies show that SWAT has been successfully used to model impacts on climate change, pollutant and sediment transport, the impact of agricultural and pesticide management practices (Gassman et al., 2007).

Climate change impacts can be studied using the SWAT model by using a downscaled model projection from General Circulation Models (GCMs) (Gassman et al., 2007). This downscaled model projection for this study was obtained from the MarkSim weather generator, details of which are presented in Section 2.4.5.

SWAT has been assessed successfully for the simulation of return flow upon the implementation of the canal irrigation in Andhra Pradesh by Gosain et al., (2005). SWAT was used successfully for water management and planning under various scenarios (Gassman et al., 2007). Gosain et al., (2006) has also looked at the impacts of changes in climate from 2041-2060 in 12 major river basins in India. Similarly, successful application of SWAT model with good NSE and R^2 values were used to study the impacts of climate change by Mishra et al., (2016) (Mishra & Lilhare, 2016). In this study, the SWAT model has been used to study the impact of climate changes in a watershed in Punjab, India.

The SWAT model extension on ArcGIS requires inputs in multiple stages. Each stage and the corresponding input requirement are shown in Figure 2.

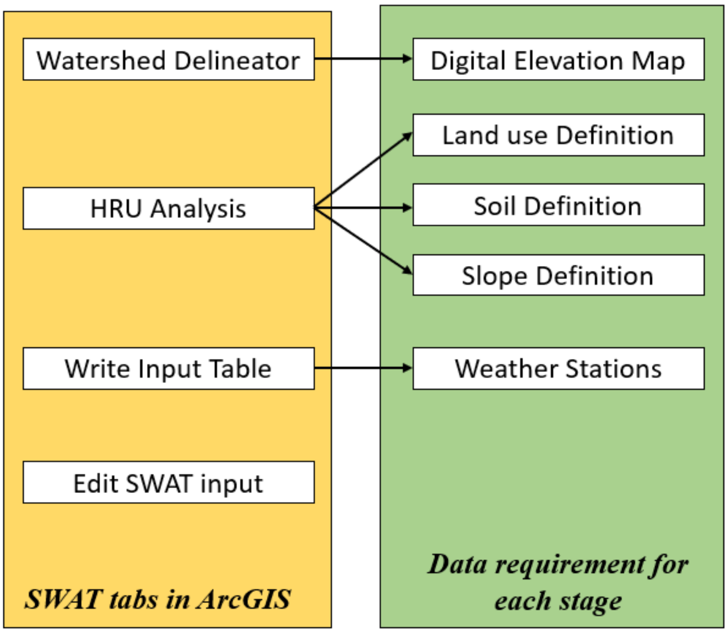

Figure 2. The stages of ArcGIS extension of SWAT and the corresponding inputs required at each stage.

As shown in Figure 2, the spatial input data required for running the model are elevation data (DEM), land use data, soil data and weather data (Narsimlu et al., 2013). The next section details how the data for these inputs were obtained and modified for the specific watershed.

2.4. Model Input Data

The inputs needed for the model were the digital elevation map (DEM), land use data, soil data, weather data. The inputs used and the sources from which they were obtained are detailed in Table 1. The required data for the specific study location was extracted for the study area using ArcGIS tools. All the extracted inputs were then set to the geographical data parameters of the DEM obtained from the USGS (United States Geological Survey) database.

Table 1.Sources of the inputs used for the SWAT analysis.

INPUT	SOURCE
DEM	USGS
Weather Data	Indian Meteorological Department (IMD)
Land Use Data	Global Integrated area Mapping (GIAM) by International Water Management Institute (IWMI)
Soil	Digital Soil Map of the World (DSMW) from the FAO database

2.4.1. Digital Elevation Map (DEM)

The DEM forms the base in the SWAT for the watershed delineation process which forms the watershed boundary, sub-basins and creates a stream network. The DEM defines the topography of the region which describes the elevation of the at any point with a specific spatial resolution in a digital file. The file also gives an impression of the drainage patterns of the area along with the slope, slope length as well as the characteristics of the stream network including channel slope, length, width etc. As shown in Table 1, the DEM for this study was obtained from the USGS website in SRTM 1 arc second (Shawul, Alamirew, & Dinka, 2013).

2.4.2. Soil Properties

Soil classification for the study area was obtained from the DSMW (Digital Soil Map of the World) which is the digitisation of the soil map at 1:5,000,000 scale. The global map created by FAO has 4931 mapping units which consist of soil associations that are made up of mixtures of different soil types that were classified according to the FAO-UNESCO legend, the slope in three classes and phases and texture in three classes (Food and Agricultural Organization of the United Nations (FAO) & United Nations Educational Scientific and Cultural Organization, 1974).

2.4.3. Land use and Land Cover

As mentioned in Table 1, land use data was obtained from the Global Irrigated Area Map (GIAM) by International Water Management Institute (IWMI). The GIAM was created using multiple satellite sensors along with the use of data from Google Earth and ground truth data (Thenkabail et al., 2009). GIAM produced 28 classes of global irrigated area which included different sources for irrigation namely surface water, groundwater and conjunctive use meaning both groundwater and surface water. Each irrigated area was further classified into single, double and continuous cropping systems (Thenkabail et al., 2009). The classifications of the land use are detailed in Table 2.

2.4.5. Meteorological data

The climate data were obtained from different sources for the different timelines (detailed in later sections) used in the study. The climate data used in this study include the temperature in °C and precipitation in mm.

Climate data for the baseline scenario was obtained from the Indian Meteorological Department (IMD). This includes the data from 1969-1979.

For the future scenarios, the downscaled climate data was obtained from an online weather generator MarkSim GCM (General Circulation Models). This was developed by Waen Associates, UK, and is also supported by other partners including the CGIAR's (Consultative Group on International Agriculture Research) CCAFS (Climate Change, Agriculture and Food Security) program (Nelson, Brown, Cuellar, & Fox, 2015) (Trzaska & Schnarr, 2014).

MarkSim weather generator is a third-order markov rainfall generator which was developed over 20 years. The initial design of this was not as a GCM downscaler , but now it works as such and uses both stochastic downscaling and climate typing (Jones, Thornton, Associates, & Waen, 2013). MarkSim is able to simulate and deliver data about minimum and maximum temperature, daily rainfall and solar radiation (CCAFS, 2011). MarkSim is a weather generator that simulates daily information for future changes in the climate at any point on the globe based on the existing GCM projections (CCAFS, 2011). It uses google earth and GHG emission scenario and the GCM models can be chosen by the user (CCAFS, 2011). It allows the user a choice of 17 GCMs. For this study, all the models were chosen and hence the results are an average from all the model projections (Appendix shows all the 17 models used by MarkSim).

The weather generator downscales the climate data for the selected regions using the following methods to generated downscaled climate projections (Jones et al., 2013):

- Spatial downscaling of the GCM output by using the delta method. Delta method or the change factor method is a statistical way to downscale the GCM projection. The ratio between the future simulation from the GCM and the current climate is called the change factor and this is used as a multiplicative factor to use for obtaining the future regional changes.
- Generates daily results stochastically by using previously calibrated data which involved cluster analysis of the observations from over 10,000 stations worldwide.
- By choosing an analogue among the clusters that would best match the values generated by the Global Climate Models.

For this study, the downscaled weather data for RCP scenarios 4.5 and 8.5 from 2025-2050 and also uses an average of all 17 GCM models for the data.

The next section of this document details the model set-up data for the selected watershed.

2.5. Model Set-up

2.5.1. Watershed delineator:

This first step of the SWAT model required the Digital Elevation Map (DEM) which was obtained from the USGS database. The DEM resolution used for this project was NASA SRTM 1 arc second equivalent to 30m. The obtained DEM was projected at UTM 1984 WGS 43N, before being used as the input for the SWAT tool. Two outlets were selected during the water delineation. The final delineated watershed is shown in Figure 4.

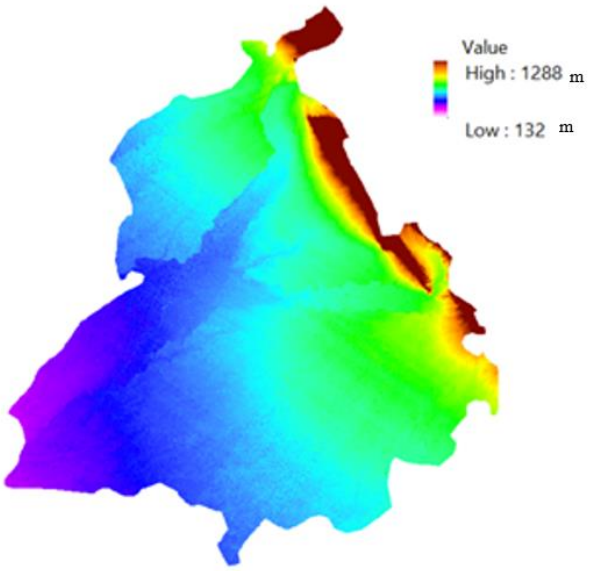

Figure 3.DEM of the study area.

2.5.2. HRU Analysis

The land use data for the HRU analysis was obtained from the IWMI GIAM database. The land use file was also projected to the same projection as that of the DEM projection and clipped to the specific region before being used as input for the land use tab of the HRU analysis. The slope selection of multiple slopes was used for this project. Table 2 shows the land use table used for the HRU analysis and Figure 4 shows the SWAT land use classification of the study area.

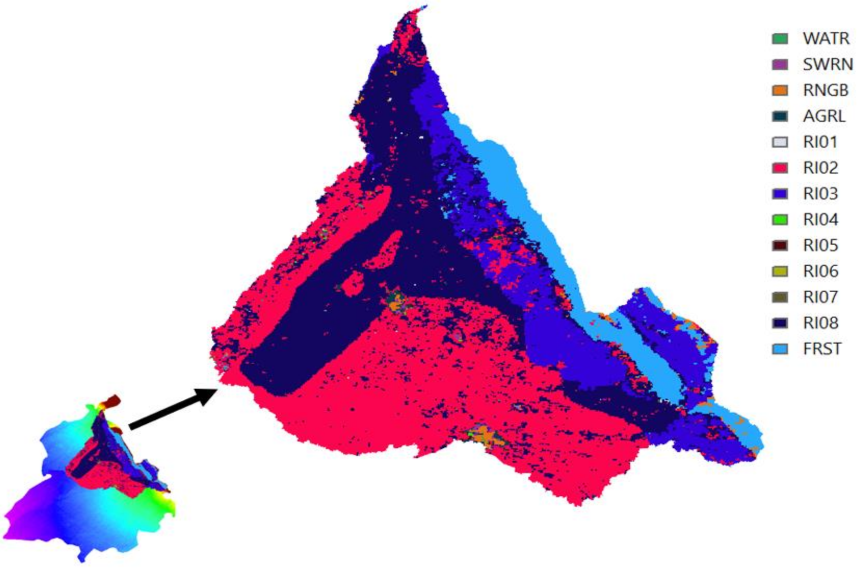

Figure 4. Land use classification for the study area. The land use areas in the legend are described in Table 2.

Table 2.Land use classification used in the SWAT land use table. The table also shows the land use applicable to the selected watershed.

Land Use Code	Land use	Agricultural Land use Applicable to the watershed
WATR	Water	
WETL	Wetland	
SNOW	Snow	
SWRN		
RNGB	Rangelands	
URMD	Settlements: builtup/barren/home gardens	
ORCD	Homegardens: plantations/shrubland/mixed cropland	
AGRL	Rainfed croplands	
RI01	Irrigated, surface water, single crop	
RIO2	Irrigated, surface water, double crop	✓
RIO3	Irrigated, surface water, continuous crop	✓

RIO4	Irrigated, groundwater, single crop	
RIO5	Irrigated, groundwater, double crop	
RIO6	Irrigated, groundwater, continuous crop	
RIO7	Irrigated, conjunctive use, single crop	
RIO8	Irrigated, conjunctive use, double crop	✓
RIO9	Irrigated, conjunctive use, continuous crop	
FRST	Forest	

The HRU analysis by SWAT shows that most of the area in the study is under agricultural production either with double crop or continuous crops. The soil characteristics of the study area was obtained from the DSMW and Figure 5 shows the soil classifications within the study area.

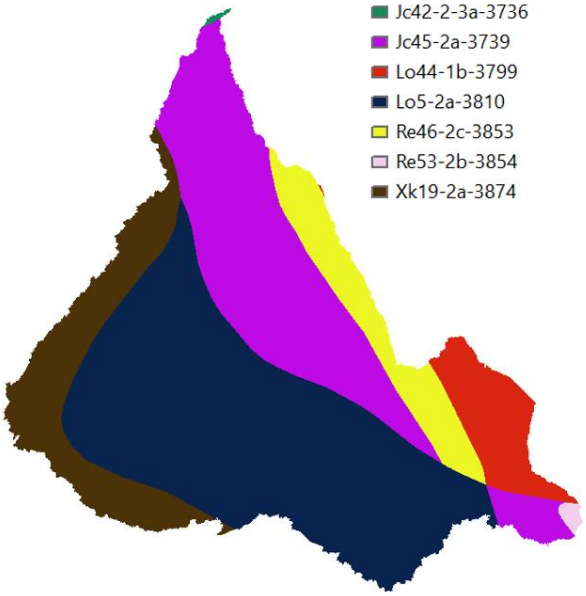

Figure 5. The different soil types in the watershed.

2.5.3. Model Assumptions

The crop rotation used for the purposes of this study are based on the data obtained from the National Food Security Mission (NFSM). This study considered two cropping seasons namely- *Rabi* (dry season) and *Kharif* (wet season). Within the boundaries of this study, the Kharif season is considered from May to September and the Rabi cropping season is considered from October to April. Rice is the primary Kharif crop considered for this study and Wheat is the primary Rabi crop considered for this study. Within the SWAT model, the user can set the values for the several of the operations in the watershed among which are the plant/growing season operation, harvest and kill operation, auto-irrigation etc.

In this study, May is considered as the Plant/growing season of rice is in the year one of crop rotation and September is considered as the Harvest and Kill (operation in SWAT). Similarly, October is considered as the Plant/growing season of wheat in the year two of crop rotation and April as the Harvest and Kill operation. In case of both the crops, the auto-irrigation operation was set to start at the same month as that of Plant/growing season (Abeysingha, Singh, Islam, & Sehgal, 2016). Also, for this study, the source of irrigation was set as shown in Table 3.

Table 3. Source of irrigation assigned in the SWAT simulation for this study.

Source according to GIAM	**Source set during the modelling**
Surface water	Reach
Groundwater	Shallow Aquifer
Conjunctive use	Shallow Aquifer

For more realistic simulation of rice cultivation, the release and impound feature of the SWAT operations was set. The paddy cultivation area is considered as a pothole. The water release feature was set to operate five days before harvest or kill operation and the impound feature was set to operate five days before the planting or growing season.

Within the study, the land use RI02 and RI08 have double crop and are assumed to follow a rice-wheat cropping pattern. Whereas the RI03 is not set to a specific crop but set to generic agricultural crop in SWAT simulation.

2.5.4. Model calibration and validation

SWAT models physical parameters and thus requires these modelled parameters to be with a realistic uncertainty range (Arnold et al., 2012). In order to choose the parameters for calibration and validation, firstly a sensitivity analysis is carried out to choose the most sensitive parameters. Once the parameters are identified, this is followed by calibration of the model.

An autocalibration software along with an uncertainty software was developed for SWAT called SWAT-CUP. For calibration and uncertainty analysis, SWAT-CUP uses a semi-automated inverse modelling routine (SUFI-2) (Arnold et al., 2012). The software allows the user to manually adjust the ranges as well as the parameters iteratively in between the auto-calibration process (Arnold et al., 2012). The 95 Percent Prediction Uncertainty (95PPU) plot provides the overall uncertainty of the model (Mehan, Neupane, & Kumar, 2017). The uncertainties in the model outputs are further propagated by the uncertainties in the parameters and this uncertainty is expressed in the 95% probability distribution. The 95PPU plot gives an envelope of good-solutions based on certain parameter ranges (Abbaspour, 2015). The best solution is further selected based on statistical parameters Nash-Sutcliffe Model Efficiency (NSE) and Pearson's coefficient (R^2) values.

Calibration helps to better model local conditions through better parameterisation thus reducing the model uncertainty. Calibration is carried out by adjusting the values of the model inputs and comparing the model output with the observed values for the same period (Arnold et al., 2012). In this study, that period is from 1969-1975 and the model output used for calibration is stream flow.

Calibration is followed by validation. Validation is the process of comparing the model outputs after using the calibrated parameters with the observed results not used in the calibration process (Arnold et al., 2012). The observed streamflow data from 1976-1979 was used for the validation process in this study.

The next section describes in detail the hydrological data used for calibration and validation.

2.5.5. Hydrologic data used for calibration and validation of the model

The river discharge data or streamflow data were required for the calibration and validation of the model. This data was obtained from the Global Runoff Data Centre (GRDC). The GRDC acts as a source of primary data on global discharge data which can be used to support hydrological studies (Xie, Longuevergne, Ringler, & Scanlon, 2012). The river discharge data from the gauge stations have been made available by the Central Water Commission (CWC) in India. But the CWC does not publicly release data for international basins, which are classified and hence the data had to be obtained from GRDC (Mishra & Lilhare, 2016). The streamflow data for the gauge station within the study area was only available for 1968-1979.

Due to this limitation in data availability and only data from 1968-1979 thus the calibration and validation was done using a process of hindcasting.

Hindcasting for calibration and validation

Due to lack of streamflow data needed for calibrating and validating the SWAT model for the recent past decades, hindcasting approach was employed to calibrate and validate the model. Streamflow data was available from 1968-1979, and the meteorological data was only available from 1969-1980. Thus, the calibration period was set from 1970-1974 and validation period was set from 1976-1979. The SWAT modelling software suggests using a minimum warm-up period of 1 year. Thus, the year 1969 was used as a warm-up period. Also, the period selected for the validation was from 1976-1979 because there was no data available for the year 1975, possibly due to the then political situation.

2.5.6. Model performance evaluation parameters

In order to measure the performance capability of the SWAT model the following parameters were used: R^2, NSE and PBIAS were used (Koch & Cherie, 2013).

1) R^2 or square of Pearson's coefficient is defined as

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i - S_i)(S_i - \bar{S})}{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2 \right]^{0.5} \left[\sum_{i=1}^{n}(S_i - \bar{S})^2 \right]^{0.5}} \right\}^2$$

R^2 is also called the coefficient of determination and is the correlation between the observed and the simulated values. Values of R^2 above 0.5 are considered acceptable (Moriasi et al., 1983).

2) NSE or Nash-Sutcliffe model efficiency coefficient is defined as

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}[O_i - S_i]^2}{\sum_{i=1}^{n}[O_i - \bar{O}]^2} \right]$$

3) 3)PBIAS or Percentage of bias is defined as

$$\text{PBIAS}(\%) = \frac{\sum_{i=1}^{n}(O_i - S_i) * 100}{\sum_{i=1}^{n}(O_i)}$$

The limitation of using R^2 as a parameter for the performance capability is that it only assesses a linear relationship between the observed and the simulated values and thus not highly sensitive to the other parameters and the proportional differences between the predicted and the observed values.

According to Moriasi et al., (1983), based on the value of NSE, R^2 and the PBIAS values, the model performance can be classified as the following – Very good, Good, satisfactory and unsatisfactory. Table 4. shows the values of NSE and PBIAS for which the model is classified into the above-mentioned categories (Moriasi et al., 1983).

Table 4. Model performance ratings values for NSE, PBIAS.

Performance Rating	**NSE**	**PBIAS**
Very Good	0.75 <NSE ≤ 1.00	PBIAS ≤ ±1.00
Good	0.65 <NSE ≤ 0.75	±10 ≤ PBIAS <±15
Satisfactory	0.50 ≤NSE ≤ 0.65	±15 ≤ PBIAS <±25
Unsatisfactory	NSE<0.50	PBIAS ≥±25

2.6 Water use scenarios for the SSP1 and SSP3 scenarios

To understand the impact of population, increase on the consumption of water resources in the study area, the scenarios developed by Hanasaki et al., (2013) was used. The scenarios developed by the study indicated the percentage increase in water consumption and irrigation efficiency for the different SSP scenarios based on their narratives.

The percentage increase in per capita water consumption per litre per day was developed in the study Hanasaki et al.,(2013a). This percentage increase was appplied to obtain the per capita water consumpton per litre per day for the scenarios SSP1 and SSP3 in the study area from the baseline values. The baseline water consumption was set based on the studies by The Department of Water Supply and Sanitation by the Government of Punjab[3].

[3] The Department of Water Supply and Sanitation by the Government of Punjab (http://www.pbdwss.gov.in/prwssp/Downloads/docs/MTR_Bslinsurvey_rpt/Bslin_hsholdsurvey_final_rpt/Final/ChapterII.doc)

3.0. Results

3.1. Model Performance

As detailed in the previous section the calibration and validation were done using data from 1969-1979. Similarly, the statistical parameters used for the model performance have been detailed in the earlier section. The performance section explains the identification of sensitive parameters based on sensitivity analysis. Based on these, 22 parameters were identified and was the model was calibrated through several iterations. Table 5 shows all the 22 parameters used and their parameter ranges along with the fitted values used for the modelling. The parameter ranges were defined based on multiple iterations of calibration carried out for the model base on the discharge data.

Table 5. The parameters identified as most sensitive along with the parameter ranger identified through several iterations and the fitted values finally used for the modelling the baseline and future scenarios.

Parameter name	Description of Parameter	Fitted Value	Min	Max
r__CN2.mgt	Initial SCS runoff curve number for moisture condition II	0.00499	0.00489	0.005174
v__SHALLST.gw	Initial depth of water in the shallow aquifer (mm H_2O)	4959.248	4955.294	4965.58252
v__DEEPST.gw	Initial depth of water in the deep aquifer (mm H_2O)	9674.023	9300.000	9919.500
v__GW_DELAY.gw	Ground water delay time (in days)	308.403	241.328	310.000
v__ALPHA_BF.gw	Baseflow alpha factor (1/days)	0.012	0.012	0.013
v__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	645.791	256.896	660.000
v__GW_REVAP.gw	Groundwater "Revap" coefficient	0.041	0.041	0.041
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (mm H_2O)	206.293	189.319	220.000

v__RCHRG_DP.gw	Deep aquifer percolation fraction	0.989	0.988	0.990
v__SLSUBBSN.hru	Average slope length (m)	149.326	149.239	149.387
v__HRU_SLP.hru	Average sloop steepness (m/m)	0.001	0.001	0.001
v__OV_N.hru	Manning’s "n" value for overland flow	3.692	0.009	4.000
v__ESCO.hru	Soil evaporation compensation factor	1.000	0.999	1.000
v__EPCO.hru	Plant uptake compensation factor	0.007	0.007	0.007
v__CH_N2.rte	Manning’s "n" value for the main channel	0.010	0.001	0.011
v__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	37.679	35.946	39.407
v__SOL_BD().sol	Moist bulk density (Mg/m^3 or g/cm^3)	0.982	0.980	0.982
v__SOL_AWC().sol	Available water capacity of the soil layer (mm H_2O/mm soil)	0.036	0.033	0.036
v__SOL_K().sol	Saturated hydraulic conductivity (mm/hr)	1750.077	1749.907	1750.853
v__CANMX.hru	Maximum canopy storage (mm H_2O)	0.416	0.414	0.435
v__SFTMP.bsn	Snowfall temperature (°C)	3.666	3.639	3.667
v__SURLAG.bsn	Surface runoff lag coefficient	23.440	23.439	23.446

The 95PPU plot obtained with the use of parameter ranges in Table 5 for calibration and validation is shown in Figure 6 & 7.

The statistical evaluation of the model performance for this study for calibration and validation is shown in Table 6. Based on the values of the statistical function to measure the performance described in Table 4, and the values for the statistical function obtained for this study according to Table 6, the model rated “good” with respect to NSE and R^2 values and “satisfactory” with respect to PBIAS during calibration. Similar results were obtained during the validation of the model.

Table 6. The statistical functions - NSE, PBIAS and R^2 - values obtained during the calibration and validation of the model for this study.

Objective Function	Calibration	Validation
NSE	0.63	0.53
PBIAS	2.8	13.7
R^2	0.68	0.64

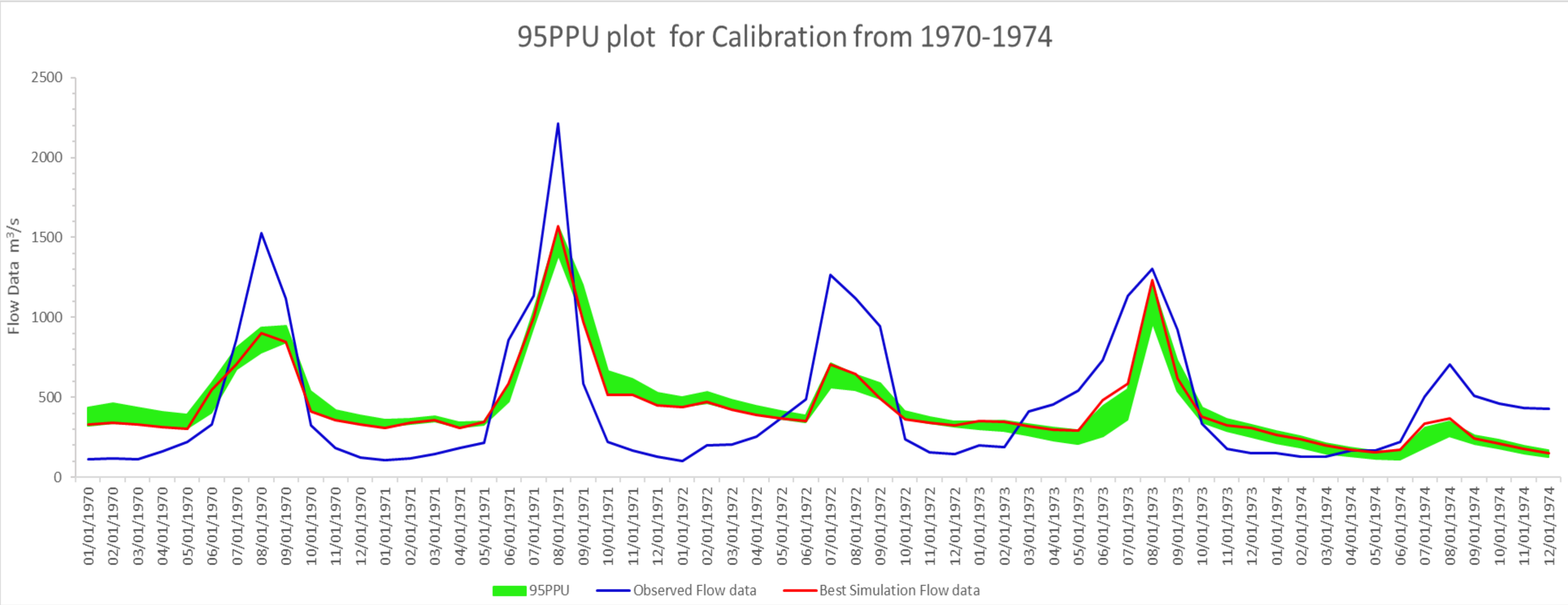

Figure 6.95PPU plot for the calibration from 1970-1974 using the discharge data.

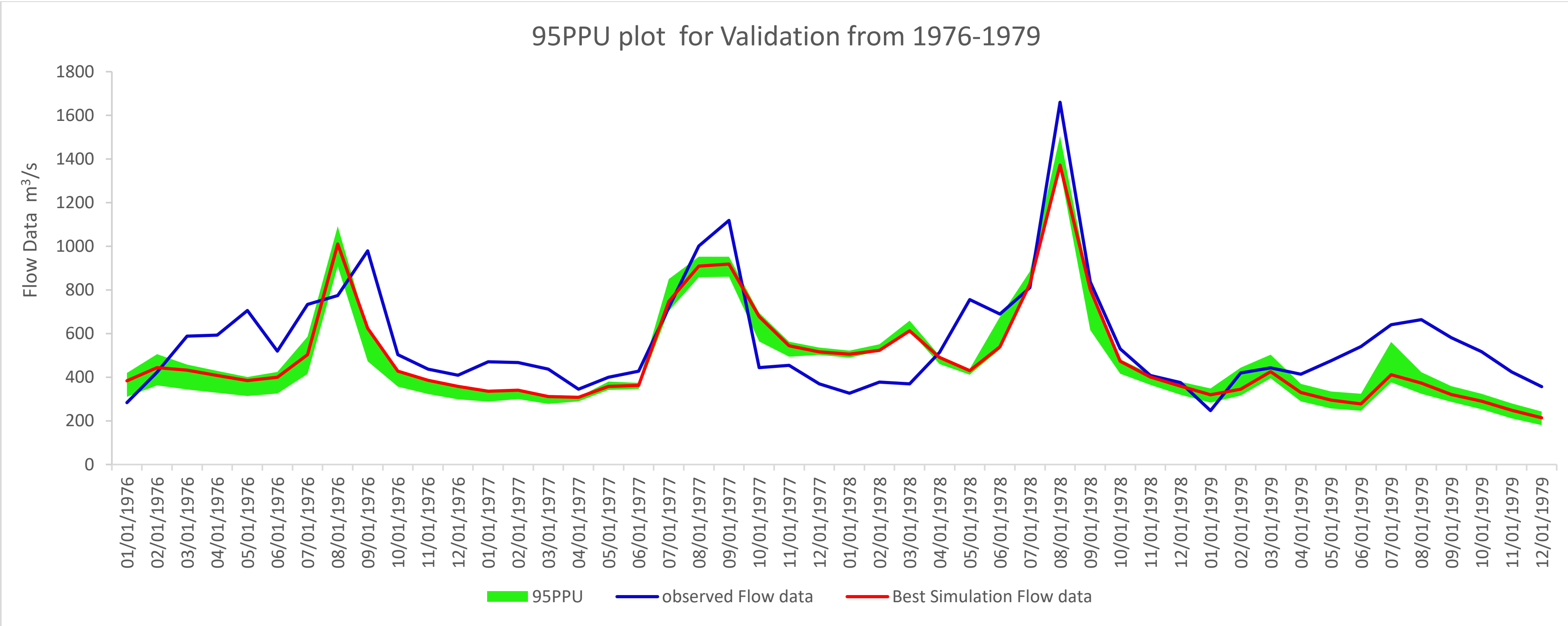

Figure 7.95PPU plot for the validation from 1976-1979 using the discharge data.

3.2. Impacts of climate change on Precipitation

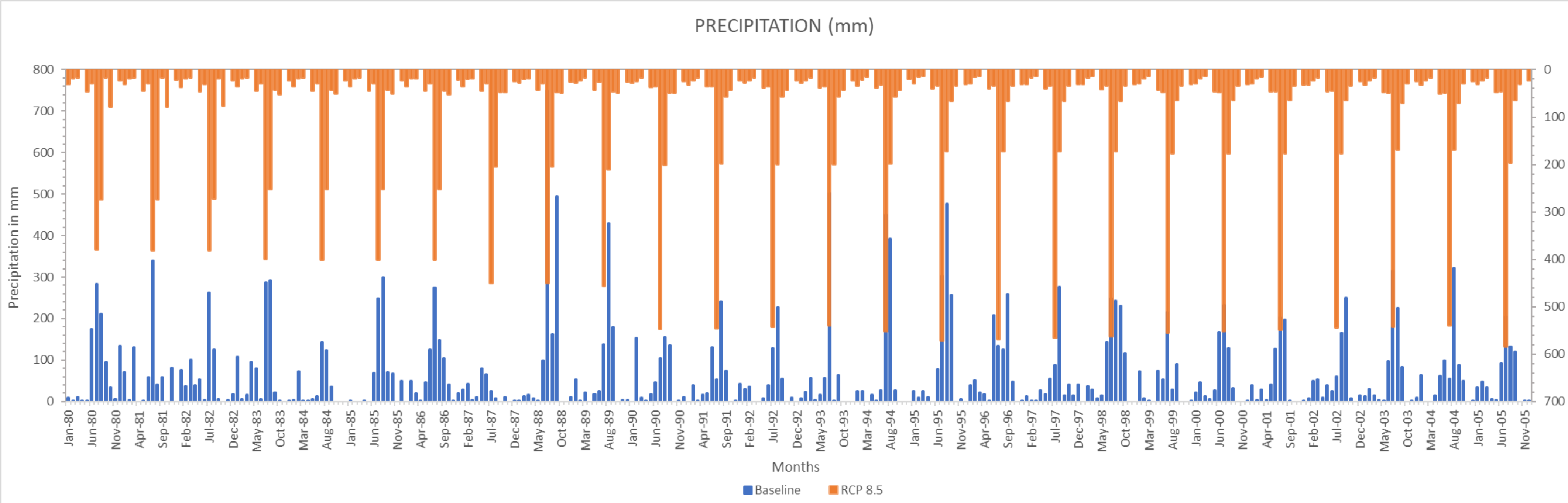

Figure 8. Graph showing the similarity in trends of precipitation patterns in Baseline and RCP 8.5 using average annual precipitation in mm.

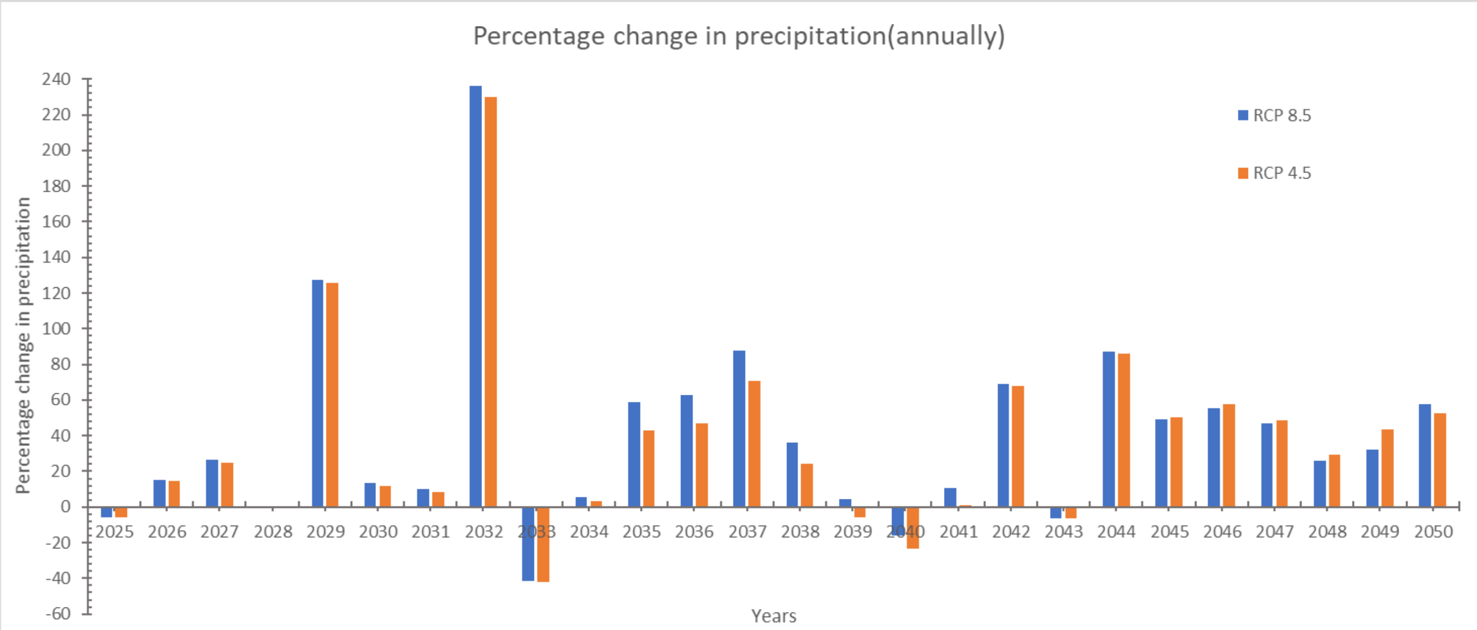

Figure 9.Percentage changes in annual precipitation in RCP scenarios 4.5 and 8.5 compared to baseline.

The pattern of precipitation, annually, was similar to that of the baseline for both the RCP scenarios. Similarly, the changes in precipitation amounts followed a similar for both the scenarios. Figure 9 shows the percentage change in precipitation for RCP 4.5 and RCP 8.5 scenarios from the baseline. Except for certain years, most of the year's show an increase in the precipitation amounts compared to the baseline annually. RCP 8.5 generally showed a higher percentage of increase than to RCP 4.5. The later years especially see almost a 50% constant increase in precipitation in the study area. The variation almost reaches a constant increase towards the end of the simulation, whereas there is more variability in the changes in the precipitation in the initial years.

The average precipitation per annum shows an increase, similarly, there is a change in the pattern of precipitation in the future scenarios compared to that of the baseline (shown in Figure 10). The rabi growing season, considered in this study from May- September, shows an increase in average precipitation in both scenarios. The RCP scenario 8.5 showed a 25 % increase whereas the RCP scenario 4.5 showed an average increase in precipitation of around 19%. But this is the opposite in the results for the Kharif cropping season. The RCP scenario 8.5 showed a decrease of around 35% and a decrease of around 28% in RCP scenario 4.5.

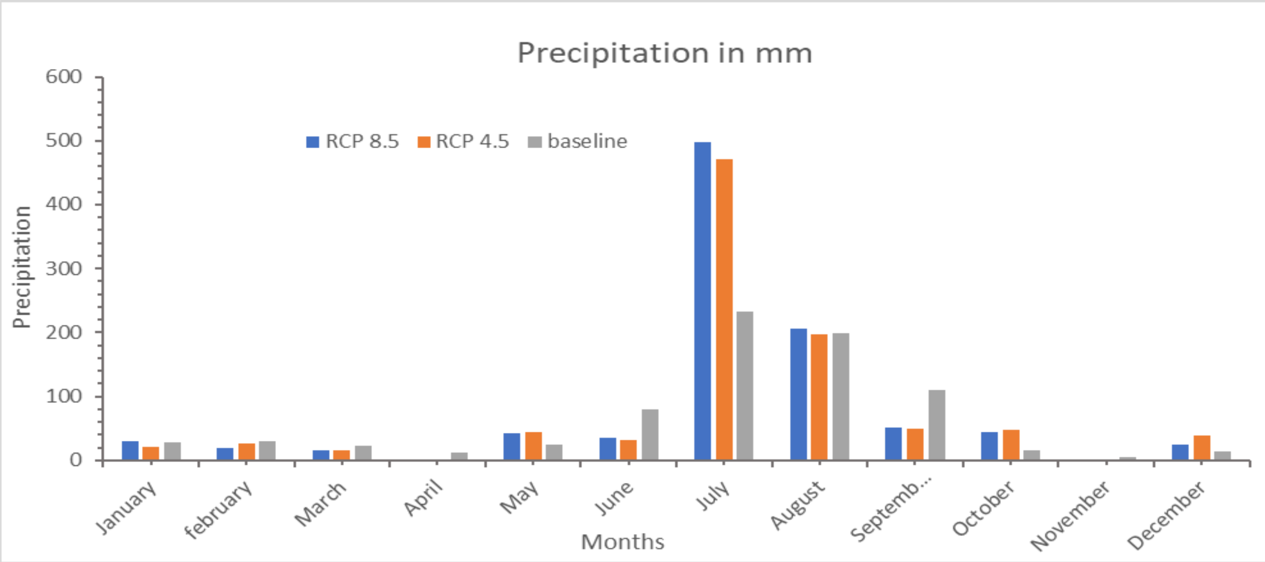

Figure 10.Average monthly precipitation (in mm) during the months for Baseline, RCP 4.5 and RCP8.5 based on the outputs from SWAT.

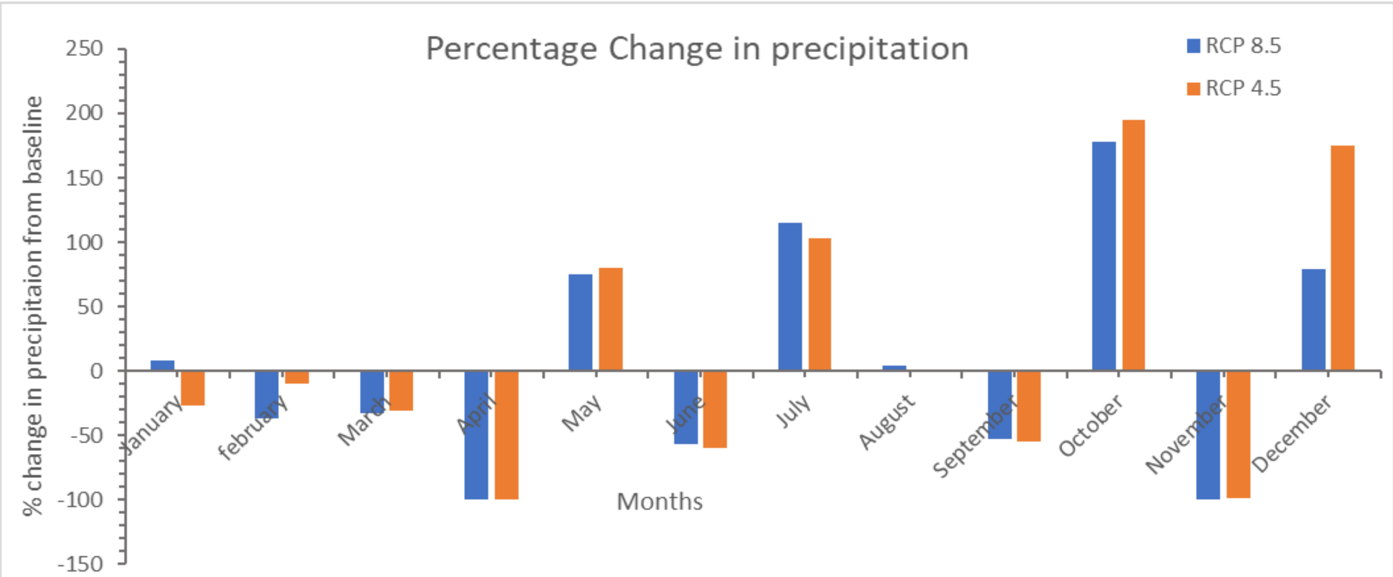

Figure 11. Percentage change in monthly average precipitation for RCP 4.5 and RCP 8.5 scenarios compared to baseline.

Even though there is an increase in precipitation the distribution of precipitation pattern is skewed. As shown in Figure 11. May and July within the rabi cropping season and October and December within the Kharif cropping season receive the maximum amount of rainfall for that duration. All other months show a decrease in precipitation compared to that of the baseline.

The 2030s shows an increase of around 23% and the 2040s shows an increase of around 28% in case of RCP scenario 8.5. Similarly in case RCP scenario 4.5 the results show an increase of around 16% and around 27% respectively for 2030s and 2040s respectively.

3.3. Impacts of climate change on Temperature

Based on the SWAT result, there is an increase in the average temperature between the three scenarios. There is an increase of about 3 °C in average temperature in RCP scenarios 4.5 and 8.5 compared to the baseline (shown in Figure 12). A percentage comparison of the yearly changes in average temperature shows an increase of 10-20% in case of both the scenarios.

Seasonal variation of average temperature also shows an increase in temperature in both summer and winter seasons. The results show an average increase of around 3.9°C in RCP scenario 4.5 and around 4.2 °C in RCP scenario 8.5 in the Kharif season from May to September. Similarly, the winter months from October to April, which is the rabi cropping season shows an average increase in temperature of around 2 °C in RCP scenario 4.5 and around 2.1 °C in RCP scenario 8.5 (shown in Figure 13).

Similarly, the 2030s show an increase of around 3 °C in RCP scenario 4.5 and an increase of around 3.2 °C in RCP scenario 8.5. The 2040s shows an increase in average temperature of around 3.1 °C in RCP scenario 4.5 and around 3.5 °C in RCP scenario 8.5.

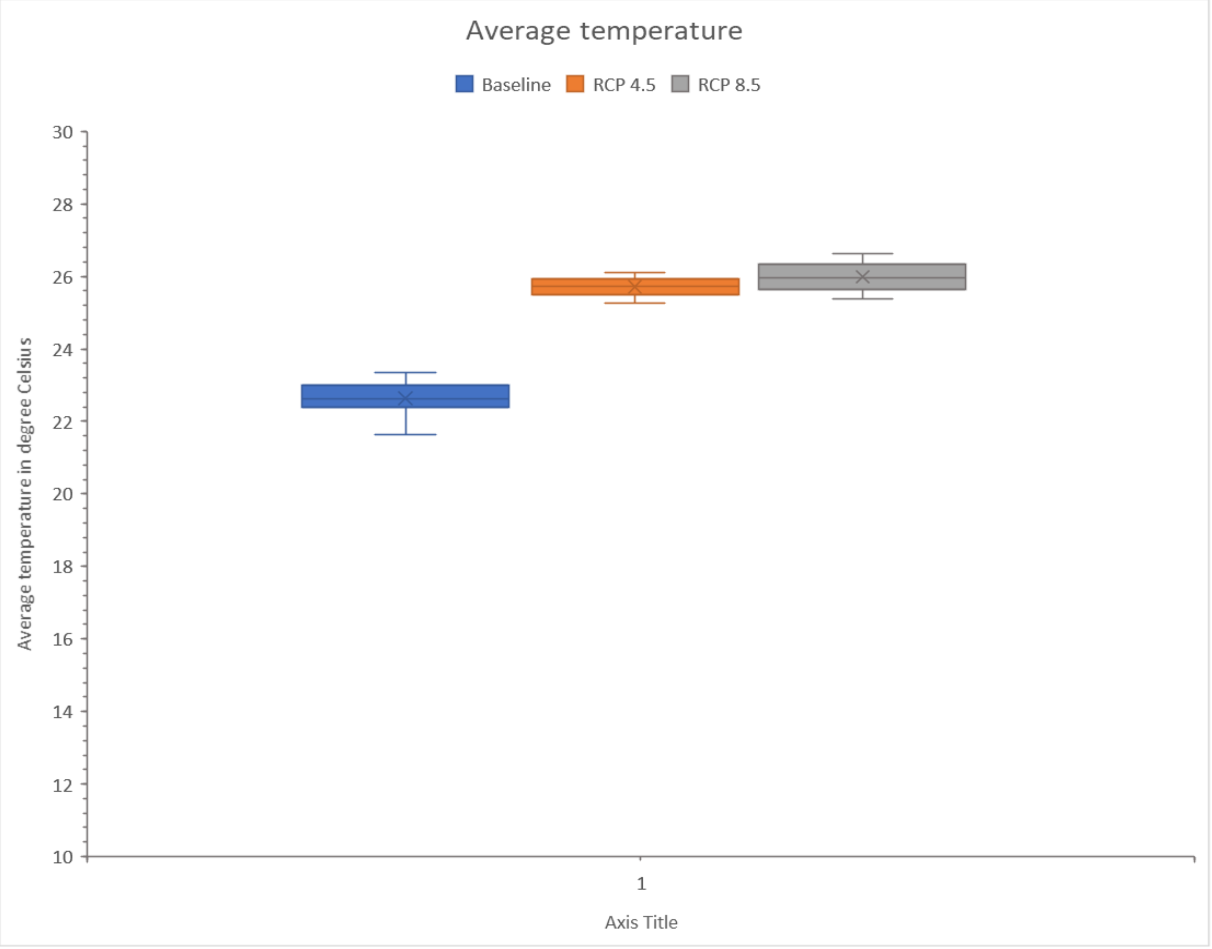

Figure 12. Average temperature during the three timelines - baseline, RCP 4.5 and RCP 8.5.

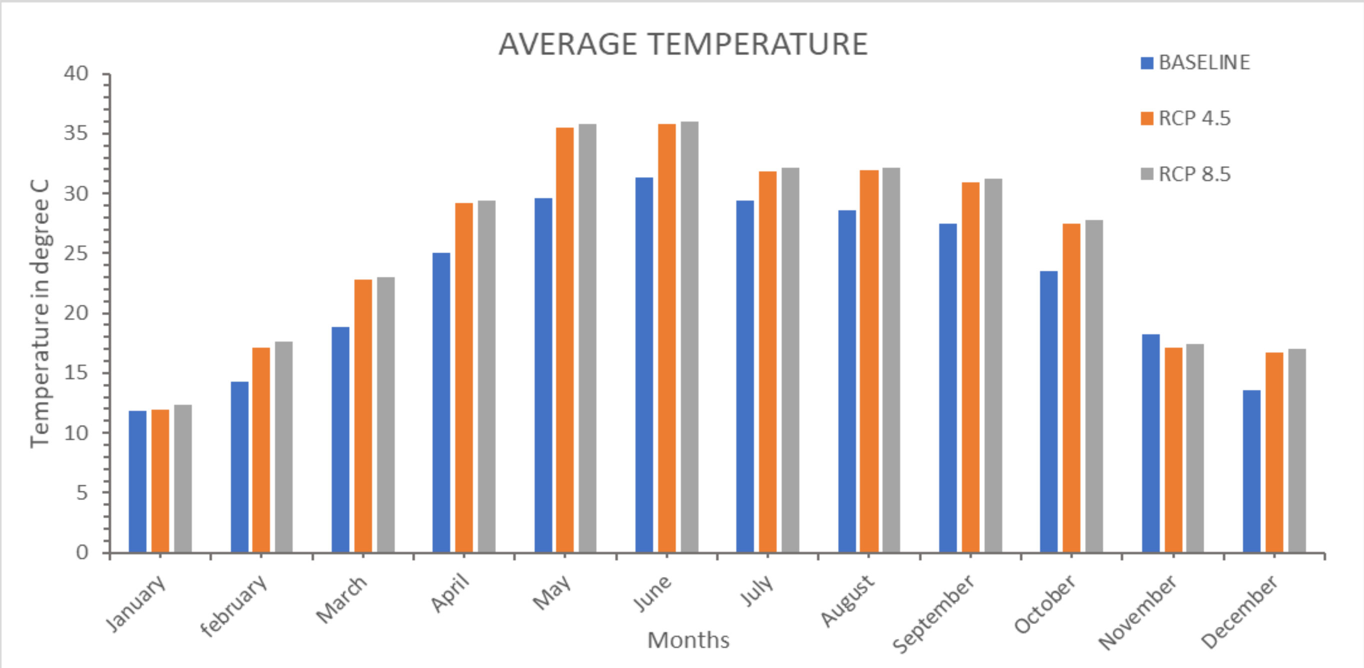

Figure 13..Monthly average change in Temperature for the baseline, RCP 4.5 and RCP 8.5.

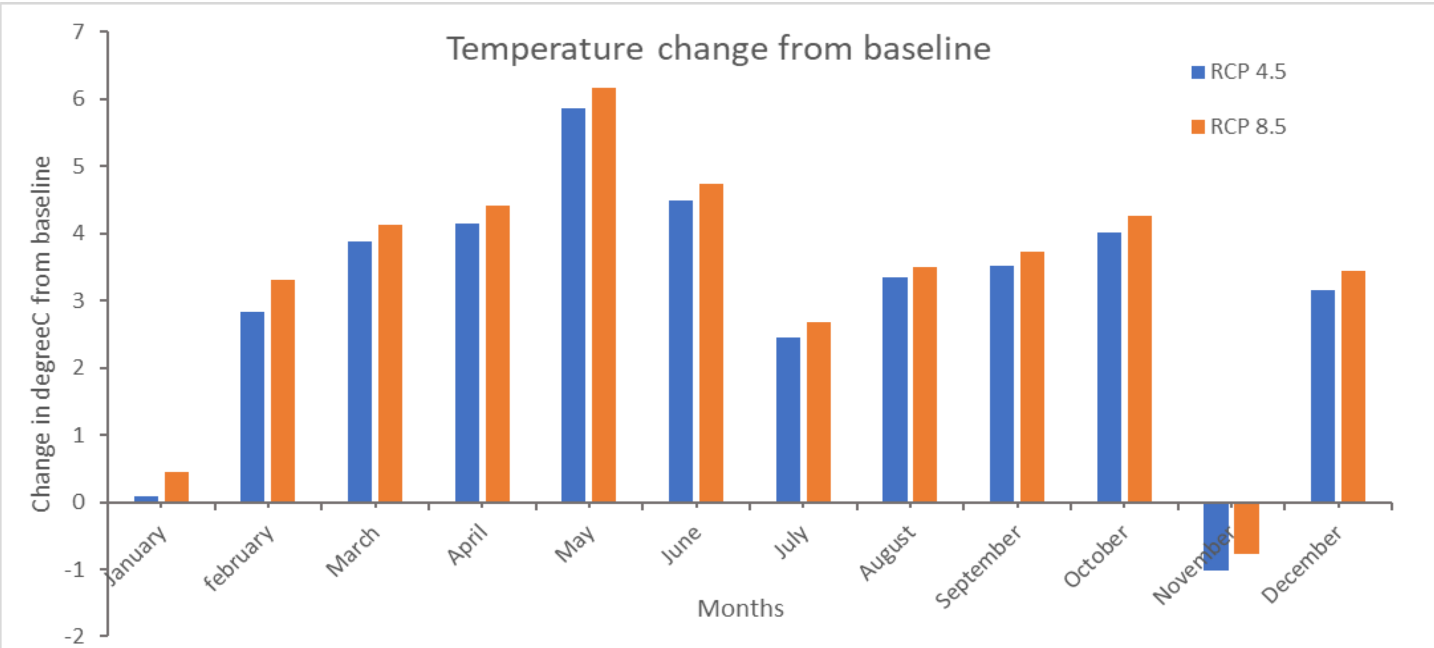

Figure 14.Monthly Change in average temperature of RCP4.5 and RCP 8.5 compared to the baseline.

3.4. Impacts of climate change on groundwater recharge

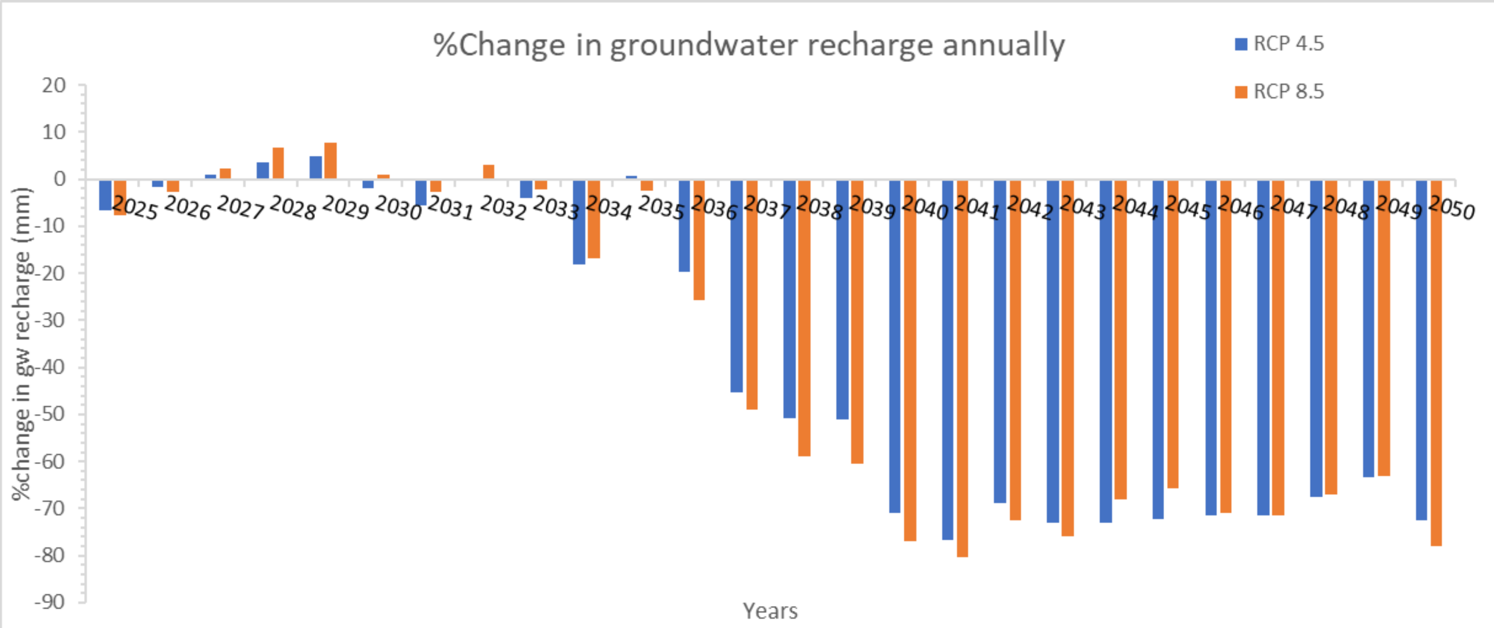

Figure 15. Percentage change in average annual groundwater recharge in RCP 8.5 and RCP 4.5 compared to the baseline.

The groundwater recharge shows a decreasing trend in all three scenarios. The baseline scenarios show a drastic decrease in the later years. But the results show that the trend of groundwater decrease is even more severe in the case of RCP 4.5 and RCP8.5. As shown in Figure 15, there is a drastic decrease in groundwater recharge especially after 2036 in both scenarios. In the last thirteen years, there is a decrease in groundwater recharge of more than 50% in both RCP scenarios.

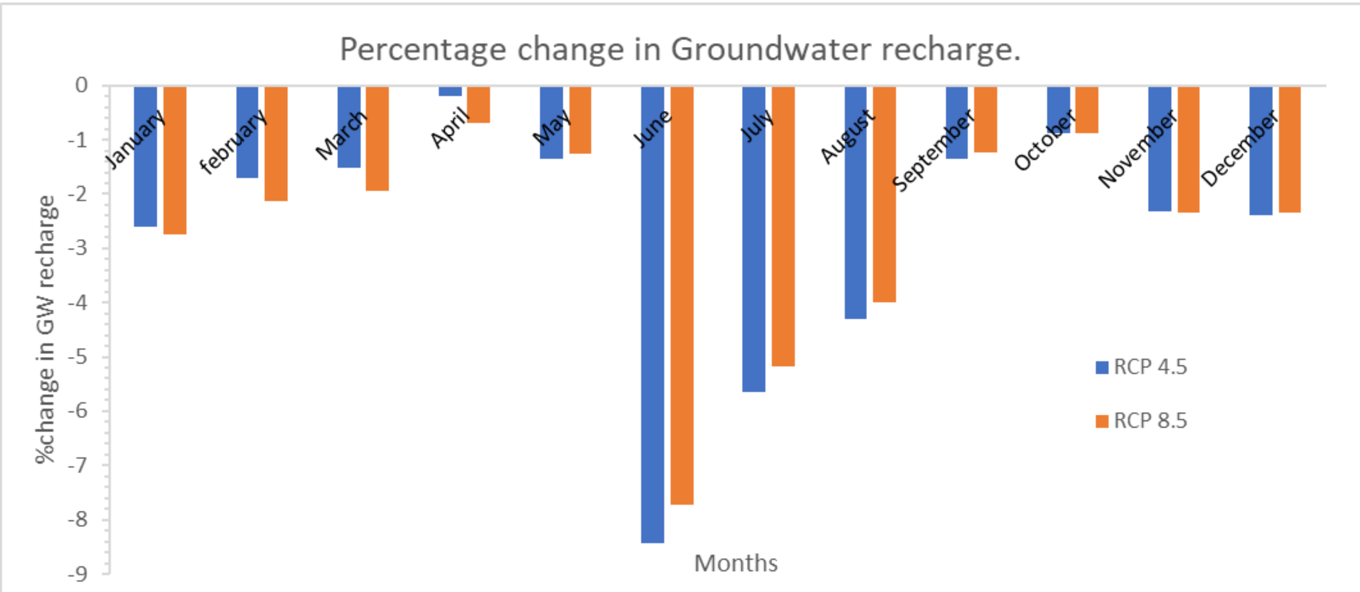

Figure 16. Percentage change in groundwater recharge levels during the months from Jan-Dec in RCP 4.5 and RCP 8.5 compared to the baseline.

As shown in Figure16. The groundwater recharge decreases the most during the months of June, July and August, the Kharif cropping months. None of the months in the future scenarios has an increase in the groundwater recharge.

3.5. Impacts of climate change on Potential Evapotranspiration

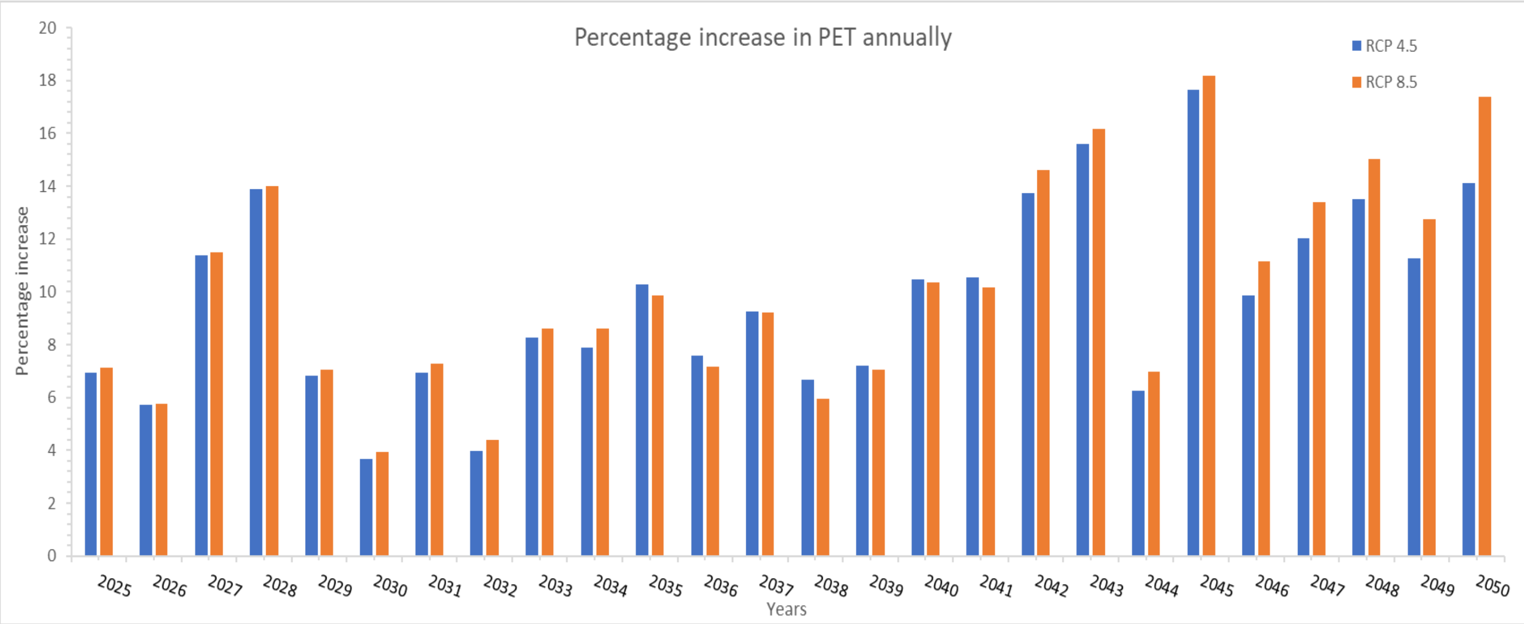

Figure 17. Percentage increase annually of the potential evapotranspiration for the RCP 4.5 and RCP 8.5 compared to the baseline.

As shown in Figure 17, there is an increase in Potential Evapotranspiration in RCP 4.5 and RCP 8.5 compared to that of the baseline scenario. The results show an overall increase of around 9.5% and around 10% in PET in RCP 4.5 and RCP 8.5 respectively.

The results obtained shows around 7.2% increase in PET in the 2030s in both the RCP scenarios and around 12.1% increase in RCP scenario 4.5 and around 12.8% in RCP scenario 8.5 in the 2040s. There is an increase in the estimated PET values from the 2030s to 2040s. When the change in PET for the entire timeline is checked there is a variation in PET between the rabi cropping season and the Kharif cropping season. The rabi cropping season shows an increase of around 8.5 & 8.9% increase in PET. In the RCP scenarios 8.5 and 4.5 respectively. Similarly, the Kharif cropping season shows an increase in PET of around 10.5-11% in the RCP scenarios 4.5 and 8.5 respectively.

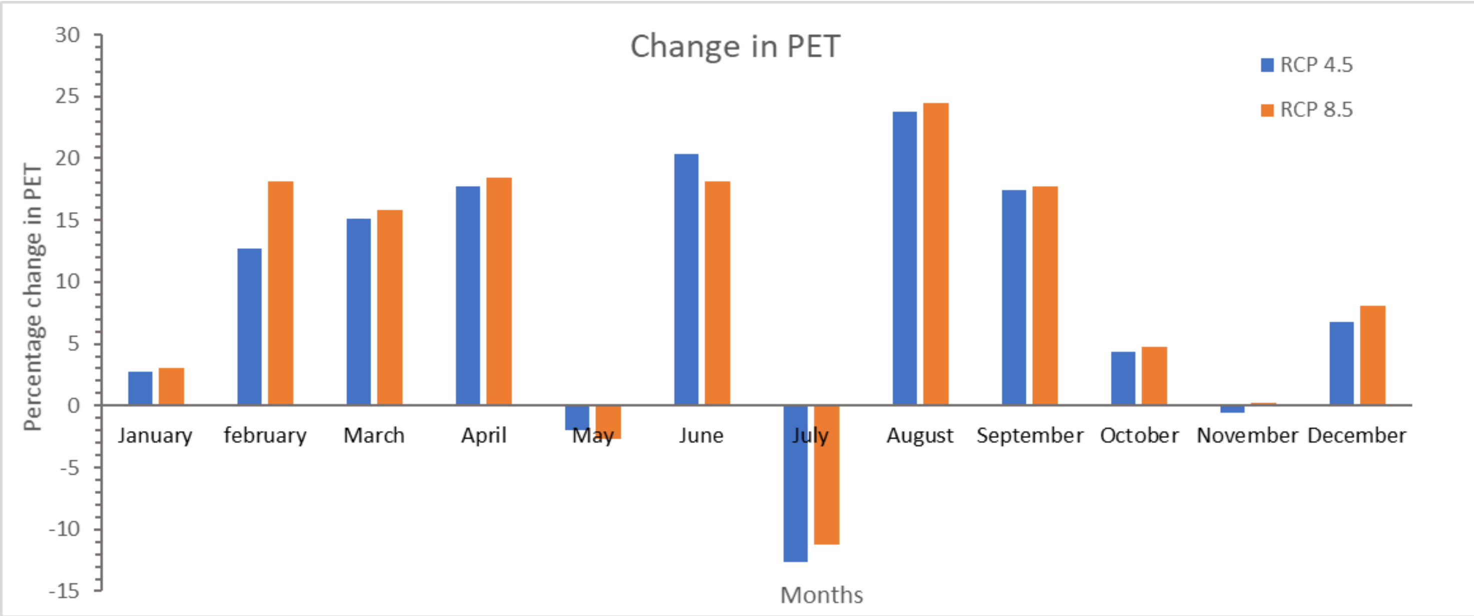

Figure 18. Percentage change in PET in RCP 4.5 and RCP 8.5 compared to the baseline scenario on a month-wise basis.

The monthly change in data for future scenarios is shown in Figure 18. All the months show an increase in the PET values except for May and July.

3.6. Impacts of climate change on Evapotranspiration

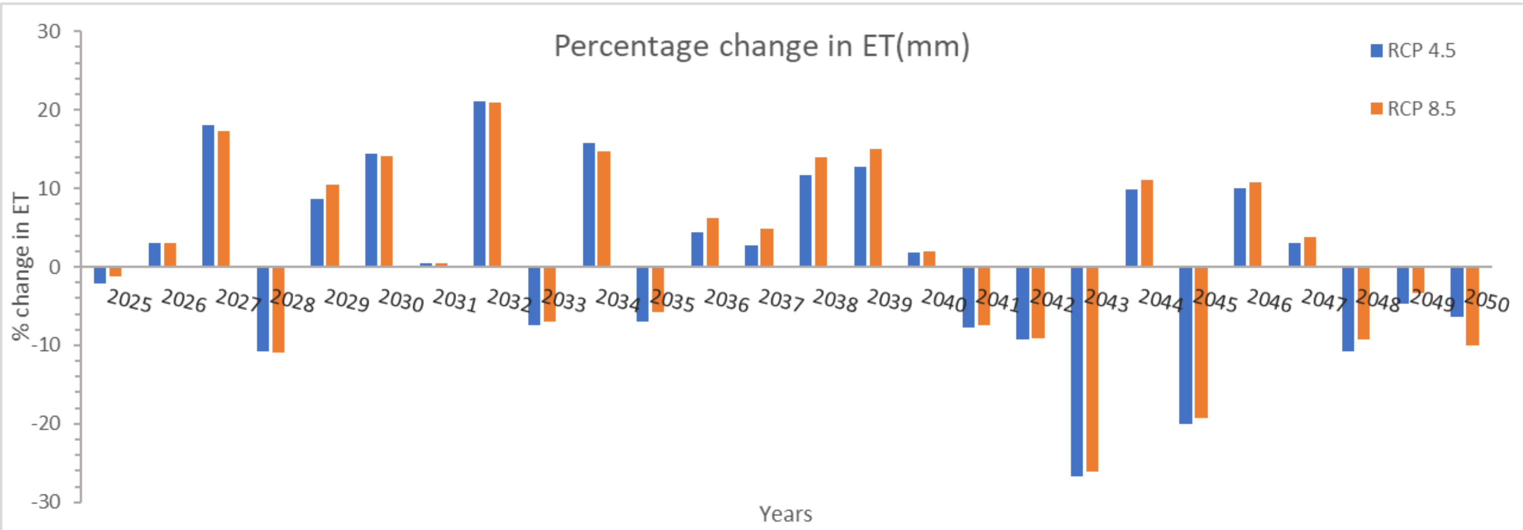

Figure 19. Percentage change in annual evapotranspiration for RCP 4.5 and RCP 8.5 scenarios compared to the baseline from 2025-2050.

Figure 19. shows the changes modelled in the Evapotranspiration (ET) for the RCP scenarios 4.5 and 8.5. Although in the initial half of the model there is an overall increase in the modelled evapotranspiration, there is an overall decrease in the ET values in the later years.

Furthermore, the 2030s shows an overall increase of around 5.9% in the RCP scenario 4.5 and around 6.8% in the RCP scenario 8.5. But the 2040s shows a decrease in the ET of around 7.3% in the RCP scenario 4.5 and a decrease of around 6.5% in the RCP scenario 8.5.

3.7. Impacts of climate change on yield

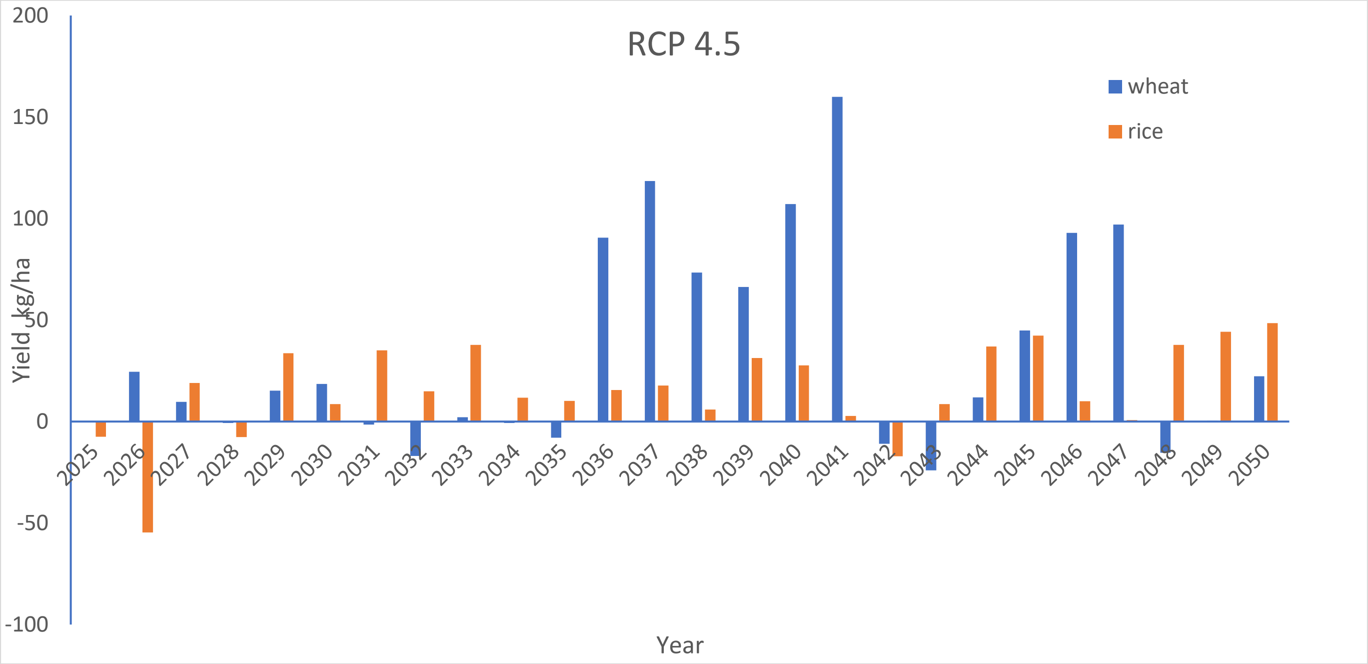

Figure 20. Percentage change in yield in kg/ha for rice and wheat for RCP scenario 4.5.

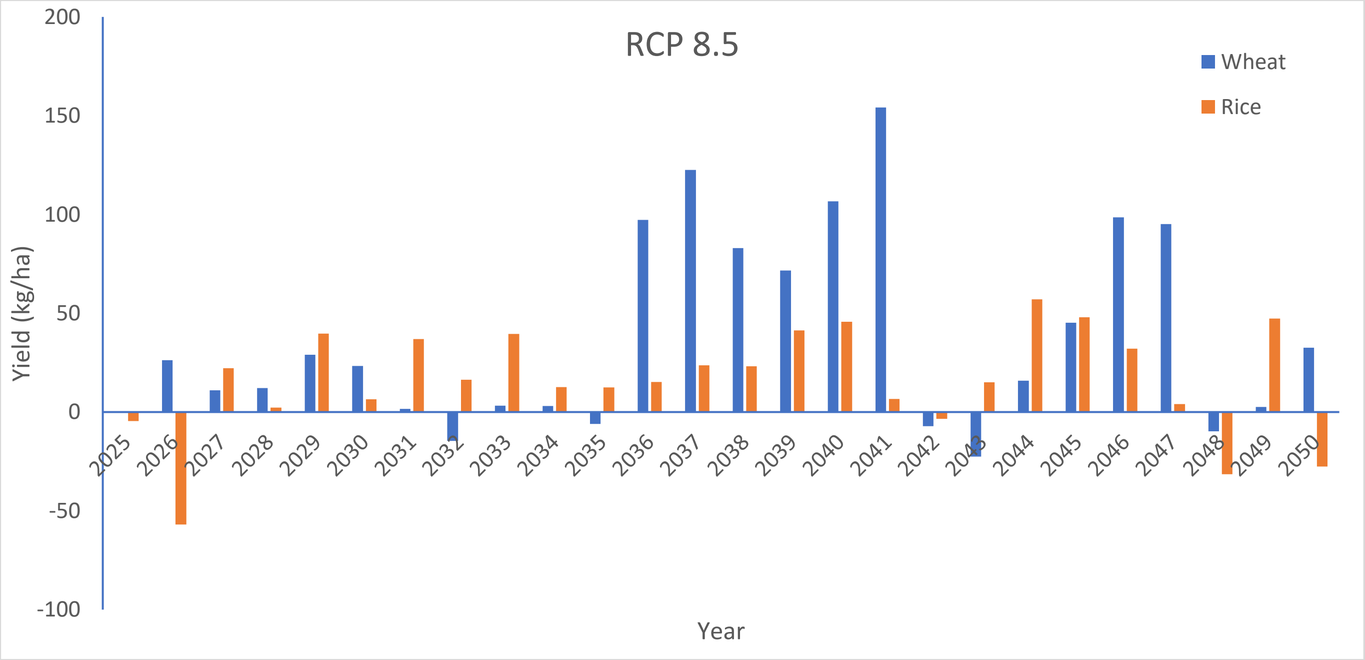

Figure 21. Percentage change in yield in kg/ha for rice and wheat for RCP scenario 8.5.

Based on the results obtained from the simulation there is an overall increase in yield for both rice and wheat in both the RCP scenarios. This has been shown in Figures 20 & 21. The increase in yield is higher for wheat than that for rice in both the RCP scenarios.

There 2030s show an increase of around 22% and the 2040s show an increase of around 26% in wheat yields for RCP scenario 4.5. Similarly, RCP scenario 8.5 showed an increase of around 25% and around 27% for wheat yield in 2030s and 2040s respectively. The rice yields showed an increase of around 24% in 2030s and around 17% in 2040s for RCP scenario 4.5. Similarly, the rice yields showed an increase of around 29% in 2030s and around 21% in 2040s for RCP scenario 8.5. The rice yield in both scenarios were higher in the 2030s compared to the wheat yield.

3.8. Water Use based on the SSP scenarios

Population increase in the two SSP scenarios is shown in Table 7. The baseline population is 27743338, which is the population of the state of Punjab according to 2011 Census results.

Table 7. Population for the study area according to SSP3 and SSP5 narratives.

	SSP1	SSP3
2020	73226868	75681893
2030	80094349	88264342
2040	85120924	100406787
2050	87974925	112709457

Based on these population according to the narrative, the resulting percentage increase in population is shown in Table 7.

Table 8. Percentage increase in population according to SSP1 and SSP3 compared to baseline.

	SSP1	% increase	SSP3	% increase
2020	73226868	163.944	75681893	172.793032
2030	80094349	188.698	88264342	218.146
2040	85120924	206.816	100406787	261.913
2050	87974925	217.103	112709457	306.258

Irrigation efficiency was set to 70% which is an average of the irrigation efficiency of both the rice and the wheat fields (Jeevandas, Singh, & Kumar, 2008). The study by Hanasaki et al., (2013) was used to assess the change in irrigation efficiency in the SSP scenarios (Duku, Zwart, & Hein, 2018; Hanasaki et al., 2013b). According to the irrigation efficiency modelled by the researchers, there is an increase of 0.30% yr^{-1} in SSP1 and no improvement in irrigation efficiency for SSP3.

Table 9. Irrigation efficiency in SSP1 and SSP3 for the years 2020,2030,2040 and 2050.

	Baseline	SSP1				SSP3			
		2020	2030	2040	2050	2020	2030	2040	2050
Irrigation efficiency	0.70	0.73	0.75	0.77	0.80	0.70	0.70	0.70	0.70

The per capita water consumption change for the SSP1 and SSP3 were calculated based on the results from the Hanasaki et al.,(2013a).The percentage increase in per capita water consumption per litre per day was developed in the study Hanasaki et al.,(2013a). This percentage increase was appplied to obtain the per capita water consumpton per litre per day for the scenarios SSP1 and SSP3 in the study area from the baseline values. The baseline water consumption was set based on the studies by The Department of Water Supply and Sanitation by the Government of Punjab[4].

Table 10. Per capita water consumption per litre per day for SSP1 and SSP3 for the years 2020,2030,2040 and 2050.

	Baseline	SSP1				SSP3			
		2020	2030	2040	2050	2020	2030	2040	2050
Per capita water consumption per litre per day	35.7	35.76	35.82	35.53	35.92	35.76	35.82	35.53	35.92

Even though the per capita water consumption per litre per day remains constant in both the scenarios there is a large increase in population (see Table 7), thus total water consumption will increase.

[4] The Department of Water Supply and Sanitation by the Government of Punjab (http://www.pbdwss.gov.in/prwssp/Downloads/docs/MTR_Bslinsurvey_rpt/Bslin_hsholdsurvey_final_rpt/Final/ChapterII.doc)

4.0. Discussion

4.1. Model Limitations and Assumptions

The SWAT model predictions for all the hydrologic components were based on the same land use, agriculture management, soil properties for the entire simulation both baseline and future scenarios. The future development plans for irrigation are not included in the study and this may also have a significant impact on the agricultural practices in the state. Also, the future changes in climate change only considered the changes in temperature and precipitation, but other factors such as extreme weather conditions, solar radiation etc. are not included in this study. But nonetheless, this study provides an idea of the changes in trends of temperature, precipitation, PET, evapotranspiration, groundwater recharge and socioeconomic changes that can be used for making possible mitigation and adaptation plans.

The results obtained from the model show the impact on food production and water resources along with the impact of population on the water resources. As the model assumes only changes in climate change and considers the other input parameters including land use data as constant and the results obtained are purely the impact of climate change. Therefore, unless there is a drastic change in the agricultural policy or policy intervention to change the current agricultural practices, a similar trend for changes in temperature, precipitation, yield and potential evapotranspiration are to be expected in reality.

Hence the potential evaporation results from this study can be attributed to a decrease in soil moisture as the chances of expansion of agriculture land are really low. With this assumption, the chances of drought-like conditions in this state are high.

The groundwater recharge rates within this study do not include the present-day levels of groundwater observed. According to various studies, Punjab currently has groundwater levels in very serious states of decline (Barik et al., 2016; TERI, 2015). Thus, the issues faced in the future may also include issues of salinity of the groundwater resources. This has not been included in the current study. But even without the addition of this change in parameter, the rates of groundwater recharge show a dire state for the future groundwater resources in Punjab.

Another pressure which has been observed in studies but not included in this study is the increased consumption of food with predicted economic development in India. This will only further increase the pressure on land and well as water resources. In this scenario, there is increasing conflict between water resources for food production versus direct human consumption as well as increasing conflict between land for human settlement versus food production.

The model assumes a cropping pattern of only rice and wheat. This acts as a limitation for the study as the cropping area also includes cotton as a crop which is not included in this study. The logic behind using only the rice-wheat cropping pattern is the majority of the area under agriculture in Punjab is occupied by the rice-wheat cropping system.

Model predictions can be improved further with calibration using more gauge stations and more recent data.

4.2. Discussion on the model results

Based on the results, there is an increase in the precipitation amounts in the RCP 4.5 and 8.5 scenarios. Agriculture can be affected both by the timing and the quantities of precipitation (Goswami et al., 2015). Precipitation and temperature also affect the soil moisture and in turn affect agriculture. The results from the model suggest an increase of almost 50% in precipitation in the study area in the future scenarios.

Further breaking down of the timeline indicated that there is a seasonal variation in the precipitation patterns. The rabi season sees an increase in precipitation trends whereas the Kharif season shows a decrease in the precipitation trends. Thus, there is an increase in the intensity of precipitation in the summer months. This result is similar to that of the various studies.

The precipitation patterns, especially, the precipitation in the months of May and June are significant for ensuring that the fields are prepared for the cultivation of rice (Goswami et al., 2015). Thus, a decrease in the precipitation patterns in these months can significantly affect the preparation of the fields, with increasing intensity in irrigation.

The Kharif cropping season from May to September, summer months, shows an increase of around 4.2 °C and 4.5 °C in RCP scenarios 4.5 and 8.5 respectively. The increased temperature also increases the demand for water resources for these crops. Combining this with the precipitation results, which shows decreasing trends in the Kharif season, shows even more pressure on the water resources from to the agricultural sector.

Both the rice and wheat yields are shown to increase in simulation for both the RCP scenarios. This might be mainly due to increase in the precipitation trends. It is possible that the increase in precipitation might outweigh the impacts from the projected increase in temperature, thus resulting in overall increase in rice and wheat yields.

Increase in temperature can also lead to earlier ripening of the grain and also affect the quality of the grain obtained decreases affecting food security. This can also cause an increase in the may also be overcome by farmers by increasing the intensity of irrigation.

The results show an overall increase in the potential evapotranspiration (PET) in both the scenarios. The overall increase in PET in Kharif season is higher than in the rabi cropping season. The Kharif cropping season is during the summer months. The increase in PET may result in the decrease of soil moisture and may also lead to an increase in the water stress of the plants. The decrease in the soil moisture can lead to more drought-like conditions in these regions. This can ultimately lead to a decrease in agricultural production and destruction of vegetation in the area (Alamou, Obada, & Afouda, 2017). These results are more severe in the rabi season than the Kharif cropping season. The decreased soil moisture can also lead to increased demand for water resources to ensure that the plants are not under water stress thus causing more pressure on the water resources.

The results show an increase in evapotranspiration in the initial years and a decrease in the latter years. The increase in the evapotranspiration is associated with the increase in temperature and precipitation. The increase in evapotranspiration can also cause a decrease in the soil moisture and thus increasing the pressure on irrigation.

Nonetheless, various studies conducted in the study area by others like Barik et al.,(2016) suggests that there is an increased dependency on groundwater for irrigation purposes. But the results from the modelling shows a decrease in the groundwater recharge by almost 50%. This suggests that a continued dependence on groundwater sources for irrigation purposes can prove to detrimental to the area. This calls for a need to implement policy measures and agricultural practices in the area that would utilise rainwater along with a more multi-functional cropping pattern. Moreover, agriculture is the largest employment sector and hence a shift to more sustainable agricultural practices making this shift very significant (Nicholas, 2016).

As shown in the previous section, in the SSP scenarios there is an increase in the irrigation efficiency in the future scenarios compared to the baseline scenario. Even though there is an increase in irrigation efficiency, the demand for water resources also rise. The population is expected to increase by more than 160% thus increasing the demand for food and water resources. The per capita water consumption per litre per day is constant for both the pathways in this study, but the increase in population is different. Even though there is an increase in yield in the study area , the increase in population is quite drastic thus most likely making the increase in the yield insufficient to ensure food security for the projected increase in population. The increase in demand for food and water resources makes it very essential for a more integrated management of water resources and the agriculture sector.

4.3. Way Forward

The state is still fighting to ensure the availability of clean water resources to all its population (Lele, Klousia-Marquis, & Goswami, 2013). This along with the increasing demand for water resources by both the increasing population and the food demand requires good planning by the authorities to ensure the future food and water security in the area as well as the country. Thus there needs to be more policies and infrastructure in place to use the excess availability of water during the monsoon season for use during the dry season (Mishra & Lilhare, 2016).Thus the adaptation plans can be implemented to reduce the impacts of climate and use the increased precipitation in certain months to be used in the drier seasons. Exploration of more alternative processes like recycling of wastewater for irrigation purposes. This can help reduce the stress on freshwater resources and reduce the conflict between water use for agriculture vs human consumption.

With regards to farming a more scientific approach would be beneficial that includes seasonal climate forecasts for better decision-making process in the agriculture sector (Misra, 2014). Also the development of water policies customised for the state to ensure the conservation of water, to assure the equitable distribution of water in the new climate change scenario (TERI, 2015).

The decrease in groundwater recharge is predicted to be one of the biggest threat to irrigation. This study which used the baseline groundwater values modelled based on the land use , soil characteristics of the study area from 1980-2005 itself shows a decrease in groundwater recharge of around 50%.Thus there is a need for rapid adaptation to restore groundwater resources. Studies have shown that artificial recharge can be used as a way around this (Misra, 2014). This method has been successfully tested in India in 2000 which was carried out by IWMI and the project was called “Madhya Ganga Canal Project” in the Ganges basin in India (Misra, 2014). This could be a possible solution for the future where the excess precipitation amounts could be positively utilised for this process.

For agricultural practices, the authorities need to identify a sustainable intensification of farming practices including market-based diversification (Hindering, 2011). Use of scientific process for identification of diversity of the crops should be used to identify more drought tolerant cultivars for continued productivity in the region along with the implementation of sustainable agronomic practices (Hindering, 2011). Also use of hardy seeds adapted to dry conditions and salinity stress can also be identified from the natural ecosystems for the use in these regions. Punjab can also consider adopting more practices from countries like Israel which extensively uses principles of “*More Crop per Drop”,* that includes the use of more water-efficient technologies like drip or sprinkler irrigation. This would be extremely beneficial especially for the cultivation of paddy.

5.0. Conclusions

The study shows an increase in precipitation and temperature in the future scenarios. The summers are expected to be drier and warmer and the winters see an increase in precipitation. The overall precipitation quantities obtained as a result shows gives a mirage of normal rainfall but most of the precipitation is concentrated in a few months. These predictions indicate a pattern for increased pressure on the water resources for irrigation in the summer season and a need for adaptation of the crops for wetter conditions in the winter. The increase in temperature also affects the increase in potential evapotranspiration. This increase further affects other physiological factors like soil moisture which again affects the water demand by the agricultural sector in order to overcome the impacts on yield. The results show a drastic decrease in the groundwater recharge. This affects both the agricultural sector which depends heavily on groundwater to supplement the water requirements for irrigation purposes along with the population of the area which also sees a drastic increase in the future.

Therefore, strategies are needed to ensure water use as well as its protection through integrated water resources management framework. The agricultural practices have helped the state reach the production capacity it has today, but these practices are becoming non-profitable and unsustainable. Thus requiring changes in agriculture practices, a change towards more scientific approach rather than sticking to conventional agricultural practices. Also, the policies of subsidised electricity for the farmers encourages increased use of groundwater resources. This calls for sustainable irrigation practices like drip irrigation and as predicted in the study an increase in precipitation can be used for rain harvesting purposes with advanced planning. The water management practices within India is not standardised thus making efficient water management even harder. Thus, a more scientific approach to agricultural practices along with integrated water management especially in each basin as well as a clear strategy to adapt to the changes in the precipitation and temperature changes are required to ensure the continued productivity of the region.

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Annexe

The seventeen models used in the MARK sim GCM was

BCC-CSM1-1	HadGEM2-ES
BCC-CSM1-1-M	IPSL-CM5A-LR
CSIRO-Mk3-6-0	IPSL-CM5A-MR
FIO-ESM	MIROC-ESM
GFDL-CM3	MIROC-ESM-CHEM
GFDL-ESM2G	MIROC5
GFDL-ESM2M	MRI-CGCM3
GISS-E2-H	NorESM1-M
GISS-E2-R	

River Discharge data obtained from GRDC for calibration purposes

YYYY-MM-DD	hh:mm	Original
01/01/1968	--:--	249
02/01/1968	--:--	297
03/01/1968	--:--	420
04/01/1968	--:--	386
05/01/1968	--:--	339
06/01/1968	--:--	575
07/01/1968	--:--	1014
08/01/1968	--:--	1246
09/01/1968	--:--	453
10/01/1968	--:--	212
11/01/1968	--:--	129
12/01/1968	--:--	121
01/01/1969	--:--	125
02/01/1969	--:--	147
03/01/1969	--:--	193
04/01/1969	--:--	285
05/01/1969	--:--	385
06/01/1969	--:--	486
07/01/1969	--:--	995
08/01/1969	--:--	2157
09/01/1969	--:--	629
10/01/1969	--:--	251
11/01/1969	--:--	151
12/01/1969	--:--	126
01/01/1970	--:--	111
02/01/1970	--:--	116
03/01/1970	--:--	114
04/01/1970	--:--	161
05/01/1970	--:--	220
06/01/1970	--:--	331
07/01/1970	--:--	857
08/01/1970	--:--	1529
09/01/1970	--:--	1117
10/01/1970	--:--	326
11/01/1970	--:--	181
12/01/1970	--:--	121
01/01/1971	--:--	109
02/01/1971	--:--	115
03/01/1971	--:--	143
04/01/1971	--:--	181
05/01/1971	--:--	213
06/01/1971	--:--	857
07/01/1971	--:--	1133
08/01/1971	--:--	2215
09/01/1971	--:--	586
10/01/1971	--:--	220
11/01/1971	--:--	166
12/01/1971	--:--	126
01/01/1972	--:--	104
02/01/1972	--:--	199
03/01/1972	--:--	202
04/01/1972	--:--	254
05/01/1972	--:--	368
06/01/1972	--:--	488
07/01/1972	--:--	1263

08/01/1972	--:--	1121
09/01/1972	--:--	946
10/01/1972	--:--	235
11/01/1972	--:--	154
12/01/1972	--:--	145
01/01/1973	--:--	200
02/01/1973	--:--	191
03/01/1973	--:--	414
04/01/1973	--:--	455
05/01/1973	--:--	541
06/01/1973	--:--	730
07/01/1973	--:--	1133
08/01/1973	--:--	1306
09/01/1973	--:--	925
10/01/1973	--:--	333
11/01/1973	--:--	179
12/01/1973	--:--	153
01/01/1974	--:--	149
02/01/1974	--:--	128
03/01/1974	--:--	126
04/01/1974	--:--	164
05/01/1974	--:--	169
06/01/1974	--:--	223
07/01/1974	--:--	505
08/01/1974	--:--	705
09/01/1974	--:--	509
10/01/1974	--:--	462
11/01/1974	--:--	435
12/01/1974	--:--	427
01/01/1975	--:--	-999
02/01/1975	--:--	-999
03/01/1975	--:--	-999
04/01/1975	--:--	-999
05/01/1975	--:--	-999
06/01/1975	--:--	-999
07/01/1975	--:--	-999
08/01/1975	--:--	-999
09/01/1975	--:--	-999
10/01/1975	--:--	-999
11/01/1975	--:--	-999
12/01/1975	--:--	-999
01/01/1976	--:--	284
02/01/1976	--:--	423
03/01/1976	--:--	588
04/01/1976	--:--	593

05/01/1976	--:--	706
06/01/1976	--:--	520
07/01/1976	--:--	734
08/01/1976	--:--	774
09/01/1976	--:--	979
10/01/1976	--:--	503
11/01/1976	--:--	437
12/01/1976	--:--	409
01/01/1977	--:--	471
02/01/1977	--:--	467
03/01/1977	--:--	437
04/01/1977	--:--	345
05/01/1977	--:--	400
06/01/1977	--:--	428
07/01/1977	--:--	720
08/01/1977	--:--	1001
09/01/1977	--:--	1118
10/01/1977	--:--	444
11/01/1977	--:--	454
12/01/1977	--:--	370
01/01/1978	--:--	326
02/01/1978	--:--	378
03/01/1978	--:--	369
04/01/1978	--:--	514
05/01/1978	--:--	756
06/01/1978	--:--	689
07/01/1978	--:--	810
08/01/1978	--:--	1660
09/01/1978	--:--	837
10/01/1978	--:--	530
11/01/1978	--:--	408
12/01/1978	--:--	375
01/01/1979	--:--	247
02/01/1979	--:--	419
03/01/1979	--:--	443
04/01/1979	--:--	414
05/01/1979	--:--	475
06/01/1979	--:--	541
07/01/1979	--:--	640
08/01/1979	--:--	664
09/01/1979	--:--	581
10/01/1979	--:--	517
11/01/1979	--:--	424
12/01/1979	--:--	357

ANOVA results for the regression analysis showing the statistical significance of the data

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.461	1	.461	116.640	.000[b]

	Residual	35.762	9046	.004		
	Total	36.223	9047			

a. Dependent Variable: YLDt_ha_4.5
b. Predictors: (Constant), TMP_AVdgC_4.5

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.480	1	.480	113.834	.000[b]
	Residual	38.158	9046	.004		
	Total	38.638	9047			

a. Dependent Variable: YLDt_ha_8.5
b. Predictors: (Constant), TMP_AVdgC_8.5

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.755	1	.755	192.527	.000[b]
	Residual	35.468	9046	.004		
	Total	36.223	9047			

a. Dependent Variable: YLDt_ha_4.5
b. Predictors: (Constant), PRECIP_4.5

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.892	1	.892	213.712	.000[b]
	Residual	37.746	9046	.004		
	Total	38.638	9047			

a. Dependent Variable: YLDt_ha_8.5
b. Predictors: (Constant), PRECIP_8.5

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.397	1	.397	100.207	.000[b]
	Residual	35.826	9046	.004		
	Total	36.223	9047			

a. Dependent Variable: YLDt_ha_4.5
b. Predictors: (Constant), PET_4.5

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.426	1	.426	100.916	.000[b]
	Residual	38.212	9046	.004		
	Total	38.638	9047			

a. Dependent Variable: YLDt_ha_8.5
b. Predictors: (Constant), PET_8.5