Integrated Hydrological Modeling for Assessment of Water Demand and Supply under Socio-Economic and IPCC Climate Change Scenarios using WEAP in Lower Indus Basin

By

Areesha Asghar

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Institute of Geographical Information Systems
School of Civil and Environmental Engineering
National University of Sciences & Technology
Islamabad, Pakistan

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CERTIFICATE

Certified that the contents and form of thesis entitled **“Integrated hydrological modeling for assessment of water demand and supply under socio-economic and IPCC climate change scenarios using WEAP in Lower Indus Basin”** submitted by Ms. Areesha Asghar have been found satisfactory for the requirement of the degree.

Supervisor: ____________________

Dr. Javed Iqbal

HoD (IGIS, NUST)

Co- Supervisor: ____________________

Designation (Dr…………………., Department)

Member: _______________________

Dr. Abdul Waheed
NICE, NUST

Member: _______________________

Dr. Muhammad Azmat
Assistant Professor-IGIS
SCEE, NUST

Member: _______________________

Mr. Junaid Aziz Khan
Lecturer-IGIS
SCEE, NUST

External Examiner: Signature _________

Name______________________________

Designation_________________________

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DEDICATION

To my late grandfather

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LIST OF NOTATIONS

Notation	**Representation**
e.g.	For Example,
Ha	Hectare
Mm	Millimeter
MCM	Million Cubic Meter
BCM	Billion Cubic Meter

LIST OF ABBREVIATIONS

Abbreviation	**Explanation**
WEAP	Water Evaluation and Planning
IPCC	Intergovernmental Panel for Climate Change
RCP	Representative Concentration Pathways
NSE	Nash Sutcliffe Coefficient
PARC	Pakistan Agriculture Research Council
PMD	Pakistan Meteorological Department
WAPDA	Water and Power Development Authority
IRSA	Indus River System Authority
PBS	Pakistan Bureau of Statistics

ABSTRACT

Pakistan is one of the most vulnerable countries to water scarcity due to deterioration in socio-economic factors and lack of climate change adoption policies. Different hydrological modeling studies have been conducted in the Indus River Basin in the context of climate change scenarios. However, none of these studies addressed the issue of sustainable water management in the situation of socio-economic scenarios in the lower Indus Basin. This study focused on Scio-economic and IPCC climate change scenarios using the Water Evaluation and Planning (WEAP) model for sustainable water resources management of the lower Indus basin. Different socio-economic (population growth rate and increased agriculture activities) along with IPCC climate change (RCP4.5, and RCP 8.5) scenarios for the period 2015-2050 were used in the WEAP model for future projection of water availability and demand analysis. Indus River discharge data (1995-2014) was used to calibrate and validate the WEAP model. For Calibration (1995-2004) the Nash Sutcliffe efficiency and coefficient of determination statistics were 0.85, and 0.86. While for validation (2005-2014) the Nash Sutcliffe efficiency (NSE) and coefficient of determination statistics were 0.89, 0.87. The results showed that the combined adverse impact of climate change and socio-economic factors would result in less surface water availability and the total water demand will drastically increase to 20 BCM by 2050. The agricultural water management practices proposed by PARC (Pakistan Agricultural Research Council) will help to reduce the agricultural water demand by 50%. The comparative analysis of different scenarios revealed that the management strategies would help to reduce the unmet water demands in the future.

Chapter 1

INTRODUCTION

1.1 Background Information

The need for water is universal and without water, life, as we know it, will just cease to exist. The availability and use of water are therefore mainly constrained by its spatial quantity and quality distribution. Earth's fresh water is stored in reservoirs such as glaciers and ice caps, surface water, underground, and in the atmosphere. The challenge to manage our water resources sustainably and appropriately is growing. Water-related disasters are not accepted anymore, and societies expect more and more that water is always available at the right moment and the desired quantity and quality. Our water resources, with different spatiotemporal distribution, are under continuous pressure due to significant factors such as population growth and increased demand (UNESCO, 2006) and climate change (Bates et al., 2008). Even though less than 1% of the world's fresh water (or about 0.007% of all water on earth) is readily accessible for direct human use, depletion of this invaluable resource continues without regard for the future. Because of continued failures by governments in safeguarding water resources, coupled with increasing poverty and inequality, 1.1 billion people (about one in six people in the world) lack access to an improved water supply (UNDP, 2006). Over the last century, water use has grown at twice the rate of population growth. The UN-WATER (2006) predicts approximately 1,800 million people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under water stress conditions by the year 2025. On a continental scale, approximately 25% of the African population is currently experiencing water stress (Bates et al., 2008).

About two-thirds of the world's water resources' total amount is abstracted in Asia, where Pakistan, India, China, Iran, and Bangladesh being major consumers. The many threats to water resources in the Asia-Pacific region reveal a complex picture and raise many concerns. Although high economic growth rates provide finances for better water resources management, many current development priorities ignore the risks from natural disasters, climate change, and poor household water and sanitation access. For example, unsustainable water-use patterns are evident in Pakistan and Uzbekistan. Globally, a country is categorized as "water-stressed" if its annual renewable freshwater supplies are between 1,000 and 1,700 m3 per capita and "water scarce" if its renewable freshwater supplies are less than 1,000 m3 per capita (World Bank, 2004).

1.1.1 Water Crisis in Pakistan

Pakistan is one of the most arid countries in the world. Rivers have been the most important water source for many years. Rainfall has additionally been an essential supply, and the third one is groundwater. It is reported by WWF, that almost 90% of the fresh water available is being used in the agricultural sector. According to IPCC, Pakistan is among the ten most vulnerable countries that will be affected due to climate change, and it is ranked 3rd in that list (IPCC, 2007). According to the Indus Water Treaty (1960), Pakistan is limited to the flow of only three western rivers Indus, Jhelum, and Chenab. The contribution of the Indus River to the total river flows is 65%, while flow from Jhelum and Chenab are 17% and 19% respectively (M. Kahlown & Majeed, 2003). Indus basin is highly dependent on snow and ice melt, and the regional warming is negatively affecting this due to accelerated glaciers melting. (Immerzeel, Droogers, De Jong, & Bierkens, 2009).The greater Himalayan region is reported to face the most rapid reduction in glaciers, which will have a negative impact on river flows, groundwater recharge, ecosystem position and human livelihoods (Bates, 2008; Nijssen, O'Donnell, Hamlet, & Lettenmaier, 2001; Parmesan, 2006; Xu et al., 2009).

Climate change is one of the most important factors among the population growth and other administrative approaches; likely to affect the availability of water for agricultural use, domestic consumption, groundwater resources in the future (Santikayasa, 2016). The current climatic conditions and water scarcity in Pakistan needs an analysis management policies on both supply and demand implications (Asif, 2013). The potential hydrological effects of climate change on the stream flow and runoff are induced by variations in precipitation, evapotranspiration, and soil moisture patterns. Due to the impacts of global warming middle latitude rivers are analyzed to exhibit marked changes along with a decrease in snowfall and temporal changes in spring melt (Arora & Boer, 2001).

The economy of Pakistan is much dependent on agriculture, and Indus River is the primary source of water for agriculture in Pakistan, as 74% of the river runoff is diverted into the irrigation canals (Ahmad & Majeed, 2001). Due to climate change agriculture will be the most severely affected sector due to use of over 70% of available water resources of the country while increased population density in the vicinity of Indus basin and all over Pakistan is only intensifying the situation.

The agricultural dependence on the Indus River would be drastically affected due to the climate variability. Climate change has direct impacts to over 100 million people, and as the population is continuously increasing, the impacts can be indirectly projected to increase to 240 million by 2035. Water resources uncertainty modeling, under different scenarios for irrigation and future climate change, is essential for adaptive planning and sustainable management of water resources in Lower Indus basin. The purpose of this study was to estimate how water demand and supply can be managed in such drastic conditions.

Water availability in Pakistan has become a grave issue owing to the increase in population growth, urbanization, extensive and inefficient water use (Bates, Kundzewicz, Wu, & Palutikof, 2008). Pakistan is one of the most water-stressed countries whose population will increase to two-thirds by the year 2025 (Morrison, Morikawa, Murphy, & Schulte, 2009; Vörösmarty et al., 2010). The demands and supply situations in comparison to the usage of water in the country present a critical picture of regional water availability (M. Kahlown & Majeed, 2003). For example, the availability of water for irrigation is about 11% less than the actual crop water requirement (M. Kahlown & Majeed, 2003; Yaqoob, 2011). Due to these hydrological and socio-economic factors, water stress conditions in Pakistan are likely to increase as the water demand will grow by 2.5% in the year 2025 (Water, 2009).

1.1.2 Water Resources Modeling in Pakistan

In Pakistan, Indus River along with its tributaries (Kabul, Jhelum, Chenab, Ravi, Beas, and Sutlej), is world’s most extensive and contiguous irrigation system (Fowler & Archer, 2005). The Indus River system is a transboundary basin which covers an area of 1,140,000 km^2. It is spread across Pakistan (47%), India (39%), China (8%), and Afghanistan (6%) (Frenken, 2012). In Pakistan, the Indus River basin starts from the north (Himalayan Mountains) to the dry alluvial plains of Sindh province in the south and finally flows out into the Arabian Sea (van Steenbergen, Basharat, & Lashari, 2015). Indus Basin covers a total area of 5,20,000 km² in Pakistan which is 65% of the country's total area (Group & 'Abbāsī, 2013). Indus basin and its tributaries are dependent on snow and glacier melt, about 50% of its base flow, which is affected due to accelerated glaciers melting (Amin, Iqbal, Asghar, & Ribbe, 2018; Immerzeel et al., 2009). It has been observed that climate change is affecting the water towers of the Himalayan region, which is affecting the downstream river flows and groundwater recharge in the Indus River Basin (Bates, 2008; Nijssen et al., 2001; Parmesan, 2006; Xu et al., 2009).

Many studies have been conducted to analyze the hydrology of the Indus River Basin, and to map the water quality of the aquifer underlain by Indus River (Hussain et al., 2016; Hussain et al., 2017). For example, Akhtar, et al. used HBV (Hydrologiska Byrans Vattenbalansavdelning) to project future water discharge in Hindukush–Karakorum–Himalaya (HKH) region (Akhtar, Ahmad, & Booij, 2009). The snowmelt runoff model (SRM) is also used in Hunza River basin to simulate the daily discharge and to analyze the impacts of climate change on the simulated discharges (Tahir, Chevallier, Arnaud, Neppel, & Ahmad, 2011).

1.1.3 Water Resources Management Modeling

Many global scholars have used different water resources assessment and management tools such as WRMM (Water Resources Management Model). It is used as a planning tool for water resources allocation within a basin (Cutlac & Horbulyk, 2010). Economical Reallocating Water Model (ERWM) was developed to improve water allocation efficiency in river basins, incorporating hydrological, agro-climatic and agro-economic components (Elmahdi, Malano, & Etchells, 2007). Amongst all the water allocation models, Water Evaluation and Planning (WEAP) is most widely used model in different basins around the world in last decades (Gunter et al., 2008; Yates et al., 2008; Yates et al., 2009). Many global scholars have used different water resources assessment by integrating it with socio-economic developments. Water Resources Management Model (WRMM) is one of such models used as a planning tool for water resources allocation within a basin (Cutlac & Horbulyk, 2010). Economical Reallocating Water Model (ERWM) was developed to improve water allocation efficiency in river basins, incorporating hydrological, agro-climatic and agro-economic components (Elmahdi et al., 2007). Spatial Agro Hydro Salinity Model (SAHYSMOD) is a combined approach of socio-economic components with physical, hydrological issues in a basin. The approach can be used to examine resources better and develop a sustainable structure for the future (Inam et al., 2017). REALM (REsource ALlocation Model) is a computer simulation of water resources in a basin, generally. It uses linear programming algorithms to assess water allocation within a water supply system (Perera, James, & Kularathna, 2005). MODSIM is a decision support system for river basin management for short/long term planning, developing strategies and water allocation analysis (Vaghefi, Mousavi, Abbaspour, Srinivasan, & Arnold, 2015).

1.1.3.1 WEAP (Water Evaluation and Planning) Software

WEAP ("Water Evaluation and Planning" system) is a comprehensive system for maintaining water demand and supply, flows, storage, discharge, and pollution. At the same time, it is a policy analysis tool, which evaluates the full range of water development and management. WEAP highlights integrated approaches for conducting water resources planning assessment, water balance, and simulation-based analysis (calculates water demand, supply, flows, storage, and discharge) and water quality under varying hydrologic and climatic scenarios. It has built-in models for rainfall runoff and infiltration, evapotranspiration, crop requirements, and yields, surface water/groundwater interaction, and in-stream water quality along with GIS-based graphical interface (SEI, 2011). The WEAP software is a computer-based tool that supports scenario-based planning, development and management, policy settings and decision making (Bakken et al., 2016). WEAP has built-in algorithms that use climate time series data and simulates rainfall runoff of basins and sub-basins (Esteve, Varela-Ortega, Blanco-Gutiérrez, & Downing, 2015).

1.2 Objectives

The objectives of the study were to map water demand and supply dynamics under the socio-economic developments and IPCC climate change scenarios. The effect of climate change and socio-economic exploitation scenarios on increased irrigation withdrawal and domestic use for the long-term availability of water were also analyzed. The sub-objectives were the calibration and validation of the model and the future projection of unmet demand during 2015-2050.

Chapter 2

MATERIALS AND METHODS

1.3 Study Area

About 65% of the total spread of the Indus River is located in Pakistan. Indus river basin, being the largest basin of the country, consists of the mountainous regions of the north, the plains (Indus plain and Kacchi plain), the desert areas of Bahawalpur and Sindh and the Rann of Kutch. The northern boundary of the basin is surrounded by Hindukush range while north-eastern side by Karakoram and Haramosh ranges. On its west, there are Sulaiman and Kirthar ranges, and the southern boundary is surrounded by Arabian Sea (Yu, Yang, Savitsky, Brown, & Alford, 2013).

The study area covers six districts, i.e., Mianwali, Khushab, Bhakkar, Jhang, Layyah, Muzaffargarh of Punjab province (figure 1). It lies between longitude 70°32'18.3"-71°26'17.1"E and latitude 29°01'01.7"-33°14'20.9"N, bordering between Punjab and Khyber Pakhtunkhwa provinces. On its west, River Indus flows, and it is underlain by Thal Doab, with the unconfined aquifer in the area. The total area of all six districts is 43,853 sq. Km. The total population of the study area is 2,677,581.

1.3.1 Climate of the Study Area

The climate of the region is arid, with scorching summers and mild winters. Mean maximum temperature is 35 °C in June and mean minimum temperature is -1 °C in January with average annual of 24 °C. Mean annual rainfall in the study area is 617 mm. The average monthly temperature and rainfall data have been plotted from 1995 to 2013. The average annual relative humidity at midnight is 77 %, and it is 42 % at noon as a mean value.

The research aims to analyze current and future water resources of Lower Indus Basin from 1995 through 2015 and simulate the hydrology of study area under several socio-economic and climate change scenarios. WEAP was simulated for calibration for ten years (1995-2004), and after that validated from 2005-2014. Five socio-economic scenarios and two climate change scenarios were defined, and their impact on the water resources condition of the study area was analyzed.

1.4 Data, Sources, Quality And Limitations

Figure 2.2 shows the datasets with their sources. To conduct the study, water resources and water demand data were collected for calibration of the WEAP model as well as developing the scenarios. The climate change projected data used in this study was gridded on 25 km which is coarse resolution and may affect the climate projection for the study area. Table 2.1 lists the description of acquired data from the corresponding department.

1.4.1 Meteorological Data

Meteorological data consisted of temperature, precipitation, humidity, wind speed and evapotranspiration.

1.4.1 Hydrological Data

Four rivers including Indus River as main river Kabul, Soan and Kurram rivers being the tributaries, are the water supply units. Groundwater is the primary source for domestic water supply in the study area.

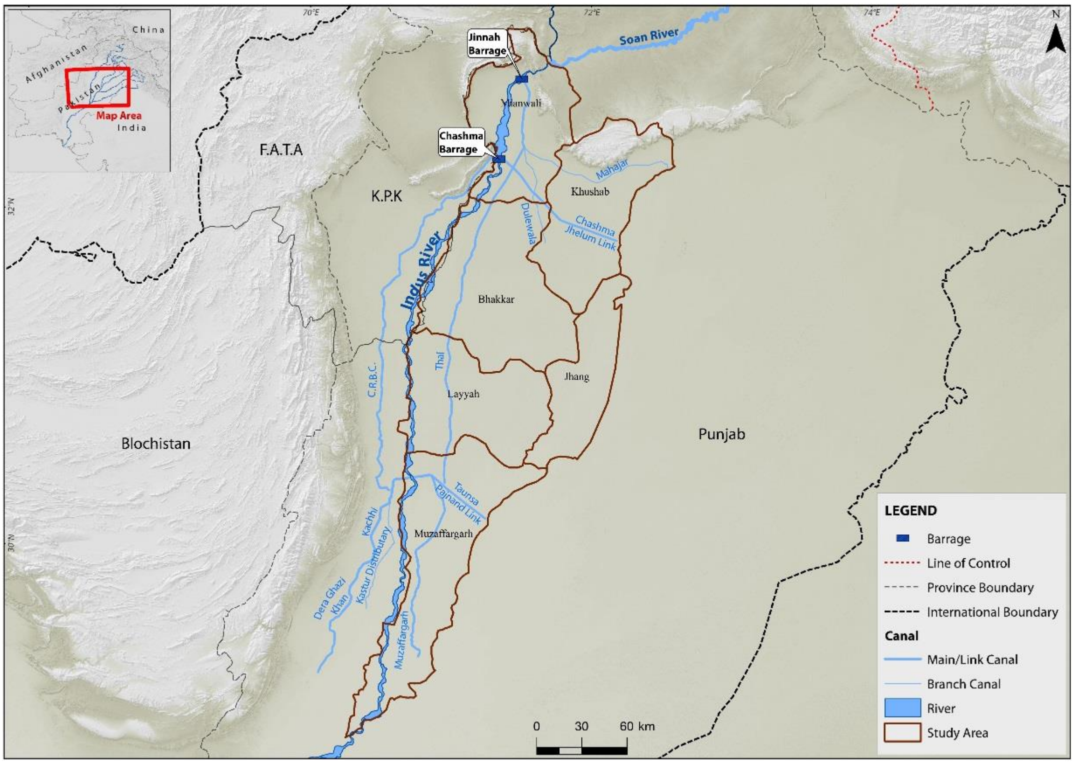

Figure 2.1. Geographical location Lower Indus River Basin.

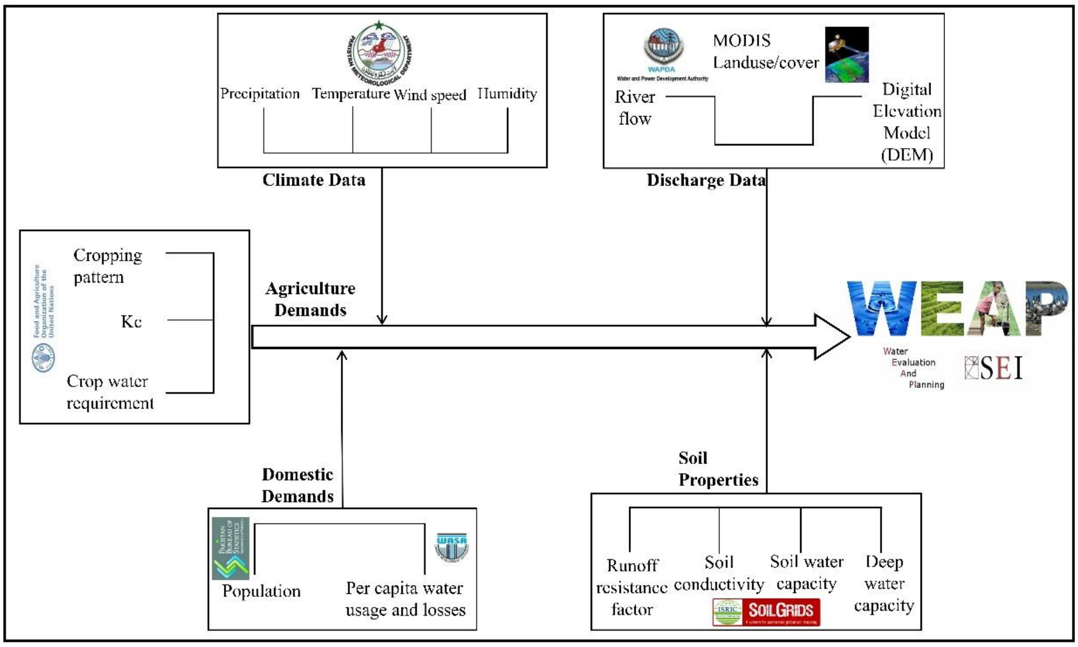

Figure 2.2. Shows a schematic diagram of data input to the Water Evaluation and Planning (WEAP).

Table 2.1. List of datasets used in the Water Evaluation and Planning (WEAP) model along with its description and sources.

Data	Description	Sources
Meteorological data (1995-2014)	Precipitation, Temperature Humidity, Wind speed	Pakistan Meteorological Department (PMD), Lahore
Climatological data (2015-2050)	RCP4.5, RCP8.5	Pakistan Meteorological Department (PMD), Islamabad
Hydrological data (1995-2014)	River Discharge data	Water and Power Development Authority Lahore, Indus River System Authority, Lahore
Land Cover data (2009)	Land cover from MODIS	USGS (https://earthexplorer.usgs.gov/)
Demographic data (1995-2050)	Land use data, Population & Growth rates, Water consumption rates, Agricultural Water Demand	Pakistan Bureau of Statistics, Islamabad. Reports of Punjab Development Statistics.

1.4.2 Climatological Data

The climate data (RCP 4.5 and RCP 8.5) were collected from the Pakistan Meteorological Department (PMD), downscaled to 25 km and 50 km resolution. The Representative Concentration Pathways (RCP) is the result of integrated work of climate modeling and impacts assessment.

Each Representative Concentration Pathway (RCP) is based on specific emissions trajectory, energy use, population, air pollutants and land use, and the resulting radiative forcing and temperature anomalies (Moss et al., 2010). The choice of two particular scenarios among a set of 4 RCPs has been made in a fashion to find the impacts on regional climate, i.e., extreme climate change scenario and relatively intermediate pathway. The RCP4.5 climate change scenario is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Clarke et al., 2007; Smith & Wigley, 2006; Wise et al., 2009). While on the high end, i.e., RCP8.5 climate change scenario, the 8.5 Wm^{-2} cases, CO_2 levels rise above a massive 1,300 ppm by the end of the century and are still rising fast (Riahi, Grübler, & Nakicenovic, 2007).

1.4.3 Land Cover Data

The land cover data, and the soil type and other soil properties data were collected from MODIS (Moderate-resolution Imaging Spectroradiometer) land cover dataset archives (https://earthexplorer.usgs.gov/). Figure 2.3 shows the land cover classes in the study area.

1.4.4 Water Demand Data

There are six domestic demand sites including Mianwali, Khushab, Bhakkar, Jhang, Layyah, Muzaffargarh, and five agriculture demand sites Mianwali, Khushab, Bhakkar, Layyah, and Muzaffargarh (Figure 2.4). The current and future water requirements were assessed for different sectors in the study area. Water demand analysis for all the sectors was performed using the WEAP model by using its disaggregated based approach.

The water demands for domestic, agriculture and livestock were estimated as a measure of socio-economic forces in the area. Water requirement for each sector was given at disaggregated level (i.e., persons, hectares, heads), which then was multiplied by the annual water use rate for each sector. The domestic water requirement for each district included urban as well as rural areas, generally populated near water sources. The total water requirement at district level was based on the population census of 1998 for the current accounts (Table 2.2).

Population growth rate presented in the above table for each district was used to estimate water demand after the baseline year. The domestic water demand provided by WASA, for urban as well as rural areas was 60 gallons per capita per day. Water requirement for cattle/buffalo and goat/sheep was given as ~42 and ~10-14 liters per head per day, respectively. The crop water requirement was estimated by using the crop coefficient (Vaghefi et al.) values from Food and Agricultural Organization (FAO) data for the existing irrigation schemes (Savva & Frenken, 2002). The value of evapotranspiration and effective precipitation were obtained from literature and PMD (Ullah, Habib, & Muhammad, 2001).

The irrigation water demand was then calculated by considering the cultivated areas

Table 2.2. District wise population and population growth rate of all the districts (Census 1998).

District	Population	Growth Rate (%)
Mianwali	1056620	2.35
Bhakkar	1051456	2.72
Khushab	905711	2.05
Jhang	2834545	2.16
Layyah	1120951	3.10
Muzaffargarh	2635903	3.38

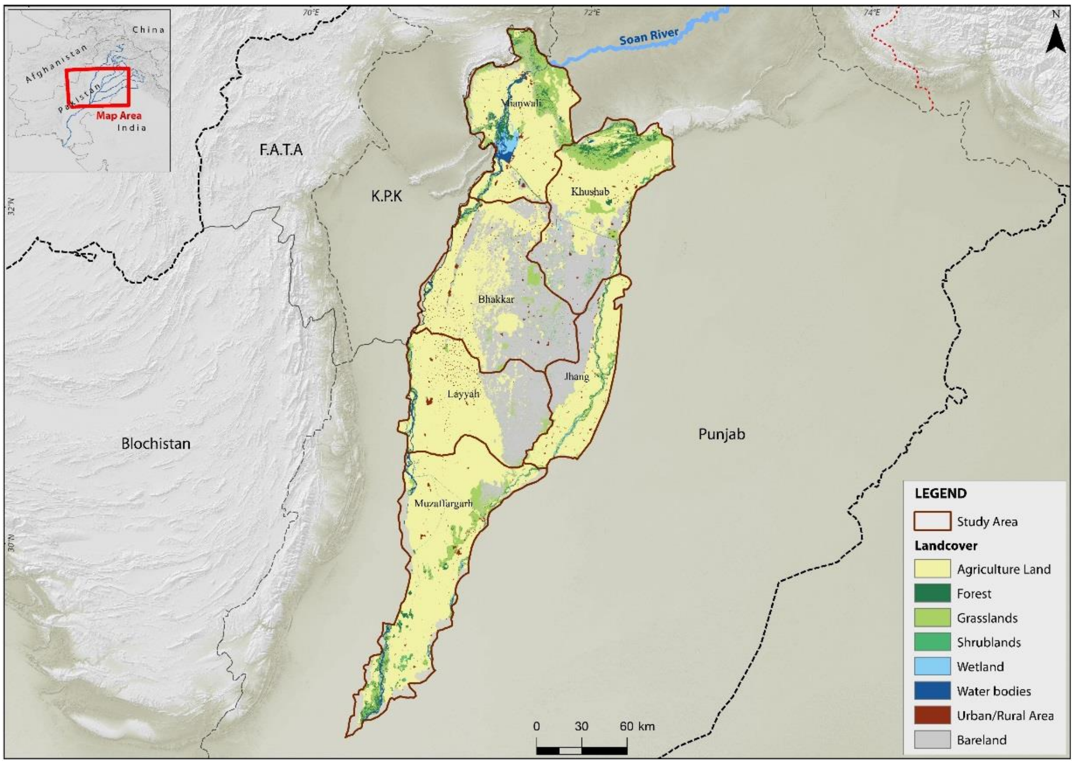

Figure 2.3. Land cover classes map of Lower Indus Basin using MODIS data.

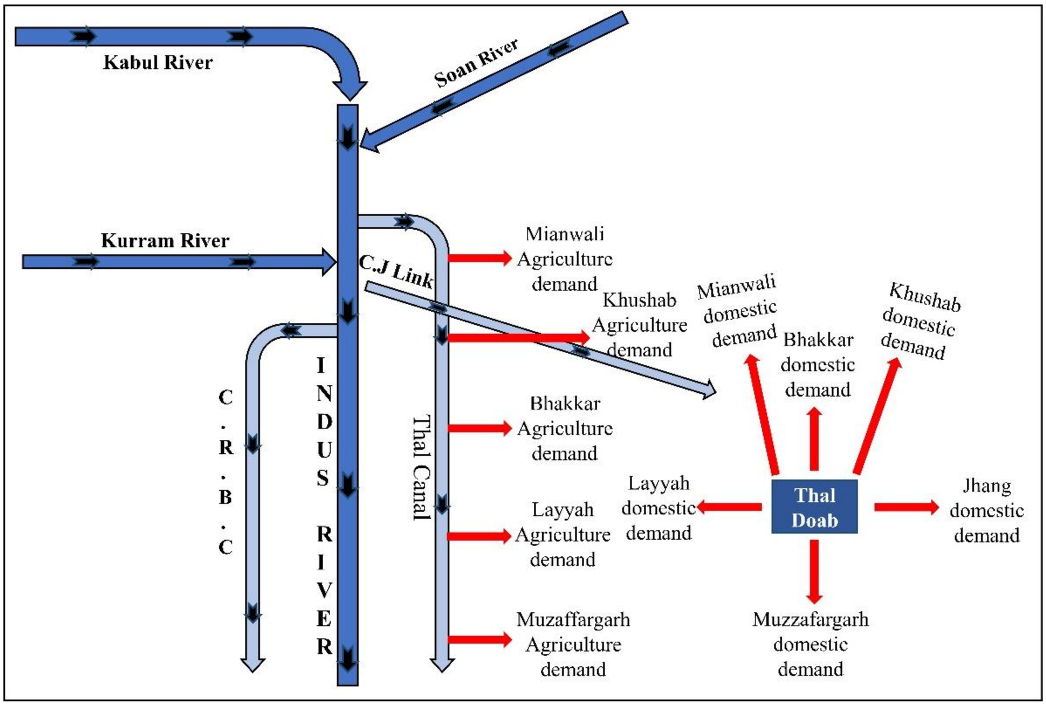

Figure 2.4. Line diagram showing the demand and supply nodes in the study area.

and patterns in the Lower Indus Basin. The water demand data for major crops such as cotton, maize, sugarcane, rice, and vegetables were computed using the crop water in the study area.

1.5 Analytical Framework

All the above-described datasets were input to the WEAP model. Modeling of WEAP starts from the input of geographic layers, which include all supply and demand nodes. The schematic view links all spatial features (supply and demand sites) by using nodes and transmission links. Then the computation of scenarios is done.

Figure 2.5 shows the schematic diagram of the Lower Indus River basin. Red points feature demand sites in the study area, which are irrigation, domestic (rural and urban), and livestock. A transmission link is drawn from the water source to the demand sites shown in the green line.

WEAP provides with a set of model objects and procedures that can resolve problems faced by water management using a scenario generated approach, which works on the natural watershed, reservoirs, streams, and canals. It has built-in algorithms that use climate time series data and simulates rainfall runoff of basins and sub-basins (Raskin, Hansen, Zhu, & Stavisky, 1992; Yates, Sieber, Purkey, & Huber-Lee, 2005). It includes different areas in which data is required.

WEAP model provides five different methods for model calibration including (1) the Rainfall-Runoff Method (2) Irrigation Demands Only Simplified Coefficient Approach, (3) the Soil Moisture Method, (4) the MABIA Method, and (5) the Plant Growth Method (Mugatsia, 2010).

1.5.1 Rainfall-Runoff Method

The Rainfall-Runoff method determines evapotranspiration for irrigated and rain-fed crops using crop coefficients. The runoff simulated to the river and flow to groundwater through catchment is the remainder that is not consumed by evapotranspiration.

1.5.2 Irrigation Demands Only Simplified Coefficient Approach

This method determines to use crop coefficients to calculate the potential evapotranspiration in the catchment. The irrigation demand is then, may be required to meet the unmet portion of the evapotranspiration requirement that rainfall cannot fulfill. Irrigation Demands only does not simulate runoff or infiltration to the groundwater processes.

1.5.3 Soil Moisture Method

The Soil Moisture Method is the most complex of the five methods. It represents the catchment with two soil layers, i.e., upper soil layer and lower soil layer as well as the potential for snow accumulation. It simulates evapotranspiration, runoff and Interflow, and changes in soil moisture in the upper layer. This method also allows for the characterization of land use and soil type. In the lower soil layer, baseflow routing to the river and soil moisture changes are simulated. Correspondingly, extensive soil and climate parameterization are used to simulate all the processes in soil moisture method.

These extensive data were not available. The rainfall-runoff method was used to simulate river flows in this study. The following type of data is required to perform rainfall -runoff simulation using this method;

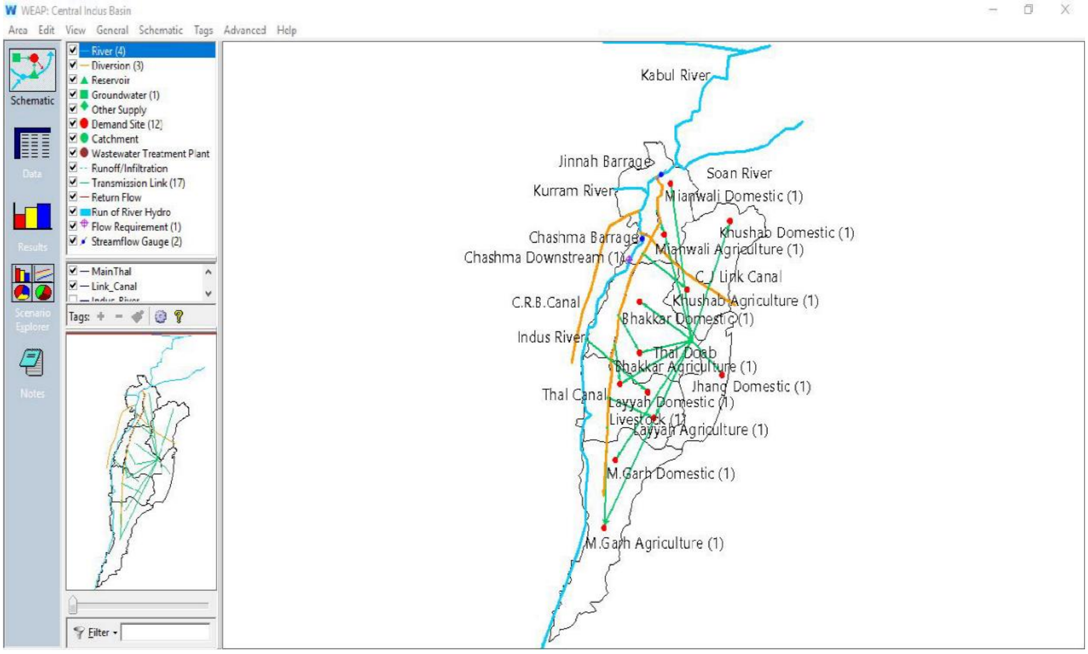

Figure 2.5. Water Evaluation and Planning (WEAP) model schematics.

i. Land use (Area, Kc, Effective precipitation)
ii. Climate (precipitation and ETo)

Where Kc- crop coefficients and ETo is the reference crop evapotranspiration

1.5.4 Rainfall Runoff Simulation Method

Rainfall-Runoff simulation method of model calibration assumes the demand sites with simplified agro-hydrological processes, i.e., rainfall, evapotranspiration, and crop growth. It also includes non-agricultural demand sites as well. Following are the equations of Rainfall-Runoff method; where subscripts LC is land cover, HU is hydro-unit, TS is time step (e.g., month), I is irrigated, and NI is non-irrigated:

$$PrecipAvailableForET_{LC} = Precip_{HU} \times Area_{LC} \times 10^{-5} \times PrecipEffective_{LC}$$
$$ETpotential_{LC} = ETreference_{HU} \times Kc_{LC} \times 10^{-5}$$
$$PrecipShortfall_{LC,1} = Max(0, ETpotential_{LC,1} - PrecipAvailableForET_{LC,1}$$
$$SupplyRequirement_{LC,1} = \sum_{LC,1} SupplyRequirement_{LC,1} \qquad \text{(Eq. 1)}$$

The above four equations are used to determine the additional amount of water that is needed to supply the evapotranspiration demand of the land cover while considering irrigation efficiencies.

Based on the model of priorities, the following quantities can be calculated:

$$Supply_{HU} = Calculated\ by\ WEAP\ allocation\ algorithm$$
$$Supply_{LC,1} = Supply_{HU} \times \frac{SupplyRequirement_{LC,1}}{SupplyRequirement_{HU}}$$
$$ETActual_{LC,NI} = Min(ETpotential_{LC,NI}, PrecipAvailableForET_{LC,NI})$$
$$ETActual_{LC,1} = Min\big(ETpotential_{LC,1}, PrecipAvailableForET_{LC,1}\big) + IrrFrac_{LC,1} \times Supply_{LC,1}$$
$$EF_{LC} = \frac{ETActual_{LC}}{ETpotential_{LC}} \qquad \text{(Eq. 2)}$$

Runoff to both groundwater and surface water can be calculated with the following equation;

$$Runoff_{LC} = Max(0, PrecipAvailableForET_{LC} - ETpotential_{LC})$$

$$RunofftoGW_{HU} = \sum_{LC}\left(Runoff_{LC} \times (1 - RunoffToGWFraction_{LC})\right)$$

All the variables with their units are described in table 2.

1.6 Modeling of Socio-Economic and Climate Change Scenarios

The loss of water can be comprehensively handled using a simulation model (WEAP), which simulates current water situation, evaluates water quality and manages water demand and supply issues (Raskin et al., 1992). WEAP provides with a set of model objects and procedures that can resolve problems faced by water management using a scenario generated approach, which works on natural watershed, reservoirs, streams, and canals (Yates et al., 2005). Hum and Talib (2016) analyzed in their study that growing population and expanding urbanization increase the demands for water availability. They studied the effects of three different scenarios using the WEAP model to calculate the impact on the supply-demand gap by the year 2050. Their results showed with proper water savings measures and water management alternatives, water deficit will be significantly reduced. Bakken et al. (2016) modeled the effect of climate change and increased irrigation withdrawals on two semi-arid basins using WEAP. The simulations showed that both factors affected the available water for hydropower production and their overall effect is in the form of reduced runoff. They compared to water consumption losses, and there were 2-4 times more considerable losses due to irrigation than the gross evaporation losses from reservoirs losses. Santikayasa (2016) developed agricultural planning model to estimate crop water requirement, water availability and future climate projection to sustain the future water use.

Table 2.3. List of all input variables in WEAP model and their description.

Variables	**Units**	**Description**
Area	Ha	Area of each land cover
Precip	mm	Precipitation
PrecipEffective	%	Percentage of precipitation that is used for ET
PrecipAvailableForET	mcm	Precipitation available for evapotranspiration
Kc	-	Crop coefficient
ETreference	mm	Reference crop evapotranspiration
ETpotential	mcm	Potential crop evapotranspiration
PrecipShortfall	mcm	ET deficit if only precipitation is considered
IrrFrac	%	Percentage of supplied water available for ET
SupplyRequirement	mcm	Crop water requirement
Supply	mcm	Amount supplied for irrigation
EF	-	Fraction potential evapotranspiration
RunoffToGWFraction	-	Area of each land cover
RunoffToGW	mcm	Precipitation
RunoffToSurfaceWater	mcm	Percentage of precipitation that is used for ET

IPCC emission scenarios (A2 and B2) were used, and the downscaled data is used as input for the WEAP model. The study showed the temperature, precipitation, water availability is projected to increase in the future. Königer and Margane (2014) used the WEAP model for the water balance (allocation and priorities), management issues for supply preferences during the period of water shortage. Esteve et al. (2015) demonstrated that there is a need to develop integrated tools for the analysis of climate change impacts and adaptation. They represented the socio-economic, agronomic and hydrologic systems using hydrologic model WEAP. For this A2 climate change scenario up to 2070 was incorporated with the model. The results provide a useful tool for supporting water and climate change policy-making about the potential impacts of climate change.

Haddad, Jayousi, and Hantash (2007) analyzed the water resources management in a watershed in Palestine (District Tulkarem) using WEAP as a Decision Support System (DSS). The objectives of their study were stakeholders' survey for an operational DSS, WEAP model to perform various scenarios of simulation and optimization of water resources management. The results demonstrated the feasibility of developing a DSS and its implementation in the district successfully. Azlinda and Mohd (2008) studied the subject of the high growth rate of population and its effects on natural resources base in Malaysia (Langat catchment, Selangor). Water supply and demand situation are investigated through an analytical approach based on WEAP. The objectives of this research were to investigate a trend of supply and demand in the catchment by assessing the availability of water. The results showed that a slight increase in population growth with current water availability condition and climate variation, the study area will experience a scarce water problem. Rayej (2012) used WEAP to project the water demands in Agricultural, Urban and Environmental sectors up to 2050 for ten hydrological regions. Different scenarios of increased population growth and climate change sequences were considered. The study found that urban demands increased rapidly undergrowth scenarios and heavily influenced by future population growth. Future climate influenced the urban water demand to a lesser extent. Agricultural demands declined because of a decrease in agricultural lands mainly due to urbanization. Hao, Huang, Wang, and Zhang (2011) studied the freshwater management challenges in China (Laohahe River Basin). Water demand and supply was stimulated in WEAP under planting structure adjustment scenario. The results showed that the scenario could effectively decrease the unmet demands of all unmet demands sites. The evaluation approach of the model assessed management options and mitigating methods for water resources vulnerability.

Awulachew et al. (2010) conducted a study for water resource development (WRD) of Blue Nile River (Lake Tana). WEAP was used to stimulate water demands for hydropower and irrigation development of the region. The study found that as a result of future WRD the mean annual water level of Lake Tana would be decreased. Purkey, Huber-Lee, Yates, Hanemann, and Herrod-Julius (2007) found that in California, the significant variations in climate change has the potential to affect hydrologic patterns. WEAP tools are used to provide an analytical framework process. The paper presented the water-related decision-making processes based on a 3S (Sensitivity, Significance, and Stakeholders support) standard.

Arranz and McCartney (2007) used different scenarios of the environmental reserve in WEAP model and showed the result that instream requirement of aquatic habitats would decrease available water for other storages. Königer and Margane (2014) used WEAP for groundwater recharge, water balance, supply management during the period of water shortage. Integrated water management by Lane, Sandoval- Solis, and Porse (2015) using WEAP was done to provide environmental flows and to develop an alternative reservoir opening policy.

1.7 Calibration Process

Calibration of the model was done using the historical data from 1995 to 2004 (10 years) and then validating from 2005 to 2014. Calibration process was started from determining the parameters and their ranges followed by the selection of one of the five (Rainfall-Runoff Method, Irrigation Demands Only Simplified Coefficient Approach, Soil Moisture Method, MABIA Method, and Plant Growth Method) calibration methods given in the model. Rainfall Run-off method for calibration of the model was selected for model calibration, because of the data availability according to method's requirements. The performance of the model was evaluated by computing the coefficient of determination and the Nash-Sutcliffe Efficiency Index for calibration and validation periods, as they found to be best indices (Gupta & Kling, 2011; McCuen, Knight, & Cutter, 2006) . Figure 2.6 is showing the steps followed to run through the calibration process.

1.7.1 Future Water Demand and Scenarios Development

The development of all other scenarios is the most important part of WEAP modeling (Figure 2.7). Scenarios were defined primarily as a set of assumptions based on the socio-economic activities or the development.

Five exploitation scenarios (Reference Scenario, Population Growth, Increased Irrigation Demand, Climate Change RCP 4.5, and Climate Change RCP 8.5), and two management scenarios (The Decrease in Basic Drinking Water Consumption, The Decrease in Basic Irrigation Water Consumption) were suggested to assess the impacts of climate change on water demand situation for present and future. Development of scenarios was based on the demographic and the climatic projection data of the study area. The Current Accounts is the dataset from which scenarios are built. The next step is the creation of the reference scenario based on current account data and to carry it forward into the entire period of simulation. Reference scenario is the point of comparison for all the possible socio-economic and climatic scenarios in which changes are made to the system data. All the scenarios were generated on the assumption of some changes (increase/decrease) in water consumption rate of agriculture and domestic sector, but the consumption rate of livestock water demand was kept constant.

The baseline (current account) in this study was 1995; it was chosen by consistent and reliable data availability. The scenario was generated with total water demand (agricultural, livestock, and domestic demand) in the baseline year 1995 and climatic condition during 1995. The reference scenario refers to business as usual, which means the water resources do not have any changes, was generated with water demand in the year 1995-2050 and climatic condition during 1995-2014. All socioeconomic and climatic scenarios were developed with water demand in the year 2015-2050 and climatic condition during the same period. Table 2.4 describes all the assumption and projections made in the development of the scenarios.

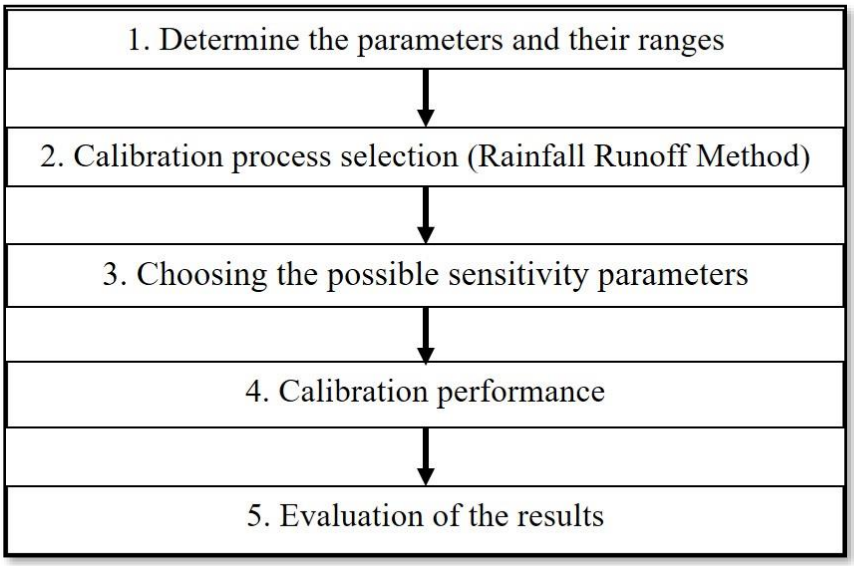

Figure 2.6. The framework of the calibration process.

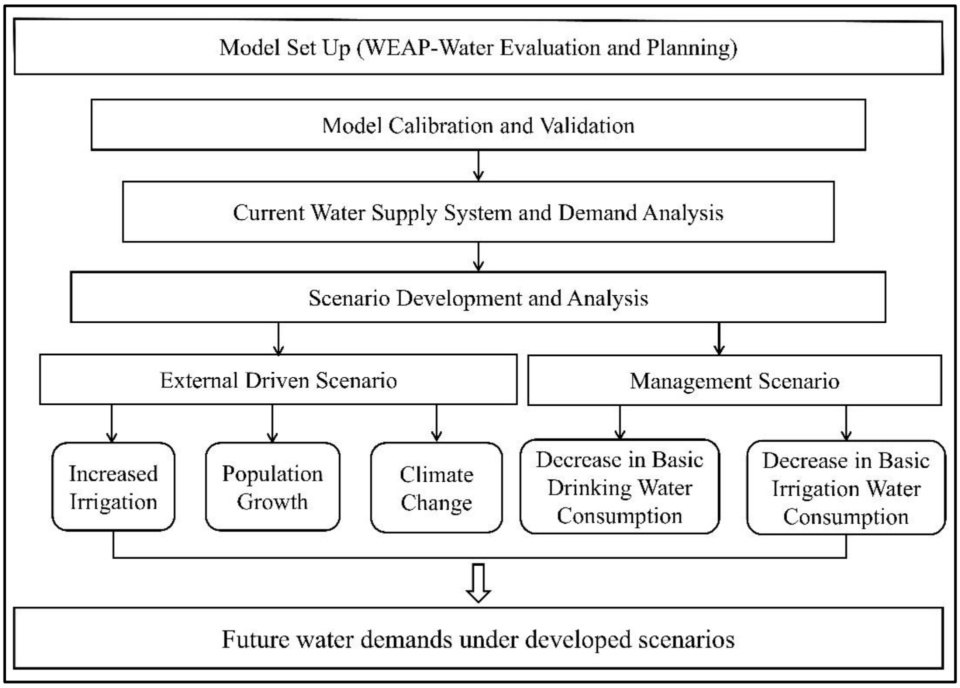

Figure 2.7. Development of scenarios within the Water Evaluation and Planning (WEAP) model.

Table 2.4. Water demand and management scenarios and its description.

No.	Scenarios	Description
1.	Reference Scenario	Reference scenario refers to the current account in which all the real-time data was used. The water demand was increasing moderately.
2.	High Population Growth Scenario	5% increased the present growth rates, and all the other parameters were used as they were in the reference scenario.
3.	Increased Irrigation Demands	The irrigated area was increased by 5-10% by the year 2050, while all other parameters are based on the reference scenario.
4.	Climate Change Scenario (RCP4.5)	The projected climate data is used from the RCP 4.5, whereas population and demand data remained unchanged.
5.	Climate Change Scenario (RCP8.5)	The data from RCP 8.5 were used, all the other parameters were based on the reference scenario.
6.	[1]The decrease in Basic Drinking Water Consumption	The decrease in basic water consumption was decreased by 5%, and all the other parameters were based on the reference scenario.
7.	The decrease in Basic Irrigation Water Consumption	The irrigation water consumptions were decreased by 15%, where all the other parameters remain the same as a reference scenario.

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[1] The scenario no. 6 and 7, decrease in basic drinking water consumption and a decrease in basic irrigation water consumption respectively, were proposed to be the management scenarios for the study area.

Chapter 3

RESULTS AND DISCUSSION

2.1 Model Calibration and Validation

The WEAP model was calibrated and validated according to the framework for the period 1995-2004 and 2005-2014 respectively (figure 3.1). The calibration result showed excellent agreement with the validation of the model. The value of evapotranspiration was kept constant (1376 mm/year), so the Kc was the only sensitive parameter to tune up the model. The values of Nash Sutcliffe Efficiency Index and the coefficient of determination was 0.85 and 0.86, respectively for the calibration period. The results showed that the WEAP model has accurately simulated the hydrological processes in the study area, similar results were reported by Firdos et al. (Khan, Pilz, & Ali, 2017).

2.2 Reference Scenario

Figure 3.2 shows the water demand simulation and analysis of the reference scenario. The reference scenario considered no changes or development in water supply system in the study area. The projected water demands were 1.3 Billion Cubic Meter (BCM) for the domestic sector, 11.6 BCM for the agriculture sector, and 0.25 BCM for the livestock sector. All the other scenarios, e.g., increased irrigation, and population growth was computed based on this simulation. The results showed that by the year 2050 the water demand would increase to 6.8 BCM, 15.4 BCM, and 0.27 BCM for domestic, agriculture and livestock sectors, respectively.

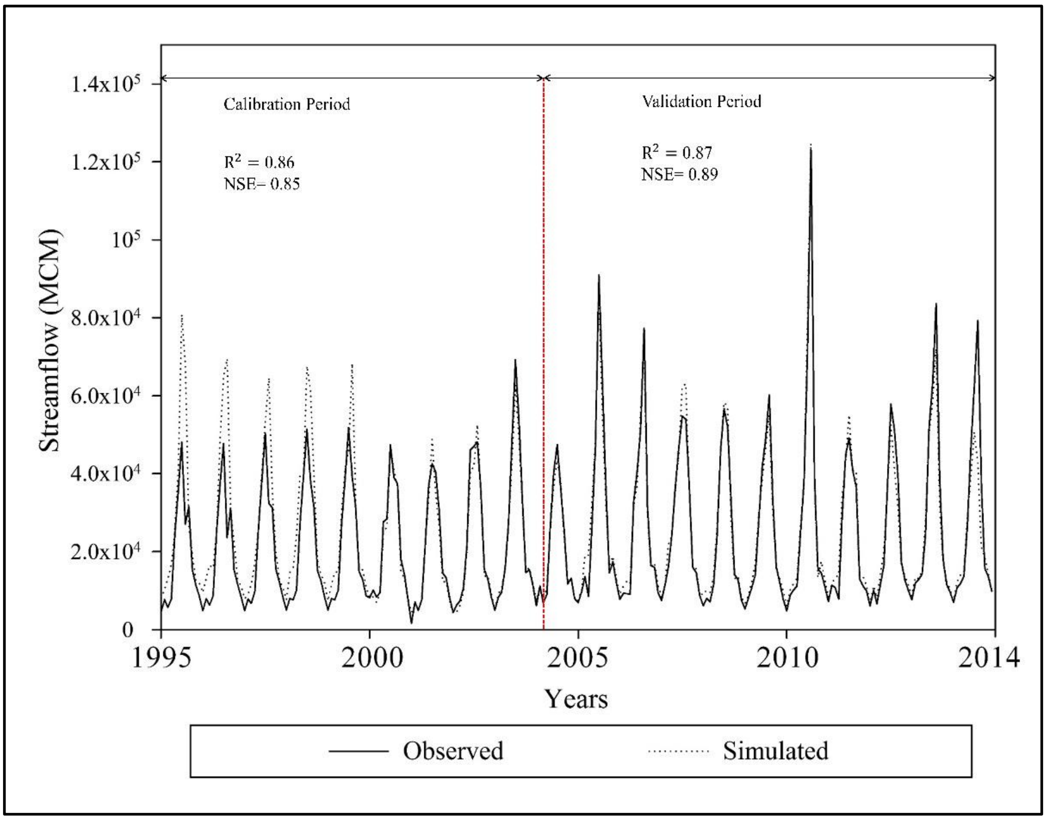

Figure 3.1. Observed vs. simulated streamflow (monthly) of Lower Indus Basin during calibration and validation process.

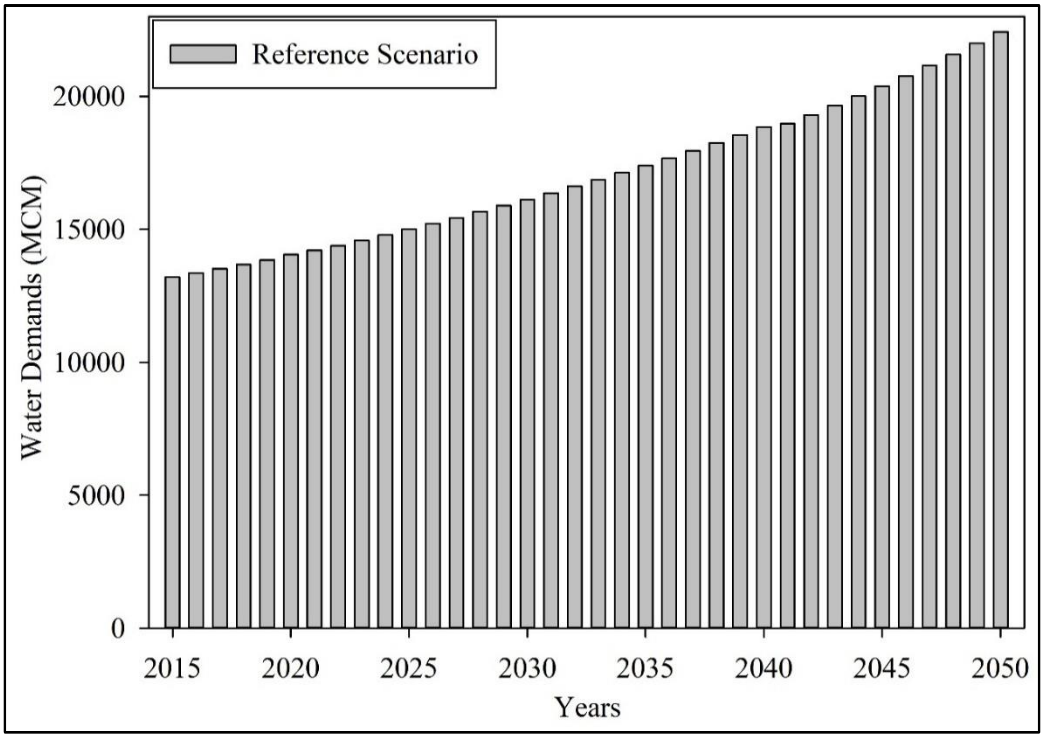

Figure 3.2: Annual water demands (MCM) for the reference (business as usual) for domestic, agriculture and livestock sectors (2015-2050)

2.3 Socio-Economic Scenarios

2.3.1 High Population Growth

Figure 3.3 shows a comparison of water demand under reference and high population growth scenarios. Under the reference scenario, the water demand was 1307 MCM in 2015 and will increase to 6800 MCM in 2050.

In comparison, the water demand in high population growth scenario was increased to 8500 MCM by the year 2050. The increase in domestic water for Lower Indus Basin (LIB) is justified by the relatively high population growth rate (5%), an increase in the water consumption by from 82.9 m^3 per capita per day by the year 2015 to 120 m^3 per capita per day by the year 2050. The domestic water demand, for population growth scenario, is higher than reference scenarios in future because of the gradual increase in population in the study area. There were still no changes considered in the water supply system in high population growth scenario. The future projection showed that no developments in water supply management would lead to severe water shortage problems.

2.3.2 Increased Irrigation Demand Scenarios

With an increasing growth rate of irrigated land, by 7%, the agriculture water demand will increase from 11 BCM in 2015 to 15 BCM in 2050 under increased irrigation demand scenario. The projected agriculture demand for the year 2015-2050 showed that the water demand in this sector is increasing gradually (Figure 3.4). The population growth is also affecting the increased demand for irrigation. The livestock demand is much less than other sectors and was set constant in all the scenarios over the simulation period. As reference scenario is the baseline to all the

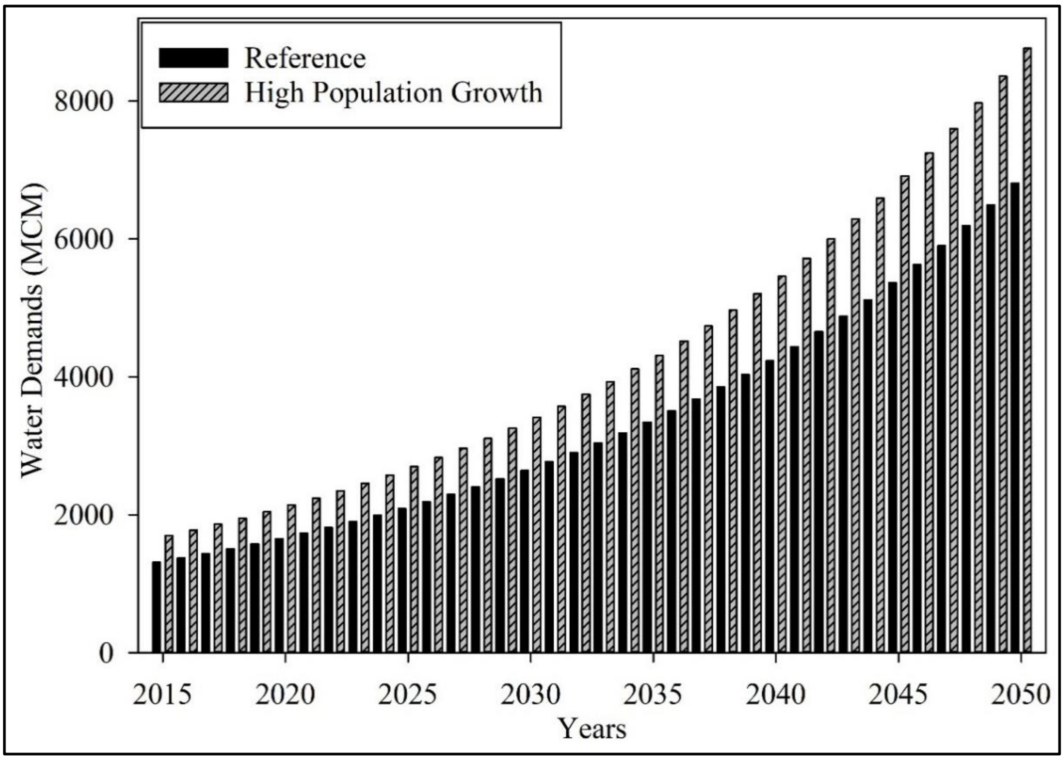

Figure 3.3. Annual water demand for domestic sector in reference and high population growth scenario (2015-2050).

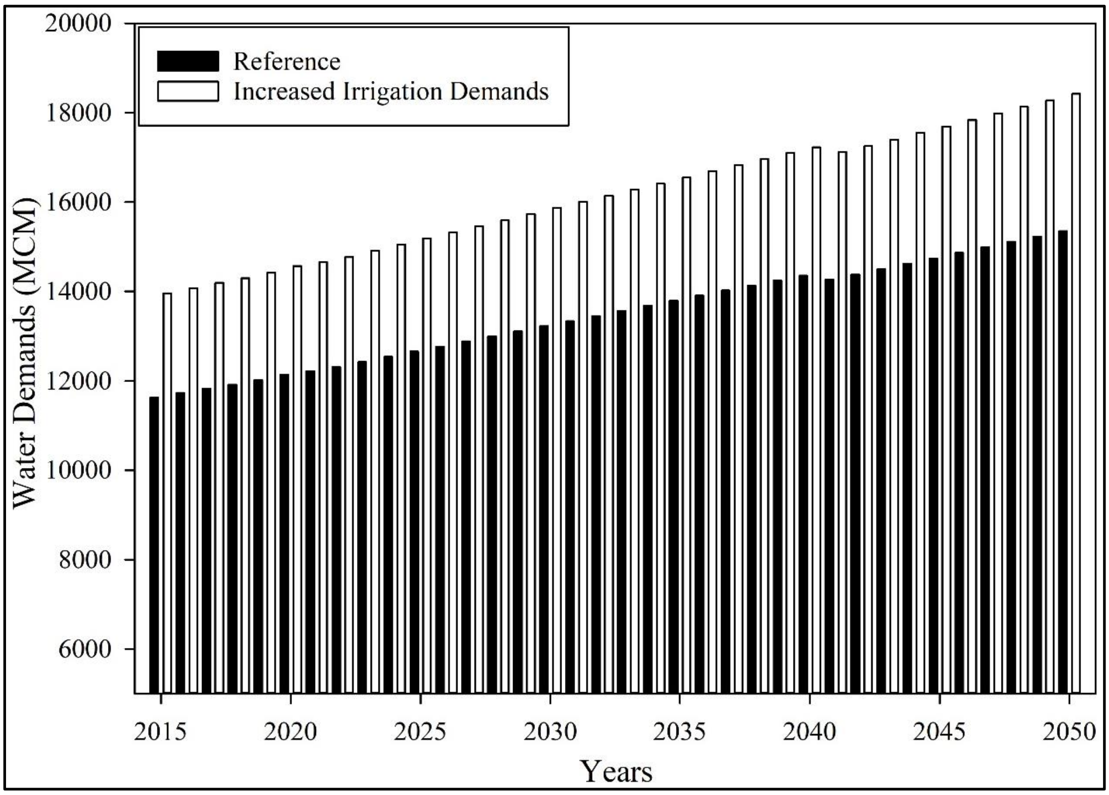

Figure 3.4. The future projection for irrigation sector under reference and increased irrigation demand scenario (2015-2050).

other scenarios for water demand data, livestock water demand, is the same in all the three scenarios. Hence only reference scenario is shown in figure 3.5.

2.4 Climate Change Scenarios

The development of climate change scenarios, i.e., R.C.P 4.5 (relatively wet climate) and R.C.P 8.5, (extreme dry climate) are based on the changing trend in a climate of the study area. According to the scenarios, the average projected change in precipitation and temperature were about 15.22% and 0.92 °C to 1.77 °C by the end of 2035. The change in precipitation frequency in the study area will also affect the recharge in the thal doab aquifer (Khan et al., 2017). The future water availability projections and demand analysis were done to highlight the water deficiency that is resulting from these climate change scenarios (Figure 3.6).

2.5 Management Scenarios

2.5.1 Decrease in Basic Domestic Water Consumption Scenario

In this scenario, 5% reduction was assumed in the domestic water consumption of all the districts. The decrease could be the result of mass education and knowledge sharing about water conservation in the masses. Other possible technological solutions are also expected to be developed to reduce losses. For example, the water supply must be according to the demand node, whether it is urban or rural. The rural water demand is always less than the urban water demand, so the rural water allocation must be different from urban water allocation. The results show that even with the smaller percentage of 5% decrease in water consumption, water demand is reduced in all the six districts, i.e., 4200 MCM in the year 2050,

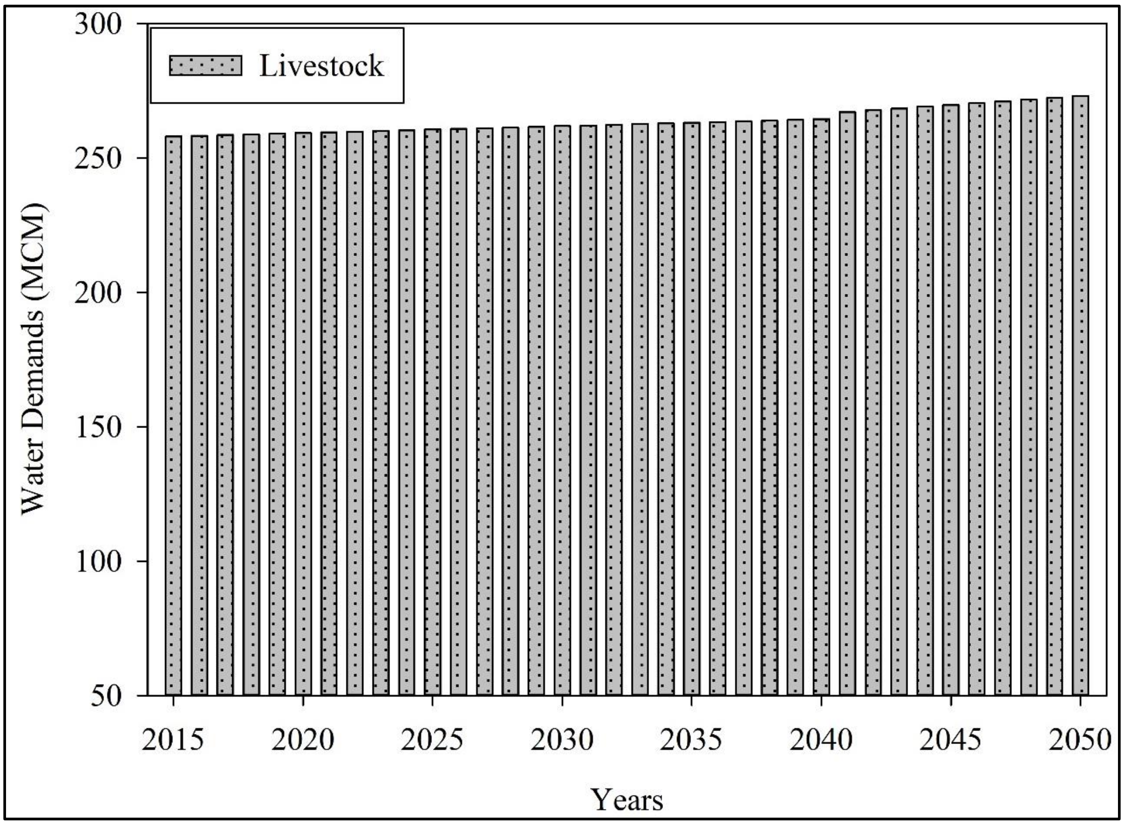

Figure 3.5. The future projection for the livestock sector.

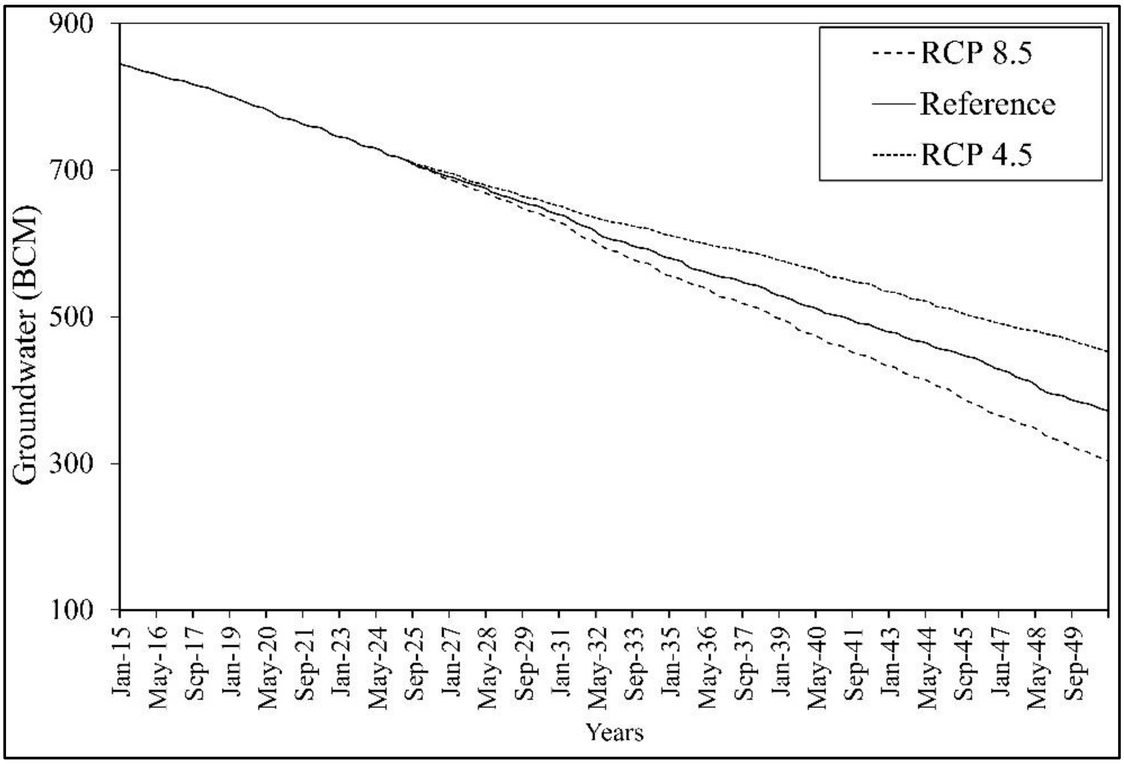

Figure 3.6. Projection of groundwater under reference, RCP 4.5 and RCP8.5 scenarios (2015-2050).

while under reference scenario the demands would be more than 6000 MCM (Figure 3.7).

2.5.2 Decrease in Basic Irrigation Water Consumption Scenario

The assumption made for this scenario was that a decrease of 15% in the basic irrigation water consumption were executed. This scenario was developed based on the low irrigation efficiency in the study area. The losses in the current irrigation schemes are reported to be 40 % (M. A. Kahlown, Raoof, Zubair, & Kemper, 2007). The decrease in water consumption is possible because of the awareness of the farmers, introduction of new and efficient irrigation techniques like central pivot, drip, sprinkler irrigation systems and the use of precision agriculture. Water demand would be reduced if the efficient irrigation schemes were introduced and getting control of losses and leakages. Figure 3.8 is showing the difference in water demand under reference and decrease in basic irrigation water consumption scenario.

We analyzed and proposed water management practices and policies for current and future water availability based on the socio-economic and climate change scenarios. Water demand analysis was done based on different exploitation and potential management scenarios for sustainable water availability in the future. The first step was to identify the water demand of each sector in the study area, followed by the conditions of exploiting forces such as high population growth, increase in irrigated land, and impact of climate change. The second step was to develop different potential management scenarios, i.e., reduction in water demands in each sector, to cope up the results of exploiting scenarios.

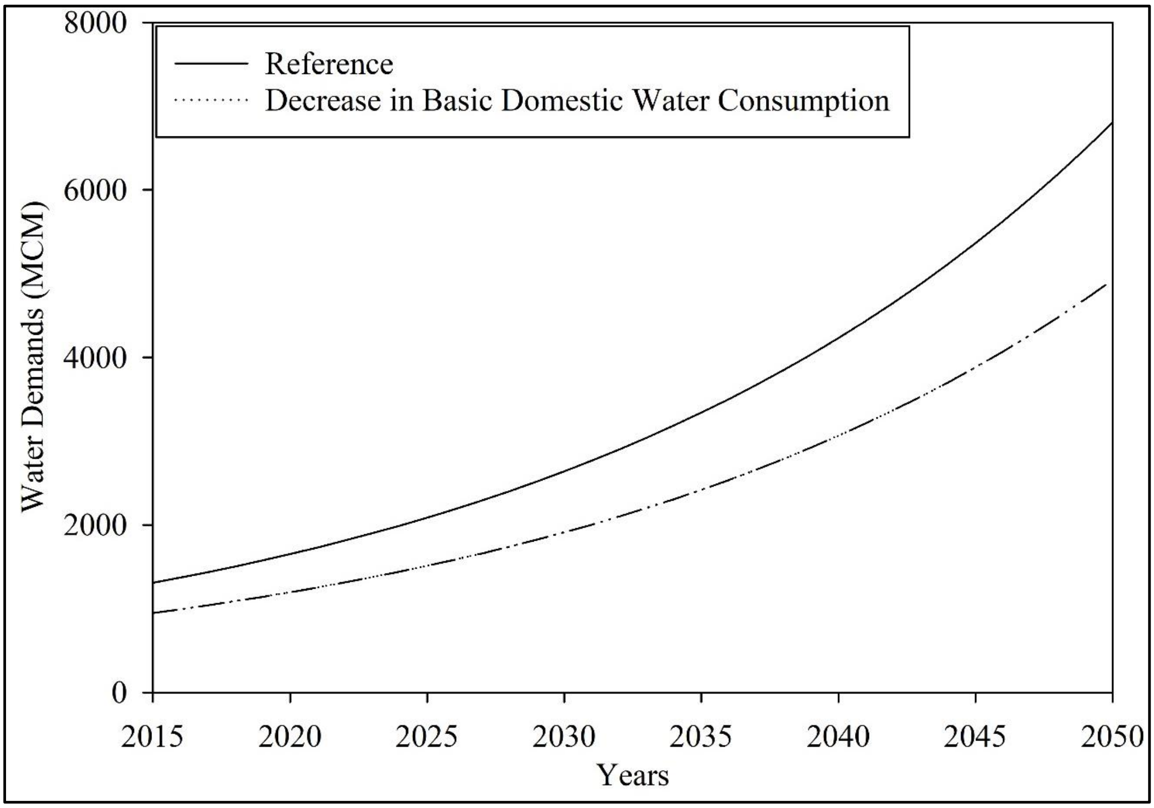

Figure 3.7. Annual water demand projections for reference and decrease in basic domestic water consumption scenarios (2015-2050).

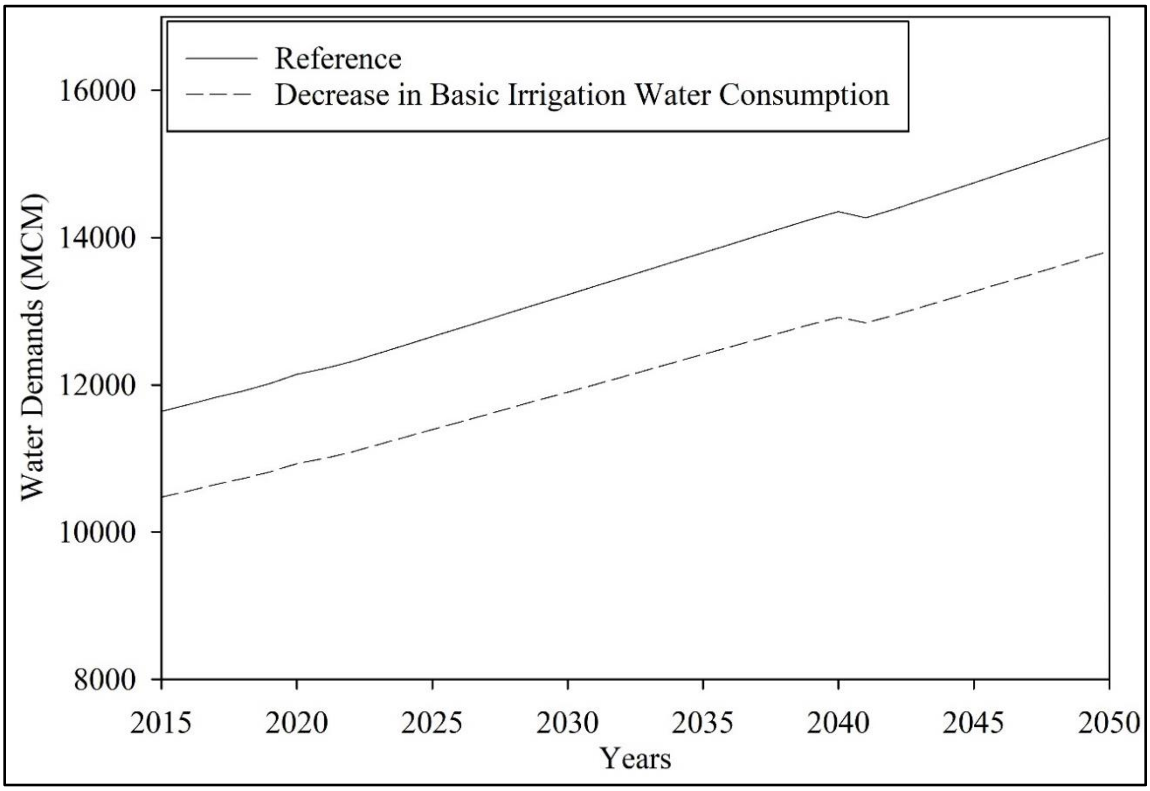

Figure 3.8. Annual water demands under reference and decrease in irrigation water consumption scenarios (2015-2050).

The projected water demand in Lower Indus Basin under 5% high population growth scenario was 8500 MCM. Similar results were reported in Klela basin in southern Mali where the calculated water demands for this socio-economic scenario was increased from 76 MCM in the reference scenario to 224 MCM by the year 2050 (Toure, Diekkrüger, Mariko, & Cissé, 2017). They used the population growth rate and climate change scenarios in the WEAP. Similar results were observed in a study in Kathmandu Valley by Chitresh et al. (Saraswat, Mishra, & Kumar, 2017). The study was focused on integrated urban water management under different scenarios. They found that the population growth rate of 6% will increase the water demand from 135 liters per capita per day (Lpcd) in 2015 to 150 Lpcd by the year 2030. In another study in Morocco, water demands under climate and land use change were estimated to be 252 MCM in 2007. The results showed the water scarcity in the basin due to the increase in agriculture and non-sustainable water management policies (Johannsen, Hengst, Goll, Höllermann, & Diekkrüger, 2016).

This study also showed the results of other socio-economic scenarios, which answered the what-if question that arises by executing the scenarios. The results showed how these external factors such as population growth and climate change are impacting future water demand in the Lower Indus Basin. The water demands under high population growth, increased irrigation demands, climate change, and decreased demand of domestic and agriculture sectors were increasing gradually. The results showed that there is an urgency to adopt water management practices. The combined simulation of water resources for various policies such as exploitation scenarios and potential management scenarios is one of the best method

(DE SURFACE). A comparative analysis of all the scenarios was analyzed to identify the best possible management strategy in the study area (Figure 3.9).

The exploitation scenarios' results showed that the water demands are increasing drastically. So, the designed potential management scenarios were applied to compare the water supply and demand analysis of the Lower Indus Basin. Figure 3.10 shows the unmet water demand in the exploitation (High population growth, increased irrigation demands) and potential management scenarios (Decrease in domestic water consumption and Decrease in irrigation water consumption) with reference scenario. Water demand is still increasing in management scenarios, despite the decrease in consumption rates. This is due to the relatively high growth rates of the population and the increase in irrigated land in the study area.

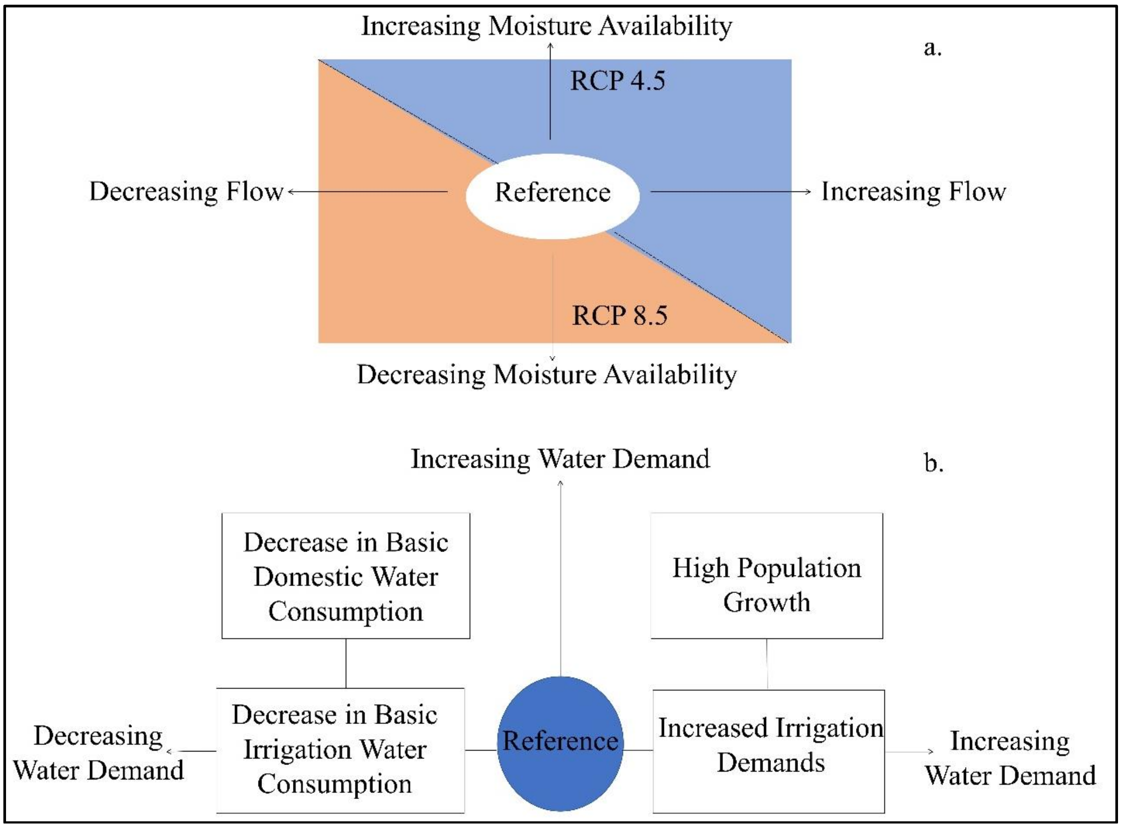

Figure 3.9. (a) Climate Change and (b) socio-economic scenarios, the red circle indicates the current or present-day conditions in the Lower Indus Basin. The dashed line dividing the two climate change scenarios indicates the possible change in precipitation. The upper (blue) triangle covers RCP 4.5 and shows increasing precipitation with a consequent change in moisture availability. The lower (brown) triangle is covering RCP 8.5 and indicating the decrease in precipitation. The socio-economic scenarios are indicating the functions of agricultural and domestic water demands.

Figure 3.9 highlight how these potential management scenarios can be a useful adaptation for the study area. The unmet water demands in the reference scenario were estimated to be 14.8 BCM in the year 2050 with no adaptation measures. In the exploitation scenarios, the unmet water demand is going to be increased to 18.1 BCM by the year 2050. In both high population growth scenario and increased irrigation demand scenario, no mitigation technique was adopted. No adaptations to climate change scenario and socio-economic scenarios could result in severe water shortage in the thal doab. Under the potential management scenarios, the unmet water demands are considered to a significant lowest amount (figure 3.10).

Two-third of the world population, about 4 billion people, experiencing water scarcity during at least part of the year. In Pakistan, 120 million people experience water scarcity during part of the year and about 85% of which live in the Indus basin which indicates the severity of the issue (Mekonnen & Hoekstra, 2016). Pakistan is one of the arid countries, which have low water storage capacity, which is 15% of the annual river flow. The per capita water availability in Pakistan was reduced 5260 m3 in 1951 to 1050 m3 by the year 2010 (Bhatti & Nasu, 2010). The shortfall of water is projected to 32% by the year 2025, and the consequent food shortage will be of 70 million tons (Qureshi, 2011). The role of groundwater in the agricultural economy of Pakistan plays a significant role. Climate change is affecting the water resources of Pakistan severely (Farooqi, Khan, & Mir, 2005). The economic effects of climate change on agriculture of Punjab were estimated to be very serious. Impacts of climate change on the river flow are likely to raise scarcity in the Indus Basin irrigation system (IBIS), particularly in the downstream areas having reduced river flows in the dry season. The observed increase in temperature and the offsets

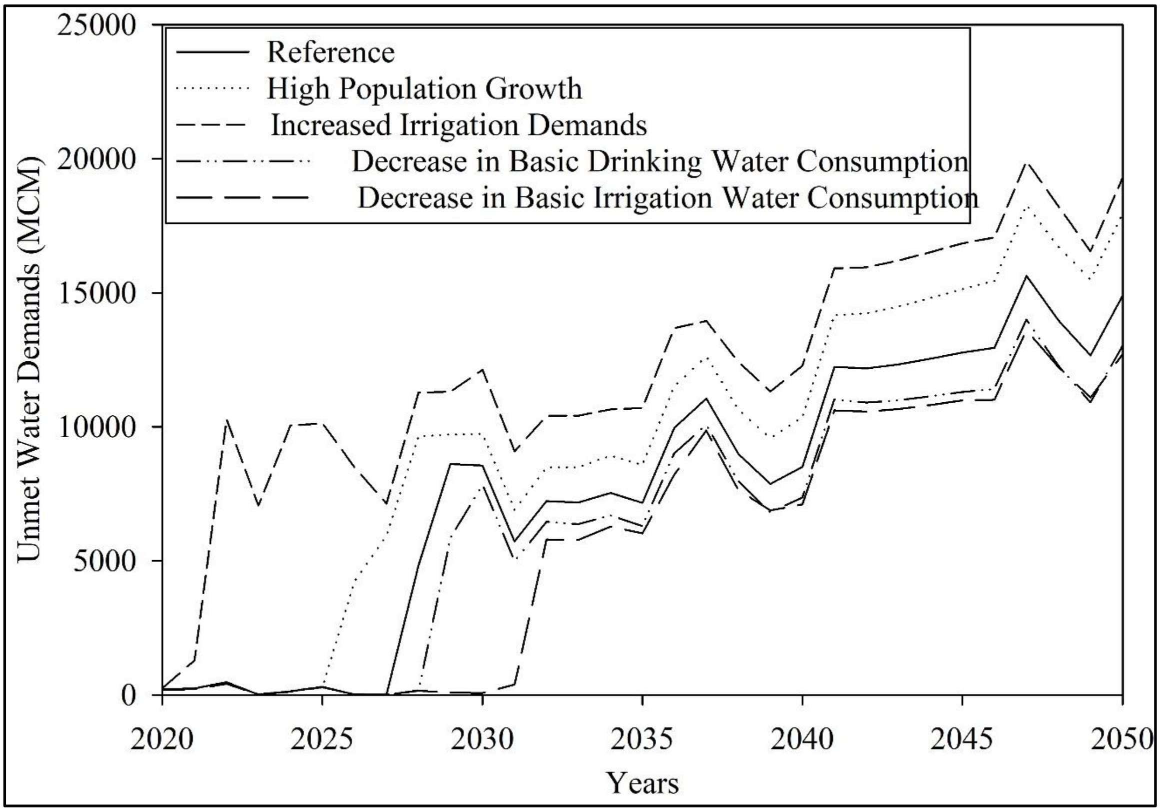

Figure 3.10. The unmet water demands exploitation and potential management scenarios (2015-2050).

in precipitation in the area will have a very harmful impact on the farming patterns (Frenken, 2012; Syaukat, 2012). The Pakistan Agricultural Research Council has identified the key input-output issues in agricultural efficiency in Pakistan. The primary reform areas included water at the top of the list of six basic reforms. As India is building different water storage infrastructure on the transboundary rivers, it will have a negative impact on the water availability for the lower riparian country, Pakistan. So, the water security will be the critical issue in the coming years (Afzal & Ahmad, 2009). Through the implementation of different water conservation strategies, such as sprinkler Irrigation System (35% reduction in agricultural consumption), Drip Irrigation System (25% reduced irrigation demands) and canal lining (50% reduction in agricultural consumption) (Hassan, Bano, Burian J., & Ansari, 2017; M. A. Kahlown et al., 2007). The Water and Power Development Authority (WAPDA) of Pakistan has also suggested the up-gradation of watercourses of entire IBIS, which would reduce 5 MAF (Million Acre Feet) worth of water losses (Ahmed, Iftikhar, & Chaudhry, 2007).

Chapter 4

CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

The WEAP was applied to assess the impact of climate change and other socio-economic scenarios on water resources of lower Indus basin. The resulting pressure from the increasing demands of these scenarios is used to develop water management capacities in the future. The model calibration and validation showed that WEAP could be a useful tool for analyzing the impacts of climate change on hydrological processes in the Indus basin. The evaluation of the model results showed that the values for NSE and Coefficient of Determination are 0.85 & 0.86 for calibration and 0.89 & 0.87 for validation. WEAP modeling study projected the future water demand under socioeconomic and IPCC climate change scenarios. The water demands in reference scenarios increased to 11%in 2050. The high population growth scenario reveals that an increase in the water consumption from 82.9 m3 per capita per day by the year 2015 to 120 m^3 per capita per day by the year 2050. Irrigation demands increased to 25% with the increase in irrigated areas. Water management scenarios revealed that the unmet demands could be reduced by ~50% by eliminating conventional irrigation techniques. The combined simulation of water resources for various policies such as exploitation scenarios and potential management scenarios is one of the best methods.

3.2 Recommendations for Further Research

In future studies, it is recommended to use high-resolution climate projection data to improve the future projections. It is recommended that the development of planned water storage, such as Kalabagh Dam, and adoption of modern efficient irrigation techniques. The policy on household water supply system should be updated; which should consider the rural and urban areas different units or demand nodes and supply them water according to their demand as rural domestic water demand is always less than urban water demands. Similarly, new projects must be introduced in the region including the development of hydrological risk assessment plans, which should consider all the factors affecting the surface water availability and groundwater water resources.

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Appendix-A: Meteorological data for Lower Indus basin (Downstream Tarbela dam)

Year	Month	Humidity	Precipitation	Temperature	Windspeed
1995	1	83	1	13.2	0.8
1995	2	81	36	13.9	1.2
1995	3	72	44.7	17.3	1.3
1995	4	60	126.5	24.1	2.1
1995	5	40	2	33	2.2
1995	6	40	2.5	35.1	1.5
1995	7	69	127	33.9	2.3
1995	8	72	121.3	32.4	1.6
1995	9	72	98	31.7	0.7
1995	10	72	26	24.3	0.9
1995	11	86	10.4	19.5	0.6
1995	12	91	8.7	13.1	1.2
1996	1	87	1	11.3	0.9
1996	2	80	22.5	13.2	1.0
1996	3	73	140	18.5	1.1
1996	4	72	68.3	22.7	2.4
1996	5	47	22	29.5	3.1
1996	6	43	34	34.3	2.2
1996	7	68	250	34.5	1.9
1996	8	77	206.6	33	2.0
1996	9	76	11	30.9	1.4
1996	10	75	24	24.3	0.9
1996	11	82	0	18.9	0.6
1996	12	84	6.8	14.9	0.6
1997	1	86	61.7	12.5	0.7
1997	2	82	24	13.5	0.8
1997	3	82	142.2	18.1	1.5
1997	4	59	4	22.9	2.0
1997	5	42	73	28.9	2.1
1997	6	51	121	33.9	2.3
1997	7	61	47	32.5	2.0
1997	8	72	147	32.5	2.4
1997	9	73	10	28.9	1.7
1997	10	72	10	24.7	1.0
1997	11	76	2	18.4	0.4
1997	12	82	6	15.1	1.0
1998	1	86	27	11.1	1.3
1998	2	77	7	16.4	1.2
1998	3	68	12	17.3	1.3

Year	Month	Humidity	Precipitation	Temperature	Windspeed
1998	4	70	185	26.1	1.9
1998	5	54	29	32.8	3.1
1998	6	51	50	34.3	2.5
1998	7	68	59	32	3.4
1998	8	77	129	33.5	3.1
1998	9	73	35	29.5	0.8
1998	10	85	147	24.7	0.7
1998	11	88	9	19.7	0.6
1998	12	92	10	14.3	0.7
1999	1	87	26	12.9	0.7
1999	2	87	118	13.3	2.0
1999	3	84	86	21.1	2.2
1999	4	69	86	23.9	2.7
1999	5	45	7	32	2.6
1999	6	54	63	35.8	2.8
1999	7	69	141	33.1	3.1
1999	8	75	157	32.6	2.5
1999	9	75	31	29	2.4
1999	10	80	45	24.1	0.6
1999	11	83	0	19.7	1.3
1999	12	90	0	13.1	0.7
2000	1	94	83	11.7	0.9
2000	2	83	1	14.7	1.2
2000	3	74	62	18.5	2.0
2000	4	43	13	22.6	2.4
2000	5	41	20	31.3	3.0
2000	6	49	21	35	4.0
2000	7	70	242	33.4	3.3
2000	8	74	132	31.5	2.9
2000	9	71	9	30.1	2.1
2000	10	78	0	25.3	1.0
2000	11	80	9	19.1	1.1
2000	12	89	0	13.5	1.2
2001	1	88	37	12.3	1.0
2001	2	85	32	15.4	1.5
2001	3	71	11	19.9	1.5
2001	4	47	0	26.5	1.9
2001	5	42	12	28.9	2.4
2001	6	45	15	33.3	3.3
2001	7	67	111	33.3	4.3
2001	8	69	136	31.8	2.7

Year	Month	Humidity	Precipitation	Temperature	Windspeed
2001	9	70	49	30.7	1.2
2001	10	72	2	24.5	0.7
2001	11	76	0	18.2	1.1
2001	12	80	19	12.7	0.8
2002	1	91	9	11.7	1.1
2002	2	68	0	14.4	2.1
2002	3	65	38	19	2.0
2002	4	60	100	23.2	3.0
2002	5	44	7	28.3	3.5
2002	6	56	74	33.1	3.6
2002	7	66	108	34.3	2.7
2002	8	69	48	31.8	2.9
2002	9	70	44	31	2.1
2002	10	74	28	23.1	0.5
2002	11	70	0	18.3	0.5
2002	12	81	1.5	12.1	0.7
2003	1	87	0	11.5	0.4
2003	2	80	86.5	14.1	1.6
2003	3	75	28	17.9	1.5
2003	4	45	5	26.2	2.6
2003	5	29	12.5	31.8	3.3
2003	6	46	8	34.3	2.5
2003	7	56	29	34.4	4.1
2003	8	67	71	33.1	1.9
2003	9	70	27	30.5	1.9
2003	10	77	3	26.5	0.2
2003	11	79	1	19.1	0.6
2003	12	79	31	14.1	0.8
2004	1	93	15	11.2	0.6
2004	2	81	41	15.5	1.3
2004	3	76	115	19.5	0.4
2004	4	58	22	27.7	3.2
2004	5	36	18	32.8	2.5
2004	6	42	17	34.3	3.5
2004	7	67	128	33.3	3.3
2004	8	73	113	32.1	3.1
2004	9	74	53	31.6	1.3
2004	10	72	0	25.9	1.7
2004	11	75	12	19.7	0.3
2004	12	82	4	14.3	0.7
2005	1	88	84	11.9	1.0

Year	Month	Humidity	Precipitation	Temperature	Windspeed
2005	2	84	42	13.3	1.6
2005	3	66	0	19.3	2.7
2005	4	47	74	28.8	2.7
2005	5	39	1	35.3	4.0
2005	6	51	74	35.5	4.5
2005	7	59	42	32.9	4.2
2005	8	76	98	32.7	3.6
2005	9	72	36.5	30.2	2.5
2005	10	70	13	26.4	1.3
2005	11	82	0	19.3	2.1
2005	12	82	11	14.1	1.9
2006	1	91	77	10.6	2.5
2006	2	88	119	15.3	2.6
2006	3	85	156.5	20.5	2.8
2006	4	56	18	26.3	3.1
2006	5	46	30	34.1	2.4
2006	6	39	0	33.9	4.6
2006	7	72	173	33.5	5.3
2006	8	72	99.5	32.9	3.0
2006	9	77	39	30.1	2.6
2006	10	71	0	26.3	0.8
2006	11	75	0	20.1	0.8
2006	12	81	0	15.1	1.9
2007	1	82	13	12.2	1.9
2007	2	79	23	14.5	1.5
2007	3	79	53	21	2.4
2007	4	50	17	28.1	2.1
2007	5	44	40	34.1	3.9
2007	6	41	2	35.3	3.9
2007	7	64	84	35	3.8
2007	8	76	122	33.5	3.1
2007	9	71	3.5	29	2.6
2007	10	76	13	25.8	0.2
2007	11	87	28	19.7	0.5
2007	12	82	26	14.7	1.4
2008	1	79	0	10.7	2.0
2008	2	86	192.5	14.6	2.5
2008	3	84	77.5	19.3	2.1
2008	4	60	13	26.5	3.4
2008	5	52	19	30.9	3.9
2008	6	63	146	35.1	4.9

Year	Month	Humidity	Precipitation	Temperature	Windspeed
2008	7	73	159	32.7	3.8
2008	8	75	69	31.8	2.7
2008	9	77	75	30.4	1.9
2008	10	74	0	24.9	1.3
2008	11	88	2	18.1	0.9
2008	12	86	0	14.1	1.6
2009	1	87	20	12.9	1.9
2009	2	79	28	16	2.4
2009	3	70	1	23.5	2.4
2009	4	62	122	29.1	4.3
2009	5	48	52	32.2	3.6
2009	6	61	83	33.3	3.9
2009	7	72	158	34.1	3.4
2009	8	80	227	31.5	3.6
2009	9	80	134	30.7	1.9
2009	10	77	6	24.1	0.7
2009	11	78	2	19.7	1.2
2009	12	86	25	15.1	1.3
2010	1	87	9	11.3	0.8
2010	2	81	29	12.9	1.3
2010	3	76	76	19.3	1.3
2010	4	58	75	25	1.0
2010	5	41	29	28.9	1.7
2010	6	38	18	35.3	1.9
2010	7	63	63	32.3	1.8
2010	8	75	116	32.6	1.3
2010	9	74	51	30.9	0.6
2010	10	72	60	25.9	0.6
2010	11	77	0	19.1	0.6
2010	12	80	0	12.8	0.3
2011	1	87	22.1	12.1	0.9
2011	2	81	5.1	18.5	0.9
2011	3	76	33.1	20.3	1.5
2011	4	59	1.4	27.3	1.3
2011	5	43	2.6	34.3	2.1
2011	6	49	105.5	34.3	1.6
2011	7	65	530.6	34	2.3
2011	8	78	134.2	31.7	1.5
2011	9	74	113	30.3	1.7
2011	10	74	2	26.8	0.8
2011	11	81	1.1	19.5	0.7

Year	Month	Humidity	Precipitation	Temperature	Windspeed
2011	12	84	0	13.7	0.6
2012	1	87	0.2	12.3	0.9
2012	2	81	29.5	14.8	0.8
2012	3	76	11.4	18.5	1.4
2012	4	48	30.5	28.6	2.0
2012	5	43	3.4	32.2	2.9
2012	6	49	16.2	34.2	1.8
2012	7	66	255.4	32.4	2.8
2012	8	74	69.3	32.5	2.1
2012	9	70	90.5	30	1.0
2012	10	75	4.4	24.9	0.5
2012	11	78	13.1	19.5	0.2
2012	12	83	0	13.4	0.4
2013	1	87	11.4	9.4	1.0
2013	2	81	12.2	13	0.6
2013	3	76	0.5	22.8	1.3
2013	4	48	37.9	25.2	1.0
2013	5	43	28.3	31.5	1.8
2013	6	49	26.4	33.9	1.4
2013	7	66	44.4	32.9	1.4
2013	8	78	174.8	30.5	2.1
2013	9	72	124.6	28.6	0.4
2013	10	74	124.6	26.8	0.5
2013	11	80	14.1	19.5	0.5
2013	12	83	27.1	14.8	0.4
2014	1	87	2	13.7	0.6
2014	2	80	167.5	15.6	0.5
2014	3	76	137.4	20.5	1.0
2014	4	44	36.3	24.9	1.1
2014	5	43	31.1	32.1	2.1
2014	6	49	121.2	34	1.4
2014	7	66	169.3	33.8	1.3
2014	8	74	151.1	32.9	1.1
2014	9	71	42.1	30.8	0.4
2014	10	74	17.1	25.4	0.5
2014	11	80	0.1	18.5	0.5
2014	12	83	0.4	14.4	0.4