An Analysis of Water Supply and Demand in Lower Bari Doab Canal under different Scenarios: An Integration of WEAP and Nash Bargaining Solution

By

Jawad Saleem

(MS WRE&M 2020, 00000329862)

A thesis submitted in partial fulfillment of

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DEPARTMENT OF WATER RESOURCES ENGINEERING AND MANAGEMENT

NUST INSTITUTE OF CIVIL ENGINEERING

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

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Has been accepted in partial fulfillment of the requirements

Towards the award of the degree of

Master of Science in Water Resources Engineering and

Management

Dr. Hamza Farooq Gabriel

Professor

NUST Institute of Civil Engineering (NICE)

School of Civil & Environmental Engineering (SCEE)

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THESIS ACCEPTANCE CERTIFICATE

It is certified that Mr. Jawad Saleem, Registration No. 00000329862, of MS Water Resources Engineering and Management (WRE&M) of batch 2020 has completed his thesis work and submitted the final copy which was evaluated and found to be complete in all aspects as per the policy of NUST/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for the award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have been incorporated in the said thesis.

Signature: ______________________________

Supervisor: __Dr. Hamza Farooq Gabriel__________

Date: __________________________________

Signature (HOD): _________________________

Date: __________________________________

Signature (Principal & Dean SCEE): ________________

Date: __________________________________

DEDICATION

I like to dedicate this work to my parents, who have been always a source of motivation and strength for me when I was on the edge of giving up, and who keep on providing me moral, religious, passionate, and financial support. Also, to my brother and friends who urged me to finish my research with their guidance and blessing. Lastly, I'd want to thank Allah Almighty for his strength, mental power, guidance, and protection, also providing me with a healthful life.

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All glory be to Allah Almighty, who has provided us with this universe of knowledge. He is The Merciful, The Gracious. He gave man intellectual strength and understanding, as well as spiritual insight. After all, it is His Messenger, Hazrat Muhammad (SAW), who is an everlasting light of guidance and knowledge for the entire human race.

I owe a dept of thanks to many people who have been supportive and helpful to me during this work. I am much thankful to my research supervisor Dr. Hamza Farooq Gabriel who has provided me with invaluable assistance, feedback, advice, and encouragement during my work. I have learned a lot from him like how to conduct research and how to solve problems. I would also like to thank my Co-Supervisor Dr. Shahmir Janjua, who's teaching technique and can-do attitude tremendously inspired and assisted me. I would like to acknowledge and give my kindest thanks to my GEC members for helping me with their guidance and advises during my research.

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ABSTRACT

Management and allocation of water resources has turned out to be more challenging than before due to increase in population. Increase in water demand due to rapid surge in population has also resulted in water scarcity issues in Pakistan. The Lower Bari Doab Canal region in Punjab, Pakistan is classified as a semi-arid area due to its climatic conditions. The expansion of urban developments and rapid population growth has resulted in the shortage of water supply in the region. The aim of this study was to assess the impacts of future water demands on the Lower Bari Doab water resources in year 2035. In order to find the best combination of scenarios that met the future water demands, a scenario-based modeling was used in conjunction with Water Evaluation and Planning (WEAP) software. The baseline scenario was based on the year 2015 and for each scenario, the water resources implications were compared with that baseline scenario. The Water Evaluation and Planning (WEAP) modeling was used in this research to evaluate the complex water resource system and to inspect supply and demand management policies related to different sectors in Lower Bari Doab Canal Area. To address gap between water supply and demand, Nash Bargaining Solution (interval linear programming) was used for better allocation of water resources. Results showed that the supply demand gap continues to increase under the current condition. More than 55.847 BCM of additional water is needed by year 2035 to satisfy the water demands. The unmet water demand also varies as per proposed scenarios. The high agriculture scenario shows that the demand for agriculture can increase up to 90.77% by the year 2035. High population and high industry scenarios show that the unmet demand for these sites can increase up to 14.28% and 66.66% respectively. A careful control of the population growth rate is necessary in future to control the growing water demands. In order to address the supply-demand gap, water allocation under different scenarios was done using Nash Bargaining Solution. This approach helps in analyzing future water demand along with better and more efficient addressing of water resources to address the supply and demand gap.

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List of Abbreviation

BCM	Billion Cubic Meter
ILP	Interval Linear Programming
IWR	Integrated Water Resources
LBDC	Lower Bari Doab Canal
MCM	Million Cubic Meter
NBS	Nash Bargaining Solution
WEAP	Water Evaluation and Planning

CHAPTER 1

INTRODUCTION

Water, air, and soil are the essential elements of earth that assure the continuance of life. For a balanced living and ecological environment, it is necessary to conserve these components without altering them. Furthermore, to achieve a sustainable natural environment, economic and environmental judgments should be assessed together following the goal of long-term growth. The natural elements should be seen collectively to transmit their values to the future. Water is one of the essential requirements of life. Only about 0.3% of the world's water is usable. There is currently a water shortage in several areas, and around 1 billion people don't have access to drinking water. This circumstance is an indicator of why we must be cautious and aware of our water provisions. "With the growth in the world's population, the demand for water resources is also increasing. Water resources, on the other hand, are lessening, and also polluted and exploited unconsciously due to several effects, mainly human activities as a response we must act and execute measures as soon as possible and we must carefully manage our water supplies" (Kılıç, 2020).

1.1 CURRENT WATER AVAILABILITY

Water is crucial for maintaining an adequate food supply and a good habitat for all living organisms. Shortages in water resources have significantly degraded biodiversity in both terrestrial and aquatic ecosystems, adding to endangering human food supplies. The global increase in population, changes in climate, and lifestyle changes are putting a collective strain on our vital water provisions, causing water stress in many countries. As a result, people are becoming aware of the need for safe water. Water is essential for life since it has a substantial impact on health and living standards. Water is distributed unevenly over the world. Water is essential for human vital activities such as nourishment, breathing, excretion, circulation, and reproduction to continue.

Due to the increase in urbanization, water scarcity has become one of the most prominent issues in developing countries. Pakistan, being an arid country is also facing this problem. Due to the increase in temperature the glaciers which are the key sources of freshly available water in Pakistan are melting, resulting in water shortage. This is affecting the water resources and causing a shortage of drinking water (Muhammad, 2022). Various factors, including urbanization, population growth, high living standards, etc. are correlated to each other and play their role in affecting the global water system. Increase in agriculture demand is resulting in groundwater over exploitation causing groundwater overdraft (Maqbool, 2022). If the water demand keeps on increasing at this current rate, then there might be a 20% to 30% rise in water demand in future years. According to studies, Pakistan extracts 74.3% of its freshly available water per year, which is also an alarming factor for future sustainability (M. Hassan, 2016). All these factors, including urbanization, population growth, high living standards, etc. are correlated to each other and play their role in affecting the global water system (Read & McKinney, 2010). The population growth and per capita available water in Pakistan is given in Figure 1.1.

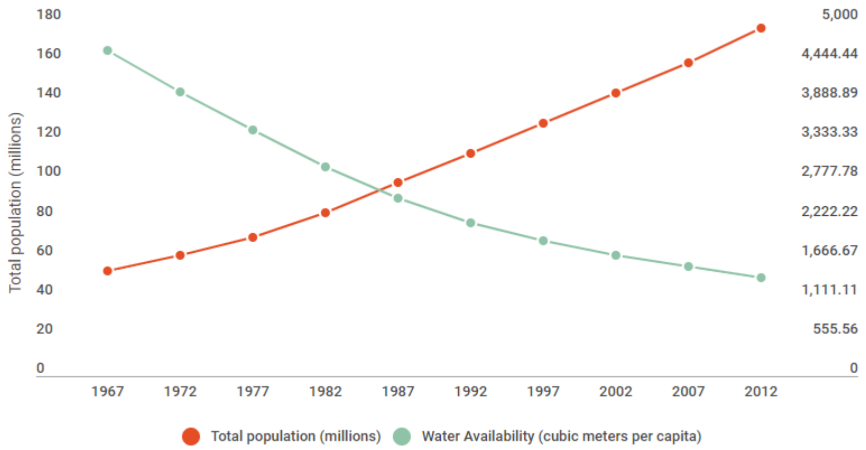

Figure 1. 1: Water availability per person and population growth in Pakistan (Source: FAO)

An increase in agriculture demand causes the groundwater level to deplete to an extent. If the water demand is kept on increasing at this current rate, then there might be a 20% to 30% rise in water demand in future years. According to studies, Pakistan extracts 74.3% of its freshly available water per year, which is also an alarming factor for future sustainability (M. Hassan, 2016). Water trend in Pakistan over the years is shown in Figure 1.2.

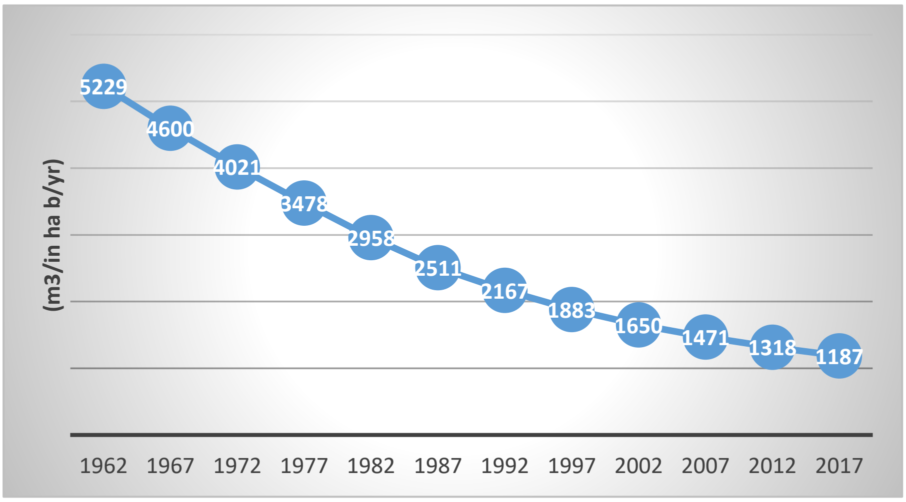

Figure 1. 2 Water Availability Trend in Pakistan, 1962-2017 (Source: FAO)

According to Water Aid reports Pakistan has the 4th largest groundwater aquifer, which covers an area of about 1,137,819 square kilometer (Imran, 2019). This makes the area of Pakistan’s aquifer to be slightly greater than that of entire England. Also, Pakistan ranks third in the world in groundwater usage and fourth in extracting groundwater, contributing to around nine percent of the global groundwater withdrawal (Imran, 2019). This high extraction makes the Indus basin the world’s 2nd most overstressed groundwater basin. All over Pakistan, the influence of groundwater to agriculture is around 60% and 90% for drinking purposes, and 100% of it to Industries. About 65 BCM is estimated to be withdrawn from the ground and the renewable resources are estimated to be about 55 BCM (Qureshi, 2020). So, this shows that Pakistan has moved from a water stress to a water-scarce country. There are around 0.8 million tube wells that extract the groundwater in Punjab, Pakistan. And around 60% of irrigation water is wasted during the conveyance and application in the field.

1.2 SINGLE RIVER INDEPENDENCE

Pakistan's water resources are dependent on the Indus River and its tributaries (Kabul River to the west and Jhelum, Chenab, Ravi, Sutlej, and Beas to the east). The Indus River is 2900 kilometers long and drains 966,000 square kilometers. Snow melt and glacial water, as well as rainfall in the catchments, provide most of the inflow to these rivers. Most rivers which are not included in the Indus Basin are ephemeral and only flow during the rainy season and hence do not meet the Indus system's water requirements. The Indus Basin is underlain by a largely unconstrained aquifer that covers around 16 million hectares of land, with 6 million hectares of fresh water and 10 million hectares of saline water (Haider et al 1999). According to studies, the average safe groundwater yield is expected around 63 BCM, compared to 52 BCM for agriculture, household, and industrial use. As a result, the remaining groundwater capacity is around 11 BCM (PWP 2001). However, evidence like rising salinity in groundwater due to aquifer salt restructuring and falling groundwater concentrations confirms that the capacity for additional groundwater utilization is quite restricted. Water stress map of world is shown in Figure 1.3. Pakistan is ranked 160th in the world for the ratio of water withdrawals to water resources, outperforming only 18 countries. “Agriculture uses the most water, accounting for 94% of annual withdrawals, followed by homes (5.3%) and industry (including power production) (0.8%). Pakistan's reliance on a single river system is exceedingly dangerous, the Indus River System accounts for 95.8% of the country's total renewable water resources. Furthermore, water supplied from outside Pakistan accounts for more than three-quarters (78%) of the country's total water resources, leaving it susceptible” (Maqbool, 2022).

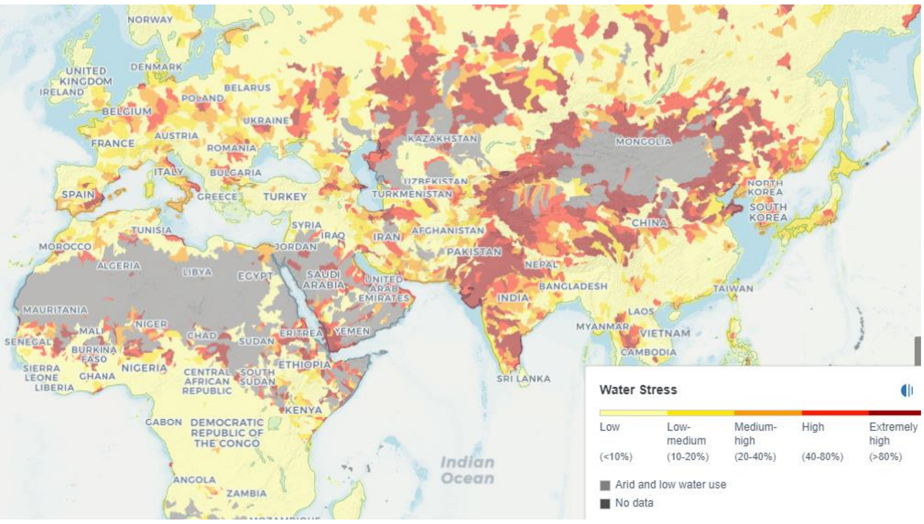

Figure 1. 3: Water Stress Map (Source: WRI aqueduct)

1.3 PAKISTAN WATER MANAGEMENT

Four cash crops (rice, wheat, sugarcane, and cotton) consume almost 80% of the country's water resources despite contributing only 20% of GDP. In comparison to other major agricultural economies throughout the world, Pakistan's crop productivity is poor. Canal water is grossly understated, recovering only one-fifth of yearly running and maintenance costs (20 percent in the form of abiana), while collecting 60 percent of total receivables. Despite accounting for one-fifth of GDP and over half of the country's employment, the agricultural sector generates less than 0.1 percent of total tax receipts, leaving little money for irrigation system maintenance. The deterioration of water infrastructure contributes to a large amount of water waste. With an overall efficiency of 39 percent, Pakistan's irrigation system is one of the minimum efficient in the world, owing to aging and poor conservation. This means that only 55 BCM out of 143 BCM of water accessible at the canal heads is used for agriculture. "The outstanding water (61% or 87 BCM) is lost during transportation through canals, distributaries, minors, and watercourses, as well as during field application. Furthermore, Pakistan can only save 9% of the available water in the Indus River System over a year, compared to a global average of 40%" (Maqbool, 2022).

Pakistan's economy is based on agriculture, which generates 18.5% of the nation's GDP and employs 38.5% of its workforce. Despite significant investments, notably in irrigation, the productivity of land and water is quite poor for a variety of reasons. Up to 60% of the freshwater used for agriculture—a whopping 95% of total use—is lost owing to inefficiency. Pakistan's limited ability to store rainfall during the three-month monsoon season reduces the amount of water available for year-round agriculture. Unsustainable use has resulted in an alarming pace of groundwater depletion. Attempts to build modern agricultural systems are hampered by aging infrastructure, antiquated technologies, and a lack of departmental cooperation.

Pakistan's urbanization rate is higher than anywhere else in South Asia, which strains the country's already limited resources and services. Only 20% of the population has approach to clean water, and 40% lack adequate sanitary facilities. Men and women have a huge income and social disparities; as a result of restrictions placed by culture and education, women are typically limited to menial work. Climate change is tremendously dangerous for Pakistan. In recent years, the nation has experienced devastating floods, droughts, cyclones, and heat waves that have killed or displaced thousands of people, destroyed livelihoods, and severely harmed the economy (M. Hassan, 2016).

For Pakistan's future, effective supervision of both surface water and groundwater is important. Hopefully, there are numerous possibilities to enhance the nation's water management. However, the provinces are experiencing constant instability as a result of the expanding supply-demand disparity. Major crops yield in the world is shown in Figure 1.4. Problems have gotten worse due to a rise in droughts, particularly in Sindh province. As a result, it is necessary to develop and put into practice water preservation measures, construct new water reservoirs, and manage and distribute water resources more effectively (Shakir et al., 2010).

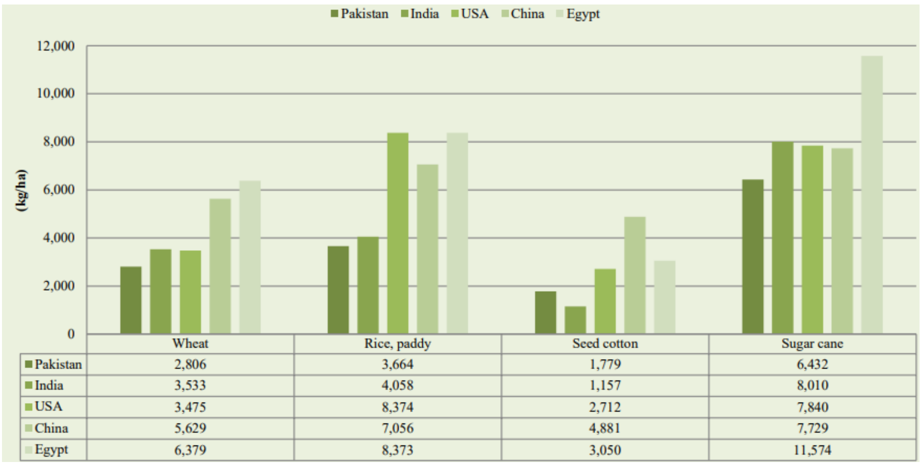

Figure 1. 4: Major Crops yield in the world, (2019) (Source: FAO)

1.4 OBJECTIVES AND SCOPE OF STUDY

Punjab province of Pakistan is one of the most valuable agricultural regions. The increase in urbanization has surged the struggle for available water resources. Lower Bari Doab Canal (LBDC) is an important canal in Punjab. Water is diverted from the left side of the River Ravi from Head Balloki. However, in recent years sustainable water resources management has become more challenging. Furthermore, the increase in agriculture, environmental, industrial, and domestic demand will have an impact on these resources. There is a proper need of identifying the water unmet demand and the need of addressing this issue.

The following are the objectives of the study:

- Identification of various demand sites in the Lower Bari Doab Canal (LBDC) region.
- Calculations of water demand for each site.
- Predict future water demands in the Lower Bari Doab, Punjab, Pakistan using WEAP.
- Analyze future water demands under various scenarios.
- Resolve water supply-demand gaps in different demand sites using Nash Bargaining Solution.

1.5 THESIS STRUCTURE

- Chapter 1 provides a detailed introduction of the topic along with the water availability and objectives and scope of the study.
- Chapter 2 is a Review of the papers that are followed up and used in understanding the methodology and basic information like water conditions, factors affecting the water demand, and introduction and application of the WEAP model.
- Chapter 3 describes the geographical detail of the study area along with some salient features and location maps. It is also about data sources and methodology. It describes the processes of different scenarios on the WEAP model and provides detail about the Linear Programming process.
- Chapter 4 is presenting the integrated results along with conclusions and future recommendations linked to the subject.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Hydro- Local water allocation policies and how this work got renewed interest on a global scale. This interest is driven by a combination of factors, including the extensive water area reforms that have taken place in many nations since the 1990s, the continually rising global water demand, and the rising need for better, more moral local water distribution decisions. Solutions for global water shortages should be provided locally. This study is conducted to examine regional issues with water scarcity for irrigation and other demand sites. Additionally, local approaches and solutions that have developed and been implemented locally to address the issues of water scarcity have been explored (Kılıç, 2020).

Due to the pricing of groundwater sources and poor allocation of surface water, farmers are facing water deficiency. However, it amplifies the detrimental impact on farm productivity. From a future scope, it is alarming because the small farms, in terms of yield, are most affected and, with rising water prices, are no longer profitable and may cease production (Shakir et al., 2011).

2.2 PUNJAB WATER CONDITION

Punjab is experiencing acute water scarcity despite receiving a considerable supply from dams, rivers, and other sources. Experts warn that a lack of water is a serious concern for the province, which accounts for much of the country's agriculture and is a major source of revenue. Punjab is utilizing groundwater for irrigation through tube wells due to a lack of canal water. The cherry on top is that most of the available water is wasted before it even enters the fields (Mehmood, 2021).

2.3 INCREASE IN WATER DEMAND

Pakistan is one of 36 countries with a water shortage. The growing urban population, agriculture, poor water system management, and climate change are only a few of the causes that have exacerbated Pakistan's water shortage. The effects seen by Pakistan's citizens would worsen if the country's water crisis were not resolved. Although irrigation accounts for most of the water consumption in the nation, the four main crops (wheat, sugarcane, rice, and cotton) contribute only 20% of the GDP. It is tentatively estimated that poor water management costs 4% of GDP or about $12 billion annually (Government of Pakistan, 2010). These rates, which also include the expenses associated with floods and droughts, are mostly caused by insufficient residential water supply and sanitation. Water-borne infections kill 40 thousand children each year due to poor hygiene and a lack of effluent treatment. Significant ecological services are being undermined by the significant degradation of rivers and lakes.

2.4 DEMAND SITES

2.4.1 Environmental

Water accessibility to maintain environmental values and benefits is endangered by competing national and international government policy decisions. Proponents of freshwater conservation are pushing for the distribution of environmental flows, which would force communities to weigh the socioeconomic benefits of instream ecosystem services against those from consumptive water usage (Pittock & Lankford, 2010).

2.4.2 Agricultural

Roughly 60% of Pakistan's population depends on agriculture and related industries, and its contribution to the country's Gross Domestic Product (GDP) is about 24%. Since water is the primary input in agriculture, timely and sufficient water availability is essential to both the productivity and sustainability of agriculture. Over 95% of the country's water reserves are used by agriculture, which is Pakistan's main consumer of water. 90% of agricultural output comes from irrigated land, which covers around 80% of the farmed area. Changes in climate and global warming also have an impact on water supply at crucial points in crop growth (Asif M. Bhatti, 2009).

2.4.3 Domestic

A basic human right is the availability of clean, sufficient drinking water. The major source of drinking water in Pakistan is ground-water. However, surface water is one of the only sources of drinking water for the cities of Hyderabad and Karachi. Surface water also contributes to the supply of Islamabad and Rawalpindi. Domestic water supply and demand are not consistent throughout Pakistani cities and range greatly depending on factors including socioeconomic status, geographic location, and climate changes. It is frequently discovered that household income, house size, the number of water-using appliances, and the number of family members are all favorable factors of residential water consumption (Bhatti & Nasu, 2010).

2.4.4 Industrial

According to an estimate, Punjab's industrial and commercial subsector's water demand will increase to 67%, mostly due to future expansion-driven demand. According to forecasts in the Draft Punjab Water Policy, industrial water demand is expected to reach 2.44 MAF in 2025, indicating an increase of 1160 million cubic meters/year or 0.94 MAF.

In Punjab, the industrial sector grew at a rate of 5% between 2001 and 2011, and Punjab Growth Strategy predicted that this rate would increase to 8% over the following ten years. Figure 2.1 shows the water consumption by different sectors.

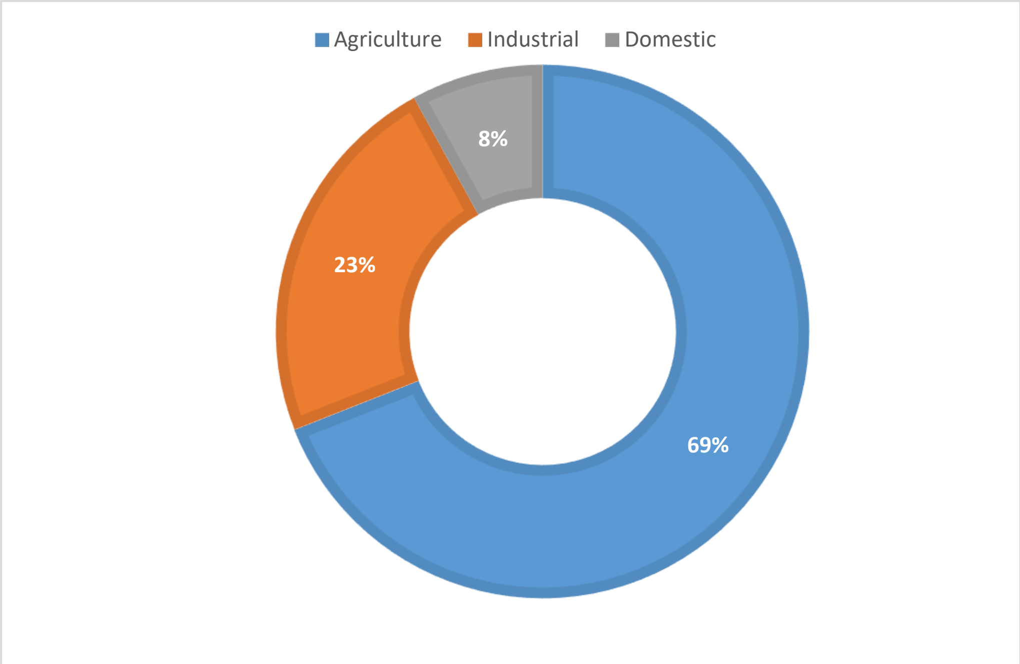

Figure 2. 1: Water Consumption by different sectors (Khoso et al., 2015)

2.5 SELECTION OF HYDROLOGICAL MODEL

Several different models are studied and reviewed to choose an appropriate hydrological model. The data requirements must be considered while choosing the model, in addition to the research objectives, as the lack of data may prevent the model from being improved. The appropriate model is chosen for this study by considering the accurate evaluation of the impact of land development on catchment flows.

To attain the objectives of this research study, the Water Evaluation and Planning (WEAP) software tool was selected to simulate the hydrological process. WEAP was developed to analyze the water supply-demand gap and future analysis. Different studies have used the WEAP model to assess the water supply demand impacts on different areas and to evaluate the discrepancy in residue return due to these alterations.

2.5.1 Water Evaluation and Planning (WEAP) System

Many areas are confronted with significant freshwater management difficulties. Water resource planners are increasingly concerned about the allocation of restricted water resources, ecological considerations, climate adaptability and ambiguity, and the need to create and implement viable water use plans. Traditional supply-positioned simulation models are not always sufficient for examining all the managing possibilities. Water supply schemes have been placed in the framework of demand-side management, water quality, and ecosystem conservation and security throughout the previous decade. WEAP takes these values and turns them into a useful tool for water resource scheduling and strategy analysis. WEAP's unified approach to modeling both environmental (e.g., evapotranspiration water demands, runoff, and baseflow) and artificial (e.g., reservoirs, groundwater abstraction, etc.) components of water systems set it apart (Institute, n.d.). WEAP (Water Evaluation and Planning System) is a user-friendly hydro-economic software program for water resource planning that adopts an integrated approach. Freshwater management issues are becoming more widespread. Supply, water quality, water demand, and ecological factors must now be fully integrated when allocating restricted water resources between agricultural, metropolitan, and environmental applications. WEAP tries to integrate these concerns into a useful yet powerful instrument for integrated water resource planning. Flow chart of WEAP processing is shown in Figure 2.2.

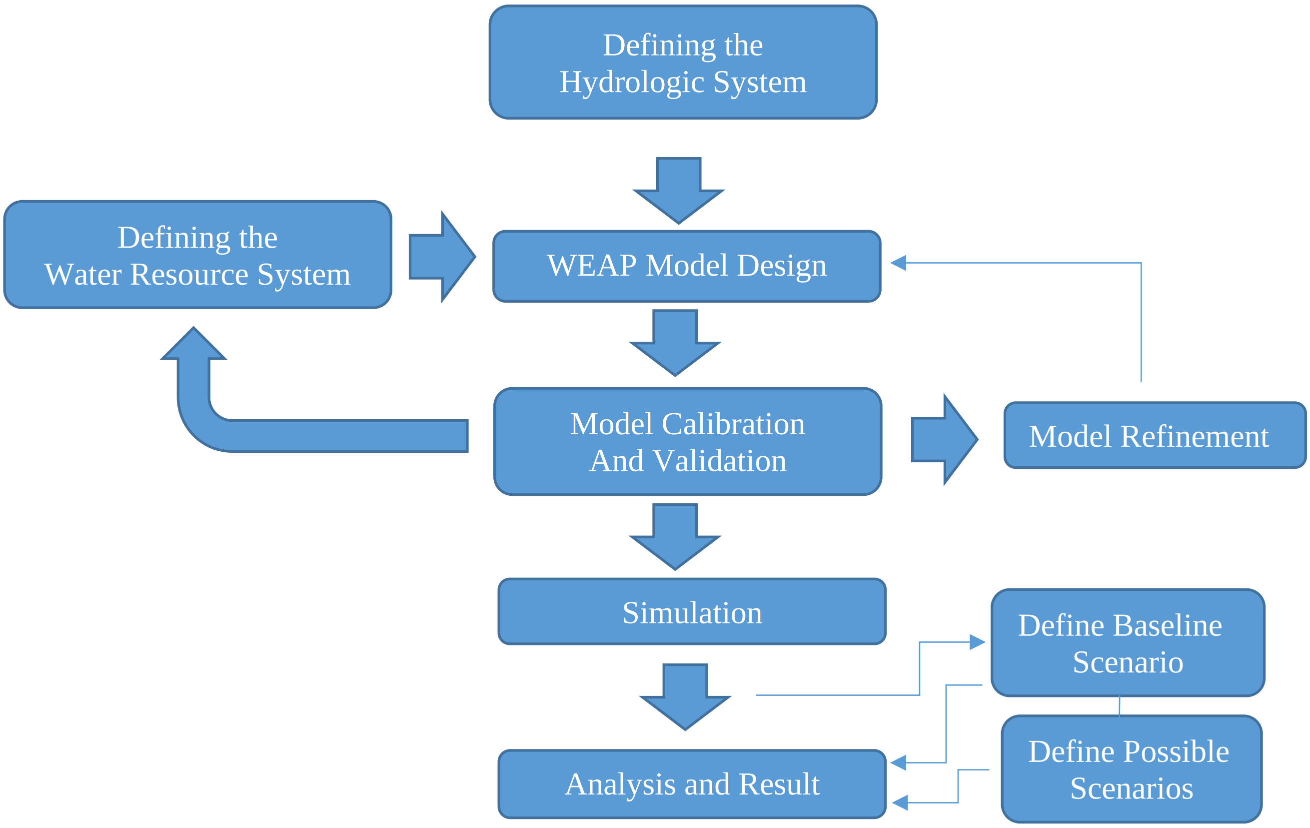

Figure 2. 2: WEAP Model Framework

2.5.2 Water Diplomacy Framework

As mentioned in the earlier section the accessibility, allocation, and access to water resources impact the well-being, wealth, and stability of societies around the world. Access to freshwater resources is becoming more uneven as demand for freshwater rises. Uneven access, when combined with other societal challenges (unemployment, systematic oppression, and so on), may widen the gap between individuals and increase the risk of conflict. In the case of a (potential) conflict, the concerned parties must identify solutions to handle the tensions to avoid escalation. Some parties, on the other hand, may benefit from or even create societal instability and conflict to obtain political power, conversational closure, and support for the ruling party (Huntjens et al, 2016). According to (Islam & Susskind, 2018) water challenges arises from the interaction of the biological and human system.

To implement the water diplomacy framework in this work, we are going to assess the effectiveness of game theoretic methods to address the supply and demand gap, and this will help in better and more effective management of water resources.

2.5.3 Water allocation using simple Bankruptcy Rules

According to economics, the bankruptcy rule is used when the existing resources are not sufficient to fulfill the stakeholder's needs. When the supply becomes less than the claimed demand, the share of each stakeholder is needed to be lowered to address this supply and demand mismatch. By this rule, these problems can be addressed efficiently. The main challenge is to plan for efficient water allocation among the stakeholders, having different demands. (O'Neill, 1982) developed some methods of bankruptcy that can be used for better allotment of water resources. In this study, we have allocated the water demands to different cities in Lower Bari Doab Canal, Pakistan. In this research study, we have used different bankruptcy rules as the current allocation cannot satisfy the agriculture, drinking, and industrial water needs of the study area.

2.5.4 Nash Bargaining Solution (NBS)

The Nash Bargaining Solution (NBS) is a robust framework that enables us to specify and distribute equitable resource allocation among participants with various concave utilities. A group of players chooses a payout allocation in an N-person game from a list of possible payoff allocations. As a result, the NBS participants bargain to maximize their payoffs.

One of the very crucial concerns in dynamic matches with non-zero-sum is the negotiating model. The members in a negotiation scenario have a common goal of working together, but they may disagree on how to share resources. The primary challenge in negotiation is moving toward a level of collaboration while taking the probability of failure into account. A negotiated solution differs from an ideal solution (Safari et al., 2018). Figure 2.3 shows the Nash Bargaining procedure under water bankruptcy.

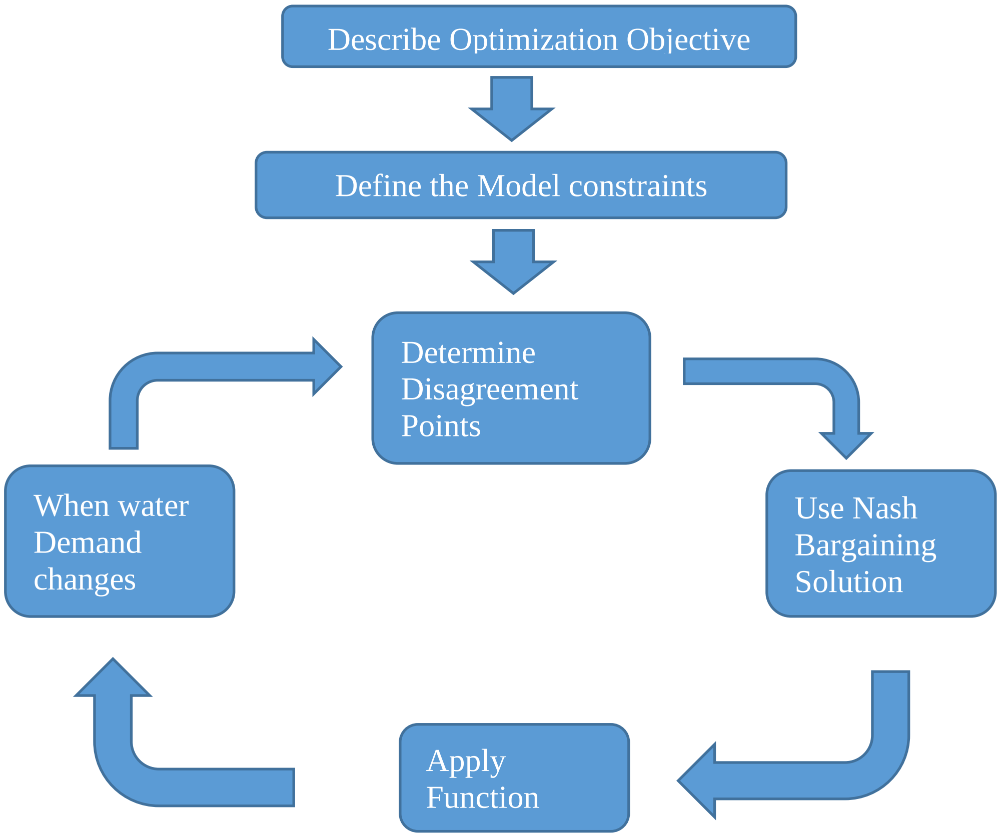

Figure 2. 3: Nash Bargaining Procedure under water Bankruptcy

2.6 Previous Studies Using WEAP System

Population growth and urbanization are one of the main reasons of water supply stress in any developing country. The study carried out by (Al-Shutayri & Al-Juaidi, 2019) focused on the evaluation and planning of water resources in Jeddah City. The year 2017 was chosen as a baseline year to analyze the water supply and demand in the year 2030 and focused on the effectiveness of desalination in the coming years. It was found that the difference between supply and demand will grow as the desalination continues and 504 MCM of water will be required to fulfill unmet demands (Al-Shutayri & Al-Juaidi, 2019).

The major cause of water scarcity is more use and less management. Urbanization and climate change cause major water issues. This study, by (Saleem et al., 2021) was carried out for urban water management and to keep in view the existing and future water supply and demand gaps. Different scenarios were discussed in this research, but this study mainly focuses on the better allocation of the resources and demand site management rather than focusing on supply. 23% of total water was conserved in National University of Sciences and Technology (NUST), Pakistan, by better conservation of demand sites. This also helped in saving money and preserving the environment (Saleem et al., 2021).

Gilgit-Baltistan is a mountainous region including almost 45% of the upper Indus basin. This study was carried out by (Mehboob & Kim, 2021), focusing on the agriculture and domestic sector under climate-socio-economic scenarios in the 5 districts of Gilgit from the year 2015 to 2050. The climate scenarios used for this work were RCP 2.6, RCP 8.5, and RCP 6.0. It was observed that socio-economic were a dominant factor in reducing food production. And the water shortage mainly depends on the demography and geography (Mehboob & Kim, 2021).

Various hydrological modeling has been conducted on the central Indus basin under climate scenarios. But the study by (Asghar et al., 2019) focuses on the effect of socio-economic along with climatic change scenarios. RCP 4.5 and RCP 8.5 were used for the year 2015 to the year 2050. It was concluded that by the end of 2050 domestic water demand will increase by 11% and agriculture demand will increase by 55%. The population scenario predicted that demand would increase by 82.9 cubic meters per capita to 120 cubic meters per capita per day. Also, the average change in temperature and precipitation will be about 274.07K to 274.9K and 15.2% by the end of 2035 (Asghar et al., 2019).

Indus river basin in one of the four major irrigation systems in the world. There are various users of this river basin. (D. Hassan et al., 2019) used WEAP to analyze the population rise in conjunction with climate change. The year 2015 was used as a baseline year and future demand was predicted including 2 growth scenarios. It was concluded that if the population will keep on rising at the year 2017 increase rate then the water demand will be increased to 192.76 billion cubic meters by the end of the year 2040, which was much more than the baseline year of water availability (D. Hassan et al., 2019)**.**

WEAP has been used for hydrological modeling like climatic change, water use, and allocation in many areas. Many early applications of water supply management and demand management have been carried out to analyze the current system and evaluate future demands. WEAP has been used to evaluate different scenarios, water demand, and efficient conservation and management of water resources. Water quality parameters and mitigation of untreated wastewater can be assessed by WEAP. Climatic effects and changes in demands are one of the applications of WEAP. WEAP (Water Evaluation and Planning System) is a user-friendly hydro-economic software program for water resource planning that adopts an integrated approach. Freshwater management issues are becoming more widespread. Supply, water quality, water demand, and ecological factors must now be fully integrated when allocating restricted water resources between agricultural, metropolitan, and environmental applications. WEAP helps to analyze future demands and supply more robustly than any other technique.

WEAP has also been used in solving different transboundary issues, keeping in view the complexity and political conflicts. Baseline scenarios and other strategic scenarios help in the analysis of different effects. The capabilities and optimization processes of WEAP helps in exploring and investigating different structure. it has been seen that many studies have been carried out related to the water supply and demand among different rivers of Pakistan. Like (Amin et al., 2018; Asghar et al., 2019; D. Hassan et al., 2019) focused on the Upper and Central Indus River system using the WEAP model. Also, some studies focused on the Lower Bari Doab Canal crop water estimation (Basharat & Tariq, 2014). (Saleem et al., 2021) focuses on the better allocation of water resources and demand site management rather than focusing on water supply in NUST. (Asghar et al., 2019) focus on the effects of socioeconomic and climatic change scenarios in the central Indus basin. (Javed et al., 2020) in his research focused on the estimation of crop photo deficiency in lower Bari Doab. (Muzammal et al., 2021) focused on surface water supplies and estimation of groundwater abstraction during the year 2018. (No & Hussain, n.d.) has done the hydraulic simulation in LBDC. (Akhter et al., 2022) calculated different hydrological parameters in lower Bari doab for surface and groundwater using different techniques. (Saeed & Muhammad Nasim khan, 2011) evaluated the groundwater depletion level in the Indus basin considering Bari doab canals. (Read & McKinney, 2010) used WEAP to evaluate future water demands under different climatic scenarios. (Shakir et al., 2011) concluded the effect of both canal water shortages in the LBDC command area.

CHAPTER 3

METHODOLOGY

3.1 DESCRIPTION OF STUDY AREA

The land between River Ravi and River Sutlej is known as Bari Doab. Covering an area of approximately 29000-kilometer square in Pakistan side, it is also among the most productive land in terms of agriculture in the sub-continent. Lower Bari Doab Canal (LBDC) lies in the center of Bari Doab (Figure 3.1) and has a gross command area of 0.80 million hectares with a cultural command area of 0.7 million hectares (Basharat & Tariq, 2014). The LBDC flow is 278 cubic meters/second which off takes from the left bank of the Balloki Headworks. The Balloki headwork supplies water to River Ravi's distributaries of around 201 km (Basharat & Tariq, 2014). The area has a semiarid climate and is the most agro-climatic zone in Pakistan having a semiarid climate.

The area of Lower Bari Doab Canal (LBDC) has the second largest irrigation system in Punjab having 65 distributaries under its administrative area (Figure 3.1). These are made up of 2261 kilometers of distributaries, minors, and sub-minors in addition to a total of 53.5 km of branch canals. Balloki, Okara, Sahiwal, and Khanewal are the four irrigation administrative divisions that oversee canal irrigation.

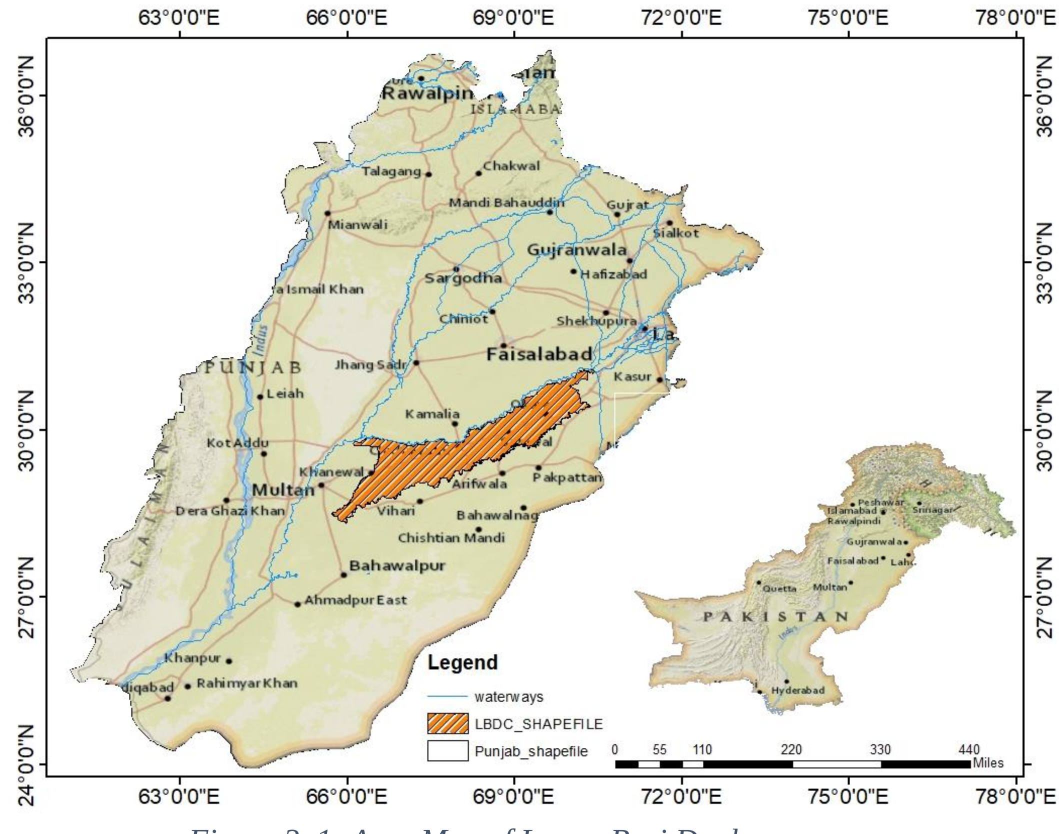

Figure 3. 1: Area Map of Lower Bari Doab

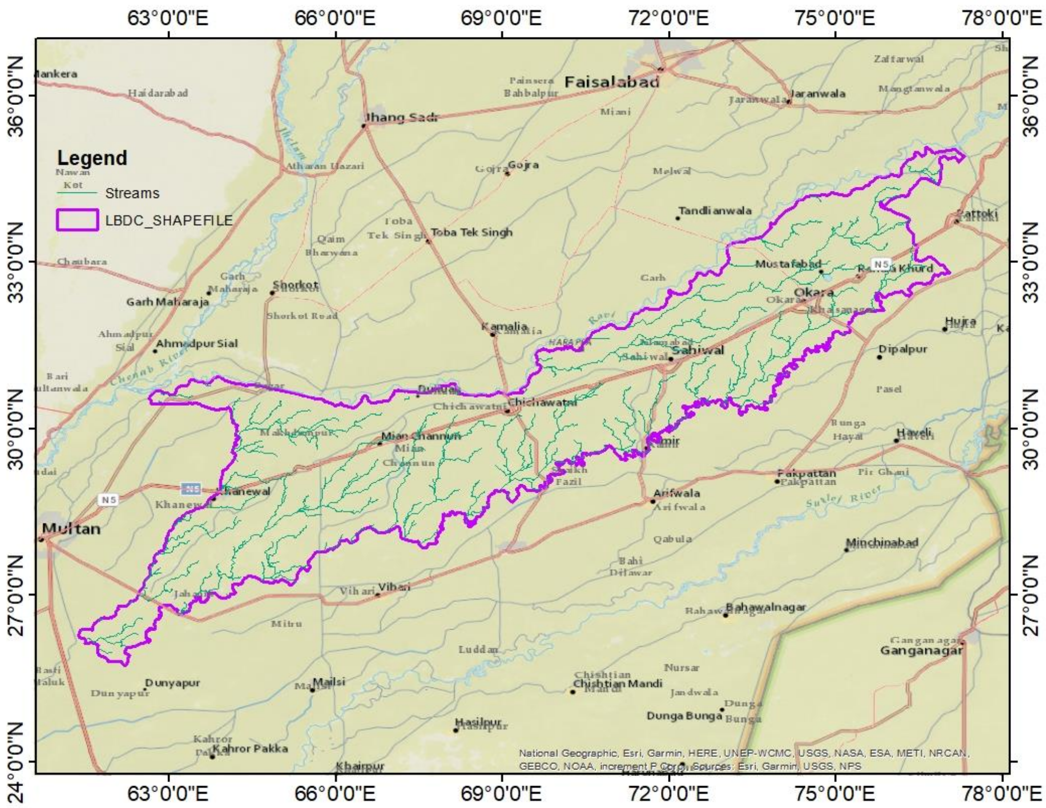

Figure 3. 2: LBDC command area streams

In the Kasur region, the concentration of the rice crop is above average at the canal head than at the tail end, where it accounts for 61% of the cultivated farmland during the Rabi season, while cotton is more prevalent at the tail end and least covered at the head end, as shown in Figure 3.2. These crop patterns recommend using the appropriate crop where groundwater abstraction is more prevalent near Khanewal. While it is true that rice requires more water, it is also incorrect to imply that farmers should not produce water-tolerant crops like feed, oilseed, and greenery.

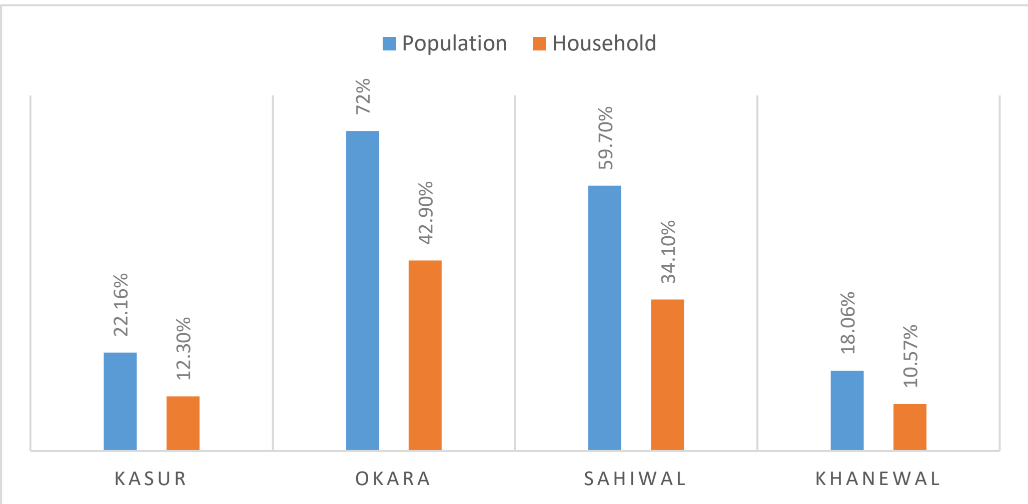

Figure 3. 3: LBDC Command area Population and Household

Okara, Sahiwal, Balloki, and Khanewal are the irrigation administrative divisions in LBDC (Figure 3.3). Surface water and pumped groundwater from confined aquifers are being used for irrigation and other purposes. In LBDC canal water is highly significant and dependable source of water for agriculture and as well as groundwater recharging.

3.1.1 Geographical Features

LBDC is part of large alluvial deposits, churned by the Indus tributaries i.e., River Ravi and River Sutlej. Its slope generally varies from 1 in 4000 to 1 in 10000, and there is a slightly mild slope in the southwest part. It is sub-categorized by Bari upland and flood plains. The soil of Bari upland is silty (brighter in color) with distinctive profile development. The soil of flood plains is less developing and greyish (Akhter et al., 2022).

Silt and clay layers are often dinners in the middle of the LBDC command area. towards the Harappa region, the characteristics of aquifers tend to be sandy. Also, the bore holes in the LBDC Depict sandy aquifers and don't show any mark of clay soil. as removed towards the downstream of the LBDC the soil appears to be sandy and a rare mixture of clay and silt. Hard Rock gravels are not encountered in the alluvium (coarse or very coarse sand) (Basharat & Tariq, 2015).

3.1.2 Availability of Surface and Ground Water

Usually, the canals in the Punjab region are designed on seasonal fixed water allocation. The supply obviously cannot meet the demand. There is no extra capacity or resources of water that can help to meet the unmet demand. It only depends on the farmers and their requirements for what to cultivate and sow according to their water availability. In Pakistan Water, Apportionment Accord is being followed to allocate the water to canals. According to that accord, the lower Bari doab canal system has allocated an average annual flow of 5.9 BCM with around 2.7 BCM for the rabi season and remaining for the Kharif season. However, this availability also varies depending on the inflows of the Indus River system. Apart from its command area, LBDC also distributes around 0.8 BCM of water to the MP link canal during the Kharif season (Shakir et al., 2011). Water ways of LBDC command area is given in Figure 3.4.

Due to projected growth in population, development, and people's higher level of living, the required water demand is expected to increase. Apart from surface water, rainfall and groundwater are also among the major water suppliers in the LBDC system. Annually around 6.5 BCM of water is extracted from groundwater, which is used for domestic, industrial, and agricultural purposes, and about 3.5 BCM of water is received from rainfall including all the losses.

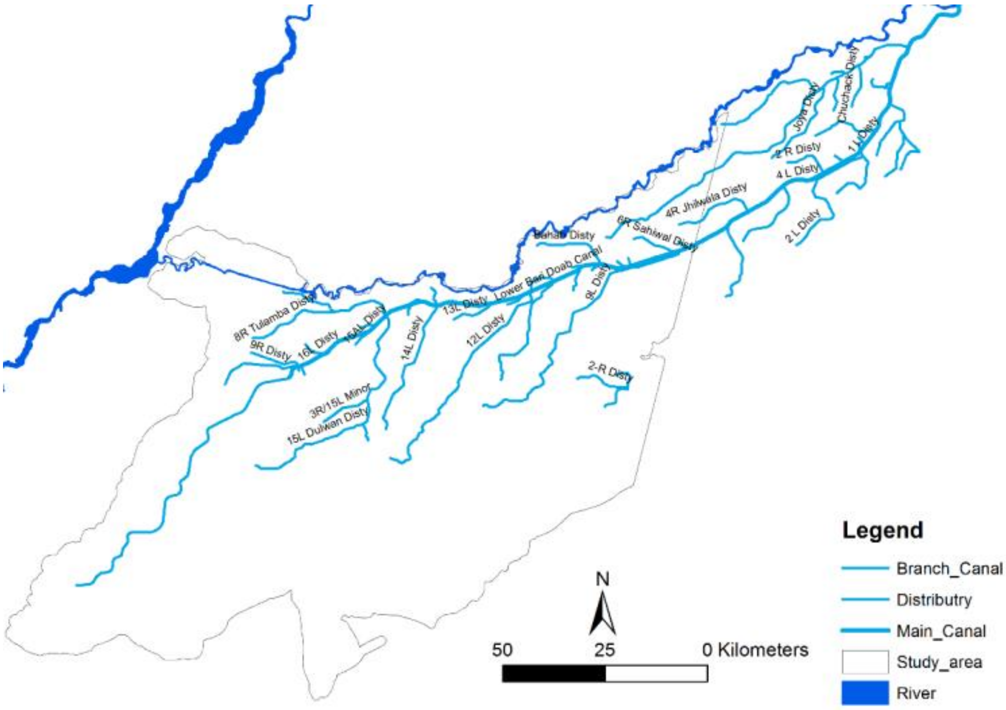

Figure 3. 4: Waterway map of LBDC

3.1.3 Water Quality in LBDC

As ground water is also the primary source of irrigation water after surface water, so the quality of groundwater has an impact on crop yield. Many parameters are assigned by the water quality assurance department that should be kept in mind while using the water for irrigation as well as drinking purposes.

Over the last few years, the areas with usable quality groundwater have been decreasing dramatically. And the areas under harmful groundwater quality has been improved from 7% to 19% (Nawaz et al., 2015). The deterioration of groundwater quality over time during different survey periods is shown in Table 3.1.

Table 3. 1: Water Quality Deterioration Over Time

Serial No.	Unit	Result
pH	-	7.8
Turbidity	NTU	1
TDS	mg/l	480
Coli Form	Number/100ml	N.D
Aresenic	mg/l	0.01
Hardness	mg/l	127

3.1.4 Climate

Farming or agriculture is the main principle in the LBDC area. There are usually two seasons known as the Rabi and the Kharif season. The Rabi season is usually dry also the winter season starts in September and ends in April and Kharif season is usually a wet or rainy season starting from April and ending in September. The climate of the LBDC region is semi-arid to arid and average annual rainfall ranges from 102 mm to 508 mm in the south and north respectively. The temperature in the LBDC region usually ranges from 20 °C to 41 °C in the winter and summer periods respectively. (Akhter et al., 2022)

3.1.5 Land Use and Major Crops

A portion of the earth's surface and direct sub-surface's characteristics are referred to as land cover in a more specific sense. These characteristics include biota, soil, geography, surface and ground-water, and human structures. The land is crucial for the development of agriculture and the provision of a living. Agriculture dominates the region's economic activities.

The major crops include Wheat, Cotton, Tomato, Onion, Rice, and Sugarcane. The detail of these crops with their area's intensities in the districts of LBDC Command Area is given below in Figure 3.5.

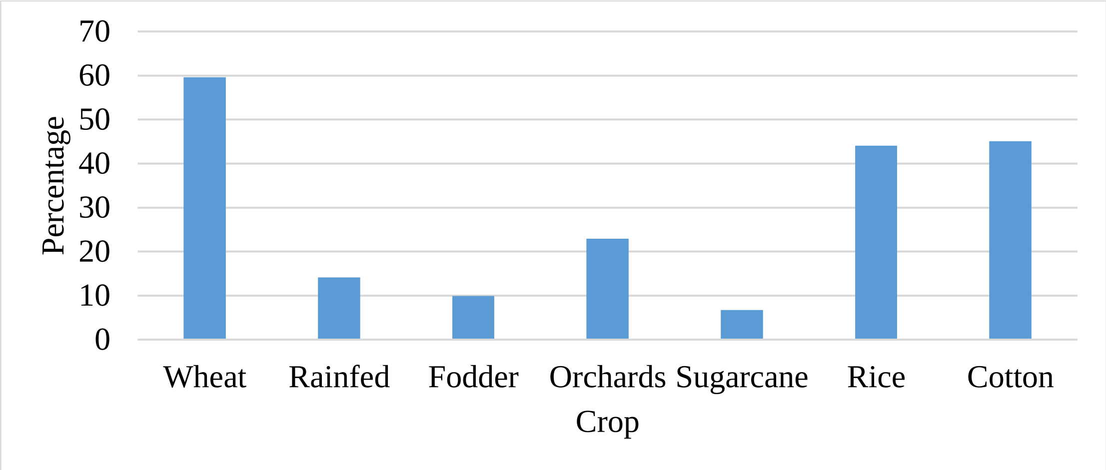

Figure 3. 5: Percentage Coverage of Agriculture Area in LBDC

3.1.6 Population Growth

The major contribution to the population in the LBDC command area is the three main districts which are Okara, Sahiwal, and Khanewal. There are around 275000 farm families located in this study area. The domestic people depend on the surface and ground water. Detail of the population census is given below in Table 3.2.

Table 3. 2: Population Data per District

District	Total Population	Population Density per Sq. km	Urban Proportion %	Avg Annual Growth Rate %
Okara	3040826	694.73	27.71	1.64
Sahiwal	2513011	785.07	20.52	1.64
Khanewal	2920233	671.47	20.08	1.83

3.2 MATERIALS AND METHODS

In this section, the methodology that has been carried out during the research, will be discussed in detail. Presentation of the Water Evaluation and Planning Model and analysis of the Nash Bargaining Method have been done. Firstly, the main characteristics of WEAP and Linear programming are described, and then the WEAP model along with the integration of linear programming for the LBDC Area is presented.

3.2.1 Data Source

The data used in this research is collected from different governing bodies of Pakistan. The detail of the data collected, and its organization is provided in Table 3.3.

Table 3. 3: Data used in research and its source

Serial No.	Data Type	Duration	Source
1.	Maximum and Minimum Temperature (^{o}C), Precipitation Data (mm)	(2010-2021)	Pakistan Meteorological Department PMD, Islamabad
2.	Crop Pattern and Area (Acres)	(2015-2020)	Crop Reporting Service, Punjab
3.	Canal Inflow Data (cusec)	(2010-2020)	Punjab Monitoring and Implementation Unit, Lahore
4.	Crop Coefficient (Kc)	Crop wise	FAO 98 Paper
5.	Digital Elevation Model	(2021)	USGS Earth Explorer, Landsat 8
6.	Water Demands	(2015)	Australian Centre for International Agriculture Research

3.2.2 Meteorological Data

Lower Bari Doab, being an agricultural region, also depends on rainfall for meeting the demands of its agents. Precipitation data indicates that the rainfall is maximum in July and

August month, and minimum in month of October and November. The temperature is recorded in different gauging stations by Pakistan Meteorological Department, in the Punjab region the minimum temperature ranges from 2.57 °C to 23.61 °C and the maximum temperature ranges from 16.46 °C to 36.44 °C. Detail is given in Figure 3.6.

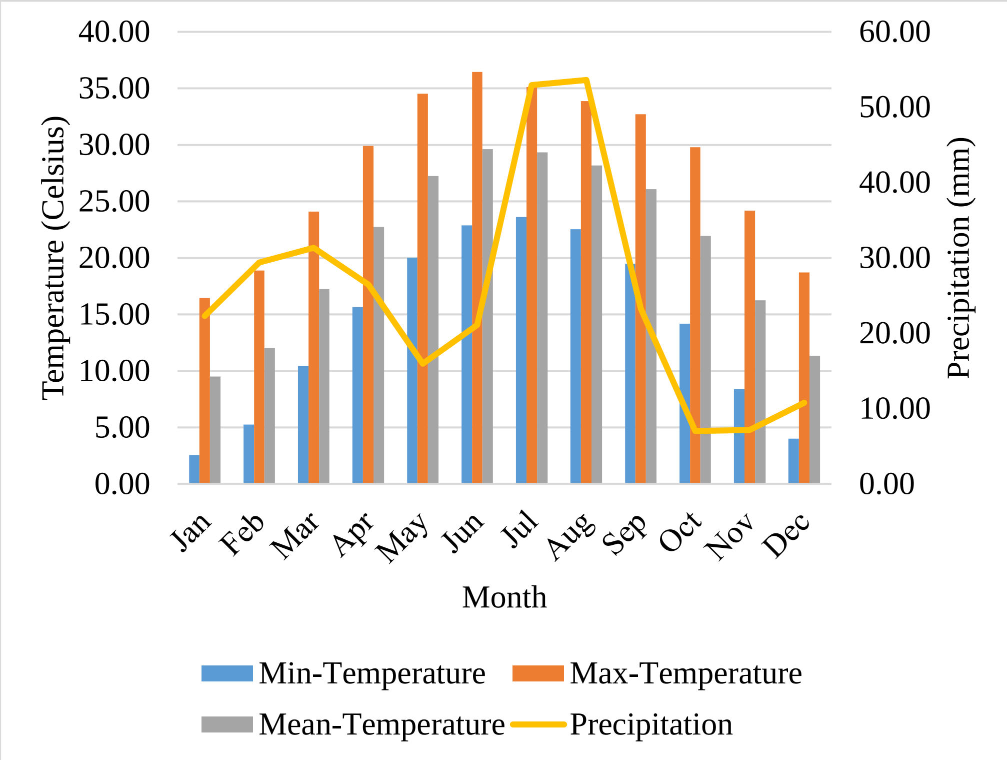

Figure 3. 6: Max, Min, and Mean Temperature Along with Precipitation

3.2.3 Irrigation Water Requirement

LBDC is no different from the fact that agriculture is the foundation of developing nations everywhere. A larger variety of crops can be grown year-round with less reliance on rainfall due to irrigation technologies. According to PMIU the water available for inflow in LBDC is about 5.2 BCM per the year 2015, and the total evapotranspiration (ET) in the area turned out to be 8.02 BCM in the year 2015 (Nawaz et al., 2015). This show that the total surface inflow is not sufficient for the agricultural demand. It means that there is a need for any other supply to full fil agricultural demand.

For the purpose of crop water necessity, the ET and Kc (crop-coefficient) are obtained from the governing bodies. The crop coefficient for major crops in Punjab is given in Figure 3.7.

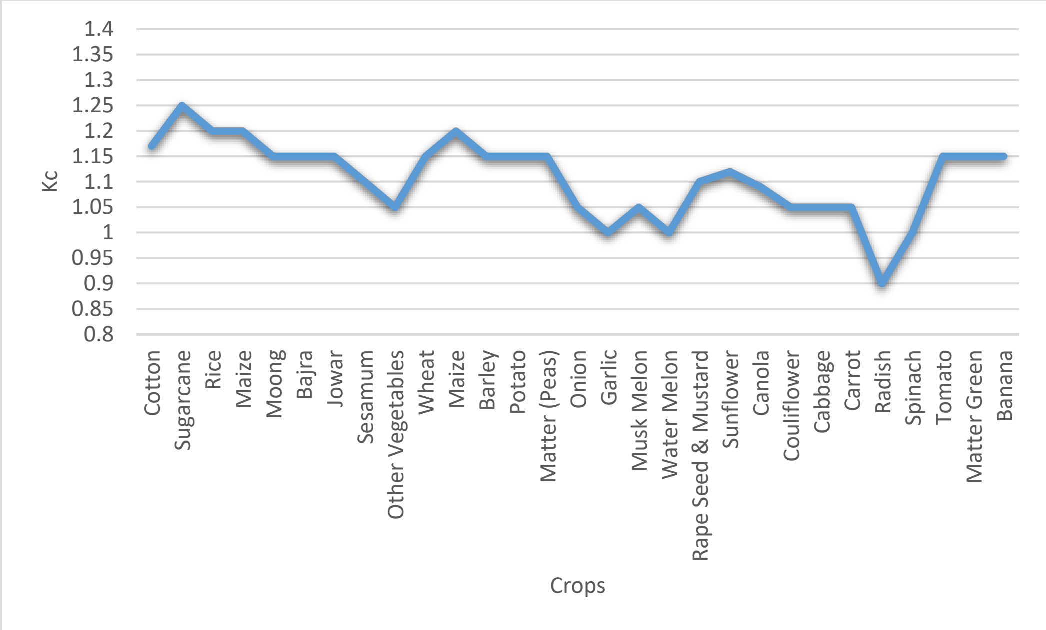

Figure 3. 7: Crop Coefficient for different Crops

Kc is an important factor in predicting crop Evapotranspiration. Then ET can be calculated by many numerical approaches like Penman Equation, Delta SPMP, etc. monthly average values of ET are given in Figure 3.8.

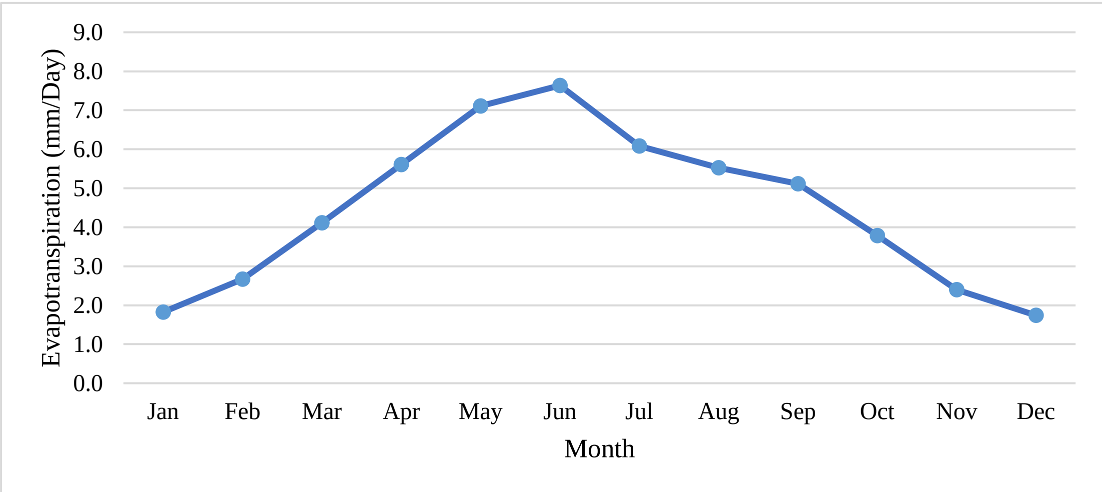

Figure 3. 8: Monthly Evapotranspiration

For the calculation of land use in the Bari Doab region, the Digital Elevation Model DEM was imported in ArcMap, then the catchment delineation was followed after that stream order was generated by the pour point method. Most of the land is occupied by water, trees, grass, vegetation, built area, etc. LULC map of Bari Doab is depicted in Figure 3.9.

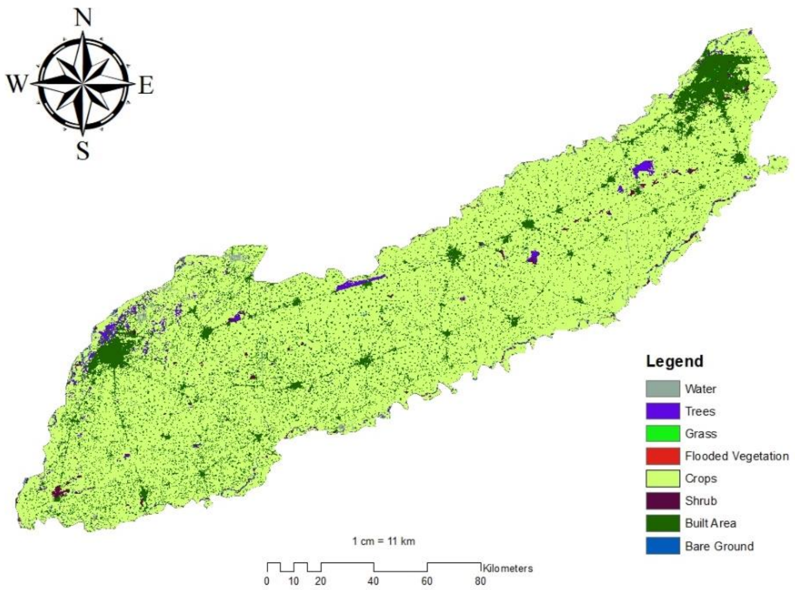

Figure 3. 9: LULC of Bari Doab, 2021

The major districts included in the LBDC region are Sahiwal, Okara, and Khanewal. Being agricultural land most of the areas in these districts produce crops. The LULC maps of these districts are given in Figure 3.10.

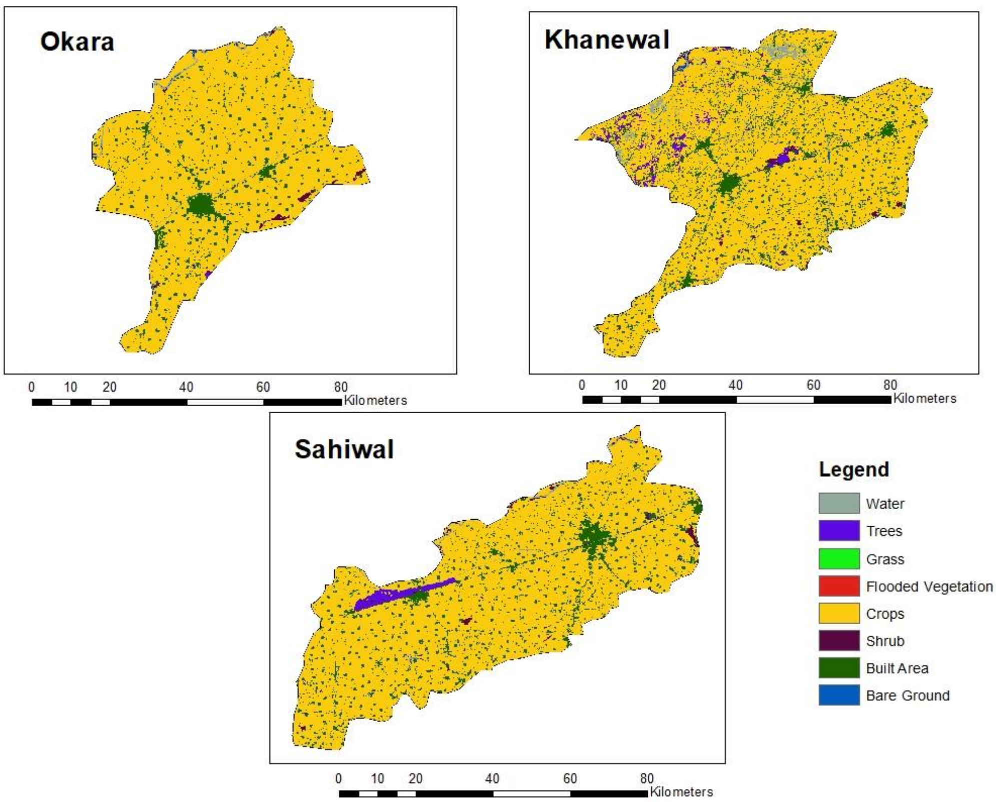

Figure 3. 10: LULC maps of Sahiwal, Okara, and Sahiwal, 2021

Based on how vegetation reflects specific electro-magnetic spectrum ranges, Normalized Difference Vegetation Index (NDVI) is a amount of vegetation condition. We must study the electromagnetic spectrum to comprehend crop growth. It is important too, how NDVI functions and enables us to assess a plant's health based on how it displays light and energy. A plant looks green to the naked eye because of the chlorophyll pigment, which reflects green wavelengths and absorbs red ones. Plants' cell architecture reflects near-infrared (NIR) wavelengths. As a result, the plant progresses and grows and contains more cell structures when photosynthesis occurs.

To determine how healthy a plant is, we must compare the values of red and NIR light absorption and reflection. The basic mathematical equation (below) determines the NDVI, which converts unprocessed spatial information into vegetation indices.

$$NDVI = \frac{NIR - RED}{NIIR + RED} \quad (3.1)$$

Red and NIR band data are combined into a single, representative value using the NDVI algorithm. By deducting the reflectivity within red spectra from the reflection in the NIR, it achieves this. This is then divided by the total of red and near-infrared reflectance. Major crops in LBDC are given in Table 3.4. The Vegetation index will forever have a value between -1 to +1. Plants that are dead or inorganic structures like stones, roads, and homes are shown by values from -1 and 0. The NDVI maps of Rabi and Kharif seasons are generated on ArcMap and given in Figure 3.11 below.

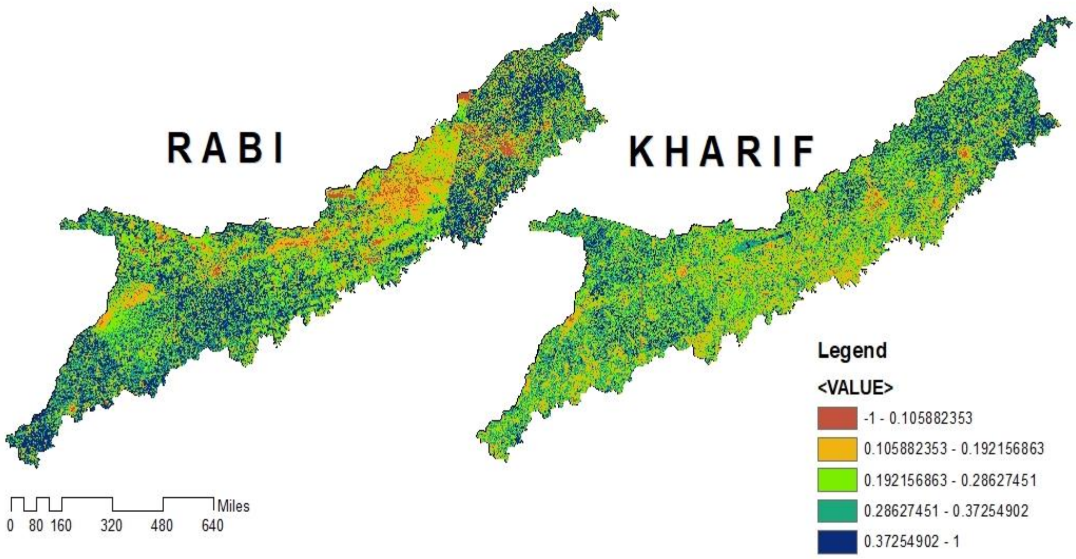

Figure 3. 11: NDVI maps of Rabi and Kharif season in LBDC region.

Table 3. 4: Crops in LBDC Region

Kharif Crops	**Rabi Crops**
Cotton	Wheat
Sugarcane	Maize
Rice	Barley
Maize	Potato
Moong	Bersim, loasan, etc
Bajra	Matter (Peas)
Jowar	Onion
Guar seed	Garlic
Sesamum	Musk Melon
Chilies (Red)	Watermelon
Chilies (Green)	Tobacco
Lady Finger	Rape Seed & Mustard
Mango	Sunflower
Guava	Canola
Dates	Cauliflower
Peaches	Cabbage
Pomegranate	Carrot
Other Kharif Fruits	Radish
Kharif Vegetables	Spinach
Kharif Fodder	Tomato
	Matter Green
	Coriander
	Banana
	Guava Rabi
	Kinnu
	Lemon
	Musambi
	Other Citrus Fruit
	Sweet Lime Fruit
	Other Rabi Fruit

Crop water necessity is described as the amount of water in (mm) required by a crop through evapotranspiration. The idea of irrigated water requirement (IWR), which represents the gross depth of water (millimeters) that must be applied to a crop to fully satisfy its crop water requirement, must be added to the concept of crop water requirement (CWR) for irrigated crops. The portion of the CWR that is not met by rainfall, soil water reserve, and groundwater contribution is the IWR. This water depth is also considered in IWR when it is required to add a dumping fraction to ensure proper leaching of salts present in the soil profile. To account for the effectiveness of the irrigation used, IWR must be transformed into net irrigation requirements in practice. The Crop water requirement in the Lower Bari Doab Canal (LBDC) region turned out to be 3.6 BCM for Rabi Season and 3.98 BCM in Kharif Season. Th average annual growth rate for agriculture was set to 2.77% and average annual maximum growth rate was set to 4.4% taken from World Bank Development Indicators.

3.2.4 Domestic Water Requirement

Water is a necessary need for living for Human Beings. According to a survey, the total annual water for a person is decreased to 915 m^3 from 935 m^3, due to the depletion of water resources in Pakistan. There are around 275000 farm families in the LBDC area. The maximum annual average population growth rate was taken from UN (World Population Prospects 2019) which was about 2.2%. The annual total demand for the population has turned out to be 0.251 BCM (Muzammal et al., 2021). Growth rates are given in Table 3.5.

Table 3. 5: Annual Population Growth Rate in LBDC

District	Annual Population Growth Rate
Kasur	2.03%
Sahiwal	1.64%
Okara	1.64%
Khanewal	1.83%

3.2.5 Industrial Demand

According to the findings of a survey done in the LBDC command area to estimate industrial water requirements, practically every industrial sector gets all of the water they need from GW withdrawals. But for cooling purposes, the “Sahiwal Thermal Coal Power Project” utilizes 0.82 cumecs (29 cusecs) of water as of LBDC (Nawaz et al., 2015). Studies showed that the annual industrial demand in LBDC turned out to be 0.149 BCM. The average annual growth rate was set to 1% taken from Pakistan Industrial Production Index Growth and the maximum growth rate was set as 3.6%.

3.2.6 Environment Sustainability

For the study area's ecosystem to be sustained, environmental flow is necessary. There are 28,956 acres (117 km^2) of forests in the Sahiwal district. According to the National Water Policy (NWP) 2018, 0.3 BCM of water is delivered through the Forest Distributary to restore and sustain ecological integrity.

3.2.7 Ground Water

As surface water is not enough for fulfilling the demand of different sectors in the LBDC Command Area, ground water plays a vital role in this condition as most of the irrigation and domestic demand is satisfied by groundwater extraction. In 2015 the amount of groundwater was expected to be 6.5 BCM annually but in 2018 the groundwater extraction increased up to 8.4 BCM (Muzammal et al., 2021).

The groundwater level of the districts involved in the LBDC command area is likely to deplete their water table depth in the future at an increasing rate.

3.2.8 Surface Water

To meet the average water needs of the high delta plants cultivated in the area, the canal water supplies are at their highest from May to July (i.e., rice and sugarcane). Due to canal closures to clear silt, canal water resources are at their lowest or non-existent in December and January. The typical annual canal supply for LBDC is 737 mm that only meets 23% of agriculture water needs. This is ascribed to the system's restricted supply or farmers' decision to irrigate their crops with less water to be able to irrigate more lands with a given amount of water. Precipitation and GW extraction take care of the remaining needs (Nawaz et al., 2015).

According to PMIU the total annual flow in the year 2015 turned out to be 5.2 BCM. The flow in future calculations and analyzation is kept same because according to Indus Water Treaty the water allocated to Indus Basin was limited and haven’t increased with increase in water demands of different sectors (Nawaz et al., 2015). The variation in flow during the year 2015 is depicted in Figure 3.12 below.

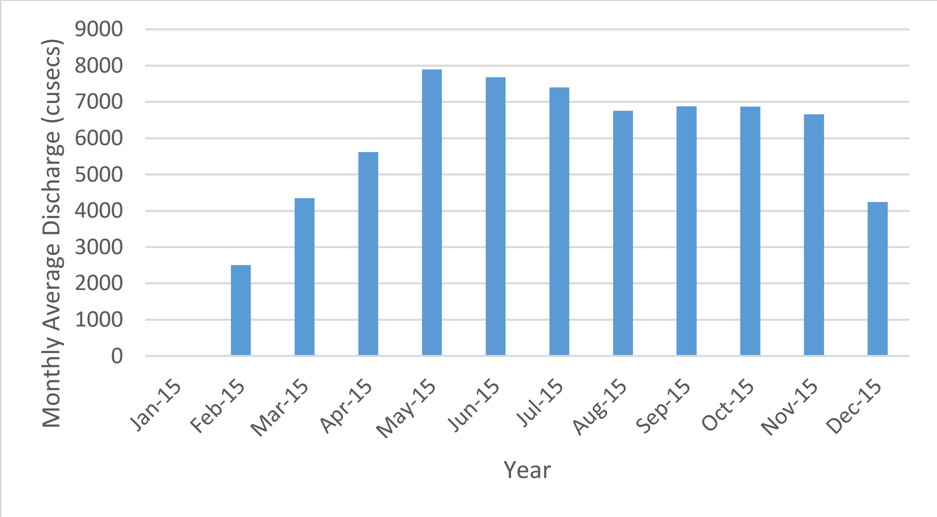

Figure 3. 12: Monthly Average Discharge in LBDC for the year 2015

3.2.9 Rainfall

The mean annual rainfall for the LBDC region is 347 mm, according to the results. August had the highest monthly rainfall, at a maximum of 80 mm. The monsoon season, which lasts for three months, produces about 65% of the total annual rainfall. In October and November, there is hardly any rain. Farmers must rely on GW extraction and canal water sources during these months to meet the crop's water needs. The moderately higher slope and increased field limits in the area aid in preventing runoff during periods of heavy rainfall during the rainy season, which also boosts groundwater infiltration in the studied area. Rainfall in total contributes about 3.5 BCM to the total supply in the LBDC command area.

3.2.10 Losses in LBDC

A deep, unconsolidated, unconfined aquifer constitutes the hydrogeology of LBDC. Outflow from streams, waterways, and farmer' fields with very modest lateral flows is the main source of groundwater level. This indicates the close relationship between surface and groundwater levels, which is mostly attributable to the soils' light texture (Nawaz et al., 2015).

From the head to the tail of the LBDC control, the irrigation network's primary and secondary canals) surface runoff reduces. This is brought on by the channels' diminishing density as they discharge into the irrigation system's tail (the main canal, branches, and distributaries). Recharging of Groundwater from canal supplies and rainfall decreases from 430 mm at the head end to 285 mm at the tail end due to the current canal supplies and rising climate intensity in a downstream direction (Shahid & Rahman, 2020). The annual seepage loss in LBDC is about 2.7 BCM. And about 0.8 BCM of the water is diverted to the Montgomery

Pakpattan Linkage canal from LBDC to fulfill its supply requirement. And about 1.9 BCM of water losses due to low groundwater irrigation efficiency.

3.3 WATER EVALUATION AND PLANNING (WEAP) MODEL

The Water Evaluation and Planning System (WEAP) model is used in this study. It combines a hydrologic model with a depiction of how water is distributed and provided for various human activities, allowing for the analysis of subsequent implications on ecosystems. WEAP is a semi-distributed technique to model hydrologic processes, with the water balance estimated over a user-defined area with comparable hydrologic features. This allows the user to associate locations with comparable land cover, soil, elevation, slope, aspect, and other characteristics that are expected to have the same hydrologic response (Harma, 2001).

User-defined water demands can include public and industrial demand, irrigation demand, and instream flow requirements in WEAP. Each water-demanding location is given a priority (1-99) and is linked to the available supply sources. Because each supply source may have one or more demands to meet, the model prioritizes the allocation of available supply to all demands. A schematic flow chart of the WEAP modeling process is shown in Figure 3.13 below.

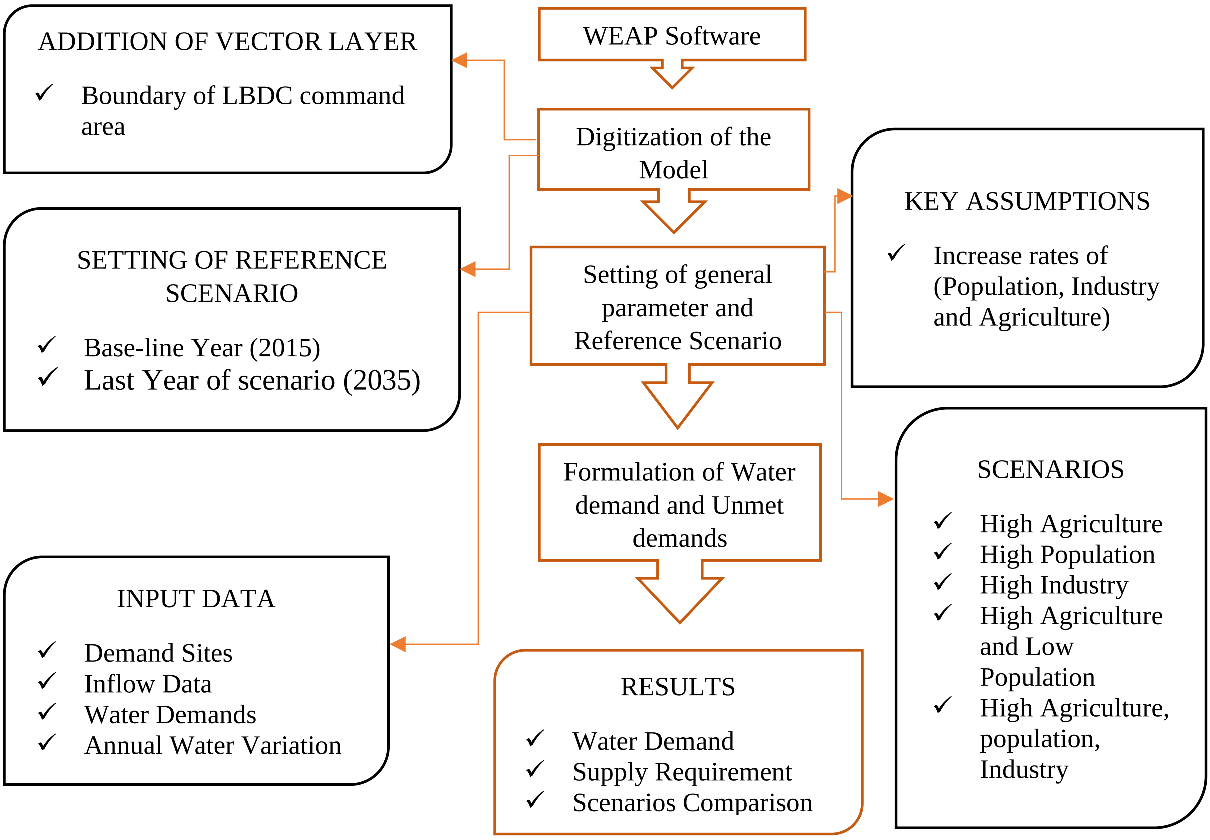

Figure 3. 13: Flow Diagram of WEAP Model

3.3.1 Model Structure

The model's structure is such that the groundwater, river input, transmission, ecological requirements, water demands, and inflow generation are all represented as components of the water resource system. To satisfy the needs of a specific analysis, the specialist can select the level of difficulty. Additionally, the limitations brought on by restricted data can be reflected with this option. WEAP has five views namely Schematic view, Data View, Results View, Scenario Explorer, and Notes.

- In the schematic diagram, the study area is identified. It is a GIS-based program that enables the importation and use of raster or vector layers as background layers. Its drag-and-drop mechanism allows you to position objects like demand nodes, reservoirs, groundwater supply, etc. This makes it simple to adjust and changes in the region. Figure 3.14 depicts a schematic view of the study area.

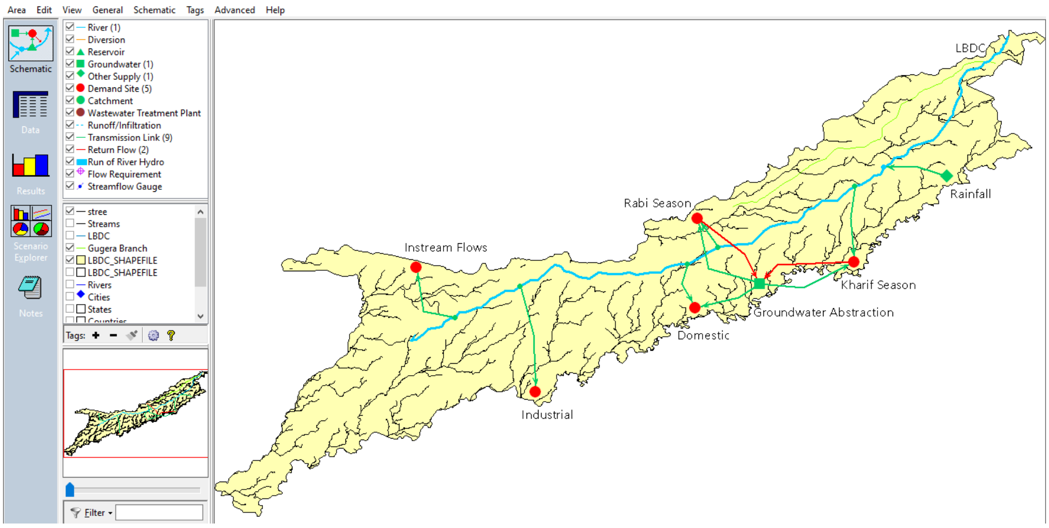

Figure 3. 14: Schematic Diagram of LBDC WEAP model

- In the Data view we can simply add values to demand and supply sites. We can also import data from excel. This view also helps in making key assumptions and creating mathematical relations.
- The resulting view is easily assessable and shows the result for the current and reference scenarios.
- Overview or Scenario Explorer helps in putting different data variables to see the future analysis.
- Notes help in making proper documentation of the models and parameters and assumptions used in the model.

3.3.2 WEAP Modelling Process

WEAP modeling process consists of the following steps:

- The scope and duration of the study are defined. The initial year of application and the last year of scenario production are included in the time frame's setup.
- Creating the current account, which roughly reflects the state of the study area's water resources. The current account specifies the numerous demand nodes that currently exist as well as the available water resources. Since it serves as the foundation for the entire modeling process, this is important.
- The formulation of scenarios based on projected growth in the various indicators and future assumptions. This is what makes up the primary body of the WEAP model since it enables the adoption of potential methods for managing water resources based on the model's output. The scenarios are utilized to address many "what if" questions, such as what if operating guidelines for reservoirs are changed, what if ground-water supplies are fully utilized, and what if there is an increase in population.
- Analysis of the possible outcomes considering the research area's water resource availability.

3.3.3 Input Data

First, GIS vector and raster layers are added in the schematic view to easily locate the canal command area and easily trace the canal path. Then four demand nodes are added to the study area each for agriculture, domestic, industrial, and stream flow respectively. The year which is chosen to be the current year is 2015. And reference period is from the year 2016 to the year 2035. The model's demand priority was set to 1. According to the importance of the demand locations, the model utilizes demand priorities that can be set among 1 and 99. The greatest demand priority is 1, while the lowest is 99. As long as there is flow in the system, a demand priority of 1 indicates that it is necessary to fulfill the need of the river or streams.

3.3.4 WEAP Model Processing

Water Evaluation and Planning (WEAP) is a scenario-based hydrological model, which uses different scenarios to analyze and estimate future water demand and water supply. Different scenarios were enerated in this research to see the future demand and availability. The water resource impacts of the scenario were compared to a base-case scenario from 2020. For this scenario, the model let us to examine unmet demands of water, water supply, water delivered, and water requirements. Water demand and losses are included in the supply requirements. Some of the basic parameters were assumed in this study like annual water availability, etc. The scenarios and their key assumptions are given in Table 3.6 below.

Table 3. 6: WEAP Future Scenarios

Scenario	**Scenario Name**	**Main Key Assumptions / Description**
Base-Line		The Base-Line scenario represents the current year account that was set up for 2015. It shows the current state of the system, including the demand zone and water supply. With existing water distribution as well as existing irrigation systems. WEAP is implemented for the following 20 years in this scenario (starting from 2016 until 2035).
Scenario 1	Reference Scenario	This is the reference scenario. In this, the demands of each sector increase with the annual average rate. The increase rate of industrial, agricultural, and domestic demands are 1%, 2.77%, and 1.8% respectively.
Scenario 2	High Agriculture	As Pakistan is based on an Agri economy, so there is a need to keep in mind the agricultural water demand. In this scenario growth in agriculture, and water demand will be calculated from the year 2016 to 2035 with a high increase rate of 4.4% in different districts respectively.
Scenario 3	High Population	In this scenario, the High population growth is kept in mind and all the other sectors have the same reference growth rates. The annual growth of Pakistan according to the Pakistan Bureau of Statistics is about 2.2%.
Scenario 4	Low Population and High Agriculture	In case, the population decreases then there will be different demands for domestic use so in this scenario low population growth is kept in the model key assumptions which are likely to be 1.5%. and also it is compared with the high agriculture scenario.
Scenario 5	High Industrial Growth	This scenario is based on high Industrial demand. According to the Industrial GDP of Pakistan, the industrial demand can increase up to 3.6%.
Scenario 6	High Agriculture, High Industrial, and High Population	This is a comparison scenario between Domestic, Industrial, and Agricultural Demands. What if all the demands increase at their highest rates?

3.3.5 Nash Bargaining Solution

We intend to utilize a framework for water allocation that combines the bankruptcy theory and the uneven NBS idea to resolve the water sharing issue between four demand sites in the LBDC.

When the total amount of accessible water is lesser than the overall amount of water demanded, the bankruptcy concept can be utilized to address the issue of the least water distribution to each site. For each riparian, the minimal water-sharing formula is provided.

$$m_i = max\left(0, E - \sum_{k \neq i} c_i\right) \quad (3.2)$$

Where,

$$E < C$$

By applying the technique of the Bankruptcy Concept for the minimal water allowance, the least water distribution to every site, particularly to the site with lower claims, may turn into zero. However, while allocating water resources, each site will want a minimal amount of water.

The site's water claims work as the upper bound core for the optimisation issue. The optimisation issue for the distribution of water under a bankruptcy setting is presented by (Janjua & Hassan, 2020), and it is as follows:

$$Maximize\ N^w = \left(x_1^- - \left(E - \sum_{i \in N/\{1\}} c_i\right)\right)^{w_1} \left(x_2^- - \left(E - \sum_{i \in N/\{2\}} c_i\right)\right)^{w_2}$$
$$\left(x_3^- - \left(E - \sum_{i \in N/\{3\}} c_i\right)\right)^{w_3} \left(x_4^- - \left(E - \sum_{i \in N/\{4\}} c_i\right)\right)^{w_4} \quad (3.3)$$

Here,

$\sum_{i=1}^{n} w_i = 1$

In the Equation Above:

x_1^- is the maximized water allowance for Agriculture.

I_1 is the smaller core bound for Agriculture.

x_2^- is the maximized water allowance for Domestic.

I_2 is the smaller core bound for Domestic.

x_3^- is the maximized water allowance for Instream Flow.

I_3 is the smaller core bound for Instream Flow.

x_4^- is the maximized water allowance for Industry.

I_4 is the smaller core bound for Industry.

"N^w is the weighted Nash objective function which should be maximized."

While allocating the water subsequent constraints should be kept in mind;

- The water portion to each site should be more than or equal to its low core bound value.

$$x_i^- \leq I_i, i = 1, 2, \ldots, n$$

- The allocation to any site should be more than its low core bound value and must be greater than its own claim.

$$I_i \leq x_i^- \leq c_i$$

- The sum of water allocation in all the sites should not be more than the total available water.

$$\sum_{i=1}^{n} x_i^- \leq E$$

3.3.6 Calibration and Validation

The method of calibrating groundwater models involves contrasting actual field observations with hydraulic heads that the model has simulated. By modifying the constraints to make sure that the observed and modeled heads are within an normal range, calibration aims to reduce residuals. The remaining statistical parameters like sum of squares of residuals, residual mean error, and absolute mean are used to measure the accuracy of model calibration.

To try to fit the field conditions within allowable standards, model calibration entails modifying the values of the model input parameters. Model calibration is an iterative procedure that adjusts aquifer parameters, boundary conditions, and stresses within an acceptable limit to bring model outcomes (such as water head) into accordance with chronological field data. The likelihood of obtaining non-unique model results and the variety of variables available for target calibration are also factors in this process. Different methods were compared in calculating the ET value (Kaleemullah, Muhammad., habib, Zeigham., Muhammad, 2001). The comparison is shown in Figure 3.15 below.

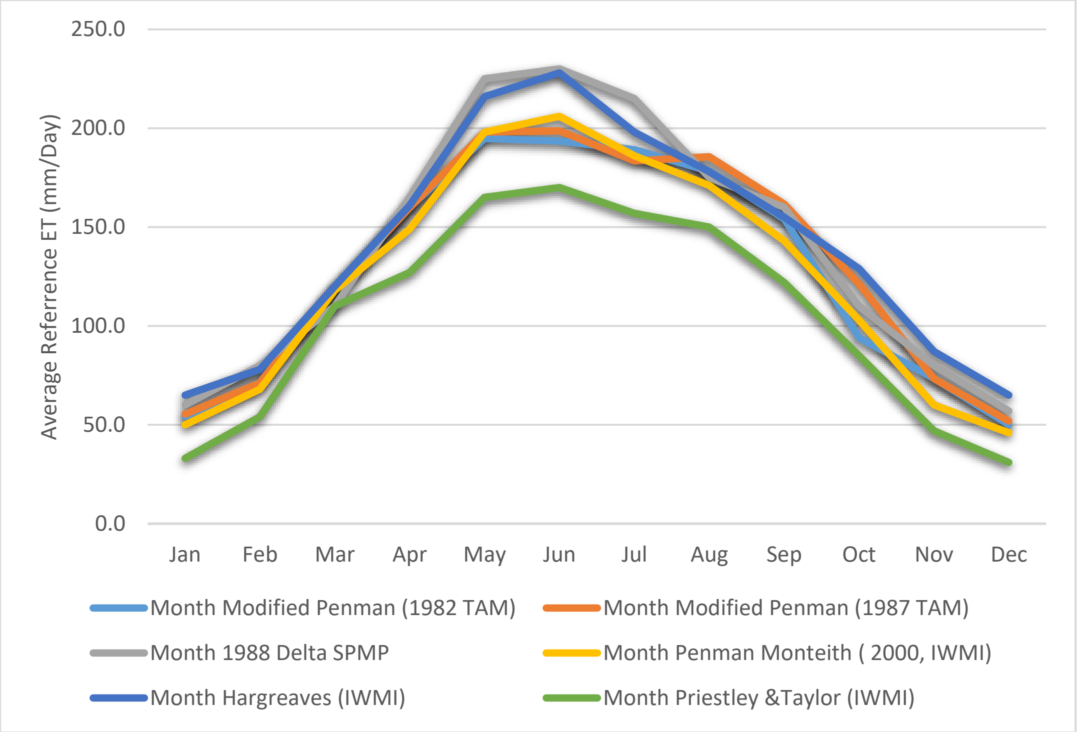

Figure 3. 15: Comparison of reference ET among different methods

CHAPTER 4

RESULTS AND DISCUSSION

The outcomes of the WEAP analysis of the Lower Bari Doab Canal and interval linear programming are discussed in this chapter. Keeping in view the reference scenario, 5 scenarios were generated. These scenarios were high Agriculture, High Population, High Industrial Growth, and two other comparison scenarios. Nash Bargaining was done based on demand priorities and future water allocation is discussed.

An analysis was done on the canal command area to simulate its hydrology aspects. These majorly include precipitation, industrial demands, population growth, and agriculture, including catchment size and crops grown in it, which are one of the main aspects of this region. Groundwater abstraction analysis was also considered in this research. The base data used in this study is from 2015 because in other years the data was not sufficient to perform the analysis. Losses were also kept in mind while calculating future unmet demands.

4.1 RESULTS

4.1.1 Current Accounts

The current account in this research was set on the information and data provided by the Australian Centre for International Agriculture Research (Nawaz et al., 2015) of the year 2015. All the demands and supplies were collected from that report, which is already calibrated and doesn't need any calibration or validation. The evaluated data is given in Table 4.1. The data was crosschecked by the manually calculated demands and supply and hence was ready to use.

Table 4. 1: Total Water Supply and Demand in LBDC command area

Total Water Available	**Water Loss**	**Water Supply**	**Water Demand**	**Total Demand**
(BCM)	(BCM)	(BCM)	(BCM)	(BCM)
Canal Inflow = 5.2 Rainfall = 3.5 Groundwater Abstraction = 6.5	Seepage = 2.7 Rainfall =1 Groundwater = 1.9 MP link Canal = 0.8	8.8	Agriculture = 8.02 Domestic = 0.251 Instream = 0.3 Industrial = .149	8.72

4.1.2 Reference Scenario

In this research, the reference scenario was based on the Current Account year 2015 and some growth rates from the Pakistan Bureau of Statistics. It was seen that the agriculture growth rate of LBDC is increasing by 2.77% annually. Also, the population in the region of LBDC is increasing with an increment of 1.8%. Instream flow remains the same and industrial growth is kept at 1%.

For setting up the reference scenario the growth rates were entered in the WEAP key Assumption and then the Growth function was used to enter these rates in the Current year account values. The simulated calculations showed the water demands and unmet demands of each site like agriculture, industrial, inflows, and domestic. The results were analysed from the year 2016 to 2035. The graphs show the steep rise in these demand sites annually with a constant rate of growth. The increase in demand for the agents and water use are given in the Figure 4.1, 4.2 and Table 4.2, 4.3 below.

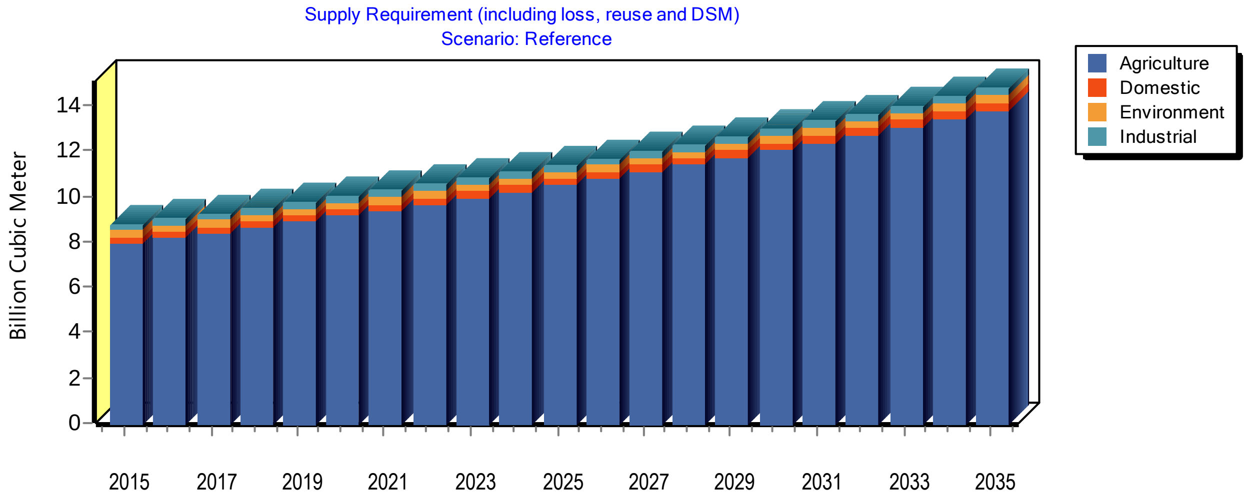

Figure 4. 1: Reference Supply Requirements

Table 4. 2: Reference Supply Requirement

Supply Requirement (including loss, reuse and DSM) (Billion Cubic Meter)
Scenario: Reference | All Branches | Branch: Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	8.02	8.24	8.47	8.71	8.95	9.19	9.45	9.71	9.98	10.26	10.54	10.83	11.13	11.44	11.76	12.08	12.42	12.76	13.11	13.48	13.85	224.38
Domestic	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.30	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.34	0.35	0.35	0.36	6.35
Industrial	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.19	0.19	3.53
Instream Flow	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	6.30
Sum	8.72	8.95	9.18	9.42	9.67	9.93	10.19	10.46	10.73	11.02	11.31	11.61	11.92	12.23	12.56	12.89	13.23	13.58	13.95	14.32	14.70	240.57

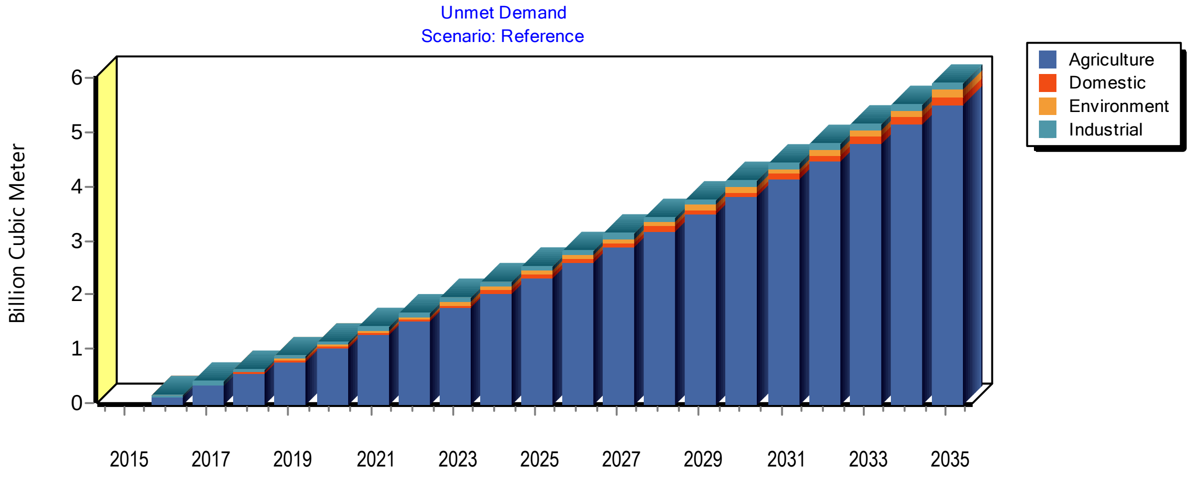

Figure 4. 2: Reference Unmet Demand

Table 4. 3: Reference Unmet Demand

Unmet Demand (Billion Cubic Meter)
Scenario: Reference | All Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	0.00	0.14	0.35	0.58	0.81	1.05	1.29	1.54	1.80	2.07	2.34	2.62	2.91	3.21	3.52	3.84	4.16	4.50	4.84	5.20	5.56	52.32
Domestic	0.00	0.00	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.07	0.07	0.08	0.09	0.10	0.10	0.11	0.12	0.13	0.14	0.14	1.42
Industrial	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.08	0.77
Instream Flow	0.00	0.00	0.01	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.11	0.11	0.12	0.12	1.33
Sum	0.00	0.15	0.38	0.62	0.87	1.13	1.39	1.66	1.93	2.22	2.51	2.81	3.12	3.43	3.76	4.09	4.43	4.78	5.15	5.52	5.90	55.85

4.1.3 High Agriculture Scenario

In this scenario, the maximum rate of agriculture growth according to the GDP of Pakistan was used for the increase in agriculture demand calculation. This scenario was based on the reference scenario, only the agriculture demand rate was increased, and all the other demands were set the same as the reference. This scenario shows that about the end of the year 2035 the agriculture demand can increase up to 90.77%. The details of graphs and tables are given in Figure 4.3, 4.4, 4.5 and Table 4.4, 4.5 below.

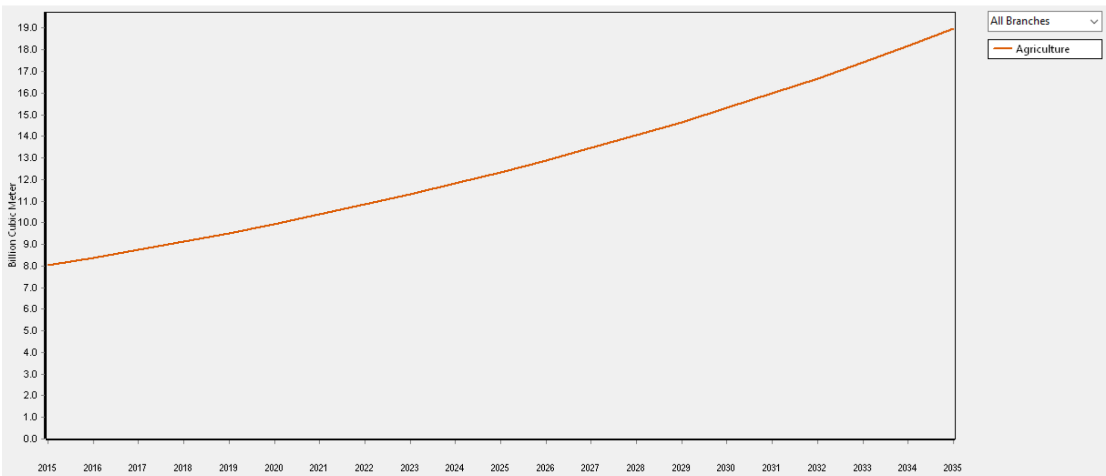

Figure 4. 3: High Agriculture Growth

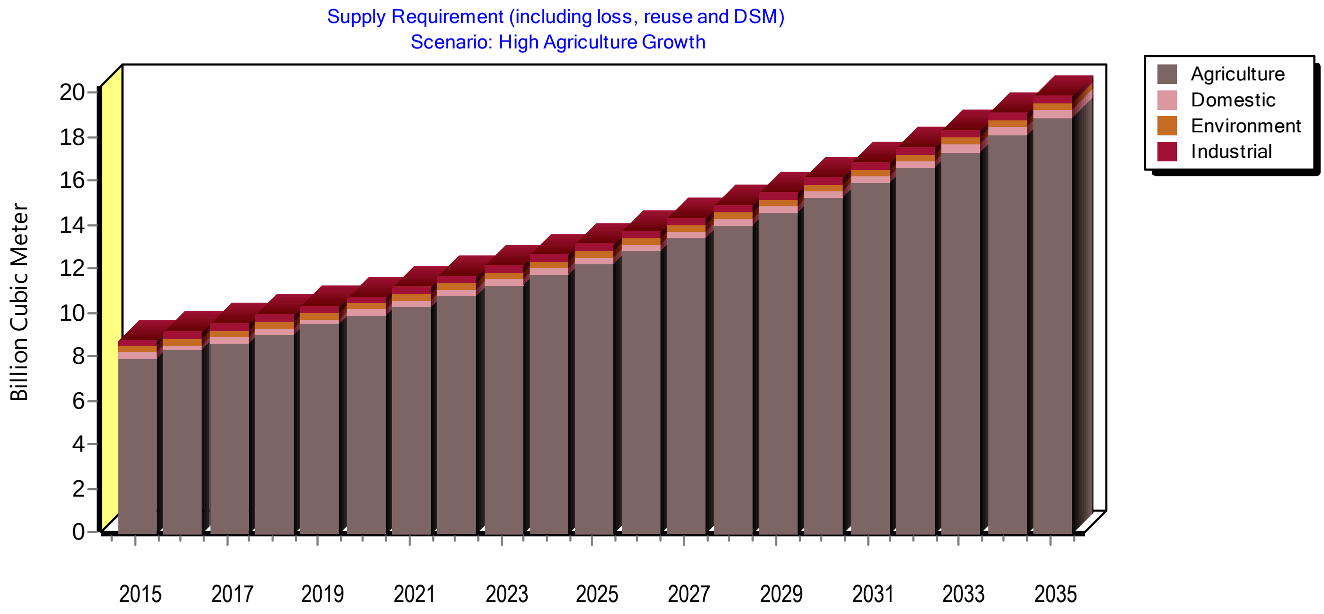

Figure 4. 4: High Agriculture Scenario Supply requirement

Table 4. 4: High Agriculture Scenario Supply requirement

Supply Requirement (including loss, reuse and DSM) (Billion Cubic Meter)

Scenario: High Agriculture Growth | All Branches | Branch: Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	8.02	8.37	8.74	9.13	9.53	9.95	10.38	10.84	11.32	11.82	12.34	12.88	13.45	14.04	14.65	15.30	15.97	16.68	17.41	18.18	18.98	267.95
Domestic	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.30	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.34	0.35	0.35	0.36	6.35
Industrial	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.19	0.19	3.53
Instream Flow	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	6.30
Sum	8.72	9.08	9.45	9.85	10.25	10.68	11.12	11.59	12.07	12.58	13.10	13.65	14.23	14.83	15.45	16.11	16.79	17.50	18.24	19.02	19.82	284.14

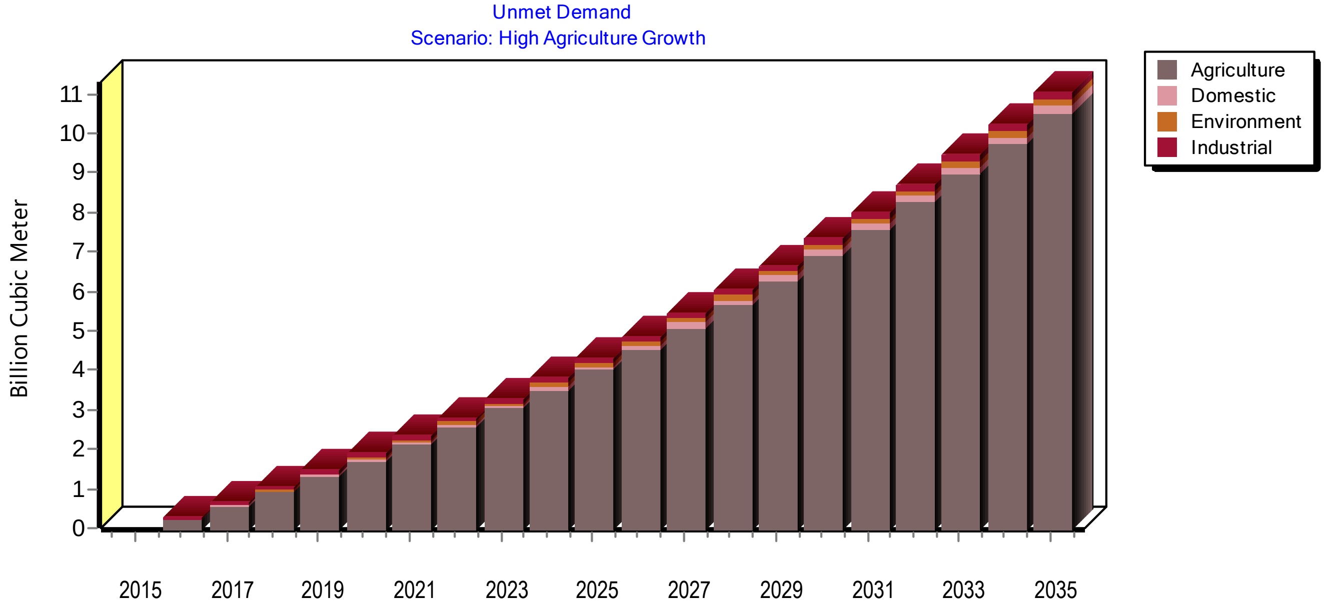

Figure 4. 5: High Agriculture Scenario Unmet Demand

Table 4. 5: High Agriculture Scenario Unmet Demand

Unmet Demand (Billion Cubic Meter)

Scenario: High Agriculture Growth | All Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	0.00	0.26	0.61	0.97	1.35	1.75	2.17	2.61	3.07	3.55	4.05	4.58	5.13	5.71	6.31	6.94	7.60	8.29	9.01	9.77	10.55	94.31
Domestic	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	2.06
Industrial	0.00	0.00	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.10	1.12
Instream Flow	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.11	0.12	0.13	0.14	0.14	0.15	0.15	0.16	0.17	1.93
Sum	0.00	0.28	0.65	1.05	1.45	1.88	2.32	2.79	3.27	3.78	4.30	4.85	5.43	6.03	6.65	7.31	7.99	8.70	9.44	10.22	11.02	99.42

4.1.4 High Population Scenario

In this setting, the data of population is used from the Pakistan Bureau of statistics. The population increase rate in this scenario was set as 2.2%. All the other demand sites were kept the same as their reference scenario. This scenario shows that the population's unmet demand can increase up to 14.28% by the end of the year 2035. The details are given in the Figure 4.6, 4.7, 4.8 and Table 4.6, 4.7 below.

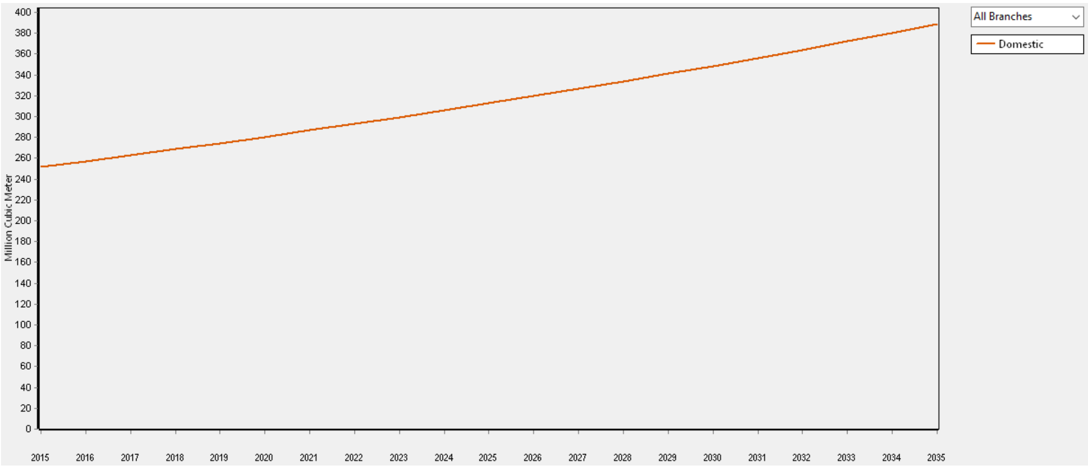

Figure 4. 6: High Population Growth

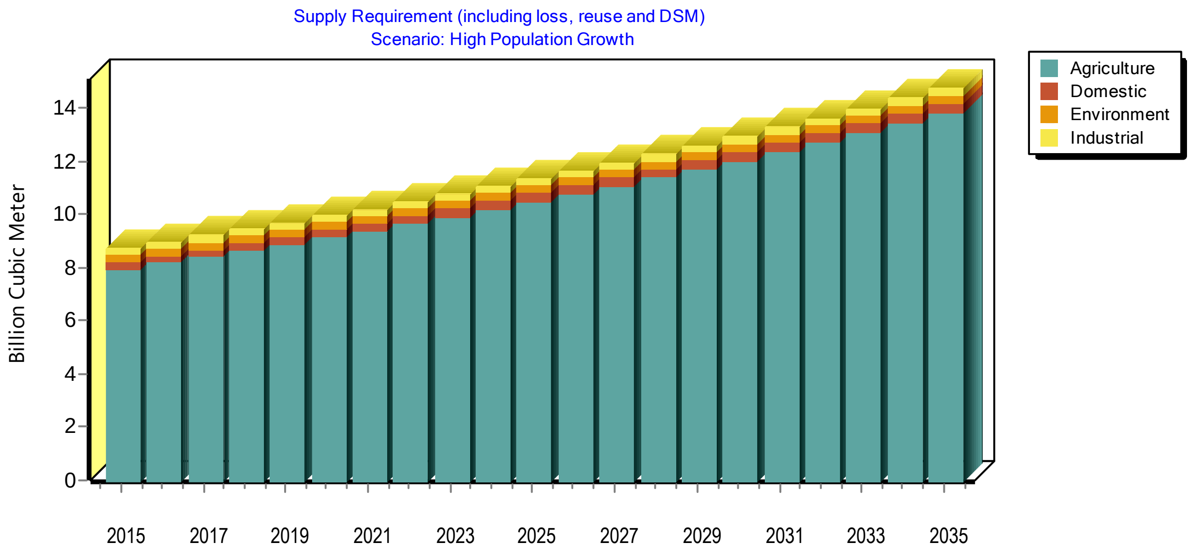

Figure 4. 7: High Population Scenario Supply requirement

Table 4. 6: High Population Scenario Supply requirement

Supply Requirement (including loss, reuse and DSM) (Billion Cubic Meter)
Scenario: High Population Growth | All Branches | Branch: Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	8.02	8.24	8.47	8.71	8.95	9.19	9.45	9.71	9.98	10.26	10.54	10.83	11.13	11.44	11.76	12.08	12.42	12.76	13.11	13.48	13.85	224.38
Domestic	0.25	0.26	0.26	0.27	0.27	0.28	0.29	0.29	0.30	0.31	0.31	0.32	0.33	0.33	0.34	0.35	0.36	0.36	0.37	0.38	0.39	6.63
Industrial	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.19	0.19	3.53
Instream Flow	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	6.30
Sum	8.72	8.95	9.19	9.43	9.68	9.93	10.20	10.47	10.74	11.03	11.32	11.62	11.93	12.25	12.57	12.91	13.25	13.61	13.97	14.35	14.73	240.84

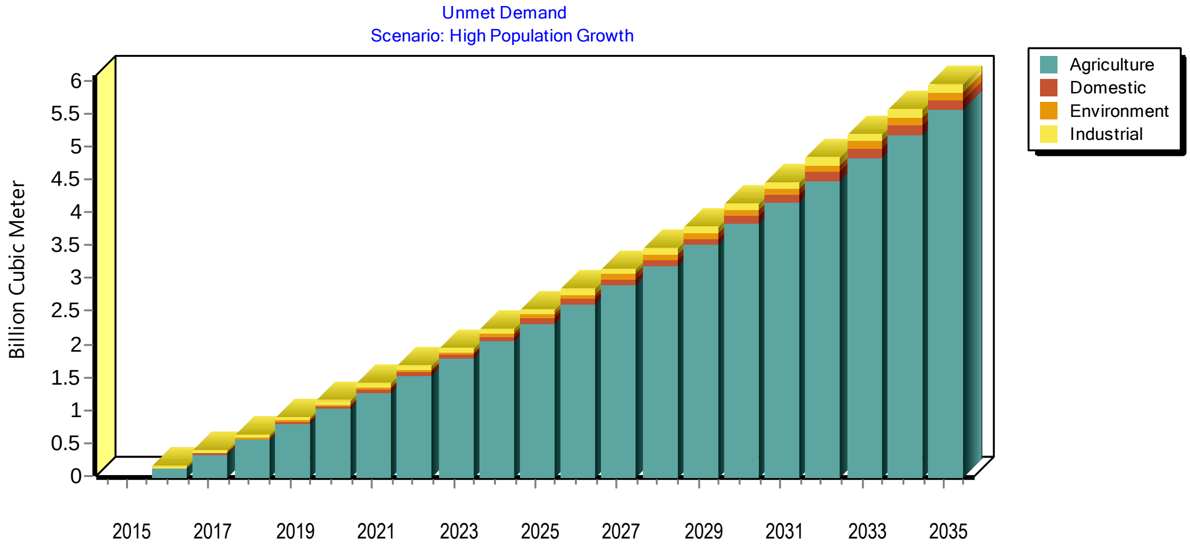

Figure 4. 8: High Population Scenario Unmet Demand

Table 4. 7: High Population Scenario Unmet Demand

Unmet Demand (Billion Cubic Meter)
Scenario: High Population Growth | All Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	0.00	0.14	0.36	0.58	0.81	1.05	1.30	1.55	1.81	2.07	2.35	2.63	2.92	3.22	3.53	3.85	4.17	4.51	4.86	5.21	5.58	52.51
Domestic	0.00	0.00	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	1.51
Industrial	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.08	0.78
Instream Flow	0.00	0.00	0.01	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.11	0.12	1.33
Sum	0.00	0.15	0.39	0.63	0.88	1.13	1.40	1.67	1.94	2.23	2.52	2.82	3.13	3.45	3.77	4.11	4.45	4.81	5.17	5.55	5.93	56.12

4.1.5 High Industrial Scenario

In this scenario, the industrial demand increase was kept in mind, according to the Pakistan GDP survey, Industrial demand can increase up to 3.6%. All the other demands were kept the same as in the reference scenario. This scenario analyzed that Industrial demand can increase up to 50% in the year 2035. The detailed graphs and tables are given in Figure 4.9, 4.10, 4.11 and Table 4.8, 4.9 below.

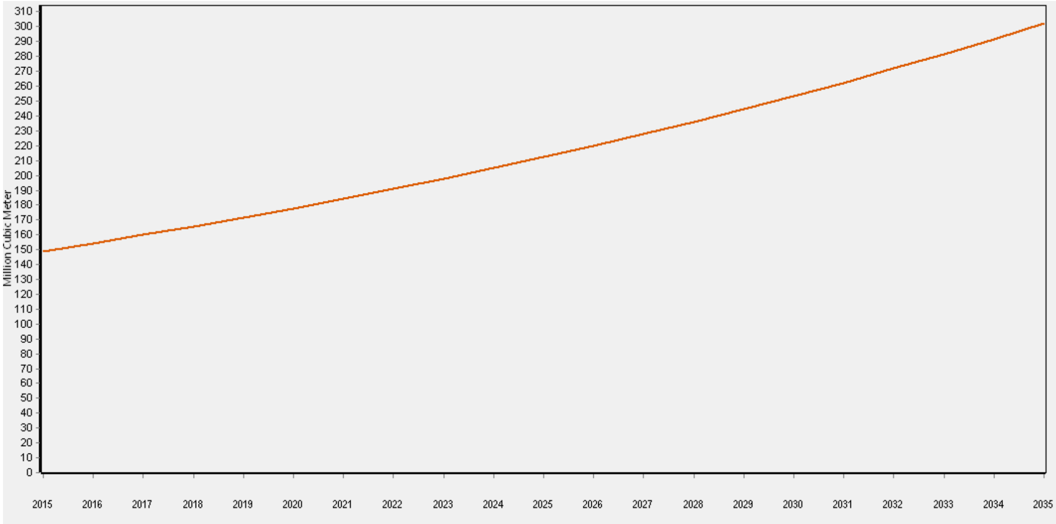

Figure 4. 9: High Industrial Demand

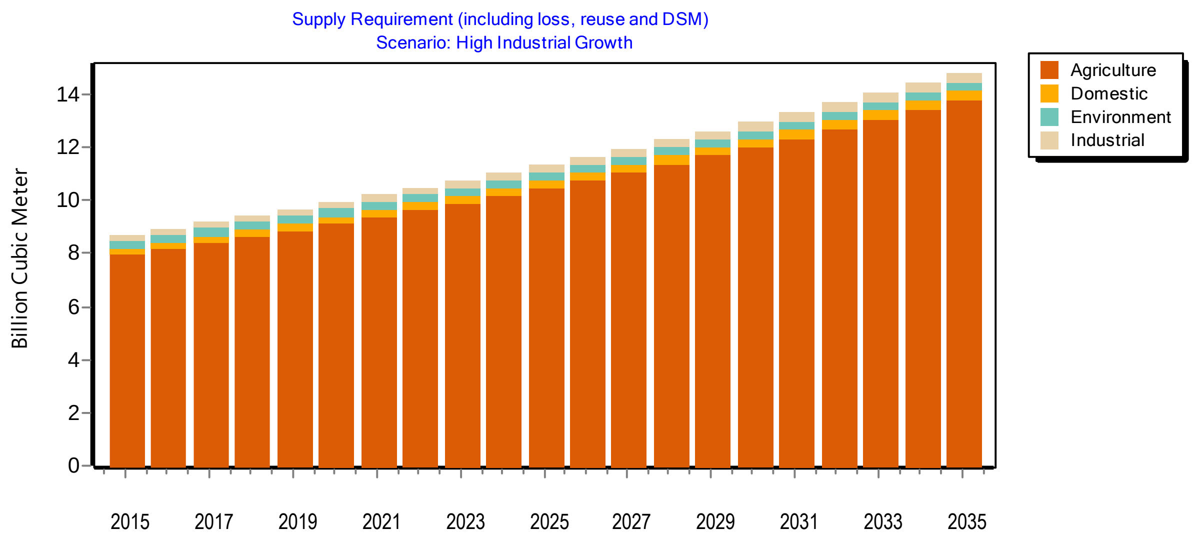

Figure 4. 10: High Industry Scenario Supply Requirement

Table 4. 8: High Industry Scenario Supply Requirement

Supply Requirement (including loss, reuse and DSM) (Billion Cubic Meter)

Scenario: High Industrial Growth | All Branches | Branch: Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	8.02	8.24	8.47	8.71	8.95	9.19	9.45	9.71	9.98	10.26	10.54	10.83	11.13	11.44	11.76	12.08	12.42	12.76	13.11	13.48	13.85	224.38
Domestic	0.25	0.26	0.26	0.27	0.27	0.28	0.28	0.29	0.29	0.30	0.30	0.31	0.31	0.32	0.32	0.33	0.33	0.34	0.35	0.35	0.36	6.35
Industrial	0.15	0.15	0.16	0.17	0.17	0.18	0.18	0.19	0.20	0.20	0.21	0.22	0.23	0.24	0.24	0.25	0.26	0.27	0.28	0.29	0.30	4.56
Instream Flow	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	6.30
Sum	8.72	8.95	9.19	9.44	9.69	9.95	10.21	10.49	10.77	11.06	11.35	11.66	11.97	12.29	12.62	12.96	13.31	13.67	14.04	14.42	14.81	241.59

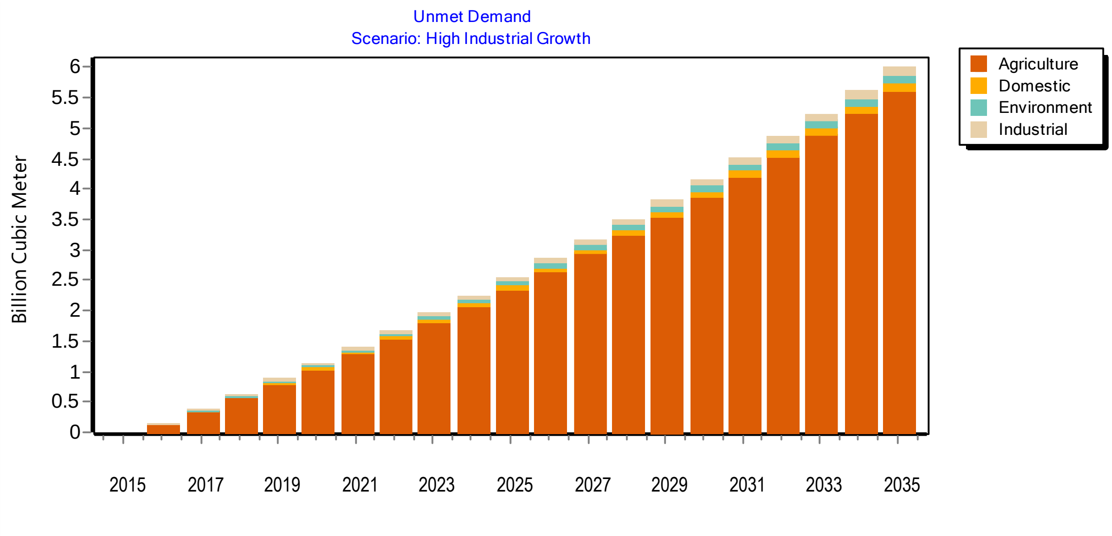

Figure 4. 11: High Industry Scenario Unmet Demand

Table 4. 9: High Industry Scenario Unmet Demand

Unmet Demand (Billion Cubic Meter)

Scenario: High Industrial Growth | All Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	0.00	0.14	0.36	0.59	0.82	1.06	1.31	1.56	1.83	2.09	2.37	2.66	2.95	3.25	3.56	3.88	4.21	4.55	4.90	5.26	5.63	53.00
Domestic	0.00	0.00	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.06	0.07	0.07	0.08	0.09	0.10	0.10	0.11	0.12	0.13	0.14	0.14	1.44
Industrial	0.00	0.00	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.09	0.10	0.10	0.11	0.12	1.09
Instream Flow	0.00	0.00	0.01	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.08	0.09	0.10	0.10	0.11	0.11	0.12	0.12	1.34
Sum	0.00	0.15	0.39	0.64	0.89	1.15	1.41	1.69	1.97	2.26	2.55	2.86	3.17	3.49	3.82	4.16	4.51	4.87	5.24	5.62	6.01	56.87

4.1.6 Low Population and High Agriculture Scenario

Low Population growth was also kept in mind while analyzing the future water demands. The low Population was set as a 1.5% increase in growth annually. And it is compared with the first scenario of high agriculture growth. Both scenarios were compared in this scenario. Details are given below in Figure 4.12, 4.13 and Table 4.10, 4.11.

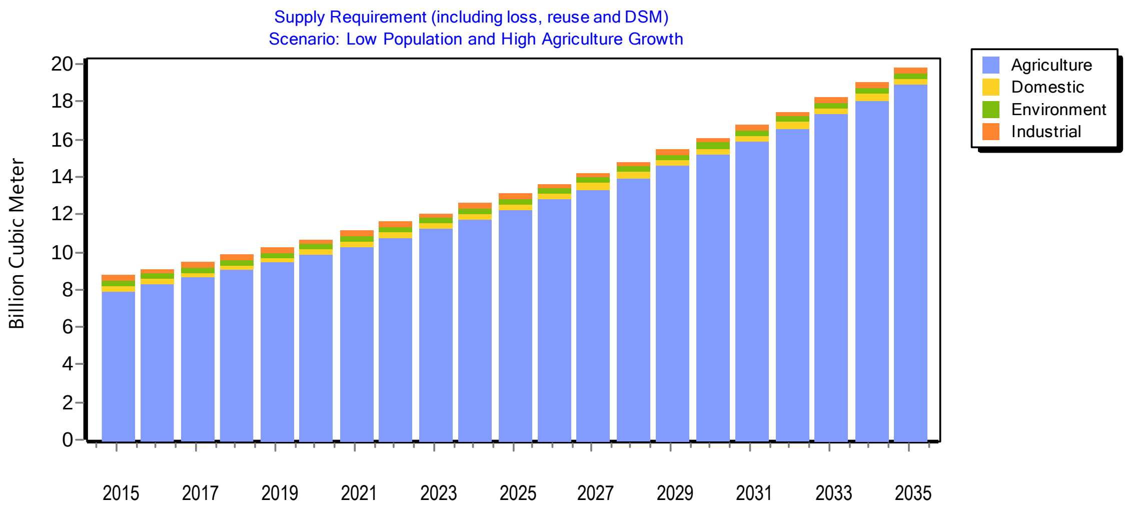

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Figure 4. 12: High Agriculture and Low Population Scenario Supply Requirement

Table 4. 10: High Agriculture and low Population Scenario Supply Requirement

Supply Requirement (including loss, reuse and DSM) (Billion Cubic Meter)
Scenario: Low Population and High Agriculture Growth | All Branches | Branch: Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	8.02	8.37	8.74	9.13	9.53	9.95	10.38	10.84	11.32	11.82	12.34	12.88	13.45	14.04	14.65	15.30	15.97	16.68	17.41	18.18	18.98	267.95
Domestic	0.25	0.26	0.26	0.26	0.27	0.27	0.28	0.28	0.28	0.29	0.29	0.30	0.30	0.31	0.31	0.31	0.32	0.32	0.33	0.33	0.34	6.16
Industrial	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.19	0.19	3.53
Instream Flow	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	6.30
Sum	8.72	9.08	9.45	9.84	10.25	10.68	11.12	11.58	12.07	12.57	13.10	13.65	14.22	14.82	15.44	16.09	16.77	17.48	18.22	19.00	19.80	283.95

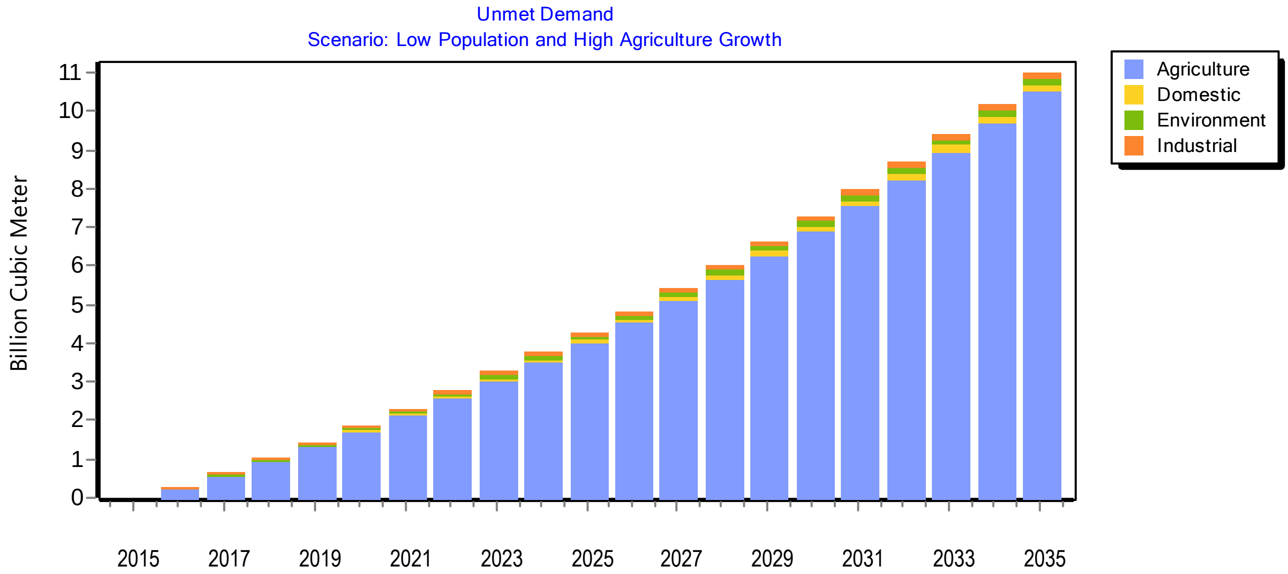

Figure 4. 13: High Agriculture and Low Population Scenario Unmet Demand

Table 4. 11: High Agriculture and Low Population Scenario Unmet Demand

Unmet Demand (Billion Cubic Meter)
Scenario: Low Population and High Agriculture Growth | All Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	0.00	0.26	0.61	0.97	1.35	1.75	2.17	2.61	3.07	3.55	4.05	4.57	5.13	5.70	6.31	6.94	7.59	8.28	9.00	9.76	10.54	94.20
Domestic	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	1.98
Industrial	0.00	0.00	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.07	0.07	0.08	0.09	0.09	0.10	0.10	0.10	1.12
Instream Flow	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.11	0.12	0.13	0.13	0.14	0.15	0.15	0.16	0.17	1.93
Sum	0.00	0.28	0.65	1.04	1.45	1.88	2.32	2.78	3.27	3.77	4.30	4.85	5.42	6.02	6.64	7.29	7.97	8.68	9.42	10.20	11.00	99.23

4.1.7 High Agriculture, High Population, and High Industrial Demand Scenario

This scenario represents the supply requirement and unmet demands of all the demand sites with high annual increases. The annual growth rate of agriculture, population, and industry was entered as 4.4%, 2.2%, and 3.6% respectively. It shows that if all the demands will increase with their high growth rate, then the total water unmet demand can be increased by 80.3% by the year 2035. The details are given below in Figure 4.14, 4.15 and Table 4.12, 4.13.

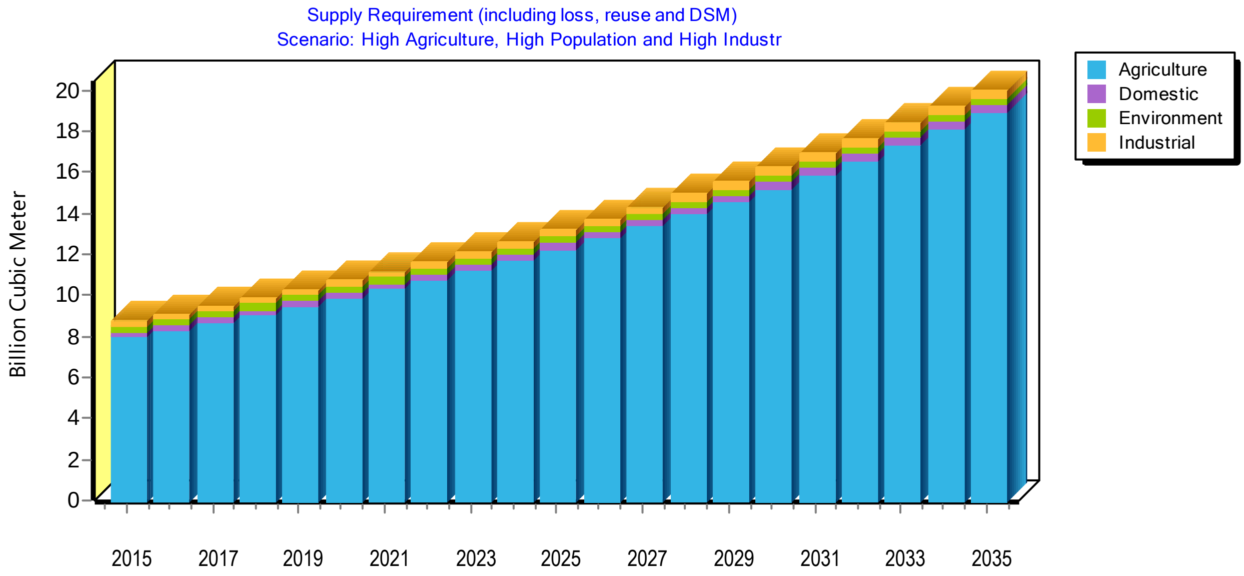

Figure 4. 14: High Agriculture, High Population, and High Industry scenario Supply Requirements

Table 4. 12: High Agriculture, High Population, and High Industry scenario Supply Requirements

Supply Requirement (including loss, reuse and DSM) (Billion Cubic Meter)
Scenario: High Agriculture, High Population and High Industr | All Branches | Branch: Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	8.02	8.37	8.74	9.13	9.53	9.95	10.38	10.84	11.32	11.82	12.34	12.88	13.45	14.04	14.65	15.30	15.97	16.68	17.41	18.18	18.98	267.95
Domestic	0.25	0.26	0.26	0.27	0.27	0.28	0.29	0.29	0.30	0.31	0.31	0.32	0.33	0.33	0.34	0.35	0.36	0.36	0.37	0.38	0.39	6.63
Industrial	0.15	0.15	0.16	0.17	0.17	0.18	0.18	0.19	0.20	0.20	0.21	0.22	0.23	0.24	0.24	0.25	0.26	0.27	0.28	0.29	0.30	4.56
Instream Flow	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	6.30
Sum	8.72	9.08	9.46	9.86	10.27	10.70	11.16	11.63	12.12	12.63	13.16	13.72	14.30	14.91	15.54	16.20	16.89	17.61	18.36	19.15	19.97	285.44

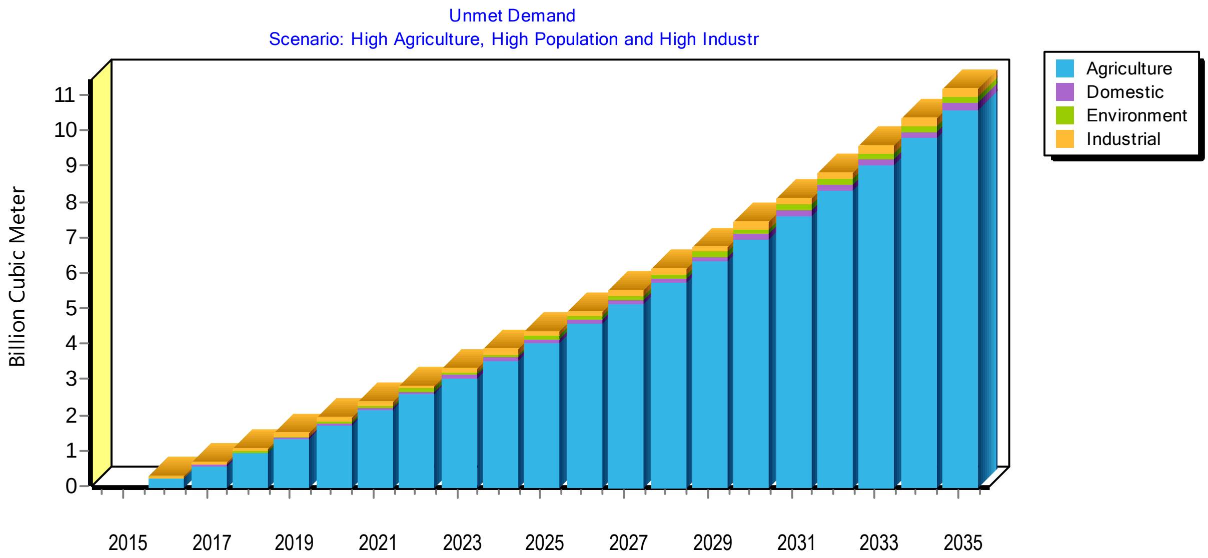

Figure 4. 15: High Agriculture, High Population, and High Industry scenario Unmet Demand

Table 4. 13: High Agriculture, High Population, and High Industry scenario Unmet Demand

Unmet Demand (Billion Cubic Meter)
Scenario: High Agriculture, High Population and High Industr | All Demand Sites | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
Agriculture	0.00	0.26	0.62	0.98	1.37	1.77	2.20	2.64	3.10	3.58	4.09	4.62	5.17	5.75	6.36	6.99	7.65	8.35	9.07	9.82	10.62	95.01
Domestic	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.14	0.15	0.16	0.17	0.18	0.19	0.21	0.22	2.19
Industrial	0.00	0.00	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.11	0.13	0.14	0.15	0.16	0.17	1.57
Instream Flow	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.11	0.12	0.13	0.14	0.14	0.15	0.16	0.16	0.17	1.95
Sum	0.00	0.28	0.66	1.06	1.47	1.90	2.36	2.83	3.32	3.83	4.36	4.92	5.50	6.11	6.74	7.40	8.09	8.81	9.56	10.35	11.17	100.72

4.1.8 All Scenarios

This shows the unmet demands of all the scenarios that have been analyzed in this research. Details are given in Figure 4.16, 4.17 and Table 4.14

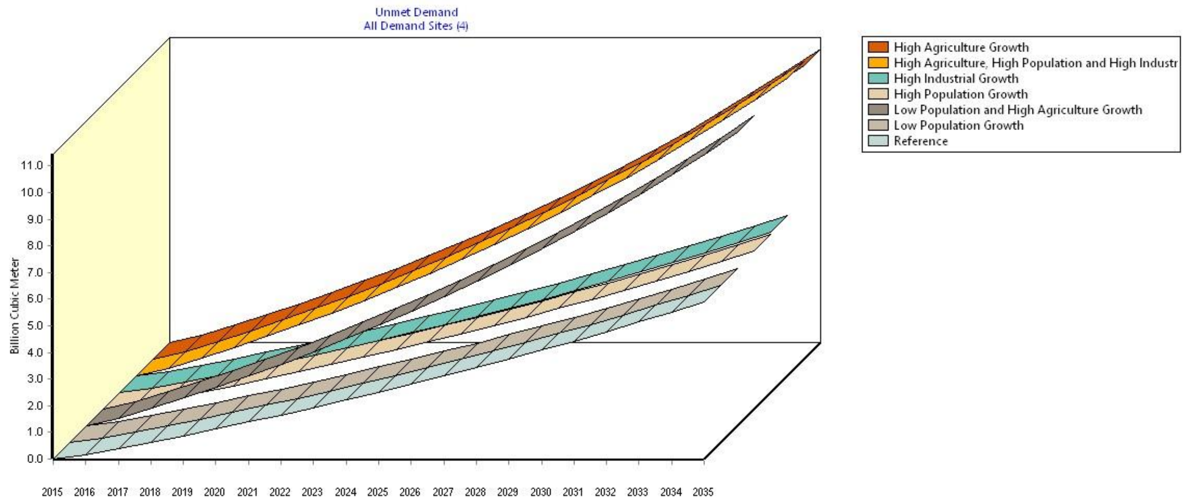

Figure 4. 16: All Scenarios Unmet Demands

Table 4. 14: All Scenarios Unmet Demands

Unmet Demand (Billion Cubic Meter)
All Demand Sites (4) | All Scenarios | No comparison

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	**Sum**
High Agriculture Growth	0.00	0.28	0.65	1.05	1.45	1.88	2.32	2.79	3.27	3.78	4.30	4.85	5.43	6.03	6.65	7.31	7.99	8.70	9.44	10.22	11.02	99.42
High Agriculture, High Population and High Industr	0.00	0.28	0.66	1.06	1.47	1.90	2.36	2.83	3.32	3.83	4.36	4.92	5.50	6.11	6.74	7.40	8.09	8.81	9.56	10.35	11.17	100.72
High Industrial Growth	0.00	0.15	0.39	0.64	0.89	1.15	1.41	1.69	1.97	2.26	2.55	2.86	3.17	3.49	3.82	4.16	4.51	4.87	5.24	5.62	6.01	56.87
High Population Growth	0.00	0.15	0.39	0.63	0.88	1.13	1.40	1.67	1.94	2.23	2.52	2.82	3.13	3.45	3.77	4.11	4.45	4.81	5.17	5.55	5.93	56.12
Low Population and High Agriculture Growth	0.00	0.28	0.65	1.04	1.45	1.88	2.32	2.78	3.27	3.77	4.30	4.85	5.42	6.02	6.64	7.29	7.97	8.68	9.42	10.20	11.00	99.23
Low Population Growth	0.00	0.15	0.38	0.62	0.87	1.12	1.38	1.65	1.93	2.21	2.50	2.80	3.10	3.42	3.74	4.08	4.42	4.77	5.13	5.50	5.88	55.65
Reference	0.00	0.15	0.38	0.62	0.87	1.13	1.39	1.66	1.93	2.22	2.51	2.81	3.12	3.43	3.76	4.09	4.43	4.78	5.15	5.52	5.90	55.85

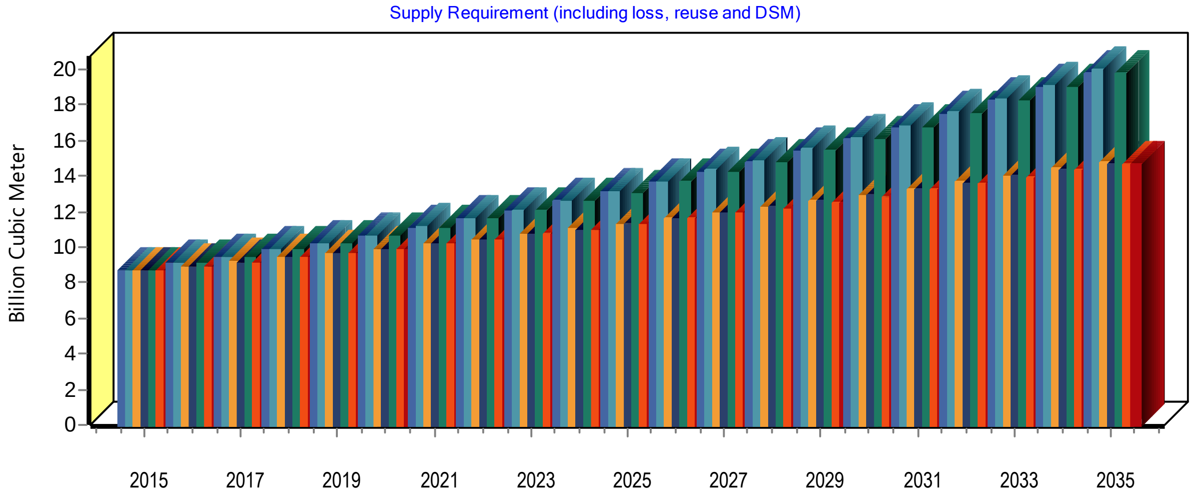

Figure 4. 17: All scenarios Supply Requirements

4.2 NASH BARGAINING SOLUTION RESULTS

Nash Bargaining Solution was used to re-allocate the water in different demand sites using Nash Bargaining Solution. Two periods were kept in mind while solving the Nash bargaining solution. Due to climatic and groundwater conditions, it was assumed that the water supply will remain constant till the year 2035. Few scenarios of Nash Bargaining were generated for the years 2025 and 2035.

4.2.1 Scenario 1 (The year 2025)

This scenario was based on the year 2025 reference scenario generated on WEAP. In this scenario, the weights of each demand side were kept as 1 and a minimum water claim was allotted to each demand site. Keeping in view all constraints of the NBS formula the finalized conclusions of this scenario are given in Table 4.15 and Figure 4.18.

Table 4. 15: Water claims and Allocation Scenario 1, 2025

Demand Site	Water Claim	Water Allocated	Percentage Allocated
	BCM	BCM	%
Agriculture	10.54	8.42	80
Domestic	0.30	0.15	50
Instream Flow	0.30	0.15	50
Industrial	0.17	0.08	50

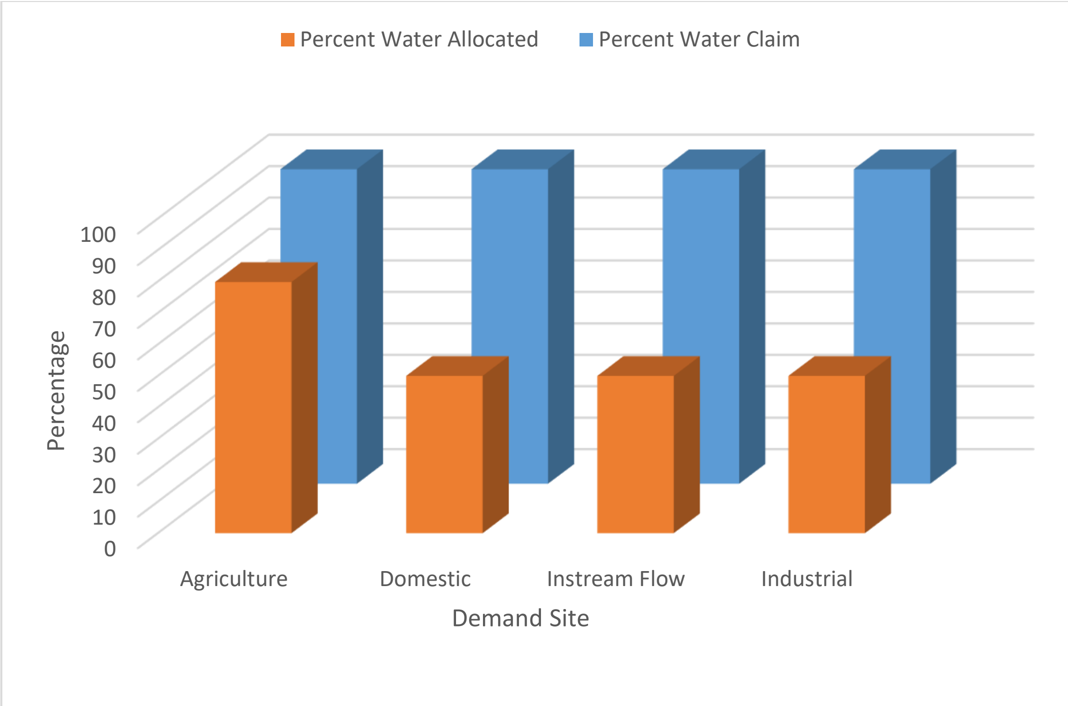

Figure 4. 18: Percent Water claim and allocated Scenario 1, 2025

4.2.2 Scenario 2 (The year 2025)

This scenario was built on the High Agriculture, High Population, and High industrial growth rate scenario of WEAP for the year 2025. In this scenario, the domestic demand site was given priority by changing the weights of the demand sites in the Nash Bargaining Solution formula. The total allocation after optimizing the equation and the percent allotted graph is given in Table 4.16 and Figure 4.19 below.

Table 4. 16: Water claim and allocation Scenario 2, 2025

Demand Site	**Water Claim**	**Water Allocated**	**Percentage Allocated**
	BCM	**BCM**	**%**
Agriculture	12.34	8.23	67
Domestic	0.31	0.31	100
Instream Flow	0.30	0.15	50
Industrial	0.21	0.11	50

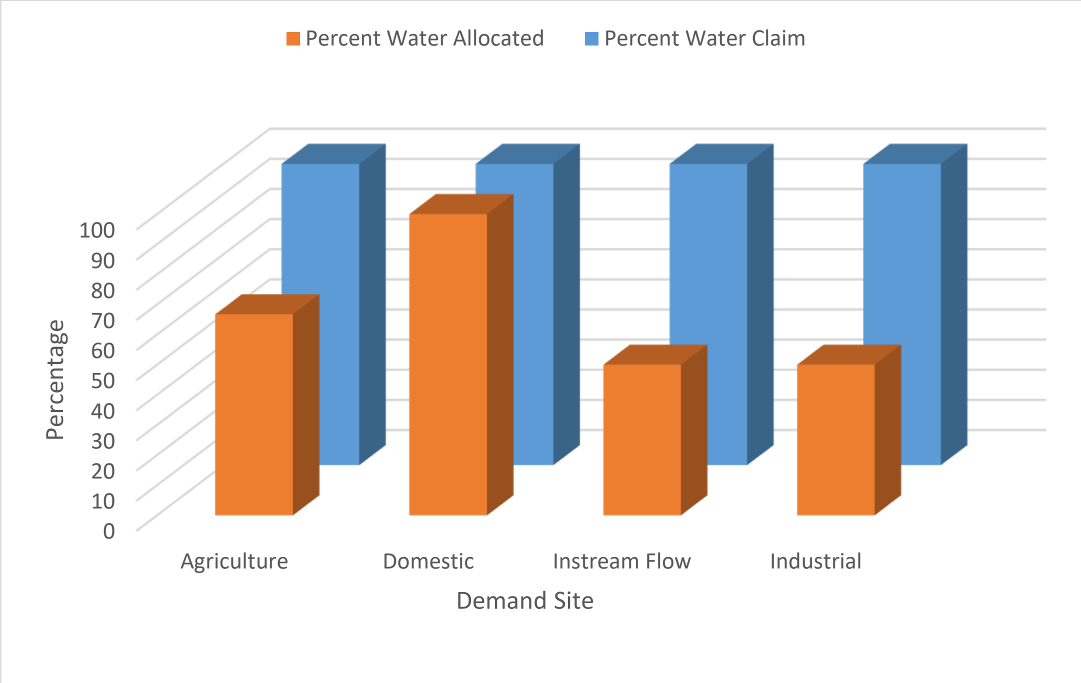

Figure 4. 19: Percent water claim and allocated Scenario 2, 2025

4.2.3 Scenario 3 (The year 2035)

This scenario of the NBS is based on the year 2035 of the reference scenario of the WEAP. In this scenario, the water claims and water allocations for the year 2035 are analyzed. Again, there are no changes in weights and every demand has one priority. The detail of percent allocation and water claims and demands are given in Table 4.17 and Figure 4.20 below.

Table 4. 17: Water claim and Allocated Scenario 3, 2035

Demand Site	**Water Claim**	**Water Allocated**	**Percentage Allocated**
	BCM	**BCM**	**%**
Agriculture	13.85	8.38	60
Domestic	0.36	0.18	50
Instream Flow	0.30	0.15	50
Industrial	0.19	0.09	50

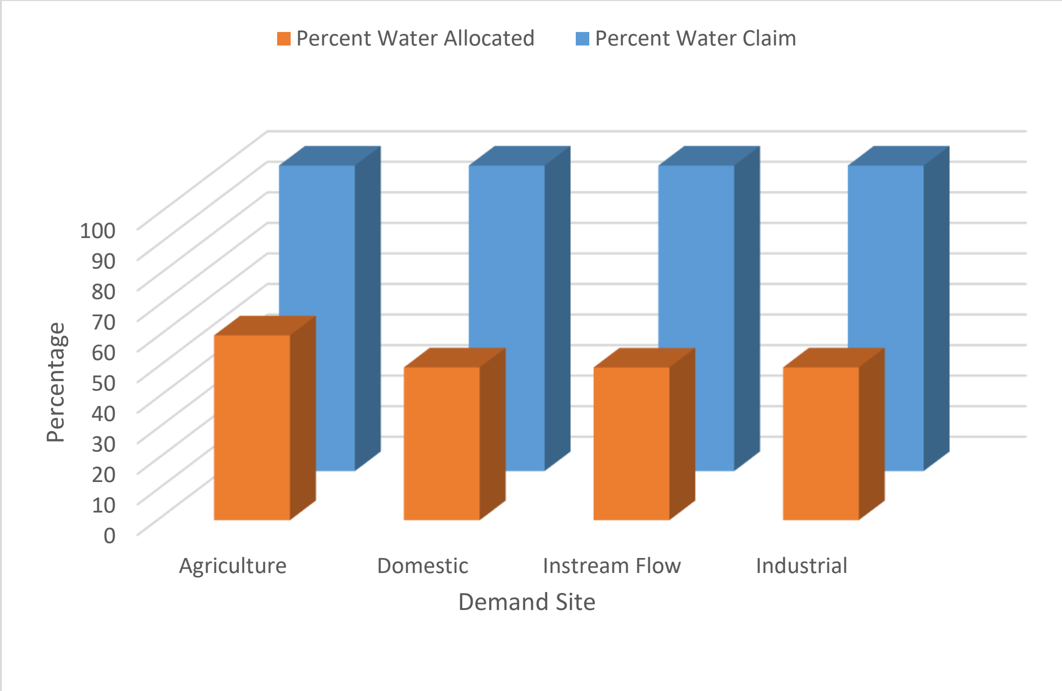

Figure 4. 20: Percent water claim and allocated Scenario3, 2035

4.2.4 Scenario 4 (The year 2035)

This scenario was generated on the high population scenario of WEAP for the year 2035. In this scenario, the weights were assigned, and the domestic demand site was weighed number one priority. The results are given below in Table 4.18 and Figure 4.21.

Table 4. 18: Water claim and allocation Scenario 4, 2035

Demand Site	Water Claim	Water Allocated	Percentage Allocated
	BCM	BCM	%
Agriculture	13.85	8.17	59
Domestic	0.39	0.39	100
Instream Flow	0.30	0.15	50
Industrial	0.19	0.09	50

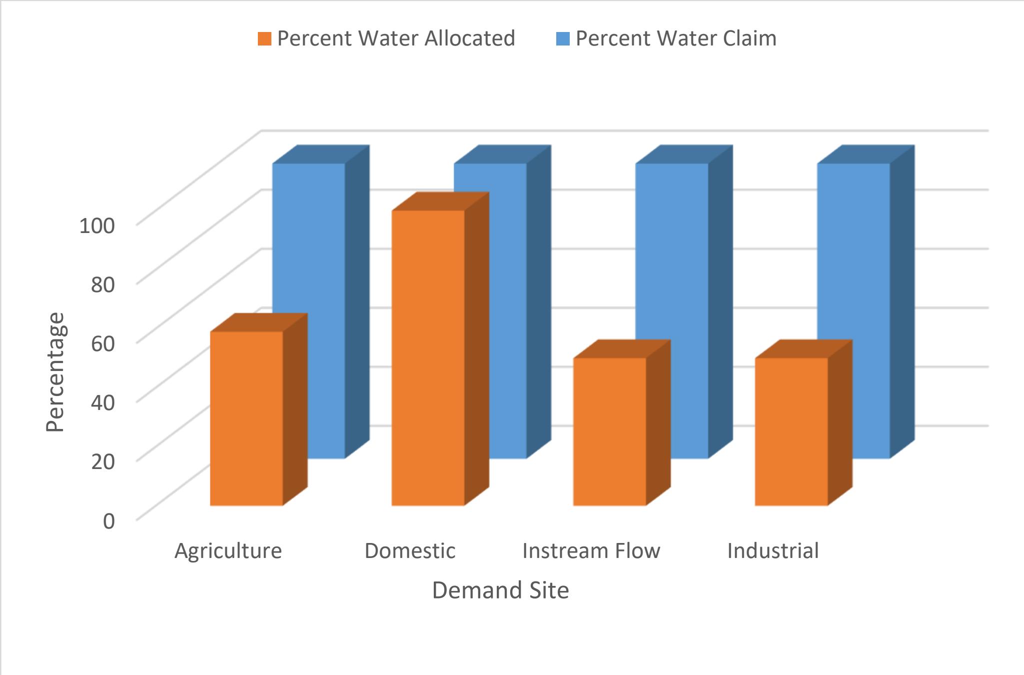

Figure 4. 21: Percent Water claim and allocation Scenario 4, 2035

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This research study aimed to implement the WEAP model on Lower Bari Doab Canal to analyze future water demand and supply in this region. The model was accurate while performing the scenario analyses. The results of the WEAP simulation showed a huge water supply and water demand gap in future years. The water supply was kept the same because in this region most of the demands are fulfilled by the groundwater. The agriculture requirement showed a rising trend due to changes in climatic conditions and less availability of water source. In this study, the water for agriculture was dependent on the evapotranspiration ET. Other demand sites like industrial, instream flow, and domestic also have a huge impact on water supply and coverage.

High-quality management is required to manage the current water availability to demand sites. The scenarios generated in WEAP were developed based on the reference scenario which was created by keeping in view the annual increase rate in the demand of sites. Different scenarios were generated like high agriculture, high population, high industry, and the low population just to the impact of these on the current system.

The increase in demand over years is also dependent on the poor efficiency of surface and groundwater along with poor irrigation efficiency. Water is lost due to poor canal systems in Pakistan. The seepage is far higher in unlined canals than in lined canals. The irrigation efficiency of this system is around 65% to 70%. The groundwater efficiency of the Lower Bari Doab Canal is around 35% to 45%.

The issues related to water allocation have always been an important factor and reason for debate. In this thesis, the Nash Bargaining Solution was also used to address the supply-demand gap generated from WEAP modeling. The Nash Bargaining Solution (NBS) system helps us to allocate the available water resources among different demand sites by keeping in view the claims of each demand site. Apart from only allocating the available water, we can also distribute the resources among the demand sites based on their priorities. This is dependent on how the resource managers wanted to allocate the water.

Different scenarios were also generated for the NBS system, to check water allocation and water allocation percentages for different demand sites. These results imply that the Nash Bargaining solution can concurrently address the supply-demand imbalance and increase benefits for all stakeholders. Nash Bargaining solution is a cooperative problem-solving strategy that involves combined fact-finding and modeling. I anticipate more creative uses for this suggested framework in various studies throughout the globe.

5.2 RECOMMENDATIONS

Based on the finding of this model and the analyses of the scenarios, different strategies are proposed for improved water resource's management. Seeing the high growth rate of demand sites, there can be some practical implementations on groundwater and surface water efficiency.

This study can be carried out on the Rabi and Kharif seasons individually. For better findings of unmet demands of agriculture demand site and better allocation of water resources. The canals can be operated at full supply and a proper reservoir system can be implemented. For rainwater harvesting, small storage can be made to save that water for future use. This study was carried out annually, but it can be done on a seasonal or monthly basis to better find the demand of each site and calculate site claims.

The scenarios generated in this research can be a topic of discussion for the stakeholders of the resource managing team to evaluate the supply and demand gap and issues facing this canal. The same study can be carried out by using climatic scenarios in the same area to better see the effect of climatic parameters on the demand rate.

It is estimated that in future years the groundwater level will be depleted drastically, so proper measures can be followed for recharging the aquifers and increase the groundwater level for future sustainability.

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