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Water Resources and Hydroelectric Power Management of the Indus Basin of Pakistan

by

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Water Resources and Hydroelectric Power Management of the Indus Basin of Pakistan

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To my beloved late father, my mother and my family

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List of Publications

It is certified that following publication(s) have been made out of the research work that has been carried out for this thesis:-

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Abstract

River basin comprises of many complex systems and its complete modeling is a tedious task. It is an active area of research for scientists, engineers and policy makers for past many decades. Many basin models have been developed for world's famous river basins and so is the case of Indus Basin. Indus Basin model was jointly developed by WAPDA and World Bank and went through many iterations and the latest available model is Indus Basin Model Revised 2012. The model has been used for planning water distribution for the Indus Basin for last three decades. It covers not only the cost functions related to consumer producer surplus (CPS), but also the water balance and agricultural scenarios. In the past, it has been employed for climate change impacts of assessment as well. It is useful for analyzing agro-economic scenarios for various purposes including water distribution among provinces. In addition to this, the current IBMR model uses IRSA rules according to 1991 Water Accord for water distribution. In the current research the two areas related to Indus Basin have been investigated and results are compared with existing IBMR-20212. A novel water distribution scheme instead of IRSA rules has been employed for water distribution and effect on basin wide income calculated and observed that basin-wide income increases without any change in infrastructure. For this purpose, a novel approach has been proposed and evaluated with existing IBMR model available with GAMS (General Algebraic Modeling System). Bankruptcy rules (Proportional Rule, Constraints Equal Award Rule, Constraints Equal Loss Rule, Telmud Rule, Piniles Rule & Mianabadi Rule) have been used for canal water distributions and CPS have been calculated. The results show that CPS increases by using newly proposed water distribution mechanism using bankruptcy rules. Secondly, we have incorporated hydropower contribution in Indus basin model objective function using three different scenarios and observed around 6.50% increase in basin wide income without compromising agricultural benefits. In addition to this, energy generation mix for year 2040 has been calculated and observed that hydropower takes the largest share of around 40%.

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Abbreviations

ACZ	Agroclimatic Zone
AEDB	Alternative Energy Development Board
AIS	Agricultural Impact Study
BRW	BLCH Baluchistan rice wheat
CCI	Council of Common Interest
CPS	Consumer Producer Surplus
DNLP	Discontinuous Nonlinear Program
GAMS	General Algebraic Modeling System
GRG	Generalized Reduced Gradient
IBMR	Indus Basin Model Revised
IRSA	Indus River System Authority
IWRM	Integrated Water Resources Management
IWT	Indus Water Treaty
KPKS	KPK Khyber Pakhtunkhwa kabul swat
KPMW	Khyber Pakhtunkhwa mixed wheat
MAF	Million Acre Feet
MDG	Millennium Development Goals
NEECA	National Energy Efficiency and Conservation Authority
NTDC	Nation Transmission and Distribution Company
PCWE	Punjab cotton wheat east
PCWW	Punjab cotton wheat west
PMW	Punjab Punjab mixed wheat
PRW	Punjab rice wheat

PSLM	Pakistan Social And Living Standards Measurement
PSLM	Pakistan Social And Living Standards Measurement Survey
PSW	Punjab sugarcane wheat
RCC	Roller-Compacted Mass Concrete
SCWN	Sindh Sindh cotton wheat north
SCWS	Sindh cotton wheat south
SDG	Sustainable Development Goals
SRWN	Sindh rice wheat north
SRWS	Sindh rice wheat south
TAPI	Turkmenistan Afghanistan Pakistan-India
WAA	Water Appointment Accord
WAPDA	Water and Power Development Authority

Symbols

A	Animal index
a	Intercept
b	Slope of demand supply curve in IBMR
G	Groundwater type index
C	Crop index
D	Total Deficit
E	Total Asset
I	Inflow node index
L	Tolal Loss
M	Index for Month
N	Node or reservoir index
P	Price
Q	Quantity Supply
S	Index for cropping sequence
t	Time
W	Index for water stress
Z	Index for Agroclimatic Zone
α	Control Parameter
β	Upper bound multiplier for constraints
μ	lower bound multiplier for constraints
∇	vector differential operator
λ	Proportional constant
Σ	Summation

$\prod$	Product
η	efficiency

Chapter 1

Introduction

"Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to it. People move when there is too little of it. People move when there is too much of it. People journey down it. People write, sing and dance about it. People fight over it. All people, everywhere and every day, need it."

1.1 Overview

Water is the most essential element of life and it is one of the most scare resource on the earth. Despite the fact that 75% of the world is covered in water, drinking water is extremely scarce. Fresh water constitutes about 2.50% of the whole available water on the Earth. The remaining water other than this is unusable and saline. Unfortunately, most of the fresh water is in the form of glaciers and snow fields. In practice, a very small amount about 0.007% of the earth's water is available for its 8 billion inhabitants [1, 2].

1.1.1 Water Significance

Water is a scarce resource and the lifeblood of agriculture. It has many impacts on individual and society like no others. There is no concept of life without water, hence it has great influence on human's life like a religion or an ideology. Its scarcity and abundance both causes people to migrate. It has socio-economic and political impacts on human society. The total available water on Earth is estimated about 1,123,648,486.599 MAF or 1.386 billion km^3. The estimated volume of saline water is about 97.2% and 2.15% of that total volume being fresh water.

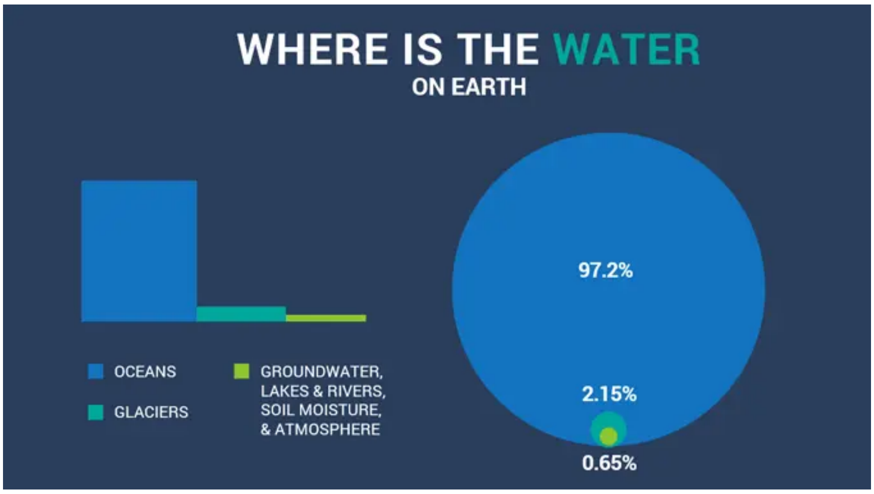


Figure 1.1: World's Water Distribution [3]

1.1.2 World's Major River Basins

The world has 35,409 MAF of total annual available surface water. South Asia has a share of 1544 MAF of average annual surface water which is around 4.454% of the world's surface water. Pakistan's side of Indus Basin has 145 MAF annual average availability of surface water which is around 9.391%.

River basins are the hydrological units of the earth and, as such, are crucial to the natural processes of the Earth. The nation's economy is largely based on its river basins, which are the foundation of its agriculture. There are 263 river basins in the world, ranging in size from small to large, according to Revenga 2016 [5]. The major basins (Amazon, California, Colorado, Congo, Danube, Ganga-Brahmaputa, Mekong, Missisipi, Murray-Darling, Nile, Indus, and Yangtze) were

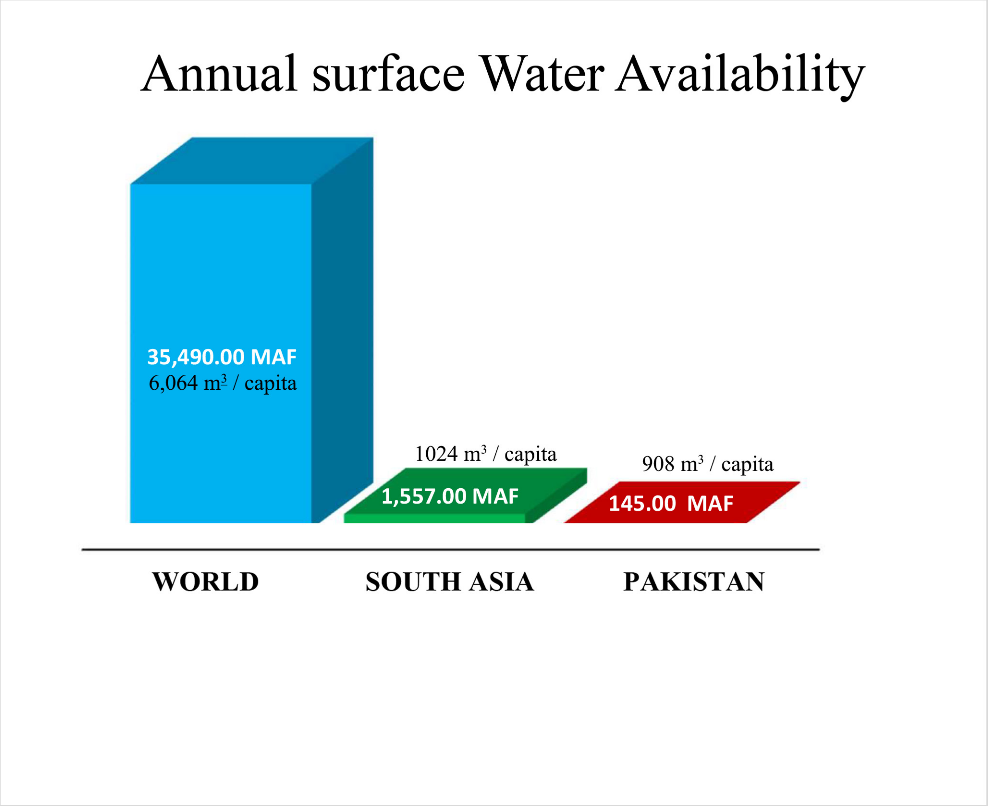


FIGURE 1.2: World's Surface Water Availability [4]

discussed by Venkat Lakshmi and colleagues in relation to precipitation, vegetation, evapotranspiration, total water, soil moisture, and runoff, as well as their variations and effects on the basins' economies. Three out of every four jobs are dependent on water globally, according to the UN Global Water Development Report 2016 [6–8].

1.2 River Basin Model

A mathematical model that illustrates a group of procedures used to predict how the basin will behave under various management scenarios is known as River Bsin Model. It assists policymakers in prudent water distribution among various users and sectors [9, 10].

The following are the main concerns shared by different river basin users:

- Resources allocation for water

- Keeping water quality intact
- Exponentially increasing demand

1.2.1 Basin Modeling Frameworks

Some major basin modeling frameworks with their brief introduction are given below:

- Indus Basin Model Revised (IBMR):The Indus Basin Model Revised (IBMR), a hydro-economic optimization model, is used to schedule agricultural investments across Pakistan's provinces. To explore the effects of climate change on water allocation and food security, this paper covers IBMR-2012, an update and modification of the model that takes into consideration the current agro-economic circumstances in Pakistan. Included are the findings of hydroclimatic parameter sensitivity studies and the effects of climate change on agricultural output at the provincial and basin levels.
- Indus River System Model (IRSM):The model was jointly developed by Sustainable Development Institute of Pakistan (SDPI) and Common Wealth Scientific and Industrial Research Organization (CSIRO) , Australia. The eWater Source modeling system was used to create the Indus River System Model (IRSM). By outlining both the physical and water-sharing systems on a daily time step, the IRSM reflects the Pakistan Indus Basin Irrigation System (IBIS). A complicated node-link network that starts at rim stations and includes the Ghazi-Brotha scheme, two significant supply reservoirs (Tarbela and Mangla), 16 barrages including Chashma) 14 major link canals, 73 irrigation sub canals, and associated irrigation demands terminating below the Kotri barrage, are used to describe this complex physical system. The model takes flow routing and distribution losses, as well as significant supply reservoir sedimentation over time. The Tarbela, Mangla, Ghazi-Botha project, and hydro capable barrages are additional sources of energy taken into account by the model [11].

- The Model for Energy Supply Systems And their General Environmental impact (MESSAGE):A modeling framework for developing scenarios, analyzing energy policies, and planning medium- to long-term energy systems. The construction of energy scenarios and the identification of socioeconomic and technological response plans to these difficulties have both benefited greatly from its adaptable framework for the comprehensive assessment of significant energy concerns. Integration of sectoral models is a crucial issue if big global challenges are to be addressed holistically. In order to evaluate significant interrelations and feedback, tools for energy supply, demand, and end-use analysis, as well as analytical representations, have been more frequently either properly integrated or linked with MESSAGE.

- Computable General Equilibrium for Water (CGE-W):The CGE-W model framework incorporates the component of water in a country's general equilibrium model, without making the standard model trade-offs associated with conventional economic models that contain in a simplified way. In an ensemble of stochastic climate change scenarios, the model assesses the economic benefits of adding new dams to the system and shows empirical results for various drought scenarios. Future improvements will incorporate the advantages of hydropower and the inclusion of the effects of recurring floods on infrastructure [12–14].

- Regional Water System Model (RWSM): A regional water system model and a dynamic, economy-wide Computable General Equilibrium (CGE) model make up the Linked Model System. With a focus on water shocks like droughts, the combined CGE-W model is applied to Pakistan in order to examine the effects of changes in water resources on the entire economy. The effects of water stress on agricultural productivity are included in the CGE-W model, which is spatially disaggregated with a variety of crops [15].

- Basin Wide Holistic Integrated Water Assessment (BHIWA): The issue of Water resources and their management has always been a burning topic among policymakers. Different countries have different policies to cater to the water issues- the core element for the survival of all living creatures. The International Commission on Irrigation and Drainage (ICID) launched the Country Policy Support Program (CPSP) sponsored by The Netherlands Government, aiming at generating effective options for water resources development and management. The main objective of CPSP is to attain a reasonable food security level in less developed countries by viable rural progress. A customizable tool was required by policymakers and other professionals who wished to forecast water scenarios at the basin level. The purpose of this tool was to simulate various policy alternatives for utilizing water and other natural resources. It led to the conception of the Basin Wide Holistic Integrated Water Assessment (BHIWA) model. The model takes into consideration all water uses and examines the complete water cycle. It aims at dealing with the entire land phase of the hydrological cycle, from precipitation to evapotranspiration, and outflow to sea, including withdrawals and returns. The range of the model is basically the Basin level but aggregated results make it possible to assess the water situation at regional, country or global scale. The model gauges the effects of water policies for past, present and future frameworks dealing with changes in sector demand and climate. The model provides for a maximum of 5 sub-basins and 25 parcels within sub basins. A maximum of 10 scenarios can be studied at a time. The socio-economic and environmental aspects of the model will be developed in a further phase. The major advantage of the model is its pliability allowing representation of changes in land use and of human involvement through irrigation [16].

1.3 Pakistan's Water Sector

Pakistan is ranked as one of the highly water scarce country in the world as per Business Recorder Report 2021. Per capita water availability has been decreased from 5,260 cubic meter per year in 1952 to 908 cubic meter per year in 2021. India stopped Pakistan's water in 1948 affecting about 1.7 MAF of field. The water was restored through interim agreement on payment- Pakistan's stand was that existing uses should be protected. Additional water to be divided according to future irrigation potential and population etc. India's stand was that Upper riparian had the prior right.

River basin management is one of the most challenging and complex problem and Indus Basin in this regard is no exception. Indus Basin constitutes the world's largest canal network. It comprises of three large storage reservoirs Mangla, Tarbela and Warsak dams. Indus basin has a very important and strategic demographic location in the world. It's a unique basin which is spread over four countries namely China, India, Pakistan and Afghanistan. Water is main source of tension between Pakistan and India and consequently impacts the relationship of two countries. The progress, peace and development heavily depend in South Asia between the relationships of these two countries. It also impacts the other countries in the region. So India and Pakistan's social, political and economic stability depends on peaceful resolution of water conflict. Similarly, the fair resolution of water conflict among the provinces of Pakistan is the key to prosperous Pakistan. The fair resolution of this issue will also increase the confidence among the provinces and lead to more trustworthy relationships [17].

Indus Basin is a life line of country and any contribution to it will serve directly or indirectly to country. The rainfall constitutes about 25-35 % of the surface water, Snow and Glacier melt contributes to 65 to 75 %, Surface flows about 166.6 MAF and 50 MAF water from Ground Water extraction.

Indus basin is a trans-boundary basin and spans the four countries of the region namely Pakistan, India, China and Afghanistan. Pakistan has the lion share of about 250,000 km^2 in terms of area where as Afghanistan occupies about 72000 km^2.

1.3.1 Per Capita Water Availability

Per Capita water availability has significantly decreased from $5000cm^3$ to less than $1000cm^3$. After Ethiopia, Pakistan is considered one of the most stressed water

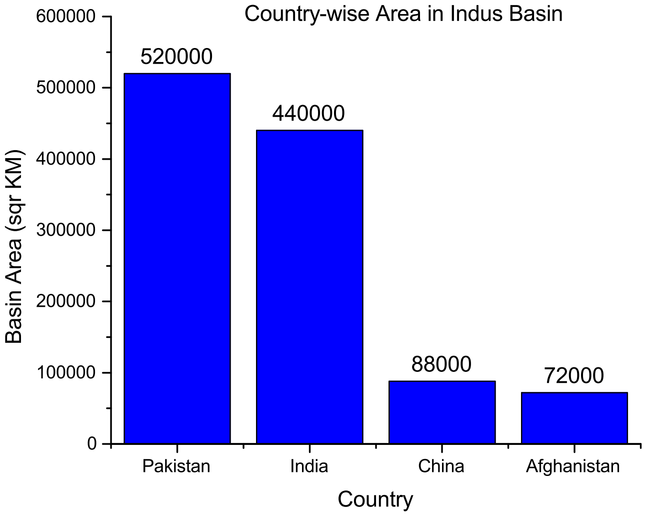


FIGURE 1.3: Country-wise Area in Indus Basin [18]

country as shown in the figure 1.4 below:

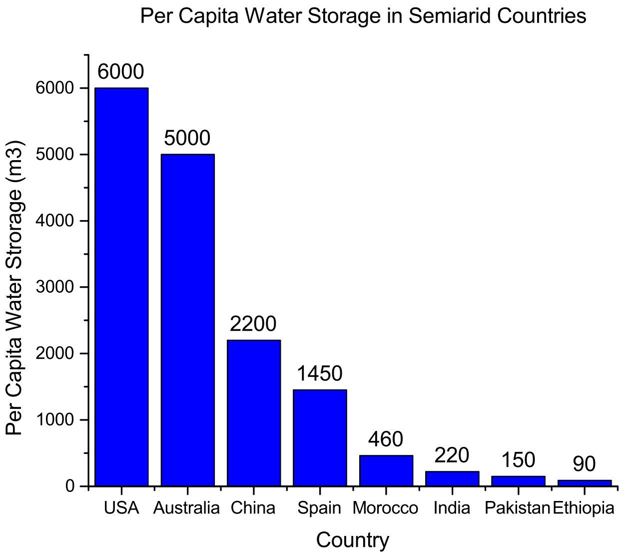


FIGURE 1.4: Per capita water storage country wise [19]

1.3.2 Water Availability vs Population

Water availability vs Population is also of great concern for a country like Pakistan where per capita water availability is decreasing exponentially with increasing population. Figure 1.6 shows the water availability vs Population.

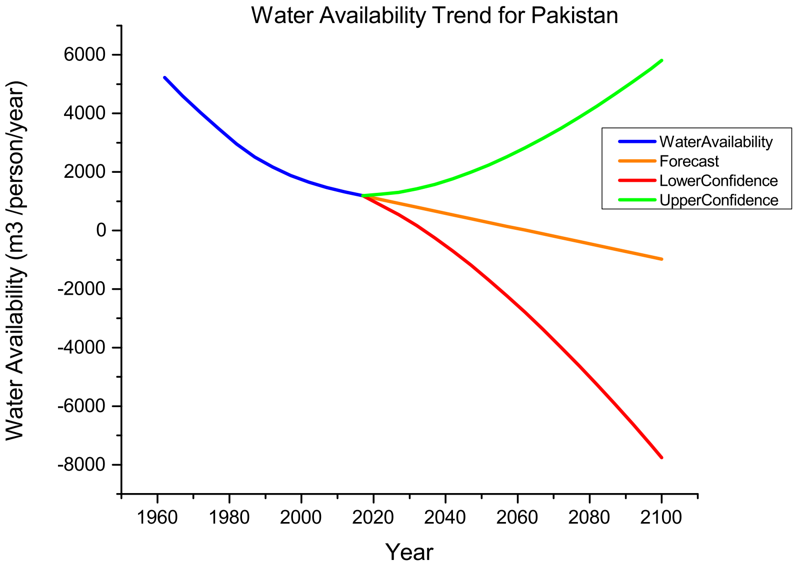


FIGURE 1.5: Historical Water Availability and Future trends [20]

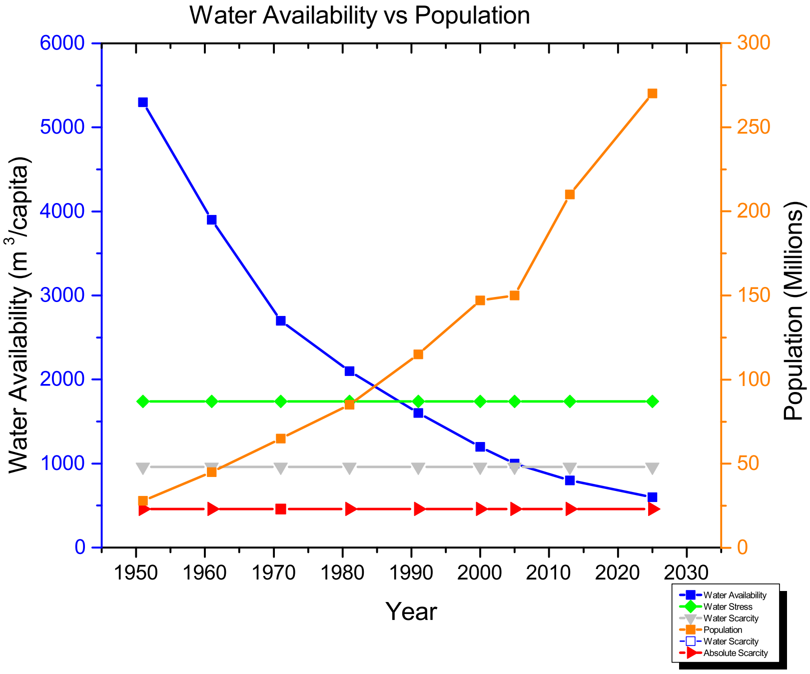


FIGURE 1.6: Water availability vs Population [21]

1.3.3 Pakistan's Water Budget and Associated Problems

Pakistan might experience a severe water shortage in 2025. Pakistan must adopt a logical, politically unbiased, comprehensive water policy that reflects its priorities of development and growth in order to prevent this result. The issue is not a lack of water; rather, it is poor management of water resources. The figure 1.7 shows the total annual available water, total losses, annual rainfall and ground water contribution:

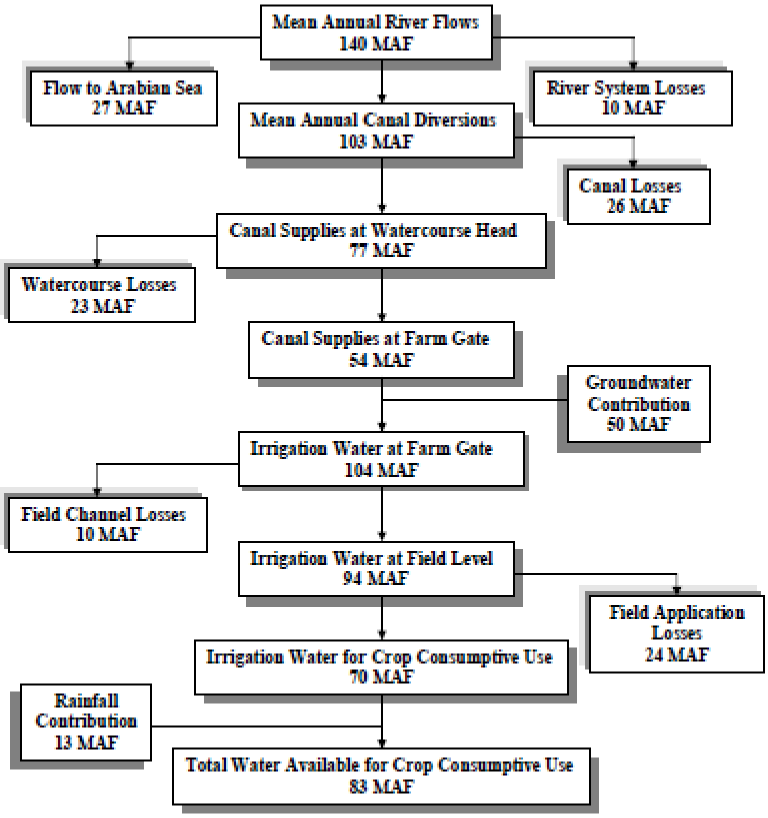


FIGURE 1.7: Pakistan's Water Budget and associated problems [22]

1.3.4 Rivers and Canal Discharges of Pakistan

The figure 1.8 shows the canal discharge diagram of Indus river and its associated canals:

1.4 Indus Water Treaty

Water is one of the major cause of strategic tension between Pakistan and India. India stopped Pakistan's water in 1948 affecting 1.7 MAF of land and threatened millions of lives. Water was restored through the interim agreement and situation

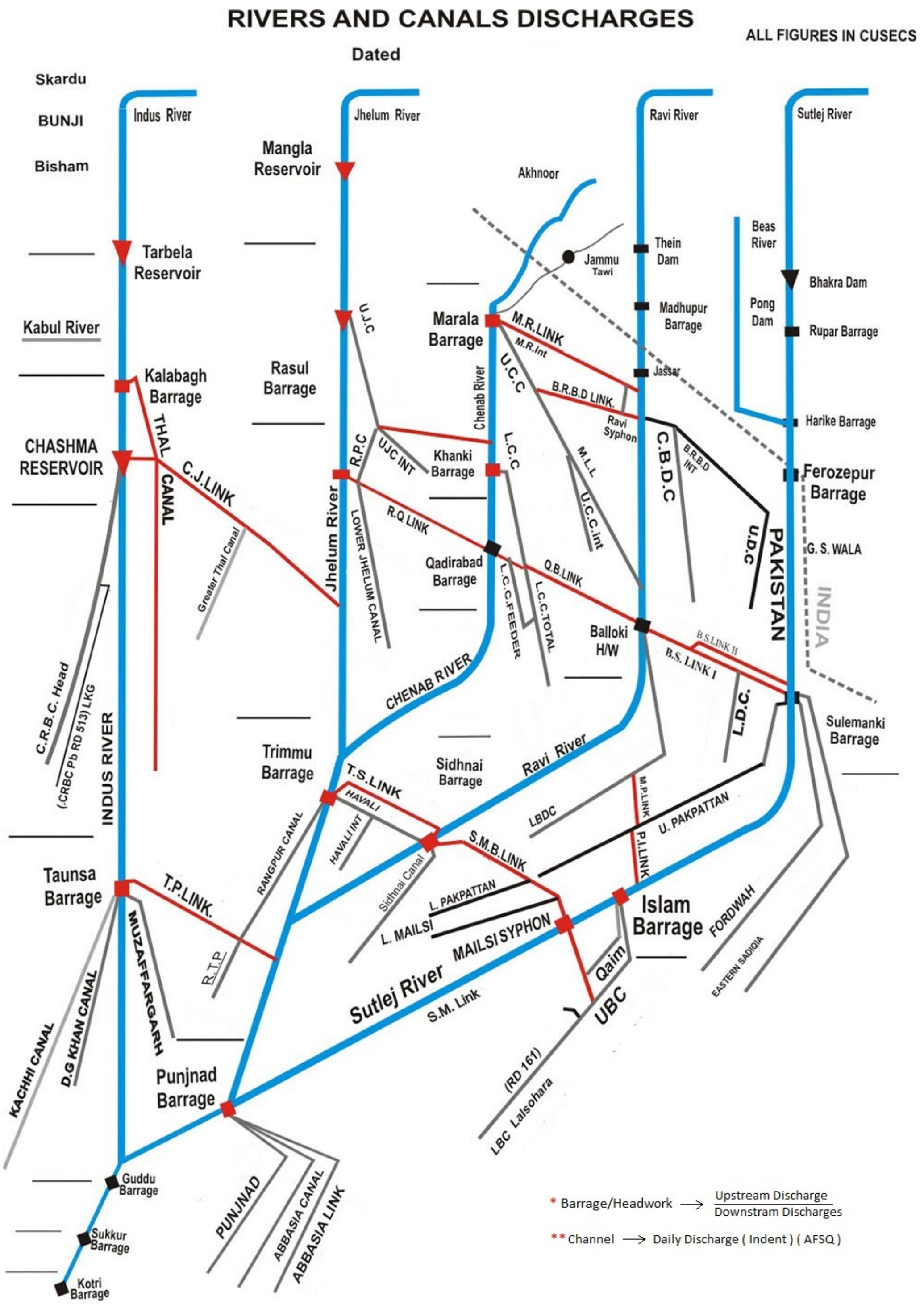


FIGURE 1.8: Rivers and Canal Discharges of Pakistan [23]

remained tense until 1961 as both the countries agreed upon an agreement called The Indus Water Treaty [24]. Pakistan is facing not only trans-border water conflicts but also inter-provincial ones. Water distribution among provinces remained a source of tension among the provinces until Provincial Water Accord 1991.

1.4.1 Indus Valley Civilization

The Indus Valley Civilization, which dates back to roughly 2600 BCE, is one of the oldest civilizations ever. It is also known as The Harrapan civilization after the village name Harrapa situated now in Pakistan alongside the Indus River Bank. It is also famous because of the two well-known cities Harappa and Mohenjo-daro. These cities were the most modern cities of their time due to their infrastructure and planning. It's also included in cultural heritage of UNESCO.

1.4.2 The River Indus

Indus is a trans-boundary river which spans among the four countries namely China,India, Pakistan and Afghanistan. Its total length is about 3200 KM and is the largest river of Pakistan. It is regarded as 21^{st} largest river in the world w.r.t annual flow. About 60% of it falls in Pakistan and Azad Kashmir , about 10% in Tibet , 25% in India and Indian Occupied Kashmir, around 5% in Afghanistan. The primary sources of water for the Indus system are the snow and glaciers found in the Himalayas, Karakoram, and Hindu Kush mountain ranges. The Upper Indus Rivers receive approximately 80% of their water from Himalayan glaciers. The Indus system is home to a variety of aquatic life, including 25 amphibian species and 147 fish species, with 22 of them being exclusive to the region. Additionally, the Indus river is of great importance as it provides essential water resources to the Punjab and Sindh plains [25].

1.5 The Indus Basin Model

Indus Basin has a unique and interesting composition. Its total area is about 1120000 square kilometers which constitutes about 54% of the Southeast Asia. It runs through four countries namely Pakistan, India, China and Afghanistan with area of 520,000, 440,000, 88,000 and 72,000 square kilometer respectively (Aquastat survey 2011). The broad agribusiness and water system framework, alluded to as the Indus Basin Irrigation System (IBIS). This is the biggest bordering water system framework on the planet. The normal yearly stream of Indus bowl is around 146 MAF. It has 2 noteworthy capacity repositories specifically Mangla and Tarbela. It consists of 19 barrages, 12 interface canals, and 45 noteworthy canal commands areas. The aggregate length of canals is around 60,000 km and around 120,000 watercourses to irrigate farms. It inundates 16.2 million hectare and contributes about 25% of GDP. Wins about 70% of the export income and utilizes 50% of the workforce straightforwardly and another 20% in a roundabout way. Indus Basin Model Revised (IBMR) is a Basin wide numerical programming model, written in General Algebraic Modeling System (GAMS). The Indus stream framework comprises of the fundamental Indus River and its significant tributaries: The Kabul, Jhelum, Ravi, Sutlej and Chenab [26].

Indus Basin Model is developed by the World Bank to address the water dependent economy of Pakistan. The data used for calculations are obtained from Indus Basin Model Revised 2012(IBMR2012) jointly developed by WAPDA and World Bank. The conceptual model is given below:

Figure 1.9: Conceptual Model of IBMR2012

There are around 280 plus river basins in the world. River basin is a complex system and consists of many subsystems and modeling entire river basin takes lot of efforts and assumption. Many river basin models have been developed and used to assess basin-wide Precipitation, Vegetation, Evapo-transpiration, Total Water, Soil Moisture and Runoff and their variations and impact on the basin's economy. Johannes BISSCHOP and et al. discussed the Indus Basin Model in context of bi-level linear programming. Indus Basin Family has been discussed and a high level Indus Basin Model description along with some assumptions have presented. Instead of presenting mathematical details of IBMR, the author focused on the multi-decision making aspect of model and posed the problem as hierarchical decision making problem. The problem of Basin has been presented as the nested optimization problem and hence choose to solve using multi-level programming problem. The goal was to maximize the overall Basin income aggregating the 53 individual polygon incomes using multi-level programming [27, 28]. G. T. O'Mara and et al. described conductive use and discussed its inherent dynamic nature. In this paper, the Indus Basin Model (IBM) family, structure, model validation and simulation results to access the conjunctive use in Indus irrigation system for alternative policies have been discussed in detail. In addition to surface and ground water, behavior of aquifer has been addressed. The main focus of the paper was an economic evaluation of Indus Basin for policy makers [29]. Ahmad and et al. prepared a report to assess impact of the Kalabagh Dam on Pakistan's Agriculture sector. The Agricultural Impact Study (AIS) was launched in September 1985 and first draft was completed in July 1986. The AIS team was comprised of Alexander Meeraus, Chief, DRDSU/World Bank ,Mr. Masood Ahmad (DRDSU/World Bank), and Messrs. The detailed analysis and impact assessment of Kalabagh was performed using Indus Basin Model Revised. The report contains all the data and listing of GAMS used to access the agricultural impact of Kalabagh Dam. The report provides good idea of addition/assessment of new dam to be evaluated/incorporated within Indus Basin [30].

1.6 The Sustainable Development Goals

The Global Goals, also known as the Sustainable Development Goals (SDGs), comprise a set of 17 interconnected worldwide objectives that aim to create a blueprint for a more sustainable and better future for everyone. In 2015, the United Nations General Assembly (UN-GA) developed the SDGs as part of the Agenda 2030 plan, with the goal of accomplishing them by 2030. The SDGs were created to replace the Millennium Development Goals, which were completed in 2015, and are part of the Post-2015 Development Agenda [31]. In the current research, a road map to SDG 7 has been presented for an energy sustainable Pakistan. A high picture of all 17 goals is given in figure 1.10.

FIGURE 1.10: The Sustainable Development Goals [31].

1.7 Motivation

One of the biggest motivations behind this research work is that it relates to our country's one of the most important and pressing hot issues that has a direct impact on the country's economy. Any contribution in this context directly or indirectly leads to the country's benefit. As the population is increasing, the demand for water is also increasing in both domestic and agricultural use, so there is a need for an efficient water allocation scheme. As electricity prices are increasing due to high fuel costs, there is a need to exploit hydropower more effectively. The multi-disciplinary nature of the problem (economics, hydrology, electrical, and civil engineering) makes it more interesting as well as challenging.

It covers the whole of the Pakistan's side of Indus basin and its modeling forms a complex optimization problem with a large number of real-world constraints.

1.8 Research Objectives and Significance

The need of power is increasing exponentially due to rapid urbanization and industrial growth. Despite the effort from the government to attract the investment in the power sector, cost of power for consumer is still high. Hydro power is a cheaper solution but it heavily depends on available water indent for power generation. Hydro-Thermal Coordination could be a better option to overcome high production cost. The main objective of this research is to maximize the basin wide consumer producer surplus by incorporating hydropower contribution under real world constraints.

1.9 Thesis Organization

The remaining chapters of the thesis are as follows:
Chapter 2: Describes the extensive literature review. The literature review covers the Indus Basin, the Indus Basin Model and its family, research gap based on literature review, research objective and problem statement.
Chapter 3: Focuses on the Indus Basin of basin, its climatology, major reservoirs, irrigation canals system, water resources management, agro-climatic zones, historical development of the Indus Basin Model (IBM), inputs, objective function, water balance at zone, introduction to GAMS and implementation of IBMR in GAMS.
Chapter 4: Provides detailed analysis of optimization of Pakistan's Water Economy using Hydro-Economic Modeling. A novel water distribution scheme has been presented using various bankruptcy rules like Proportional Rule (PR), Constraint Equal Award Rule (CEA), Constraint Equal LOSS Rule (CEL), Talmud Rule

(TR), Piniles Rule (PR), Hojjat Mianabadi (MIA) to optimize the basin wide income. A both qualitative and quantitative analysis was performed to augment the proposed water allocation scheme in comparison to IRSA rules

Chapter 5: Dedicated to the roadmap to an Energy Sustainable Pakistan focusing on SDG7. The objective function of existing IBMR-2012 has been modified by introducing a control parameter α for water allocation to both power and agriculture sector. In addition to that, hydropower electric power income has been incorporated in objective function of existing IBMR. Different execeedance probabilities are used for inflows calculation and basin wide income has been calculated using the inflows. Three scenarios have been developed and investigated with newly proposed objective function. The energy mix by year 2040 has been calculated and found that hydropower will have a major contribution of about 40% by year 2040.

Chapter 6: Covers the discussion and related results.

Chapter 7: Concludes the thesis along with future work recommendations.

Chapter 2

Literature Survey, Gap Analysis, and Problem Formulation

"I'm afraid because I feel as though I'm being enveloped in a limitless expanse of unknown spaces. I'm alarmed by the places' inescapable quiet. Find someone else to assist you in your research on numbers by looking elsewhere. I admit that they are far superior to me, and all I can do is appreciate them."

Blaise Pascal

2.1 Literature Review

The literature review of this thesis is two fold. The first part discusses the general review of the Indus Basin of Pakistan and in the second part Indus Basin Model has been discussed and comparative analysis of Indus Basin Model (IBM) and Indus Basin Model Revised (IBMR) has been performed.

2.1.1 Introduction

Water is the most essential element of life and it is one of the scarcest resources on the earth. Although the 75% percent of the earth is water but drinking water is very rare. Fresh water constitutes about 2.50% of the total available water on the planet Earth. The remaining water other than this is unusable and saline. Unfortunately, most of fresh water is in the form of glaciers and snow fields. In practice, a very rare percentage about 0.007 of the total earth's water is available to its 8 billion consumers [2].

Water is the quintessence for life. It has been common knowledge that water sustains life since dawn of civilization. However, in the recent years, the notion of what could be the applications of water has evolved. The relationship between electricity and water is the extension of one of the many diverse properties of water. Electricity - though not invented long ago - has now become a major need of life. From central heating and cooling systems to bullet trains as daily commutes, electricity has paved its way in all walks of life. River basins are the planet's hydrological units, and they play a crucial role in the planet's natural functioning. These river basins play a critical role in agriculture and contribute significantly to the economy. The world has a total of 263 river basins, varying in size from small to medium to large [5]. Venkat Lakshmi et al. [6] discussed the 10 major basins namely Amazon, California, Colorado, Congo, Danube, Ganga Brahmaputa, Mekong, Mississipi, Murray-Darling, Nile and Yangtze in context of precipitation, vegetation, evapotranspiration, total water, soil moisture and runoff with reference to their variations and impacts on the basins economy. Basin model is used to represent the relevant processes in a river basin, predicts the behavior of the basin under different circumstances or management scenarios and helps decision-makers to make rational water allocation among various users and sectors. The key issues for river basins users include water resources allocation, maintaining water quality, and rapidly growing demand [7, 8].

Hydropower dam building has increased dramatically around the globe in recent years. Currently, there are at least 3,700 large dams with installed hydroelectric capacities of more than 1 GW that are either being planned or built, primarily in developing countries. For instance, 278 dams are now being built, largely in the Balkans, out of 8,507 planned dams for Europe [32]. The Indus basin has a significant hydropower potential to be developed due to its high altitudes in the upper Indus region and ample water. It is very difficult to use water effectively since the area continues to struggle with one of the biggest water management issues in the world, which is water storage infrastructure, or because of inefficient water use as a result of water losses in outdated irrigation systems [33]. The upper Indus has almost 2,000 TWh of theoretical potential, however this figure is misleading because the majority of it is both technically and economically unfeasible. The potential is reduced even further when we take into consideration the different regionally varying sustainability restrictions [34]. There are significant hydro-political tensions due to the Indus basin, which is a trans-boundary and extremely fragile basin shared by Pakistan, India, Afghanistan, and China [35]. Integrated approaches are required to achieve Sustainable Development Goals (SDGs) for water, food and energy requirements for the Indus basin [36]. The global warming in the region is also a big threat towards water and food security. The upper Indus basin is anticipated to hit the 1.5 °C and 2.0 °C thresholds over a decade earlier than the corresponding warming at the world scale, it serves as an example of how quickly the planet is warming [37]. The discussion to follow will briefly cover the Indus basin modeling in historical perspective.

Water is the lifeblood of agriculture, and is a scarce resource. It has many impacts on individual and society like no others. There is no concept of life without water, hence it has great influence on human's life like a religion or an ideology. Its scarcity and abundance both cause people to migrate. It has socio-economic and political impacts on human society. It's a source of great tension among trans-boundary basins. Agriculture constitutes the major part of Pakistan's economy. Major part of the population is directly or indirectly involved with agriculture sector of country. It shares about 25% of the country Gross Domestic Product(GDP) and accounts for 50% of the labor. Agriculture depends on water and Pakistan's agriculture mainly depends on one of the world's largest irrigation systems known as Indus Basin Irrigation System(IBIS). Soon after independence, India stopped Pakistan's water putting the life of millions of people and livestock at risk. The situation continued till 1960 and finally both the countries agreed on an agreement brokered by World Bank known as Indus Water Treaty (IWT). River basin management is one of the most challenging and complex problem and Indus Basin in this regard is no exception. Indus Basin constitutes the world's largest canal network. It comprises of three large storage reservoirs Mangla, Tarbela and Warsak dams. Indus basin has a very important and strategic demographic location in the world. It's a unique basin which is spread over four countries namely China, India, Pakistan and Afghanistan. Water is main source of tension between Pakistan and India and consequently impacts the relationship of the two countries. The progress, peace and development heavily depends in South Asia between the relationships of these two countries. It also impacts the other countries in the region. Hence India and Pakistan's social, political and economic stability depends on peaceful resolution of the water conflict. To manage Indus Basin resources optimally, the work on Indus Basin Model (IBM) started in 1976 which resulted first Model in 1982. IBM went through many revision and now latest available version is Indus Basin Model Revised(IBMR)2012.

2.1.2 The Indus Basin Model

In the current section, a comprehensive literature review of Indus Basin Model has been presented.

G. T. O'Mara et al. addressed its inherent dynamic character and conductive application. In this paper, the Indus Basin Model (IBM) family, structure, model validation and simulation results to access the conjunctive use in Indus irrigation system for alternative policies have been discussed in detail. It is one of the most comprehensive papers on the Indus basin model [29].

The report by Ahmad and et al. assesses the impact of the Kalabagh Dam on Pakistan's Agriculture sector. The Agricultural Impact Study (AIS) was launched in September 1985 and first draft was completed in July 1986. The AIS team was comprised of Alexander Meeraus, Chief, DRDSU/World Bank, Mr. Masood Ahmad (DRDSU/World Bank), and Messrs. The detailed analysis and impact assessment of Kalabagh was performed using Indus Basin Model Revised. The report included all the necessary information and a listing of GAMS code used to determine how Kalabagh DAM could affect agriculture [30].

The Indus Basin Model was studied in relation to two-level linear programming by Johannes BISSCHOP et al. Previously described Indus Basin Family is presented, along with a high-level explanation of the Indus Basin Model and some presumptiotion. Instead of presenting mathematical details of IBMR, the author focused on the multi-decision making aspect of model and posed the problem as hierarchical decision-making problem. The problem of Basin has been presented as the nested optimization problem and hence choose to solve using multi-level programming problem. The goal was to maximize the overall Basin income aggregating the individual polygon (53) incomes using multilevel programming [27, 28]. Ahmed and et al. described the water sources of Pakistan in this report in detail. Surface water resources including the depiction of glacier melt, snow melt, rainfall and runoff add up to river flow. Pre and post storage variability of Indus River Inflow at rim stations, ground water contribution, irrigation losses, river gain and losses, pre and post Tarbela and Mangla, domestic water supply and Industrial water usage in detail [38].

J. L. Wes coat et al. have a comprehensive review related to Indus Water System in three eras namely Pre Indus Water Treaty (1947–60) period; Post Indus Water Treaty (1960–75); the Management era (1975–2000). It describes a half century perspective on the management of Indus Basin focusing crises planning, multi strategies planning to achieve governance goal, along with plantation at multiple geographic scales for water management, regional water management to variation pattern. In addition, it also focuses on the scientific planning to explore alternatives for societal experimentation with water and environmental management [39]. The country has been divided into five zones namely Zone A, Zone B, Zone C, Zone D and Zone E respectively A decreasing trend has been observed which indicates the drought in future and severe droughts have been observed in Southern and Central region of the country. The analysis was performed using Analysis of Variations (ANOVA) along Dennett T3 test and Autoregressive Integrated Moving Averages (ARIMA) model to predict downward moving trend from 2006 to 2030 [40].

Joel P. Stewart and et al. prepared a comprehensive report related to Indus River

System Model (IRSM). The model was also used as a planning tool for water management options in Pakistan, published on Aug 14 , 2018. The report was jointly prepared by CSIRO Australia and SDPI Pakistan, funded by Australian Government and supported by Government of Pakistan. The main purpose of the project was to build capacity and knowledge management in water resources management with prime focus on Integrated Water Resources Management. The existing Indus River Systems IBM/IBMR [17, 29, 41] and the Regional Water System Model, RWSM, (Robinson and Gueneau, 2014) have been discussed. IBMR is a hydro economic model where RWSM caters for only hydrology part embedded with more detailed economic model [11, 17, 42].

Kahlown and et al. presented the report related to Water Resources Management in the South Asia with reference to Present and Future Scenarios Prospects and discussed some important facts related to regional per capita water availability, population growth vs per capita water availability, decreasing live storage capacity of reservoirs, province wise soil salinity status. Mathematical modeling of the upper-Indus Glaciers and governing equation were discussed. [43]

Yi-Chen et al. articulated the impact of climate change in Indus Basin. The author along with his team spent two years in Pakistan and studied the climate changes in the basin. They also worked on Indus Basin Model Revision after 1992, the revision is known as Indus Basin Model Revised 2012 (IBMR-2012). The research resulted a book that covers all the aspects of Indus Basin viz Literature Review, Model Equations and results that reflect the current agro-economic conditions of the country. IBMR-2012 was used to explore impact of climate change for food security and water allocation in Indus Basin. Punjab would be least affected by climate change in the future, whilst Sindh would suffer the most, according to an analysis of hydro-climatic parameters sensitivity for the provinces [44].

Young et al. provided a thorough analysis of Pakistan's current water resource condition. The paper lists the present issues with water security, human and economic development, and unabated threats. Suggestions have been made to address the better management of water resources, infrastructure development and governance [20].

In [45] the authors focus is to develop an integrated modeling approach to predict trophic state changes in the reservoir, which is a measure of its water quality and the productivity of its ecosystem. The authors of the paper used a combination of hydrodynamic, water quality, and ecological models to simulate the behavior of the reservoir. The hydrodynamic model was used to simulate the physical processes of the reservoir, such as water circulation and mixing, while the water quality model was used to simulate the processes that affect water quality, such as nutrient inputs and algal growth. The ecological model was used to predict the behavior of the aquatic community, including the phytoplankton and zooplankton populations. The results of the study showed that the integrated modeling approach was able to accurately predict the trophic state changes in the reservoir. The approach was able to simulate the relationships between the physical, chemical, and biological processes in the ecosystem and provide insights into the mechanisms driving the changes in the trophic state. The authors also found that the trophic state of the reservoir was influenced by both internal and external factors, such as nutrient inputs and meteorological conditions. The paper concludes that the integrated modeling approach is a valuable tool for predicting trophic state changes in large reservoirs and can help to support management decisions related to water quality and ecosystem health. The results of the study can also be used as a basis for further research and monitoring of the reservoir ecosystem. Overall, the paper highlights the importance of using an integrated approach to model the behavior of large reservoirs and the role of various physical, chemical, and biological factors in determining their trophic state.

In [46] authors focus on the vulnerability of the Asian leaf fish in the major river basin floodplains of India. The paper aims to improve current approaches and provide a modeling framework for assessing the vulnerability of this species in the face of changing climate. The authors of the paper used a combination of field observations, climatic data, and GIS-based models to evaluate the vulnerability of the Asian leaf fish in the study area. They used statistical and machine learning techniques to analyze the relationship between the species' distribution and various environmental variables, such as temperature, rainfall, and hydrological conditions. The results of the study showed that the Asian leaf fish is vulnerable to changes in the climate, particularly changes in temperature and rainfall patterns. The authors also found that the species' distribution is influenced by a range of environmental variables and that the interactions between these variables can have complex effects on the distribution and survival of the species. The paper concludes that the modeling framework developed in the study can provide valuable insights into the vulnerability of the Asian leaf fish and other species in the major river basin floodplains of India. The authors suggest that the framework could be used to support conservation and management decisions related to the species and its habitat. Overall, the paper highlights the importance of using a multi-disciplinary approach to assess the vulnerability of species in changing climates. The results of the study can help to inform conservation and management strategies for the Asian leaf fish and other species in the major river basin floodplains of India.

In [47] authors emphasize the Asian leaf fish's susceptibility in India's major river basin floodplains. The paper uses a combination of two techniques - Principal Components Analysis (PCA) and Wavelet Analysis - to assess the drought conditions at the catchment scale. The PCA technique is used to extract the dominant patterns of drought from the drought index time series data, while the wavelet analysis is used to analyze the temporal and frequency characteristics of the drought patterns. The results show that there is a significant correlation between the drought conditions at different locations in the Indus Basin and that the propagation of drought is largely driven by the monsoon season. The paper concludes that the combined approach of PCA and wavelet analysis can provide valuable insights into the dynamics of drought propagation in large river basins, and can be useful for drought management and planning in these regions. The findings can also contribute to the development of more effective drought monitoring and early warning systems in the Indus Basin and other similar regions.

In [48] the LARS-WG6 (Larsen-WG6) model was discussed, which is a well-established climate down scaling tool, to project the future changes in temperature and precipitation in the region. The paper presents an analysis of the model's performance in simulating the observed climate and then uses it to make future projections under different greenhouse gas emission scenarios. The results show that the LARS-WG6 model is able to accurately simulate the observed climate in the Upper Indus Basin and that the region is likely to experience significant warming and changes in precipitation patterns in the future. The paper concludes that the use of down scaling models like LARS-WG6 is crucial for improving the understanding of future climate changes in regions like the Upper Indus Basin, where the resolution of global climate models is not sufficient to capture the local-scale impacts. The findings of the paper can be useful for climate adaptation and mitigation planning in the region and similar regions around the world.

Indus Basin has a unique and interning composition. Its total area is about 1120000 square kilometers, which constitutes about 54% of the Southeast Asia. It runs through four countries namely Pakistan, India, China and Afghanistan with area of 520,000, 440,000, 88,000 and 72,000 square kilometer respectively (Aqua stat survey 2012) [49]. The broad agribusiness and water system framework alluded to as the Indus Basin Irrigation System (IBIS). This is the biggest bordering water system framework on the planet. The normal yearly stream of Indus bowl is around 146 MAF. It has two noteworthy capacity repositories specifically Mangla and Tarbela. It consists of 19 barrages, 12 interface canals, and 45 noteworthy canal commands. The aggregate length of canals is around 60,000 km and around 120,000 watercourses to irrigate farms. It inundates 16.2 million hectare and contributes about 25% of GDP. Wins about 70% of the export income and utilizes 50% of the workforce straightforwardly and another 20% in a roundabout way [50]. Indus Basin Model Revised (IBMR) is a Basin wide numerical programming model, written in General Algebraic Modeling System (GAMS). The Indus stream framework comprises of the fundamental Indus River and its significant tributaries: The Kabul, Jhelum, Ravi, Sutlej and Chenab. The conceptual model is given below in figure:

The Indus Basin Model families are described in the subsequent sections.

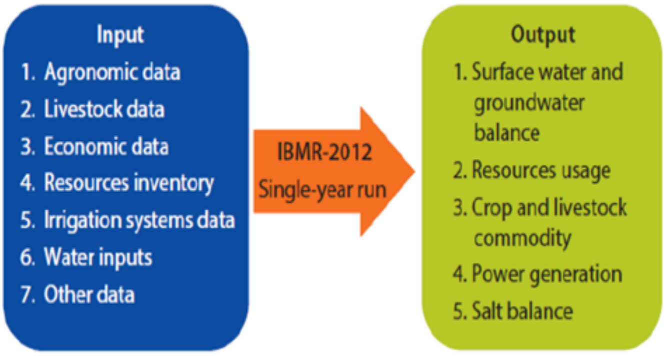


FIGURE 2.1: Conceptual Model of IBMR2012 [44]

2.1.2.1 Indus Basin Standard Model(IBM)1981-1982

The development work on Indus Basin Model initiated in 1976 which resulted first model in 1982 with many research papers publications. The model was based on popular Chac study of Mexico Basin (Goreux and Manne [1973] and employed linear programing model for irrigated agriculture of Pakistan. In addition to this, the model catered for fresh and saline water conjunctive use of surface and ground water. Soon it was realized that the model (IBM) could be used to analyze resource usage, cropping pattern and farmer income. The model was also used to analyze the Left Bank Outfall Drain project funded by World Bank and on Farm Water Management Project. It was the first ever model jointly developed by World Bank and WAPDA. It has 53 Irrigated Regions also known as Polygons. It was written in FORTRAN Language and has 8000 Constraints.

2.1.2.2 Indus Basin Model Revised(IBMR)1985-1986

The model has undergone periodic revisions and has been used to analyze many World Bank sponsored projects. The model was not handed over to Pakistan because of the three main reasons: First, the model was large and very complicated and required the most advanced technology of the time, which was at that time only available in the US. Second, the model was programmed in FORTRAN (Formula Translation Language) and had highly complex architecture and that required experts to execute and obtain the results. Third, at that time, no facility was available in Pakistan to train the staff on the model.

Until 1985, several models including IBM were assessed to analyze the impact of Kalabagh dam on the agricultural economy of Pakistan. IBM was an ultimate choice if it could be optimized. In 1986, the model went through a major revision and was updated for analysis of the proposed Kalabagh dam. For the Kalabagh version, the resource inventory was made harmonious to 1980 data for year 2000 projection. The ACZs are linked together via (Kutcher [1976]) the surface storage and distribution model. Major storage reservoirs namely Tarbela, Mangla, Chashma have been incorporated in this revision. Some version of IBMR also included Kalabagh for future planning. In this major revision, the concept of Agro-Climatic Zones (ACZ) was introduced and Indus Basin now modeled with 9 ACZs instead of 53 polygons. The 9 Agro-Climatic Zones are named as PMW (Punjab Mixed-Wheat), PRW (Punjab Rice-Wheat), PSW (Punjab Sugarcane-Wheat), PCW (Punjab Cotton-Wheat), SCWN (Sind Cotton-Wheat North), SCWS (Sind Cotton-Wheat South), SRWN (Sind Rice-Wheat North), SRWS (Sind Rice-Wheat South) and NWFP (North-West Frontier Province). Large number of constraints related to ground water equilibrium have been deleted and farm level income/expenses replaced with the price-endogenous demand supply structure. The previous model was rewritten in General Algebraic Modeling System (GAMS). GAMS was specially designed to program such models. The newly conceived model was named as the Indus Basin Model Revised (IBMR) in literature. Contrary to previous models, the whole basin was now divided into 9 Agro-Climatic zones (ACZ) and 45 command areas and had 2500 constraints. One of the major features introduced in this model was the proposed Kalabagh dam work and the model was used for future projections (Masood et al.)[23, 37]. It is worth mentioning that the Indus basin model was a critical test model for GAMS environment itself. It was one of the largest and difficult model ever tested on GAMS at that time. Indus Basin Model has been developed by the Work Bank to address the water dependent economy of Pakistan. The data used for calculations are obtained from

Indus Basin Model Revised 2012(IBMR 2012) jointly developed by WAPDA and World Bank.

2.1.2.3 Indus Basin Model Revised III(IBMR)-1992

In March 1989, the first workshop was held at WAPDA to train 16 officials from WAPDA and other Federal and Provincial institutions. The purpose of the workshop was to train the participants on computer fundamentals, modeling techniques related agriculture and water resources and allow for exposure to GAMS. In the same year in August 1989, the second workshop was held at WAPDA house. Again, sixteen participants working on Water Sector Investment Planning Study (WSIPS) attended the workshop. The IBMR went through a revision again in 1988-89 to be used by the WSIP. For the first time in its long history, the model was deployed to computers at WAPDA, and local Pakistani analysts were trained to use it locally. In revised version, the basin has been organized into 12 Agro-Climatic Zones(ACZ) instead of 9 and 45 command areas. The 12 Agro-Climatic Zones were categorized as NWMW, NWKS, PMW, PCWW, PCWE, PSW, PRW, SCWN, SCWS, SRWN, SRWS and BRW. Moreover, for the first time in the history of IBMR, Baluchistan was included and it was also written in GAMS [26].

2.1.2.4 Indus Basin Model Revised IV(IBMR)-2012

It is the latest revision of IBMR available so far. It comprises of 12 Agro-Climatic Zones (ACZ), two for KPK, five for Punjab, four for Sindh and one for Baluchistan. To optimize the complex process related to water's allocation, 26 GAMS equations have been used in the IBMR. The model contains the most latest available Social Accounting Matrix (SAM) for year 2009-2010. The revised model was used for the assessment of the climate change for water allocation and food security related challenges. The results obtained from IBMR 2012 run showed that Sindh would be the most vulnerable province to face the climate change impact. An interim update to IBMR was made in 2002 using 1999-2002 data to incorporate 1991

Interprovincial Water Accord agreed and signed by all four provinces. IBMR 2012 used year 2008-2009 hydrologic data. The main objective was to maximize the Consumer Producer Surplus (CPS) for the entire basin using demand-supply relationship [44].

2.1.3 Comparative Analysis

The summary of Indus Basin Model family is given in the table 2.1 below:

Table 2.1: Family of Indus Basin Models

IBM Family	**Features**
Indus Basin Standard Model (IBM) – 1981-82	53 Irrigated Regions (Polygons),8000 Constraints, FORTRAN Language
Indus Basin Model Revised (IBMR) – 1985-86	9 Agro Climatic Zones (ACZs), 45 Canal Commands (CC), 2500 Constraints , GAMS Language
Indus Basin Model Revised – III (IBM-III) - 1992	12 ACZs, 45 CC, 2000 Constraints, GAMS Language
Indus Basin Model Revised – III (IBM-IV) - 2012	In total, 26 GAMS equations to optimize the complex processes related to water. allocation and economic activities.

2.1.3.1 Comparison between IBM and IBMR

A brief comparison between IBM and IBMR different versions have been presented in the table 2.2: The data used in IBMR is standard data obtained from WAPDA and IRSA.

In the light of above extensive literature survey, it has been observed that the existing Indus basin Model is deterministic in nature and uses linear and non-linear sub models for CPS, Cost and water balance. The focus of this research is the probabilistic modeling of Indus basin Model considering the hydropower contribution under the real world constraints i.e uncertainties (Like variation in rainfall, extremely wet and dry weather etc.) to assess the Indus Basin. In addition

TABLE 2.2: IBM vs IBMR

IBM vs IBMR			
SNO	**Parameter**	**IBM**	**IBMR**
1	*Software*	Developed in FORTRAN	Developed in GAMS
2	*Computational Complexity*	Much Larger can only run on Main Frame.	Much Smaller and can be run on personal Computer.
3	*Aggregation*	The whole basin was divided into 53 polygons [27].	The basin reorganized into 9 Agro-Climatic Zones (ACZ)in 1985-86 version .In the next major revisions 1992 and 2013, the whole basin has been organized into 12 ACZs [41, 51].
4	*Orchard*		Activities related to orchard have been added in the model.
5	*Data*	Based on 1976 XAES survey	Updated with latest available data of Censes of Agriculture, Agricultural Statistics of Pakistan, and WAPDA.
6	*Projections to Future Years*		Has ability to predict in future with and without using project scenarios based on population, resources, productivity and physical parameter related the system. The IBMR2012 was used to forecast impact of climate change on the Indus basin of Pakistan. It uses the lastest available Social Accounting Matrix(SAM) of 2010.
7	*Water Distribution*		The IBMR2012 uses IRSA Rules for water distribution as per IRSA Rules para 2, para 4 and para 14.

to this, development of water allocation scheme for maximum productivity both in agriculture and power sector.

2.2 Research Gap Analysis

In the light of literature review, the following gaps have been identified in context of Indus Basin of Pakistan:

- Water distribution using Bankruptcy Rules and their impact on Consumer Producer Surplus (CPS).
- Objective function modification of IBMR by incorporating hydropower.
- Hydropower generation using different exceedance probabilities.
- Calculation of energy mix for Pakistan up to year 2040.

2.3 Problem Statement

The real life systems are nonlinear in nature and complex. River basin is a complex system which consists of many subsystems. River basin modeling is a complex non-linear optimization problem. The problem becomes even more complex when both the objective function and constraints are non-linear and large in number. The Indus basin model is a well established model which has been used for agriculture planning of Indus Basin of Pakistan for many decades. All the variants of IBMR focus on agriculture-related activities and emphasis the water-dependent economy of Pakistan. However, there are still unaddressed areas in the model, and some important issues are highlighted below:

- Impact of water flowing to the sea is not addressed in the existing model.
- Aquifer behavior is not modeled in the a last updated version of IBMR.
- Impact of sedimentation on reservoir capacity, agriculture and hydropower is not addressed in the existing version.
- Hydropower contribution in basin wide income is not a part of existing IBMR.
- Previous work primarily focused on IRSA (Indus River System Authority) rules, but there is still room for improvement, such as considering bankruptcy scenarios [52, 53] which can be implemented for water distribution among the provinces and canal water distribution.

The basinwide income of Indus basin is calculated using an objective function in the IBMR. This objective function calculates the consumer producer surplus (CPS) which depends on agriculture based income only. The existing IBMR uses the whole water for agriculture based income and does not include electricity generation through hydropower as potential income in its objective function in CPS calculation. The generation from thermal and other sources are also expensive as compared to hydropower. Optimization problem of IBMR should be posed in such way that the generation of hydropower should be incorporated in CPS calculation. Initially, the power generation fuel mix in the national grid was hydel-oriented with a lion share. Subsequently, the development of the hydel power projects was not in line with the proposed plan. This resulted in the tilt of balance towards the other sources like coal, nuclear, and furnace oil which caused an overall increase in the unit price of electricity. The optimization problem of IBMR needs to be modified to incorporate the share of hydropower into the objective function.

As discussed earlier in section 2.2, all the previous published literature related to Indus Basin Modeling was limited to optimization of the consumer-producer surplus (the Basin-wide income) only. However, the contribution from the research community is very low due to limited access to the Indus Basin Model. The current research addresses the following questions:

- What is the impact of hydropower on basin-wide income?
- What would be the energy mix for the year 2040?
- How the modified model will be implemented?

Considering all the points mentioned above, there is a pressing need to enhance the existing IBMR model to account for hydropower generation and its influence on the basin-wide income, considering various inflow possibilities. The current research addresses the aspects mentioned above.

2.4 Novelty

The Indus River System consists of The Indus River and its tributaries. The agriculture system of Pakistan comprises forty-five major canals and three notable dams. These dams are multi-purpose i.e., their water is being used for both agriculture and hydro-power generation. The existing IBMR model and all its previous versions focus on agricultural-related activities. The net economic benefit of The Indus Basin depends solely on agricultural income and does not account for hydropower income.

In the current research, the existing model has been modified by adding hydropower generation through these dams. The objective function i.e. CPS of existing IBMR has been modified in such a way that it incorporates the energy income in it. The existing IBMR model has been modified in such a way that it can be used only for agriculture, hydropower generation, and both. In addition to that the modified IBMR can be used for indicative generation planning and energy mix calculation.

2.5 Model Selection

Every model has its strengths and weaknesses. IRSM, MESSAGE, and CEG-W have very limited access and targeting to specific domains like economics or energy. The IBMR model was specifically designed for agricultural assessment of the Indus Basin of Pakistan. IBMR is a hydro-economic model and has agriculture and water-related data embedded in it. IBMR is implemented in a GAMS and it has many powerful solvers for large optimization problems. Complete IBMR has more than 2000 equations and constraints and can handle up to 100,000 constraints. It is also easily scalable and covers basin modeling comprehensively. In the past, it has been used for agriculture planning, Kalabagh impact assessment on agriculture, and the impact of climate change on the Indus Basin of Pakistan. All these points make IBMR an obvious choice. In the current study, IBMR is used for power generation, indicative generation planning, and water distribution for the agriculture sector using bankruptcy rules. The proposed model IBMR2020 results have been validated using world bank standard data and found that the results are in close agreement with IBMR2012. Moreover, with the incorporation of hydropower contribution, the basinwide income increases from 3.5.66 billion dollars to 39.49 billion dollars.

2.6 Research Methodology

In order to address the problem, following methodology is proposed:

- The proposed model was programmed in GAMS which used dynamic nonlinear programming solver based on generalized reduced gradient (GRG). The real time data for Indus River System at rim stations of around 80 years was used. Different exceedance probabilities were also be used for inflows calculation and IRSA Rules for water distributions among the different provinces of Pakistan. Microsoft Excel and GAMS Studio were used for calculations and optimizations.

- Numerous Bankruptcy Rules like Proportional Rule (PR), Constraint Equal Award Rule (CEA), Constraint Equal loss Rule (CEL), and Hojjat Mainabadi (MIA) were implemented as well for water distribution among the provinces of Pakistan and on the basis of these water distribution CPS was calculated using IBMR.

2.7 Thesis Contribution

- The bankruptcy rules were implemented for water distribution and the consumer producer surplus was calculated and the results were compared with IRSA rules.

- The objective function of IBMR was modified, and the inclusion of hydropower generation was integrated into the CPS calculation.

- A control parameter α has been introduced to control the water allocation for agriculture and power sector.
- he proposed model was mapped in GAMS to run on Dell Latitude Core i7 laptop with 7820HQ 2.9 GHz processor and 16 GB of RAM in order to obtain results.
- The obtained results were compared with NTDC generation indicative plan.
- Pakistan's energy mix up to year 2040 was calculated .

2.8 Summary

This chapters comprehensively covers the literature related to basin modeling and Indus Basin Model. All the variants of Indus Basin model along with their brief overview is presented in a simple yet comprehensive manner. The extensive literature review reveals that IBMR has only been used for agricultural purposes but its full potential has not been explored yet. In the current research, the IBMR has been used for both agriculture and hydropower generation with novel water distribution mechanism using bankruptcy rules and results in the subsequent chapters show that basin wide income can be increased by incorporating both power and agriculture using single objective function.

Chapter 3

The Indus Basin of Pakistan and The Indus Basin Model

"Two there are who are never satisfied – the lover of the world and the lover of knowledge." "The angel is free because of his knowledge, the beast because of his ignorance. Between the two remains the son of man to struggle."

Jalal Uddin Rumi

3.1 Introduction

Engineers all over the world are involved with efficient, economic utilization and management of renewable natural resource like water. Optimization models serve as effective tools to efficiently manage available water. IBMR is one of the most important agro-economic model to optimize consumer, producer surplus within available water resources. This complex model written in GAMS language is the base for this research work, in order to study power economy in Pakistan. Growing food and energy demands worldwide demand intelligent use of available resources. Water is one of the most precious sources; it is meeting not only with food requirements but energy requirements in the form of electricity. Pakistan is facing is water scarcity and it is one of the ten countries which are water scarce.

3.2 The Indus Basin of Pakistan

Availability of water gives rise to civilizations, the Indus is the best example of it. The Indus civilization started around 4000-5000 BC. Indus water was a lifeline for people at that time. It meets its food and income requirements. The story didn't change, as it holds over 140 million people today. It admits 2 million farms. It contributes the most in the living being of people around its basin and one of the important income source of Pakistan. Indus the major river and other contributing rivers are Beas, Ravi, Kabul, Sutlej, Jhelum, and Chenab. It is a huge system, spreading over four countries i.e. India, Pakistan, China and Afghanistan. The total area of this basin is 1.12 million km^2, and Pakistan has 47% of it [54].

FIGURE 3.1: The Indus basin of Pakistan [55]

The Western rivers comprise of the rivers Indus, Chenab and Jhelum, and eastern ones are Ravi, Sutlej and Beas. Salient features and major tributaries of the Indus are summarized in the table 3.1[56] below: This system brings each year up to 154 MAF of water i.e. 144.91 MAF of water is from Western rivers and 9.14 MAF from the Eastern. Major portions of this water is allocated for irrigation purposes i.e. 104.73 MAF, 39.4 MAF flow into the Arabian Sea. The remaining 9.9 MAF is lost by evaporation, seepage and other system losses. Contribution from main rivers is as Indus contribute 44%, Jhelum 16%, Chenab 19%, Kabul 16% and other rivers contribute 5%. IBIS consists of 3 main dams (Tarbela, Mangla and warsak), 20 barrages and head works, 45 irrigation canal commands and more than 120,000 sub canals have been built for watering the fields. Out of 45 canal commands 24 are in Punjab, 2 in Baluchistan, 5 in KPK, 14 in Sindh. Similarly, Punjab got 20 barrages and headworks, Sindh 3 and KPK 1. Indus along with its tributaries contribute to the largest irrigation system of the world, known as "Indus Basin Irrigation System" (IBIS). Agriculture is a major economy of Pakistan and 94% of the country's available water is utilized with it. Pakistan total cultivable land is 22

Table 3.1: Salient features of Indus and its tributaries

River	**Origin**	**Path**	**Length/Flow per year**	**Tributaries**
Indus	Mansarowar Lake, Tibet	Kashmir, Tarbela, Multan, Arabian sea	2880 km 100BCH	Hunza and Gilgit at Raikot,Kabul at Attoct and Chenab at Mithankot
Ravi	Rohtaag pass in Kangra (India)	Chamba,Madhopur, Lahore,Ahmedpur Sial	894 km 7.8 BCH	Chenab at Ahmadpur Sial
Jhelum	Verinag spring, Indian occupied Kashmir	Wular Lake, Muzzaffarabad, Mangla and Trimmun	820 km 28 BCH	Neelum and Kunhar at Muzzaffarabad and Chenab at Trimmu
Beas	Rohtang Pass in Kulu	Kangra,Singbol, Hoshiapur, Talwara	467 km 15.6 BCH	Sutlej at Harike
Chenab	Himachal Pradesh (India)	Kishtwar,Marala, Panjnad, Mithankot	1361 km 28BCH	Jhelum at Trimmu,Ravi at Ahmadpur Sial,Sutlej at Punjnad
Sutlej	Lake Rakshatel Western Tibet	Ludhiana,Ferozpur, Bahawalpur	1542 km 16.64 BCH	Chenab at Punjnad Kabul
Kabul	Kabul, Afghnistan	Chitral,Kabul, Warsak, Nowshera	480 km 21.4 BCH	Indus at Attock

million hectares, 16.2 million hectares of this is cultivated through irrigation that makes 74%, nearly half of the labor force of the country is linked to agriculture directly and 20% are secondarily involved. The income of farmers as well as the economy of Pakistan depend upon agriculture.

3.3 Water Resources Management of Indus Basin

Out of 20 basins, only Indus basin partially, fell in Pakistan and India. India stopped water on April 1, 1948 affecting 1.7 MAF of land. The water supply was restored through interim agreement on payment [57]. The issue became a flash point in the region. According to Pakistan's point of view the historical uses must be protected and additional water to be divided according to future irrigation potential and population. Whereas India's stand was that upper riparian had the prior right and Sovereignty over water owing through Indian or Indian held territory. The situation continued till 1960 when both nations reached on an agreement called Indus Water Treaty (IWT) signed at Karachi by Pakistan's president General Muhammad Ayub Khan and Indian Prime Minister Jawaharlal Nehru brokered by World Bank [24, 58].

The Water Resources Management in South Asia is important with reference to present and future scenarios. Some important facts related to regional per capita water availability, population growth vs per capita water availability, decreasing live storage capacity of reservoirs and province wise soil salinity status have been discussed. Mathematical Modeling of the Upper-Indus Glaciers and governing equation are discussed [43]. Pakistan's water profile has shifted dramatically, from one of abundance to one of scarcity. Per capita water availability decreased from 2,172 m^3 per tenant to 1,306 m^3 per occupant between 1990 and 2015. Pakistan takes out 74.3% of its freshwater yearly, subsequently applying gigantic weight on inexhaustible water resources [59]. The Indus basin is a trans-boundary basin. It comprises an area of 520,000 km^2 of Pakistan and around 1,165,000 km^2 of total drainage area [60–62]. It originates from Himalayan Mountains fed through glaciers, snowmelt and monsoon rains. Its water divided into two streams, western and eastern. The Western rivers comprise of the rivers Indus, Chenab and Jhelum, and eastern ones are Ravi, Sutlej and Beas. In 1960, Indus accord was signed between Pakistan and India, in which Pakistan got right over three western rivers and could use 80% water held in Indus [63].

3.3.1 Per Capita Water Availability Country Wise

Due to rapid urbanization, exponential industrial growth and missive groundwater extraction through tube wells, it has been monitored that per capita water availability has decreased over the years exponentially. Pakistan stands before Ethiopia in water scarce countries list as shown in the figure 3.2 below:

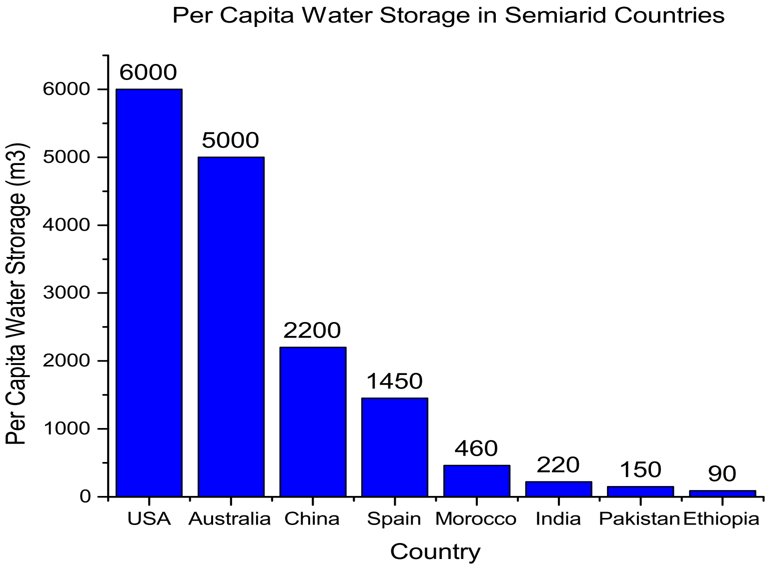


Figure 3.2: Per capita water storage country wise [54]

3.3.2 Water Stress Level in Pakistan

Since 1951 the per capita water availability is decreasing exponentially with the exponential increase in population. By 2050, it is predicted that per capita water availability will less than 1000 m^3 as compared to year 1951 as shown in the figure 3.3

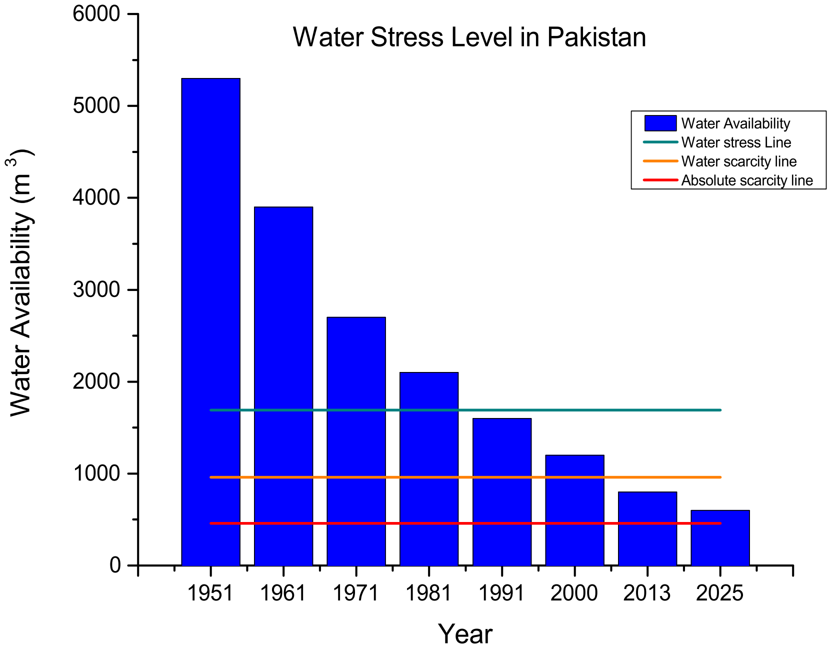


FIGURE 3.3: Water Stress Level in Pakistan [64]

3.4 Agroclimatic Zone

In IBMR whole Indus region of Pakistan is divided into 12 agro-climatic zones, out of 12, 4 are in Sindh, 5 in Punjab, 1 in Baluchistan and 2 in Khyber Pakhtunkhwa This division and naming of zones is as just depicting the word “agro” and “climatic”, for example, one of zone in Sindh is Sindh Rice Wheat South (SRWS) depicts real picture of the region. In this zone, rice and wheat are major crops and “south” indicates that this particular area is saline in nature, where there are scarce surface water resources, the water table is high and yields are lower. Each ACZ is further subdivided into subzones corresponding to different cropping patterns and nature of farms i.e. saline or freshwater availability [51].

The nomenclature and the canal associated with agroclimatic zones of Pakistan are given in the table 3.2:

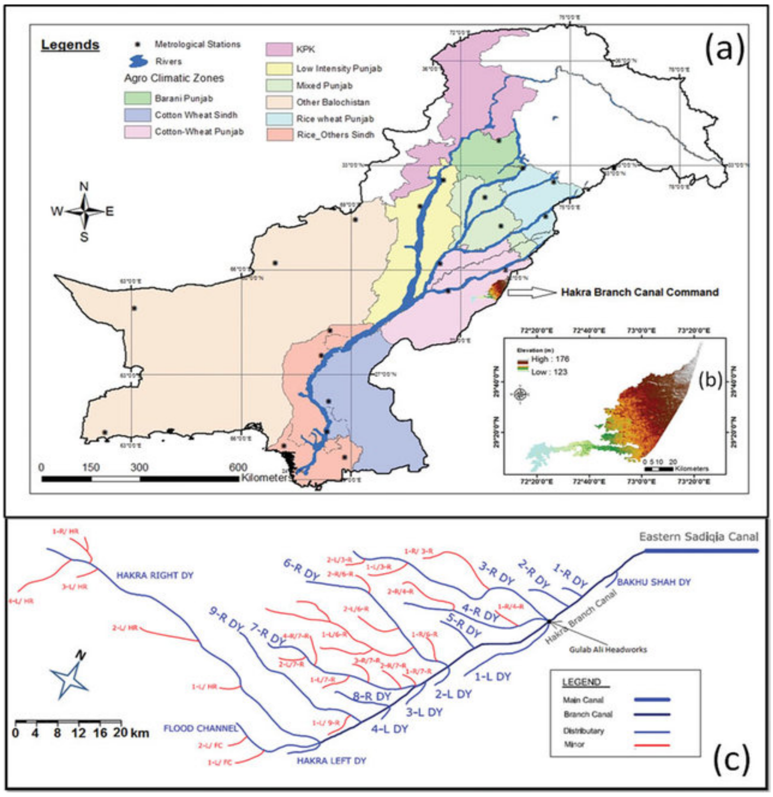


FIGURE 3.4: The Agroclimatic Zones of the Indus Basin of Pakistan [65]

3.5 Major Reservoirs of Pakistan

There are three major reservoirs and associated hydropower plants built on Indus River and its tributaries namely Tarbela dam, Mangla dam and Warsik dam. Brief over view of each is given below:

3.5.1 Tarbela Dam and Hydropower Station

In Swabi, near the little town of Tarbela, the Tarbela Dam is built over the River Indus. This is Pakistan's and the world's largest dam in terms of structural volume. The undertaking started in 1968 and was completed in 1976 at a cost of 1,497 billion. The dam rises 470 feet above the riverbed, with a reservoir covering approximately 250 square kilometers.

After India and Pakistan signed the Indus Waters Treaty in 1960, the Tarbela Dam was built as part of the Indus Basin Project. In order to compensate for the loss

TABLE 3.2: The Agroclimatic Zones of The Indus basin of Pakistan [41]

Province	**ACZ Names**	**Number of Canals**	**Available cropped land (Million Acres)**
Khyber pakhtunkhwa	Khyber pakhtunkhwa kabul swat (KPKS)	4	0.628
Khyber pakhtunkhwa	Khyber pakhtunkhwa mixed wheat (KPMW)	1	0.892
Punjab	Punjab mixed wheat (PMW)	2	3.876
Punjab	Punjab cotton wheat west (PCWW)	4	3.177
Punjab	Punjab cotton wheat east (PCWE)	10	8.556
Punjab	Punjab sugarcane wheat (PSW)	5	4.470
Punjab	Punjab rice wheat (PRW)	6	2.801
Sindh	Sindh cotton wheat north (SCWN)	7	3.941
Sindh	Sindh cotton wheat south (SCWS)	2	2.858
Sindh	Sindh rice wheat north (SRWN)	5	3.208
Sindh	Sindh rice wheat south (SRWS)	4	2.806
Baluchistan	Baluchistan rice wheat (SRWS)	3	1.858

of water resources from the eastern rivers (Ravi, Sutlej, and Beas), which were designated for India's exclusive use under the treaty's stipulations, a new plan was developed. Three successive hydro-electrical project extensions, completed in 1992, contributed a total of 3,478 MW producing capacity by the mid-1970s. The main dam wall, which is made of earth and rockfill and is 148 meters (486 feet) tall, runs 2,743 meters (8,999 feet) from the peninsula to the river right. From the peninsula to the river left, a pair of concrete secondary dams bridge the river. The two spillways on the dam are on the subsidiary dams, not the main dam. The main dam does not have two spillways; they are on the subsidiary dams. 18,406 cubic meters of water per second may exit the main spillway (650,000 cubic feet per second), while the secondary spillway can discharge 24,070 cubic meters per second (850,000 cubic feet per second). Over 70% of the total water discharged at Tarbela annually flows through the spillways without being utilized for hydropower generation [66].

The five significant tunnels were built as part of the outflow operations. Hydroelectricity is produced by turbines in tunnels 1 through 3, while tunnels 4 and 5 were constructed for irrigation. Tarbela will be able to generate more electricity by converting both tunnels for hydropower. Initially, the Indus River was directed through these tunnels as the dam construction was going on.

FIGURE 3.5: Tarbela dam [66]

On the right side of the main dam, the MA hydroelectric power station houses 14 generators that are fed by water from outlet tunnels 1, 2, and 3. Tunnel 1 has four 175 MW generators, tunnel 2 has six 175 MW generators, and tunnel 3 has four 432 MW generators, totaling 3,478 MW of generating capacity. Tarbela Reservoir is 250 square kilometers long and 80.5 kilometers (50.0 miles) wide (97 sq mi). The reservoir's initial capacity was 11,600,000 acre-feet (14.3 km^3) of water, with live storage of 9,700,000 acre-feet (12.0 km^3); however, during course of the following 35 years of operation, silting reduced this volume to 6,800,000 acre-feet (8.4 km^3). The reservoir's greatest position is 1,550 feet (470 meters) above mean sea level, while its lowest working position is 1,392 feet (424 meters). The uuper catchment of the Tarbela is significantly replenished by snow and glacier runoff from the southern Himalayan slopes, measures square kilometers (65,000 square miles). This area, which is significantly replenished by snow and glacier runoff from the southern Himalayan slopes, measures square kilometers (65,000 square miles).

3.5.2 Mangla Dam and Hydropower Station

An embankment dam on Pakistan's Jhelum River is the famous Mangla Dam. One of the main dams in the Indus Basin Project was built in 1967(the other is the Tarbela Dam). The dam's final height was 453 feet (138 meters), 10300 feet (3,140 meters) in width at its peak, 10,300 feet (3,140 meters) in height, and 85.5 million cubic yards in volume (65.4 million cubic meters). Initially erected with a generating capacity of at least 600 megawatts, it was merged with three smaller subsidiary dams in the middle of the 1990s to increase that capacity to 1,000 megawatts Although the dammed reservoir had a gross capacity of around 5.9 million acre-feet (approximately 7.3 billion cubic meters), the amount of water contained gradually decreased due to silting. A five-year project finished in 2009 increasing the dam's height by 30 feet (9 meters), increasing its storage capacity to 7.4 million acre-feet (9.13 billion cubic meters) [67].

3.5.3 Warsak Dam and Hydropower Station

Warsak is a massive concrete gravity dam in Pakistan's Khyber Pakhtunkhwa province that sits on the Kabul River in the Valley of Peshawar, some 20 kilometers northwest of Peshawar. The Colombo Plan called for the construction of the Warsak Dam in two stages, with funding provided by Canada. It was built during the initial phase, which was completed in 1960. Irrigation tunnels were completed in 1960, along with the setting up of four power generating units, each with a 40 MW capacity and a 132 kV transmission system. Two more producing units with a combined capacity of 41.48 MW were installed in the second phase in the years

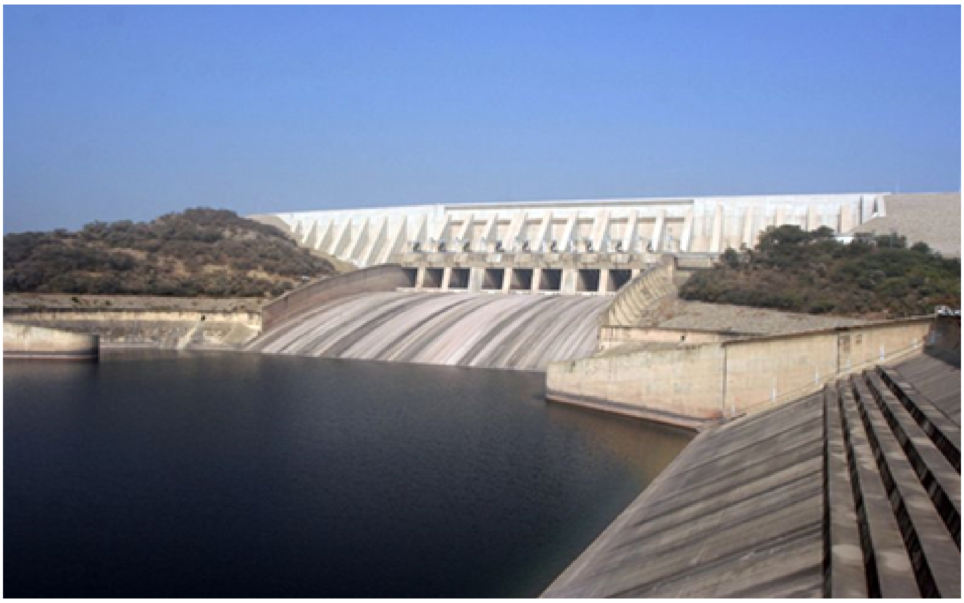


FIGURE 3.6: Mangla dam [67]

1980–1981. The overall installed capacity of the Warsak Dam Hydropower Project is 243 MW. The Pakistan Water and Power Development Authority (WAPDA) planned in June 2012 to build a 375 MW power plant to Warsak, bringing the total power output capacity to 525 MW [68].

FIGURE 3.7: Warsak dam [68]

3.5.4 Diamer Basha Dam Project

The Diamer Basha Dam Project would be a 272m high RCC [69] dam with a 9.05 Bcm water storage capacity and a 4500 MW power generation capability. The pre feasibility study was completed in 1984, followed by the feasibility study in 2004 and the detailed engineering design in 2008. The project would be built on the Indus River, 315 kilometers upstream of Tarbela Dam, and would be accessible by the Karakoram Highway. It is planned to create a massive reservoir on the Indus River with a storage capacity of 7.89 BCM (6.39 MAF). The project's second goal is to create hydropower with an average annual generation of 18097 GWH and an extra 1111 GWH per year at Tarbela Dam. This will be done by two powerhouses, one under each bank, with a combined installed capacity of 4500 MW [70, 71].

FIGURE 3.8: Daimer Basha [72]

Extreme events, such as a prolonged drought, overwhelm the Indus basin's water management system due to the basin's limited water storage capacity. The proposed dam is a sound investment, yielding advantages and Internal Rates of Return of 11 to 20 percent under various climatic scenarios. The dam's live storage is worth $0.63 billion yearly for irrigation and $2.2 billion for hydroelectricity generation with approximately eight years of return period [73].

3.6 Water Distribution in Indus Basin

The below sections briefly describe the water resources distribution in Indus basin.

3.6.1 Canal Water Distribution System

The canal water distribution network consists of river, main canal, distributary, minor, sub-minor, and watercources. The below figure shows the high level schematic diagram of canal water system distribution of Indus Basin:

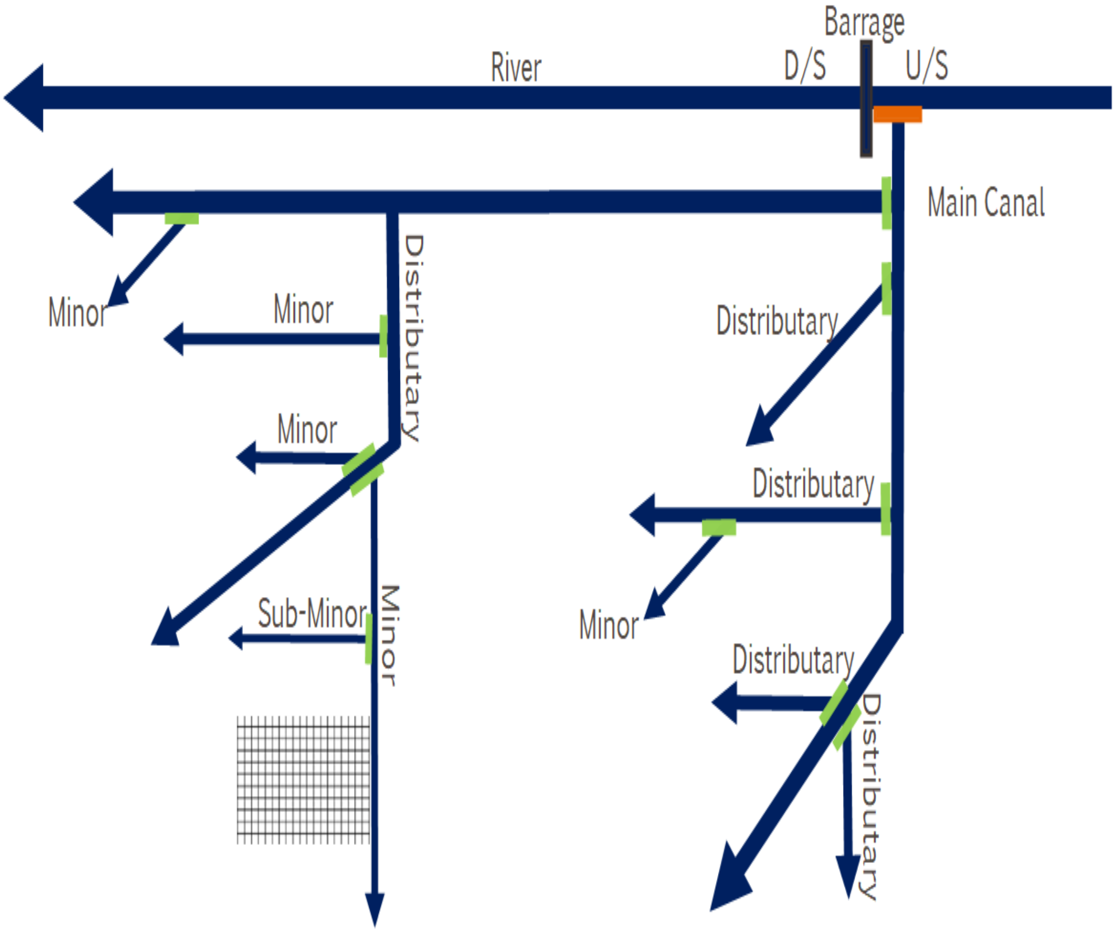
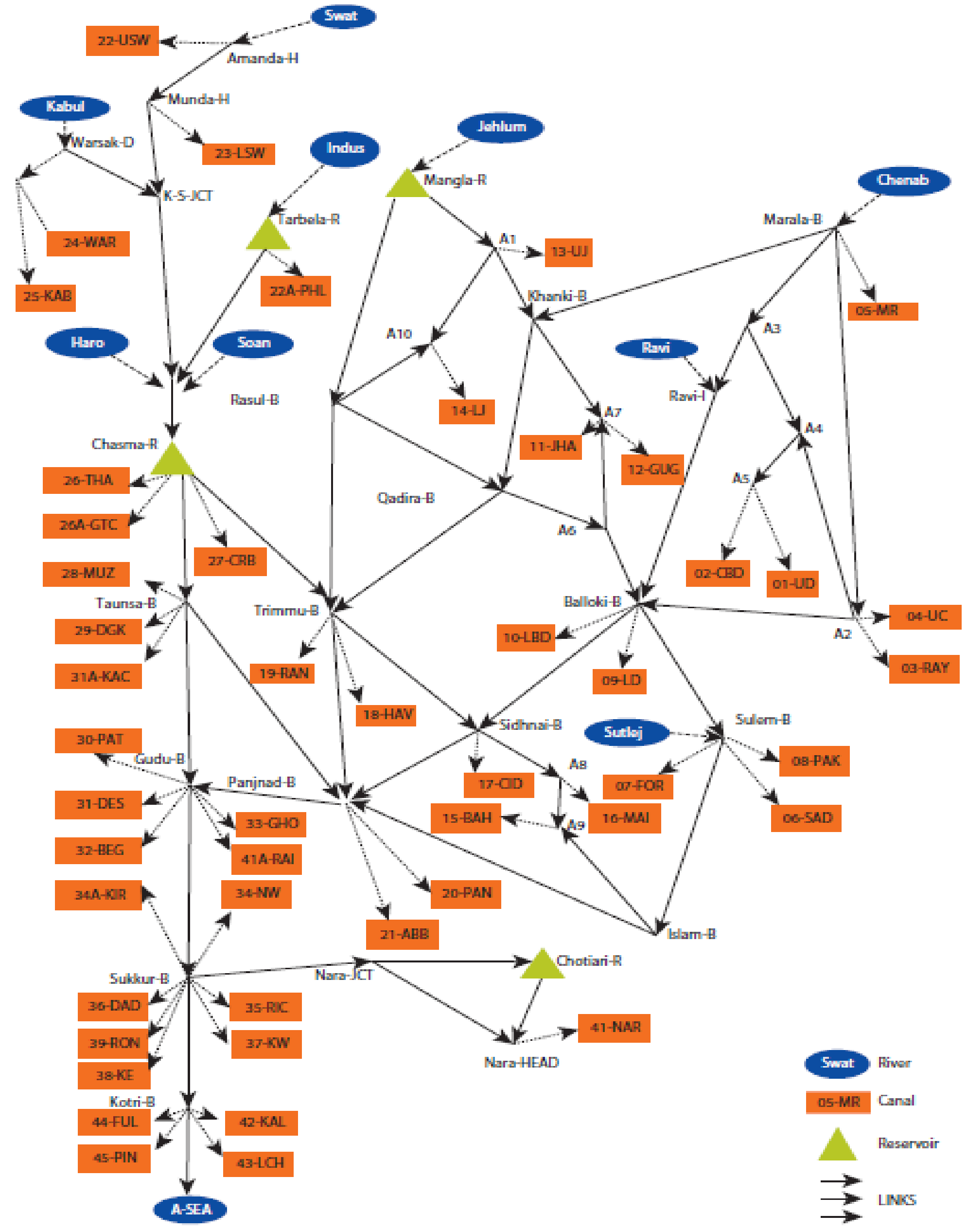


FIGURE 3.9: Canal Water Distribution System [74]

3.6.2 Node Link Diagram of Indus Basin Model Revised

The IBMR works on the concept of node-link diagram. The node link diagram shows the links among rivers, canals, and reservoirs. The has been taken from

[51] and reproduced. The node link diagram of Indus Basin Model Revised is given below in figure 3.10: In the node-link diagram, the oval node represents the



Note: IBMR = Indus Basin Model Revised. Solid line = streamflow. Bold dotted line = stream inflow. Thin dotted line = canal diversions.

FIGURE 3.10: Node link diagram of Indus Basin Model Revised [51]

river, the rectangular node represents the canal, the triangular node denotes the reservoir, the solid line shows the stream flow, the bold dotted line stream inflow, and the thin dotted line is used for canal diversions.

3.7 Indus Basin Model Input

The Indus Basin Model is a comprehensive model and it comprises of numerous input data to calculate basin-wide income and many other output under real world constraints. Following are the few major inputs used in IBMR:

3.7.1 Input Data

- Available Resources:Represents zone-wise resources like tractors, tube wells, cows and buffaloes etc.
- Canal command data : Comprises of all 45 canal and their related data like canal command area, canal command efficiency, water courses efficiency, water courses efficiency in Rabi and Kharif and field efficiency.
- Canal Command Characteristics: It's a subset of resources set and contains canal command area, canal command efficiency, water courses efficiency, water courses efficiency in Rabi and Kharif and field efficiency.
- Crop& WeedYield : Basmati, Irri, Cotton, Gram, Maize, Mus+Rap, Sc-Mill, Wheat, Potatoes, Onions, Chilli, Fodder, Citrus, Pulse, Mango,Tobacco.
- Crop Prices : Represents the cropwise prices.
- Cropeed Area : Represents the cultivable area of each crop.
- Depth to WT : Shows the water table in the particular zone.
- Different ACZ : Shows the ACZ wise demand of each crop.
- Economic : Contains the province wise data related energy demand, cost and population.
- Fertilizer Applications :Cropwise fertilizer demand w.r.t. ACZ.
- Inflows at Rim Stations: Data related to inflows of Indus river and its tributaries (Chenab, Haro, Indus, Jehlum, Kabul, Ravi, Soan, Sutlej, Swat).

- Land Occupation
- Lakes : Data related to major reservoirs (Tarbela, Mangla, Warsak, Chashma and Chotari).
- Land characteristic : Links ACZ with canals using subareas.
- Land Occupation : Land occupation w.r.t crops, ACZ, sequence and water stress level
- Link Canal Loss Factor : Represents the canal loss factor w.r.t links.
- Market and Elasticity Demand :Zonal elasticity of demand for crop & livestock commodities.
- Node to Node Transfer Capacity : Node to node water transfer capacity (MAF).
- Labor Requirements : Labor requirements for crops (man hours).
- Nodes : Contains province wise canals and their links.
- On Farm Consumption:On Farm Cconsumption of Wheat, Basmati, Irri, Maize, Mus+Rap, Gram, Chilli, Potatoes, Onions (Tons).
- Post Accord Canal Diversions : Contains 1991 Post Accord Canal Diversions(MAF)
- Probability: 10 days monthly data runoff data using 50% and 80% exceedance probability.
- Probres :10 days monthly runoff of Indus river and its tributaries.
- Proportion of Consumption by GW : ACZ wise ground water consumption.
- Public Tube well Pumpage : Water extraction from public tube wells.
- Rain& Pan Evaporation: 10 days monthly evaporation data from all canals in IBRS.

- River Loss Gain Coefficients : Canal and barrages routing and loses coefficients.
- Seeds Water Fertilizer Tractor Prices: Prices for seeds, water, Fertilizer and Tractor.
- Seepage Proportions: Used for ground water seepage.
- Sets : Provinces, ACZ, CCA and other similar components in IBMR as known as sets.
- Straw Yield Seed Data : Zone wise straw yields w.r.t. crops and water stress level.
- Total Production : Zone wise total production of crops, cow and buffaloes milk production.
- Tractor Requirements: Tractor Requirements (Tractor Hours Per Acre) mapping.
- Tributary Inflows: Tributaries inflows at rim stations.
- Water Requirements : Crop wise water Requirements(Acre Feet Per Acre).
- Water Log Saline Area& Yields :Yields of major crops (Wheat, Basmati, Irri, Cotton, Sc-Mill) in saline areas as proportion of normal yields.

3.7.2 Outputs Data

Following are the few major outputs used in IBMR:

- Consumer Producer Surplus (CPS)
- Hydropower
- Inflow
- Node to Node flow

- River Loss/Gain: Water loss or gain in MAF
- Barrage Diversion
- Canal Diversion
- Provincial Water Diversion
- Provincial Diversion Seasonal
- Surplus Deficit
- Water availability
- Prov subdivision
- Reservoir Water Balance
- Indus Basin Water Balance
- Agricultural Water Balance
- Water Delivered to Field
- Public TW Pumpage
- Private TW Pumpage
- Water from Sub irrigation
- Crop Water requirement net Sub irrigation
- Root Zone Water Balance
- Ground water Balance
- Ground water Depth
- Watercourse Head Water Balance

3.8 IBMR Equations and Cost Function

IBMR is a marvel of optimization. It is very comprehensive hydro-economic model used for planning, prediction and water distribution in one of the largest irrigation system known as Indus Basin River System. The model consists of thousands of equations in the form of objective function and constraints.

A total of 20 equations are utilized to enhance the optimization of intricate processes linked to the allocation of water and economic pursuits. These equations fall under six distinct categories: 1) objective function, 2) economic equations, 3) water balance equations, 4) canal equations, 5) crop equations, and 6) livestock equations. Only four pivotal equations are reproduced here, while the remaining ones can be found in [41] and [50]. The below mentioned sub sections contain the major equations, objective function and constraints used in IBMR.

3.8.1 Surface Water Balance Equation

The IBMR is an optimization model which optimizes the agriculture related activities of the indus basin of Pakistan. The equations presented in the subsequent subsection have been reproduced from [41, 51]. The schematic diagram of surface water balance in IBMR is given below: The continuous lines depict the elements of the water balance in the root zone, which fulfill the water needs of the crops. The dashed lines illustrate the elements of the groundwater balance that are monitored throughout the simulation experiments. All calculations related to water balance are conducted on the scale of the ACZ (dash zone).

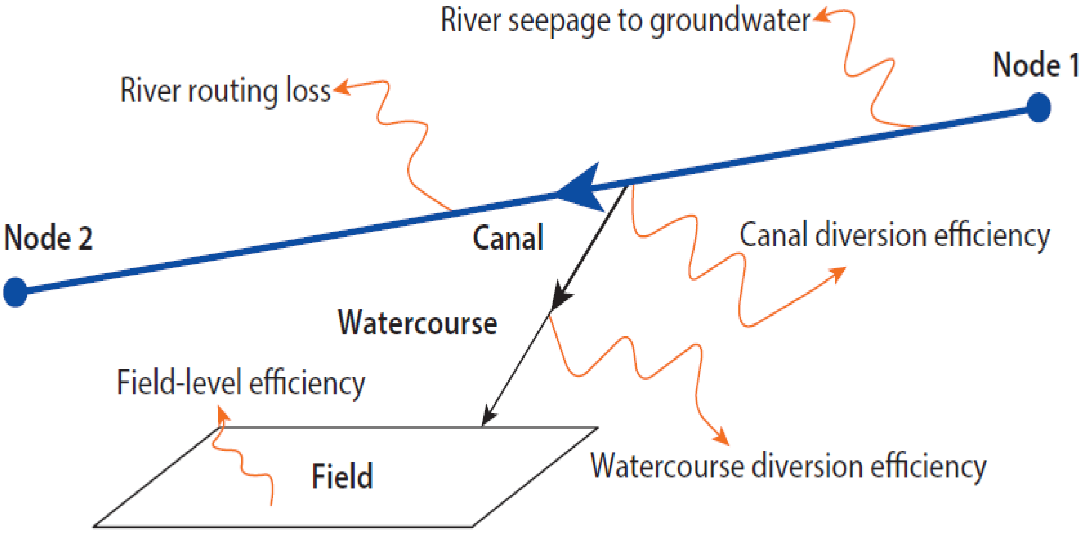


FIGURE 3.11: Surface Water Balance [51]

The surface water balance in IBMR is computed using equation:

$$\begin{aligned}\sum_{t} Inflows_{i=1}^{M} + \sum_{N} RIVERD_{N} * TRIB_{N}^{M} \\ + \sum_{N} RIVERC_{N} * TRIB_{N}^{M-1} + \sum_{N} RIVERB_{N} * F_{N}^{M} \\ + \sum_{N} RIVERC_{N} * F_{N}^{M-1} + \sum_{N} RCONT_{N}^{M-1} \\ + Prec_{N}^{M} + Evap_{N}^{M} \sum_{N} CANALDIV_{N}^{M} \\ - \sum_{N} RCONT_{N}^{M} + SlackWater_{N}^{M} = 0\end{aligned} \qquad (3.1)$$

where I is the inflow node's index; Inflow is the stream flow, RIVERD is the tributary routing coefficient, TRIB is the tributaries' flow, RIVERC is the previous month's routing coefficient, RIVERB is the mainstream routing coefficient, and F is the mainstream flow; RCONT stands for the reservoir storage monthly; Prec represents actual rainfall at the reservoir, EVAP represents evaporation loss there, CANALDIV represents canal diversion, and SlackWater represents fictitious surface water required at nodes.

3.8.2 Consumer Producer Surplus

The primary goal of the IBMR-2012 is to maximize the net economic profits for the entire basin, as depicted in equation 5.1. It's important to note that this objective function exclusively pertains to the agricultural sector and doesn't encompass aspects like hydropower generation or municipal and industrial water usage. The summation of all components is performed across agriculture commodities, groundwater types (saline or fresh), and the ACZs.

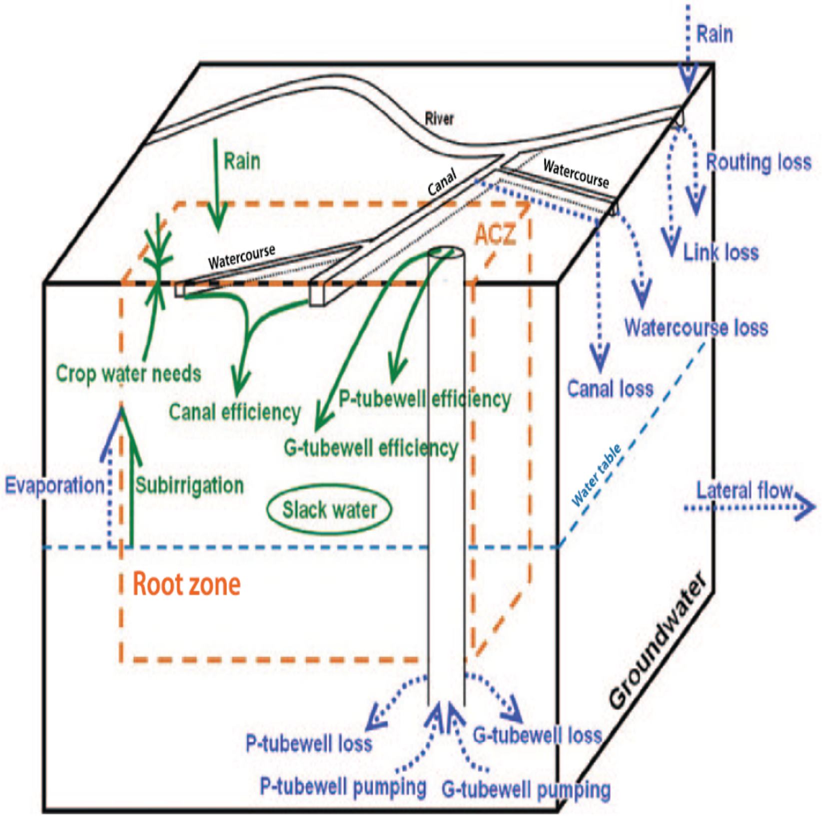
$$\begin{aligned} CPS = {} & \sum_{Z}\sum_{G}\sum_{C} Price_{z,c} * Production_{Z,G,C} \\ & - \sum_{Z}\sum_{G} Cost_{Z,G} - \sum_{Z}\sum_{C} Import_{Z,C} \\ & - ImaginaryWater + \sum_{Z}\sum_{C} Export_{Z,C} + \\ & \sum_{M}\sum_{N} WaterValue_{M,N} \end{aligned} \tag{3.2}$$

where Z is the ACZ index, G the groundwater type index, C the crop index, M the month index, and N the node or reservoir index Price × Production is the overall gain from raising crops and livestock. Cost is the sum of all production costs. Import is the sum of all costs associated with importing crops. Export is the sum of all benefits associated with exporting crops, and WaterValue is the value of water that is used up by the system or held in reservoirs but flows to the sea. This value can be used to demonstrate the economic advantage of maintaining environmental flows to the sea. The ImaginaryWater parameter in the network flow model represents the cost of having insufficient water in the objective purpose.

3.8.3 The Root Zone Water Balance

The root zone balance in IBMR is given in the below schematic: The root zone water balance in IBMR is computed using equation:

$$\begin{aligned} & Max[(WNR^{M}_{Z,G,C,S,W} - SUBIRRI^{M}_{Z,G} * LAND^{M}_{Z,G,C,S,W}), 0] * X^{M}_{Z,G,C,S,W} \\ & \leq TM^{M}_{Z,G} + WDIVRX^{M}_{Z,G} + ImaginaryRWater_{Z,G} \end{aligned} \tag{3.3}$$



Note: IBMR = Indus Basin Model Revised. The solid lines indicate the root zone water balance components used to supply the crop. The dashed lines represent the groundwater balance components tracked during the simulation runs. All water balance calculations are at the agro-climatic zone (ACZ) scale.

FIGURE 3.12: The root zone water balance

In equation 3.3, WNR stands for the water needed by crops, SUBIRRI for sub-irrigation, X for the cultivated area, TW for total private tube well pumping, GWT for total public tube well pumping, WDIVRZ for surface water diversion, and ImaginaryRWater for imaginary water at the root zone.

3.8.4 Overall Cost Function

The equation illustrates how the cost function includes all of the production expenses for crops and livestock in each ACZ.

$$\begin{aligned} Cost_{Z,G} = &\sum_{Z}\sum_{C}\sum_{S}\sum_{W}(FERT_{Z,C,S,M} + MISCCT_{Z,C,S,M} \\ &+ SEEDP_{Z,C,S,M} + TW_{Z,C,S,M} + TRACTOR_{Z,C,S,M}) \\ + \sum_{Z}\sum_{G}\sum_{A} Animal_{Z,G,A} &+ \sum_{Z}\sum_{SEA} PP_{Z,SEA} + \sum_{Z}\sum_{G}\sum_{M} Labor_{Z,G,M} \end{aligned} \tag{3.4}$$

whereby W is an indicator of the amount of water stress (such as standard, light, or heavy stress); S stands for the cropping sequence index (for instance, early, late, or standard planting); The animal index A includes cattle, bulls, and buffalo, while SEA is the season index (rabi and kharf). FERT stands for fertilizer costs, MISCCT for other costs such as insecticides and herbicides, SEEDP for seed costs, TW for groundwater pumping energy costs, TRACTOR for tractor operating costs, Animal for livestock fixed costs, PP for animal protein concentrate purchases, and Labor for labor costs.

3.8.5 Major Constraints and Limitations

Although all the equations and constraints of IBMR are very large in number and not possible to mention here, few important constraints are given below:

1. Canal Capacity: Upper limits of the canal capacity is considered in the model and there are 42 major canals are part of IBMR.

2. Canal diversion and 1991 water according: Canal water diversions are based on 1991 water accord.

3. Reservoir operation rules: No complex reservoir operating rules are implemented in IBMR. Only upper and lower bounds of reservoir storage are considered for a single year.

$$[h!]Flow(i,j,t) < Capacity(i,j,t) \tag{3.5}$$

$$Flow(i,j,t) > 0 \tag{3.6}$$

$$Family(Z,G,M) < HumanResource(Z,G) \tag{3.7}$$

$$Family(Z,G,M) > 0 \tag{3.8}$$

$$Export(Z,CE) < Production(Z,CE) \tag{3.9}$$

$$Export(Z,CE) > O \tag{3.10}$$

$$[h!]CanalDiversion(M) < Capacity(M) \tag{3.11}$$

$$CanalDiversion(M) > 0 \tag{3.12}$$

$$Slakeland(Z,G) < LandRocources(Z,G) \tag{3.13}$$

$$Slakeland(Z,G) > 0 \tag{3.14}$$

$$Volume_m < Rule(Up,M) \tag{3.15}$$

$$Volume_m > Rule(Lo,M) \tag{3.16}$$

where i and j are indexes for node i and j, Z is the Agro climatic Zone (ACZ) index, G is the groundwater type index, CE refers to the commodity index and M is the month index. These constraints are related to inflows in the canal, canal capacity, exports, canal diversions, slakeland and upper (Up) and lower (Lo) limits of volume in the reservoir.

3.8.6 The Demand and Supply

The objective function of IBMR is maximizing the CPS, i.e. consumer-producer surplus. The figure shows demand and supply curves for the zone model. The figure 3.13 shows the supply curve as nonlinear, it is due to different technologies and condition which fluctuates supply prices for farmers to supply products.
The colored area in the figure shows consumer and producer surpluses. Maximization of CPS is obtained an area under the demand curve minus the area under supply curve. The equations in the subsection sections have been reproduced from [50] Demand function can be algebraically defined as:

$$P = a + bQ \tag{3.17}$$

It's the price farmer sell final products.
An area under the curve is given by the following equation:

$$P = aQ + \frac{bQ^2}{2} \tag{3.18}$$

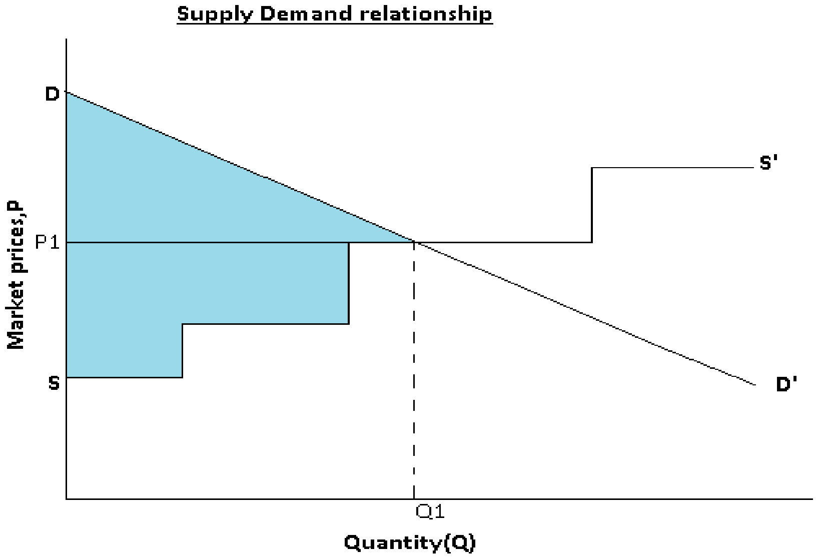


FIGURE 3.13: Supply demand relationship [51]

And the area under the supply curve is an overall cost function of Quantity supply or supply (Q). It is nonlinear, written as c (Q). For the objective function we combine two as

$$z = aQ + \frac{bQ^2}{2} - c(Q) \tag{3.19}$$

Indus Basin Model Revised has been written in GAMS [75–79] and it has 26 equations to model complex processes related to water and economic activities in the Basin [41].

3.8.7 Exceedance Probability

The probability that a specific value will be exceeded in a predetermined future time period is referred to as exceedance probability. Extreme occurrences such as earthquakes, floods and hurricanes can be predicted using the exceedance probability [80–82]. In IBMR, the exceedance probability is used for inflows calculations. Using 50% and 80% exceedance probabilities, river inflows were calculated and used for CPS calculations.

3.9 The Generalized Reduced Gradient Method

The Generalized Reduced Gradient (GRG) Algorithm is a mathematical optimization method used to find the global optimal solution of a nonlinear programming problem. It is based on the concept of reduced gradient and linear approximation of the objective function and constraints. GRG algorithms have been widely used in fields such as finance, engineering, and operations research for solving problems related to resource allocation, portfolio optimization, and production planning. The method is highly efficient and can handle large-scale problems with many variables and constraints. It has been established that the Generalized Reduced Gradient Method is a precise and accurate technique for dealing with nonlinear programming issues. Variables are divided into dependent and independent variables via the GRG algorithm. The fundamental idea behind GRG is to use Taylor's expansion equation to linearize the nonlinear objective and constraints function at a local solution [83–88]. Finally, the constraints are removed, leaving only non-basic variables in the variables space.

The GRG approach operates in a distinct manner compared to SQP (Sequential Quadratic Programming) or IP (Interior Point) techniques. When initiated within the feasible region, GRG initially moves towards a lower point until it encounters constraints or boundaries, after which it modifies its search direction to follow the constraints downwards while maintaining feasibility at each step. This method is effective for engineering problems as most engineering optimizations involve constraints, and GRG's strategy of following constraints works well in such scenarios.

3.9.1 Explicit Elimination

The equations from 3.26 - 3.42 have been reproduced from [83]. Suppose we want to minimize the following optimization problem:

$$\text{minimize} f(x) = x_1^2 + x_2^2 \tag{3.20}$$

$$\text{s.t.} \qquad g(x) = x_1 + x_2 + c = 0 \tag{3.21}$$

There are two ways to address the problem, which involves two variables and an equality constraint. One method involves solving the problem while maintaining the equality constraint, while the other approach involves using the constraint to remove one of the variables and the constraint altogether. The latter approach is the one that will be utilized. Using 3.21, we can write x_2 in the following manner:

$$x_2 = -x_1 - c \tag{3.22}$$

So, the equation 3.20 can be written as

$$f(x) = x_1^2 + (-x_1 - c)^2 \tag{3.23}$$

In mathematical terms, the problem stated in equations 3.20 and 3.21 is equivalent to the problem expressed in equation 3.22. The approach used in this scenario involves utilizing the constraint to eliminate one of the variables and the constraint itself explicitly. Once the optimal value of variable x_1 is obtained, it will be necessary to substitute it back into equation 3.21 to calculate the corresponding value of x_2 . Since only one variable is involved in this problem, a contour plot cannot be used to illustrate the solution. The reduced gradient relative to the original problem would be determined by the derivative of equation 3.22.

$$\text{minimize} f(x) = x_1^2 + (-x_1 - c)^2 \tag{3.24}$$

The derivative $\frac{df}{dx_1}$ is known as reduced gradient as compared to original problem. Normally, we cannot explicitly eliminate the variable using substitution method. Hence, implicit elimination is employed as described in the below section below.

3.9.2 Implicit Elimination

This section will focus on the implicit elimination of variables, which involves analyzing differential changes in the objective and constraints. The approach involves starting with a straightforward problem that features two variables and one equality constraint.

$$\text{minimize} f(x) \quad X^T = [x_1 \quad x_2] \tag{3.25}$$

$$\text{s.t. } g(x) = 0 \tag{3.26}$$

Starting from a feasible point, we assume that the hard constraint is satisfied and we want to further improve the objective function. the differential change in f can be written as:

$$df = \frac{\delta f}{\delta x_1} dx_1 + \frac{\delta f}{\delta x_2} dx_2 \tag{3.27}$$

To avoid the constraint violation, differential will also be zero.

$$dg = \frac{\delta g}{\delta x_1} dx_1 + \frac{\delta g}{\delta x_2} dx_2 \tag{3.28}$$

Solving for dx_2, we have

$$dx_2 = \frac{\frac{\delta g}{\delta x_1}}{\frac{\delta g}{\delta x_2}} dx_1 \tag{3.29}$$

Substituting value of dx_2 back in 3.27, we get

$$df = \left[\frac{\delta f}{\delta x_1} - \frac{\delta f}{\delta x_2} \left(\frac{\frac{\delta g}{\delta x_1}}{\frac{\delta g}{\delta x_2}} \right) \right] dx_1 \tag{3.30}$$

the term in bracket is known as $reducedGradient$.

$$\frac{df_r}{dx_1} = \left[\frac{\delta f}{\delta x_1} - \frac{\delta f}{\delta x_2} \left(\frac{\frac{\delta g}{\delta x_1}}{\frac{\delta g}{\delta x_2}} \right) \right] \tag{3.31}$$

When we replace Δx for dx, the resulting equations are merely estimations. The direction we take is tangential to the constraint and aimed at improving the objective function.

3.9.3 GRG Algorithm with Equality Constraints Only

The ideas discussed in the previous section can be applied to the broader problem that we express using vectors. If we introduce equality constraints, we can then examine this general problem.

$$\text{minimize} f(x) \tag{3.32}$$

$$\text{s.t. } g_i(X) = 0, i = 1, ..., m \tag{3.33}$$

Assuming we have n design variables and m equality constraints, we can divide the design variables into two groups: (n-m) independent variables (z) and m dependent variables (y). We will use the independent variables to enhance the objective function, and the dependent variables to meet the constraints. We can also partition the gradient vectors accordingly as well, resulting in:

$$\Delta f(z)^T = \begin{bmatrix} \frac{\delta f(x)}{\delta z_1} & \frac{\delta f(x)}{\delta z_2} \cdots & \frac{\delta f(x)}{\delta z_{n-m}} \end{bmatrix} \tag{3.34}$$

$$\Delta f(y)^T = \begin{bmatrix} \frac{\delta f(y)}{\delta y_1} & \frac{\delta f(x)}{\delta y_2} \cdots & \frac{\delta f(x)}{\delta y_m} \end{bmatrix} \tag{3.35}$$

The independent and dependent matrices of the constraints are defined the partial derivatives of ψ w.r.t to y and z.

$$\frac{\delta \psi}{\delta y} = \begin{bmatrix} \frac{\delta g_1}{\delta y_1} & \frac{\delta g_1}{\delta y_2} & \cdots \frac{\delta g_m}{\delta y_m} \\ \\ \frac{\delta g_m}{\delta y_1} & \frac{\delta g_1}{\delta y_2} & \cdots \frac{\delta g_m}{\delta z_m} \end{bmatrix}$$

$$\frac{\delta \psi}{\delta z} = \begin{bmatrix} \frac{\delta g_1}{\delta z_1} & \frac{\delta g_1}{\delta z_2} & \cdots \frac{\delta g_1}{\delta z_{n-m}} \\ \\ \frac{\delta g_m}{\delta z_1} & \frac{\delta g_1}{\delta z_2} & \cdots \frac{\delta g_m}{\delta z_{n-m}} \end{bmatrix}$$

Constraints in vector form and differential changes in objective can be represented as :

$$df = \nabla f(\mathbf{z})^T dz + \nabla f(\mathbf{y})^T d\mathbf{y} \tag{3.36}$$

$$d\psi = \frac{\delta\psi}{\delta\mathbf{z}} d\mathbf{z} + \frac{\delta\psi}{\delta\mathbf{y}} d\mathbf{y} = 0 \tag{3.37}$$

Since $\frac{\delta\psi}{\delta\mathbf{y}}$ is a square matrix, solving for dy.

$$d\mathbf{y} = -\frac{\delta\psi^{-1}}{\delta\mathbf{y}} \frac{\delta\psi}{\delta\mathbf{z}} d\mathbf{z} \tag{3.38}$$

Substituting dy into 3.36

$$d_f = \nabla f(\mathbf{z})^T d\mathbf{z} - \nabla f(\mathbf{y})^T \frac{\delta\psi^{-1}}{\delta\mathbf{y}} \frac{\delta\psi}{\delta\mathbf{z}} d\mathbf{z} \tag{3.39}$$

or

$$\nabla f_R^T = \nabla f(\mathbf{z})^T - \nabla f(\mathbf{y})^T \frac{\delta\psi^{-1}}{\delta\mathbf{y}} \frac{\delta\psi}{\delta\mathbf{z}} d\mathbf{z} \tag{3.40}$$

where ∇f_R^T is referred to as the reduced gradient. The direction of steepest ascent that remains tangent to the binding constraints is known as the reduced gradient

Substituting dy into 3.36

$$d_f = \nabla f(\mathbf{z})^T d\mathbf{z} - \nabla f(\mathbf{y})^T \frac{\delta\psi^{-1}}{\delta\mathbf{y}} \frac{\delta\psi}{\delta\mathbf{z}} d\mathbf{z} \tag{3.41}$$

or

$$\nabla f_R^T = \nabla f(\mathbf{z})^T - \nabla f(\mathbf{y})^T \frac{\delta\psi^{-1}}{\delta\mathbf{y}} \frac{\delta\psi}{\delta\mathbf{z}} d\mathbf{z} \tag{3.42}$$

where ∇f_R^T is referred to as the reduced gradient. The direction of steepest ascent that remains tangent to the binding constraints is known as the reduced gradient

3.10 An Introduction to GAMS

The General Algebraic Modeling System (GAMS) was initiated as a project an economic modeling group at the World Bank in the 1970s. GAMS was the first piece of software used to effectively define and address optimization issues by fusing standard computer programming ideas with mathematical algebra [79, 89–92].

3.11 The IBMR Implementation in GAMS

The IBMR has been implemented in General Algebraic Modeling System (GAMS) using dynamic nonlinear programing (DNLP) solver. The DNLP solver is based on state of the art Generalized Reduced Gradient (GRG) algorithm [83, 84, 87, 88, 93].

3.12 Summary

This chapter comprehensively describes the Indus basin, Indus basin model revised and its main objective function i.e. Consumer Producer Surplus used for the basin wide income calculations under real world constraints. The reduced gradient method has been used to solve the main objective function of IBMR along with the power generation contribution.

Chapter 4

Water Distribution using Bankruptcy Rules and their Impact on Basin-wide Income

"We might as well reasonably dispute whether it is the upper or the under blade of a pair of scissors that cuts a piece of paper, as whether value is governed by demand or supply."

Alfred Marshall

4.1 Introduction

Water is the most essential element of life and it is one of the most scarce resources on the earth. Although the 75% percent of the earth is water but drinking water is very rare. Fresh water constitutes about 2.50% of the total available water on the planet Earth. The remaining water is saline. The majority of fresh water is trapped in glaciers and snowfields. In practice, just around 0.007% of the world's water is available to feed and fuel the planet's 8 billion inhabitants [2]. Water is the lifeblood of agriculture, and is an inadequate resource. It individually as well as collectively affects a society unlike any other thing. There is no concept of life without water; hence, its influence on human's life is as massive as that of a religion or an ideology. Its scarcity and abundance both cause people to migrate. Its impacts can be termed as socio-economic and political. It is a source of great tension among trans-boundary basins. The agriculture sector's contribution to GDP continues around 21%, although progressive farmers acknowledge that considering the amount of surface water used in agriculture, much more may be done to increase its efficiency. According to the Pakistan Ministry of National Food Security and Research 2014-15 figures, Pakistan has lower per hectare yields of wheat, cotton, sugarcane, and rice than countries such as Australia, America, Egypt, Turkey, China, Germany, and France [94]. In the following figure 4.1, the water consumption pattern of Pakistan has been highlighted and it is evident that 90% of water is being utilized in agriculture sector.

One of the most difficult aspects of trans-boundary river management is distributing the limited and shared available water across riparian governments equally. Any country's agriculture relies heavily on water. Pakistan is no different. According to the WWF Report 2012, this resource is extremely limited. The Indus Basin Irrigation System (IBIS) is Pakistan's massive irrigation system (IBIS). This is the world's largest contiguous irrigation system. This irrigation system receives water from the main Indus River and its major tributaries, the Kabul, Jhelum, Chenab, Ravi, and Sutlej Rivers. The existing IBMR model is one of the most comprehensive models ever made, and used for planning water distribution in the Indus Basin for the last three decades. The analysis of agro-economic scenarios using IBMR is helpful for resolving disputes over water distribution between provinces, among other things. By enforcing the well-known bankruptcy laws, this research goes farther to fairly increase the provincial water allocation in IBMR and agriculture production. Our findings demonstrate that there are reliable and technologically advanced methods for allocating water to each province. Our proposed law, however, gives each province the maximum amount of water. The addition of bankruptcy rules to IBMR not only boosts the economic consumer producer surplus for the entire basin but also heightens a measure to instill confidence among the provinces.

Water Consumption Pattern in Pakistan

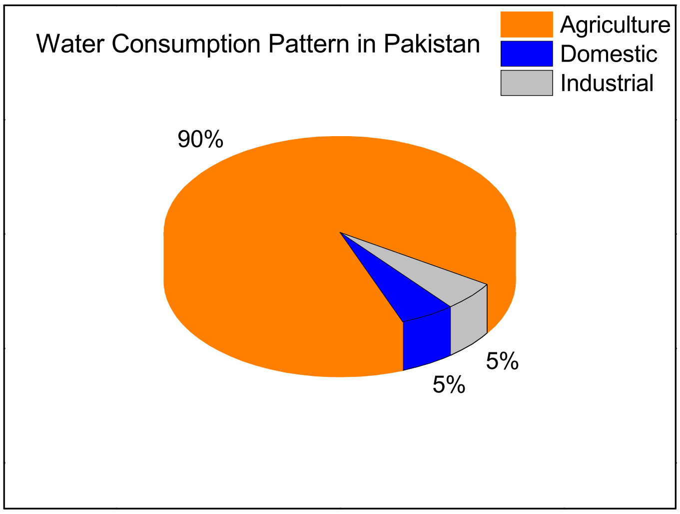


Figure 4.1: Water Consumption Pattern in Pakistan

If policymakers want to mitigate the effects of water scarcity, they need to move beyond the rhetoric of integrated water resource management and accept the challenges that lie ahead. Inadequate storage, conservation, and lack of water efficiency leading to lower per-acre productivity, unchecked groundwater abstraction and rationalization of water pricing, canal inefficiency at the provincial level, and contiguous but neglected irrigation infrastructure are all examples of Pakistan's water problems [95]. Pakistan is classified as a water-stressed country by the Falkenmark Water Stress Indicator, since our per capita water availability is less than 1,700 m^3. A country is regarded to be water scarce if its water availability falls below 1,000 m^3. Pakistan had a merely 1,223 m^3 of water available until 2010.

4.2 Inter Provincial Water Dispute

IWT is responsible for major adjustments in water allocation in every province in Pakistan. IWT also rendered the 1945 agreement between Punjab and Sindh. Furthermore, because there was no formal agreement among the provinces, WAPDA

Table 4.1: Indus Water Committees / commissions

Year	**Commission**
1938	Anderson Committee [98]
1945	Rau Commission [99]
1968	Akhtar Hussain Committee [96]
1970	Fazal-e-Akbar Committee [100]
1976	Anwar-ul-Haq Commission (Indus Water Commission) [101]
1983	Haleem Commission [102]
1991	Provincial Water Accord [103]

was put in charge on an adhoc basis. The Pakistani government has created several bodies to handle the contentious inter-provincial water issues. During the construction of two massive irrigation projects, the Sutlej Valley Canal Project in 1932 and the Sukkur Barrage in 1935, there arose an inter-provincial dispute over water distribution [96, 97].

4.2.1 Anderson Committee 1938

The Sutlej project was also contested by the government of Bombay Presidency (which included Sindh at the time), a lower riparian province. The government claimed that removing water from any tributary of the Indus basin river system in its upper reaches would disrupt the flow of the Indus itself, in support of its protest. The old inundation canals would become useless as a result of this. Despite this, the Indian government went forward with the project. As a result, the Sutlej Valley Project's water inflow has always been insufficient. The "Anderson Committee" was constituted by the Indian government to investigate the concerns of the Bahawalpur State and the Bombay Province. The Committee recognized the need for new projects on the western rivers in its 1937 report, which was later approved by the Government of India, and proposed to close down a portion of the Abbasi Canal and branches of the Bahawalpur desert Canal, which were intended to irrigate about half a million acres. The Committee also proposed that water be transferred from the Chenab to the Sutlej via link canals [98].

4.2.2 Rau Commission 1945

Sindh protested to the Punjab Government's intention to build a reservoir at Bhakkra, claiming that it would harm the inundation canals that irrigated the lower regions of Guddu and Kotri in Sindh. The Indian government established a commission to investigate the matter, with Sir Benegal N. Rau as its Chairman. This Commission unanimously agreed that the construction of the Bhakkra reservoir should be done in such a way that the canals of lower Sindh are not harmed. The Commission also advised that they should avoid any damages by constructing two barrages with common consent and financial contributions from the Punjab. Following the Rau Commission's suggestions, the Punjab and Sindh provinces agreed to work together to build the barrages at Taunsa, Kotri, and Guddu, as well as the Bhakkra reservoir. Representatives from the two provincial governments signed the agreement in 1945. However, when British India was partitioned in 1947, the incidental financial agreement had not been completed [98].

4.2.3 Akhtar Hussain Committee 1968

The Pakistani government established the Water Allocation and Rates Committee in 1968. The chairperson of this committee was Mr. Akhtar Hussain. This group was supposed to come up with reservoir release schedules, drawdown levels, and barrage apportionment. Alongside that, the use of groundwater with surface water was said to be examined by this committee too. Punjab and Sindh were the major disputed parties since the demands of Khyber Pakhtunkhwa and Baluchistan were not of large magnitude. The report formed by this committee was submitted to the government of West Pakistan on June 30, 1970. The constitutionality of four provinces was dissolved the next day so that both East Pakistan (now Bangladesh) and West Pakistan be administratively consistent. Anyhow this report could not get any attention [104].

4.2.4 Fazal-e-Akbar Committee 1970

Mr. Justice Fazl-e-Akbar –the former judge of the Supreme Court of Pakistan- set up another committee on October 15 , 1970 with the aim of being the distribution of water in the Indus River system of West Pakistan. The objective of the committee was not only to locate surface water and to store provisional considerations but also to analyze the role of groundwater. The committee was unable to create a consensus. Justice Fazl-e-Akbar prepared his suggestions and presented them. These suggestions were analyzed in October 1972 at the Governor's Conference but did not bear fruitful conclusions and the WAPDA carried on the temporary division of water [105].

4.2.5 Indus Water Commission 1976 (Anwar-ul-Haq Commission)

The Indus Water Commission was established by the president of Pakistan, on the proposal of the Council of Common Interest (CCI), in 1981. The Chief Justice of Pakistan served as the committee's chairman, while the chief justices of four different High Courts were its members. A nine-month period was allotted to the committee for the compilation of the report, but it failed to draw proposals. The committee suggested in June 1982 that the report of the Fazl e Akber Committee with the necessary adjustments might serve as the basis for the distribution of waters from the Indus and its tributaries [96, 104].

4.2.6 Haleem Commission 1983

Despite the creation of numerous committees and commissions, no clear solution to the inter-provisional water issue could be found from the initiation of the IWT in 1960 to the agreement of the 1991 Water Apportionment Act. Different causal factors may be hypothesized for this outcome. For example, the ignorance of the severity of the supply-demand gap from the Indus may be the reason. The Federal Government could not pay much attention to water issues due to its preoccupation with external conflicts under military rule [103].

4.3 Water Distribution

The Indus Basin Irrigation System is a comprehensive system that is regarded as one of the largest and most advanced irrigation systems in the entire globe. Without taking into account irrigation boundaries, it irrigates roughly 37 million acres of land split between Pakistan and India. As a trans-boundary river basin system, it gave rise to the international water dispute in April 1948, not long after the partition [106, 107]. The conflict prolonged till 1958 when some international players jumped in and resolved the issue temporarily.

4.3.1 The Indus Water Treaty

Pakistan and India signed the Indus Accord in 1960, in which Pakistan got right over three western rivers and could use 80% water held in Indus [63, 108]. The requirement to create an Indus River System Authority was acknowledged and approved under WAA 91 Clause 13 in order to implement the Accord.

4.3.2 The 1991 Provincial accord

Water Appointment Accord 1991 is a historical document signed among the Provincial March 16, 1991 and approved by the Council of Common Interests (CCI) on March 21, 1991 [108]. The accord consists of the total 14 Paras, 3 distribution paras, 6 development paras, 1 para related to escapage to downstream Kotri and

4 other paras. Under clause 13, an authority was to be established for the implementation of the accord. The authority named ”Indus River System Authority (IRSA)” was then approved and established. The IRSA has the mandate to implement the following:

- Act No. XXII of 1992, which was approved by the Parliament and signed on December 6 by the President of Pakistan, formed IRSA.
- Regulation and distribution of surface waters among the provinces in accordance with the allotments and guidelines set in the Water Accord of 1991 is one of IRSA’s primary responsibilities.
- To resolve any disagreements between two or more provinces about the allocation of river and reservoir waters;
- To resolve any dispute that may emerge between two or more provinces over the allocation of river and reservoir waters; 4- To resolve any dispute over the execution of the Water Accord by majority voting, with the Chairman having a casting vote in the event of a tie.
- If a Provincial Government or the Water and Power Development Authority is unhappy with a decision made by the Authority, they may file a complaint with the Council of Common Interests (CCI).

4.4 Three Enabling Variables for Conflict Resolution: Their Role And Use

4.4.1 Enabling Variable 1: Provincial Autonomy Recognition

The agreement of parties (four provinces) in governance to settle conflicts and collaborate on a set of agreed-upon operating standards is known as active recognition of interdependence. The contending parties' awareness of their mutual water demands, constraints, and potentials is required for such acknowledgment. Despite the formation of various committees and commissions, none of them were able to aggressively fix the problem. In 1990, a federal drive to resolve inter-provincial water difficulties prompted four provinces to engage in discussion, highlighting the importance of active acknowledgement of interdependence [109]. A new federal administrative system was created after the 1973 constitution recognised four provinces. The constitution did not establish or clarify provincial water allocation rules since water management was considered a provincial matter. In any case, the constitution preserved the provinces' active participation in the decision-making process. A new entity, the Council of Common Interests (CCI), was founded at the time, allowing provinces to actively participate in water management concerns. The CCI was given credit for bringing the four provinces together to discuss water concerns. On the request of one or more stakeholders, the CCI would hold meetings (four provinces of Pakistan). Its role was like that of the 'Indus Water Commission' of the IWT. The ICC and IWT differ anyhow on the legal basis as the former has no water treaty to refer to. Hence, the CCI dealt with any water-related issues mostly through discussion [110]. In 1990, Pakistan's new government began to handle provincial water conflicts. A subcommittee was constituted and supervised by the cabinet. The committee's principal goal was to look into various options for resolving water conflicts between provinces (Indus River System Authority (IRSA), 1991). The "Inter-Provincial Committee on the Apportionment of Indus Rivers" was constituted in 1991 by the CCI in response to the cabinet's recommendations. The Committee met for the first time on January 30, 1991. Other meetings were conducted in February to examine the technical and legal aspects of the issue across provinces. The Committee offered its recommendations to the provinces. The Chief Ministers of all provinces met again on March 3, 1991 [111].

As a result, on March 16, 1991, the four Chief Ministers reached an agreement on water distribution with the help of CCI and the federal government. The Water Apportionment Accord preserved current canal water uses in each province, taking into account the requirement for escape below Kotri for environmental reasons; the remaining river supplies, including ”flood surpluses” and ”additional supplies” from upcoming storage facilities, were allotted. It stated that 141 cubic kilometers of accessible water served as the basis for provincial water distribution. It was also proposed that increased water storage would offer roughly 12.33 cubic kilometers of more water for environmental flows [112].

It took 30 years for the Water Apportionment Accord of 1991 to make significant progress. The Prime Minister’s arbitrary role in helping this enabling circumstance become a reality cannot be overlooked (Indus River System Authority (IRSA) 1991). This arbitrary role resulted in conflict resolution because it allowed both sides to think about the matter carefully and discuss their own needs and concerns. Such mediation raised awareness and reduced mutual vulnerability, lowering the dangers of collaboration across Pakistan’s four provinces. The above discussion suggests that the provinces cannot avoid accepting their independence, working together, and understanding each other’s demands in order to accomplish Indus Waters’ long-term progress.

4.4.2 Enabling Variable 2: Mutual Cooperation for the Value Creation

Mutual value creation is based on the idea of exploring options without making a commitment. It makes it possible for both sides to benefit. No party is obligated to commit to a certain choice during this period of cooperation. It makes the zero-sum issue easier to understand by allowing parties to search for links across many resources. Moreover, it transcends the conventional notion that current water is the sole resource available [113]. By having a professionally mediated conversation between the parties to identify and explore mutual value creation, identify the reciprocal advantages and costs of cooperation, and look into measures to protect those advantages and expenses [114].

For inter-provincial water sharing, Pakistani citizens must take part in the quest for the advantages of distributing and sharing water for agricultural and environmental needs. In accordance with the Water Apportionment Agreement, each of the four provinces had to advance more quickly than they had anticipated.

Punjab received 69 cubic kilometers of water each year, Sindh received 60.14 cubic kilometers, KPK 7.12 cubic kilometers, and Baluchistan received 4.77 cubic kilometers. Local canals above the rim stations delivered an additional 3.7 cubic kilometers of water to the KPK province each year. Through the concept of ”balanced river supply” Punjab and Sindh would receive 37% of the future water storage and flood flows, Baluchistan would receive 12%, and KPK would receive 14% [96].

To counteract seawater disturbances of 12.33 cubic kilometers per year were set aside for environmental flows downstream to Kotri in order to protect mangrove trees.

Permission was also extended to provinces to plan new projects. Small projects of less than 20 square kilometers were granted permission to operate above 366 meters. It was suggested that provinces work together to reduce water waste.If one province is unable to use all of its given water, another province may be allowed to use it without obtaining a right to it [115]. The operation of existing water sources, as well as future possibilities such as the construction of new dams and storage reservoirs, are prioritized by the provincial irrigation uses and regulations (Indus River System Authority (IRSA) 1991).

The Water Apportionment Agreement provided each province with the freedom to use the water that was allotted to them while outlining the conditions, potential, and limitations. For instance, it was intended to add an additional 20234 square kilometres (5 million acres) of land to be developed. Wheat production was expected to rise by 2 million tons each year, according to estimates. Sindh received a 13 percent increase in its share from the previous agreement, receiving an additional 5.55 cubic kilometers per year. KPK received 50 percent more water than it had requested in 1983. Sugarcane production in KPK increased as a result. For instance, it was anticipated that the province of Balochistan would gain 0.6 to 1.6 million acres of additional land under cultivation as a result of the new distribution. By adding 3 million acres to its irrigated land, Punjab has seen considerable gains [116].

4.4.3 Enabling Variable 3: Establishment of the Indus River System Authority (IRSA) as an Adaptive Governance Regime

The key points are given below:

- Provide the groundwork for the provincial distribution and management of surface waters based on the divisions and policies mentioned in the Water Accord;
- The provinces according to the policies and divisions discussed in the Water Accord;
- On a regular basis, evaluate and identify water storage and river operation patterns;
- Synchronize and manage the Water and Power Development Authority's (WAPDA) operations in exchange for provincial data sharing;
- Keep an eye out for any potential conflicts between provinces over river flow allocation and water storage levels;
- Evaluate water availability in relation to provincial water allocations and make appropriate proposals;
- By a majority vote of members, answer questions about the Water Accord's performance.

IRSA's primary responsibility was to distribute water among the provinces in compliance with the 1991 Agreement. Regular meetings with ISRA were held with all pertinent stakeholders. In particular during the growing seasons, two committees assisted IRSA in making decisions about the planning and allocation of water supply for the Provinces. The Technical Committee provided information and assistance regarding the operation of water storage and irrigation systems, whereas the Advisory Committee, which was made up of representatives from IRSA and the federal government as well as the representatives of the provinces, serves as the institutional link between IRSA and its affiliated bodies [117].

4.5 How has Adaptive Governance Enhanced the Efficiency of IRSA?

The IRSA lacked the necessary data and access to the monitoring sites. WAPDA was in charge of overseeing the operation of barrages and data collection. WAPDA was responsible for making water distribution decisions for IRSA. It resulted in IRSA delaying real-time and transparent decision-making. It led IRSA to work with the federal government to create backup telemetry systems in order to update data collection. This action was very advantageous since it gave IRSA the freedom to manage precise flows without relying on information from the WAPDA and provincial irrigation authorities. IRSA was given a rare chance to monitor water availability and assess distribution patterns in the field in real time.

Concerns regarding the purported uniformity and accuracy of the telemetry system were expressed by the downstream provinces of Baluchistan and Sindh. The correctness and reliability of the telemetry system were assessed by an independent authority. In 2008, an independent authority came to the conclusion that the telemetry system simply needed minimal adjustments to continue operating as planned . Finally, the IRSA's implementation of the Water Apportionment Accord demonstrated how an adaptive regulating body could operate as an enabling condition for resolving contentious trans-boundary water issues [118].

4.6 Water Distribution as per IRSA Rules

There are three paras namely para 2, para 4 and para 14(b) [118, 119] related to distribution of water among the provinces These three cater for the different scenarios according to which water is distributed among the provinces. These three scenarios are listed below:

- Scenario I: Water Availability < Actual Average System Uses distributed as per 14 (b) of the WAA 1991.
- Scenario II: Water Availability > Actual Average System Uses but < Para 2 of WAA 1991. Actual Average System Uses are protected Balance available as per Para 2 approved by CCI.
- Scenario III: Water Availability > Para 2 of WAA 1991 Para 2 approved by CCI are protected Balance as per Para 4 of the WAA 1991.

4.6.1 Scenario I: Water Distribution as per Para 14b

If the water availability is less than the annual average water then the water will be distributed among the provinces according to Para 14b. The distribution according to the para 14b is given in the table 4.2:

TABLE 4.2: Water Distribution According to Para 14b

Province	**% Share**
Punjab	53.06
Sindh	42.37
KPK	2.98
Baluchistan	1.59
Total	100.00

4.6.2 Scenario II: Water Distribution as per Para 4

If the water availability is equal to annual average water then the water will be distributed among the provinces according to Para 4. The distribution according to the para 4 is given in the table 4.3: The distribution according to the para 4 is given in the following table:

TABLE 4.3: Water Distribution According to Para 4

Province	**% Share**
Punjab	37.00
Sindh	37.00
KPK	14.00
Baluchistan	12.00
Total	100.00

4.6.3 Scenario III: Water Distribution as per Para 2

If the water availability is equal to annual average water then the water will be distributed among the provinces according to Para 2. The distribution according to the para 2 is given in the table 4.4:

TABLE 4.4: Water Distribution According to Para 2

Province	**% Share**
Punjab	55.94
Sindh	48.76
KPK	5.78
Baluchistan	1.87
Total	100.00

4.7 Bankruptcy Rules

Water is a scarce resource and its distribution among the stakeholders is a key challenge. The situation becomes more intense when there are external parties involved in it. Pakistan is facing the same situation. The average annual water availability is about 132.02 MAF and demand is 149.71 MAF so there is a deficit of 17.69 MAF of water. Indus River system is a major source of water for Agriculture in Pakistan. It is a transboundary basin and flows across the four countries [120]. Similar to that, it shares waterways with Pakistan's KPK, Baluchistan, Punjab, and Sindh provinces. As availability is less than the demand so there is always a situation of mistrust among the provinces. Currently, water is being distributed among the provinces as per IRSA (Indus River System Authority). For fair and efficient reallocation of water, we need some rules, which do not depend on riparian states contribution, or upper and lower riparian rights. The allocation should be fair, acceptable and robust which can address spatial and temporal variability of water throughout the year. Bankruptcy Rules answer the above question.

There are many bankruptcy rules, which are used for asset allocation when demand is higher than the available asset. Most common bankruptcy rules are Proportional Rule (PR), Constraint Equal Award Rule (CEA), Constraint Equal Loss Rule (CEL) and Hojjat Mianabadi Rules. Every bankruptcy rule has advantages over other. Depending upon current availability and demand of water, we may choose an appropriate rule [121–124] .

Focus of the current study was to investigate the impact of bankruptcy rules (Proportional, Constraint equal award rule, Constraint Equal Loss Rule and Mianabadi Rule) on basinwide net economic benefit and results reflect that in case of larger provinces like Punjab and Sindh, Mianabadi Rule rule outputs and net bain income increases 16.42% for linear water network and about 20.87% for nonlinear water network. These rules also serve as confidence build measures among the provinces. For instance, Constraint equal Award rule favors the smaller provinces like KPK and Baluchistan.

A notable work on bankruptcy rules by Shahmir et al. [52, 53] was done in the recent past. The primary goal of this research was to create approaches that foster growth, unity, and collaboration instead of aggression and contention within transboundary river basins. However, in the current research, the main objective was to assess the impact of bankruptcy rules on basin-wide income using modified IBMR. IBMR inherently takes into account the contribution of groundwater extraction via tube wells in its objective.

In the current study, the real-time data of the year 2012 from IRSA used for water allocation using Bankruptcy rules have been used. There are two types of data used. First type is annual inflows for provinces and the second one is canal diversions. The average inflow of about 132 MAF has been used for calculation. The same data was used in IBMR2012. The solutions obtained from bankruptcy rules are workable, distinctive, fair, strong, and acceptable. The comparison of these rules have been given under results section. The equations in subsections 4.7.1-4.7.6 have been reproduced from [121–125].

4.7.1 Proportional Rule (PRO)

According to Proportional Rule asset is divided among the stakeholders as per their claims and mathematically it can be formulated as:

$$x_i = \lambda c_i \tag{4.1}$$

where: x_i=new allocation

λ = proportionality constant λ=$\frac{E}{C}$

c_i =the individual claim E =total asset

C= total claim

4.7.2 Constraint Equal Award Rule (CEA)

This rule ensures the equal division of available asset provided no one gets more than its claim. Mathematically it can be represented as:

$$x_i = min(\lambda, c_i); where \sum(min(\lambda, c_i)) = E \tag{4.2}$$

where: x_i=new allocation

c_i =individual claim

λ= proportionality constant

E= total asset

n = number of total claimants

This rule is supposed to favor the lower claims, normally belonging to weaker beneficiaries who can be more affected by losses.

4.7.3 Constraint Equal Loss Rule (CEL)

CEL allocates each claimant a share of the asset such that their losses in comparison with their claims are equal, subject to no claimant receiving a negative allocation.

$$x_i = max(0, c_i - \lambda); where \sum(max(0, c_i - \lambda)) = E \tag{4.3}$$

The objective function can be written as:

where:

x_i=new allocation

c_i =individual claim

$\lambda = L/n$ proportionality constant λ = L/n

L= total loss

E= total asset

n = number of total claimants.

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4.7.4 Talmud Rule (TR)

According to Talmud rule no stakeholder will receive more than 50 % of her claim if asset is less than half of the total claim, and no-one will lose more than half of her claim if the asset is more than half the total claim.

$$x_i^{Tal} = \begin{cases} CEA(\frac{1}{2}c_i, E), & \text{if } E < \frac{1}{2}D. \\ (\frac{1}{2}c_i + CEA(\frac{1}{2}c_i, E - \frac{1}{2}C), & \text{otherwise.} \end{cases} \tag{4.4}$$

where:

x_i=individual allocation

c_i=individual claim

C =Total claim

E= Total asset

4.7.5 Piniles Rule (PR)

The Piniles Rule is a combination of CEA and CEL. the rule uses CEA variant when total asset is less than half of total demand and the variant of CEL is used otherwise.

$$x_i^{Pin} = \begin{cases} x_i^{CEA}(\frac{1}{2}c_i, E), & \text{if } E < \frac{1}{2}D. \\ (\frac{1}{2}c_i + x_i^{CEL}(\frac{1}{2}c_i, E - \frac{1}{2}D), & \text{otherwise.} \end{cases} \tag{4.5}$$

where:

x_i=individual allocation

c_i=individual allocation

E= Total asset

S =Total deficit

4.7.6 Hojjat Mianabadi (MIA)

Hojjat Mianabadi (MIA) Rule is based on agent contribution. Every agent will get reward as per its contribution. Mathematically it can be formulated as:

$$D = C - Ed_i = (1 - \frac{a_i}{\sum_{i=1} a_i}) * D \qquad \forall i \tag{4.6}$$

$$x_i = c_i - d_i \qquad \forall i \tag{4.7}$$

$$d_i = (1 - \frac{a_i}{\sum_{i=1}^{n} a_i}) * D \qquad \forall i \tag{4.8}$$

$$x_i = c_i - \left[\frac{1 - \frac{a_i}{\sum_{i=1}^{n} a_i}}{n-1} \right] * D \qquad \forall i \tag{4.9}$$

where :

D =total demand

C= the total claim

E= total asset

d_i= individual deficit

a_i= individual allocation

x_i= new allocation

c_i= individual claim

n = number of total claimants.

4.8 Simulation and Results

In this research, the real time data for Indus River System at rim stations for the year 1922-2010 have been used. Different exceedance probabilities have been calculated and used for water distributions among the different provinces of Pakistan using IRSA Rules. For the allocation of water among the provinces, bankruptcy rules like the Hojjat Mianabadi Rule, the Proportional Rule, the Constraints Equal Award Rule, and the Constraints Equal Loss Rule have been used. Microsoft Excel and GAMS Studio win64 25.1.3 have been used for calculations and optimizations. The results of allocations using IBM, IRSA and Bankruptcy Rules are being presented in the Result section.

4.8.1 Water Distribution using IBMR2012

The table 4.5 shows water distribution using IBMR 2012 according to para 4 of IRSA Rules. All the numbers presented in the table are in MAF. Last row of the table shows total demand, water allocation as per IRSA rule and total deficit respectively.

Table 4.5: Water Distribution using IBMR2012

Province	**Demand**	**Allocation**	**Deficit**
KPK	10.73	8.25	2.48
Punjab	69.02	62.48	6.54
Sindh	61.84	55.30	6.54
Balch	8.11	5.99	2.12
Total	149.70	132.02	17.68

4.8.2 Water Distribution using IRSA Rules

The water distribution among the provinces using IRSA rules discussed in the section 4.6 are compared in the table 4.6 under different water availability conditions: The table 4.6 depicts the water distribution among the provinces in three different situation where Min. Max and Avg inflows are 99,183,144 MAF respectively [126]. IRSA rules para 2,4 and 14b are used for water distribution among the provinces [118].

Table 4.6: Water Distribution using IRSA Rules

Province	**Para2**	%	**Para4**	%	**Para14b**	%
KPK	9.26	5.06	20.16	14.00	2.95	2.98
Punjab	89.52	48.92	53.28	37.00	52.53	53.06
Sindh	78.03	42.64	53.28	37.00	41.95	42.37
Balch	6.19	3.38	17.28	12.00	1.57	1.59
Total	183.00	100.00	144.00	100.00	99.00	100.00

4.8.3 Water Distribution using Bankruptcy Rules

Different Bankruptcy Rules have been discussed in the subsection 4.7.1-4.7.6 and using these rules the water distribution the provinces is calculated and results are presented in the table 4.7 In the table 4.7, various Bankruptcy Rules like Proportional Rule (Pro), Constraint Equal Award Rule (CEA), Constraint Equal Loss (CEL) and Mianabadi Rule (MA) have been used for water allocation for average available water i.e. 132.02 MAF as used in IBMR2012. The results show

Table 4.7: Water Distribution using Bankruptcy Rules

	RULE			
Province	**Pro**	**CEA**	**CEL**	**MA**
KPK	9.46	10.73	6.31	5.20
Punjab	60.87	56.59	64.60	65.29
Sindh	54.54	56.59	57.42	58.41
Balch	7.15	8.11	3.69	2.48
Total	132.02	132.02	132.02	132.02

that Mianabadi Rules perform the best for larger provinces like Punjab and Sindh where as Constraint Equal Award Rule (CEA) favors the smaller provinces like KPK and Baluchistan.

4.8.4 Qualitative Comparison Using Different Rules

The quantitative results presented in the table 4.7 are summarized in the table 4.8 in a qualitative manner. Table 4.8 shows the comparison of different Bankruptcy rules. Column 2 to column 5 are ranked from highest to the lowest allocation. For example smaller provinces like KPK and Baluchistan get larger share in case of CEA rule. On the other hand Mianabadi Rule favors the larger provinces like Punjab and Sindh.

Table 4.8: Bankruptcy Rules Comparison

Province 1	**Preference1** 2	**Preference2** 3	**Preference3** 4	**Preference4** 5
KPK	CEA	PRO	CEL	MA
Punjab	MA	CEL	PRO	CEA
Sindh	MA	CEL	PRO	CEA
Balch	CEA	PRO	CEL	MA

4.8.5 IRSA vs Bankruptcy Rules

In this section, the classical bankruptcy rules and IRSA rules have been compared. A qualitative comparison is given in the table 4.9 below.

Table 4.9: IRSA vs Bankruptcy Rules

S.No.	IRSA	Bankruptcy
1	IRSA rules are based on fixed Water allocation. Fixed water distribution mechanisms may result in water allocations that are deemed unsatisfactory by the provinces, particularly when faced with uncertainty, drought conditions, and the unpredictable patterns of river flows.	Water allocation is based on demand and availability of water.
2	IRSA rules are in practice since 1991. These rules were designed by the experts at that time to provide the best possible share to all provinces.	Bankruptcy rules are in use for centuries. In the recent past, these rules have been used for water distribution and conflict resolution in different areas of the world.
3	Around three decades have passed since the signing of the Water Apportionment Accord among Pakistan's provinces. During this time, the provinces' water requirements have shifted due to population growth and expansions in irrigated land. Consequently, the disparity between water supply and demand has markedly increased in Pakistan.	Bankruptcy rules are dynamic and based on current water demand and allocation. Therefore, they provide a fair water distribution among the provinces.

4.8.6 CPS Comparison

The Consumer Producer Surplus using IRSA, MIA and PRO rules have been calculated and presented in the above table. It can be seen from results using Bankruptcy Rules, CPS has improved as compared to IRSA Rules. The *wsiszn* is the agroclimatic zones model with nonlinear objective and *wsisnn* model with nonlinear water network used in IBMR.

Table 4.10: CPS (million rupees) calculation using Bankruptcy Rules

Model	IRSA	MIA	PRO	% MIA	%PRO
wsiszn	102,224.97	122,302.27	122,438.08	16.42	16.51
wsisnn	92,563.22	116,980.09	108,304.16	20.87	14.53

It has been observed that basin wide net benefit i.e. CPS increases up to 16.42% and 16.51% using MIA and PRO rules respective with $wsiszn$ is the agroclimatic zones model with nonlinear objective function. Similarly, the net benefit i.e. CPS increases up to 20.87% and 14.53% using MIA and PRO rules respectively using $wsisnn$ model with nonlinear water network used in IBMR.

4.9 Discussion

By comparing the outcomes of IRSA and Bankruptcy regulations as outlined in Tables 4.5 and 4.7, it becomes apparent that the PRO Rule offers an equitable solution for the allocation of water resources to all involved provinces. The data in Table 4.5 indicates that the utilization of MIA rule leads to a notable 20.87% increase in CPS, which initially appears favorable. Nonetheless, this approach jeopardizes the allocation for smaller provinces, potentially giving rise to contentious situations among them. In contrast, adopting the PRO rule results in a 14.53% CPS increase, while maintaining the shares for KPK and Baluchistan intact.It is worth mentioning that following the PRO rule, KPK and Baluchistan are granted an additional allocation of 1.21 MAF and 1.16 MAF, respectively, in contrast to the water distribution guidelines set by IRSA. Similarly, through the implementation of the PRO rule, KPK and Baluchistan secure a greater water allocation of 4.26 MAF and 4.67 MAF, respectively, when compared to the utilization of the MIA Rule.

4.10 Summary

This chapter is dedicated to the water distribution conflict in Indus basin history considering pre and post partition scenarios. The conflict settled with intervention of World bank and the historical Indus Water Treaty (IWT) 1960 - signed between Pakistan and India. This results in the initiation of construction of multipurpose mega dams like Tarbela, Mangla and Warsak. Later on, the issue of water distribution became severe among the provinces and finally the provincial water accord 1991 was signed amongst all provinces and till now water is allocated to all four provinces according this this accord. In the current research, bankruptcy famous rules have been employed for water distribution among the provinces and observed that basin wide income i.e. CPS maximizes using these water distribution rules.

Chapter 5

Revisiting the Indus Basin Model for an Energy Sustainable Pakistan: A Roadmap for SDG 7

"There must be a better way to make the things we want, a way that doesn't spoil the sky, or the rain or the land."

Paul McCartney

5.1 Introduction

Water is the quintessence for life. Since the dawn of civilization, it has been common knowledge that water sustains life. However, in the recent years, the notion of what could be the applications of water has evolved. All life on earth is solely dependent on water for its survival. The relationship between electricity and water is the extension of one of the many diverse properties of water. Electricity - though not invented long ago - has now become a major need of life. From central heating and cooling systems to bullet trains as daily commutes, electricity has paved its way in all walks of life. River basins are the hydrological units of the planet and as such play a critical role in the natural functioning of the earth. These are backbone of agriculture and have a lion share toward economy. There are 263 river basins in the world ranging from small, medium to large [5]. Venkat Lakshmi et al. [6] discussed the 10 major basins namely Amazon, California, Colorado, Congo, Danube, Ganga Brahmaputa, Mekong, Mississipi, Murray-Darling, Nile and Yangtze in context of precipitation, vegetation, evapotranspiration, total water, soil moisture and runoff with reference to their variations and impact on the basins economy. Basin modeling is a mathematical model that represents the relevant processes in a river basin, forecasts how the basin will behave under various situations or management scenarios, and assists decision-makers in making sensible water distribution among various users and sectors. Water resource allocation, water quality preservation, and fast expanding demand are all major concerns for river basin users [7, 8].

The discussion to follow will briefly cover the Indus basin modeling in historical perspective. Indus basin is a trans-boundary basin. It has a unique and interesting composition. Its total area is about 1120000 square kilometers, which constitutes about 54% of the Southeast Asia. It runs through four countries namely Pakistan, India, China and Afghanistan with area of 520,000, 440,000, 88,000 and 72,000 square kilometer respectively. Pakistan and India are using 60% and 25% water of Indus basin respectively (Aquastat survey 2011). In order to use this water judiciously, both countries signed, “The Indus Waster Treaty” in 1960 [24]. Under this treaty, India got control over Beas, Ravi and Sutlej while Pakistan got control over Indus, Chenab and Jhelum. The water distribution amongst provinces in Pakistan is according to Provincial Water Accord 1991 [103]. In Pakistan broad agribusiness and water system framework, alluded to as the Indus Basin Irrigation System (IBIS). This is the biggest bordering water system framework on the planet. The normal yearly stream of Indus bowl is around 146 MAF. It has two noteworthy capacity repositories specifically Mangla and Tarbela. It consists of 19 barrages, 12 interface canals, and 45 noteworthy canal commands. The aggregate length of canals is around 60,000 km and around 120,000 watercourses to irrigate farms. It inundates 16.2 million hectare and contributes about 25% of GDP. Wins about

70% of the export income and utilizes 50% of the workforce straightforwardly and another 20% in a roundabout way [26].

The study of the Indus Basin of Pakistan carries a long legacy of planning and research. In order to manage the Indus Basin River System (IBRS) the work on Indus basin model started in 1976 by the World Bank and the Water and Power Development Authority (WAPDA) jointly with a view to address the water dependent economy of Pakistan. The preliminary work on Indus Basin Model by Johannes BISSCHOP and et al. [27] proposed high level Indus Basin Model based on linear programming. The goal was to maximize the overall basin income aggregating the individual fifty-three polygons income using multi-level programming [28]. Instead of presenting mathematical details of IBMR, the author focused on the multi-decision making aspect of model and posed it as hierarchical decision-making problem.

The work on Indus Basin Model (IBM) started by G. T. O'Mara and et al. [29] This paper comprehensively describes, the Indus Basin Model (IBM) family, structure, model validation and simulation results to access the conjunctive use in Indus irrigation system for alternative policies. Alexander Meeraus, and Masood Ahmad launched Agricultural Impact Study (AIS) [30] in September 1985 to assess impact of the Kalabagh Dam on Pakistan's Agriculture sector and first draft of report was completed in July 1986. In this report Indus Basin model using linear programming was used with computer implementation in FORTRAN language to run on main frame computer environment. This first version focused on farm level water distribution, and income assessment. Later on all other versions were developed in GAMS [26, 127] and used for the management of water resources distribution in different polygons, crops production, demand and supply of provinces, livestock etc.

The next more refined version called Indus Basin Model Revised (IBMR) jointly developed by WAPDA and World Bank Development Research Center for Water [17]. In IBMR the mathematical complexities were simplified by reducing number of equations, constraints and at same time replacing polygons into Agro Climatic

Zones (ACZ). The operational conceptual model of IBMR is shown in figure 5.1 indicating the standard inputs/outputs.

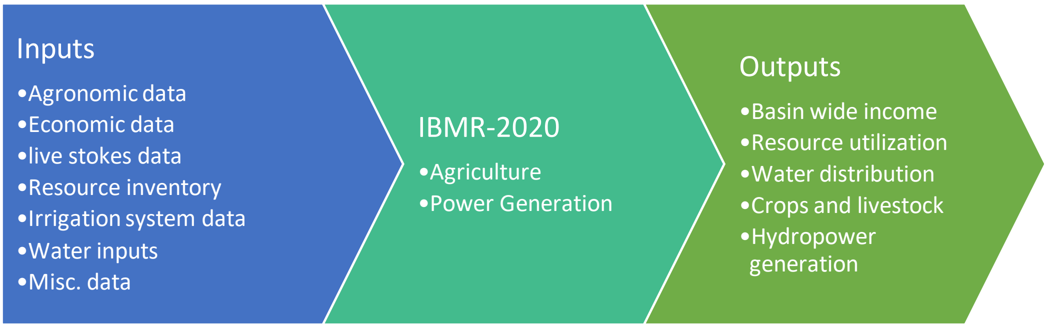

Figure 5.1: Conceptual model of IBMR

"Pakistan's Water Economy: Running Dry", a notable study [128] by the World Bank got the global attention on the Indus Basin Water Resources issues. In the recent past, the WAPDA and the World Bank analyzed to update the IBMR with reference to climate change impact on Indus Basin. A new version developed called IBMR-2012 by integrating Social Accounting Matrix (SAM) of 2008-2009 and Central General Equilibrium Model (CGE). This model was used to analyze the impact of climate change on the provinces of Pakistan using sensitivity analysis [41].

The Indus Water System can be categorized in three eras namely Pre Indus Water Treaty (1947-60) period; Post Indus Water Treaty (1960-75); the Management era (1975-2000). It describes a half century perspective on Management of Indus Basin focusing crisis planning, multi strategies planning to achieve governance goal, plantation at multiple topographical levels for water management, regional water management to variation pattern and scientific planning to explore alternative [39]. The Indus River System Model (IRSM) used as a planning tool for water management options in Pakistan, was published on August 14, 2018. The report was jointly prepared by The Commonwealth Scientific and Industrial Research Organization (CSIRO) Australia and The Sustainable Development Policy Institute (SDPI) Pakistan, funded by Australian Government and supported by

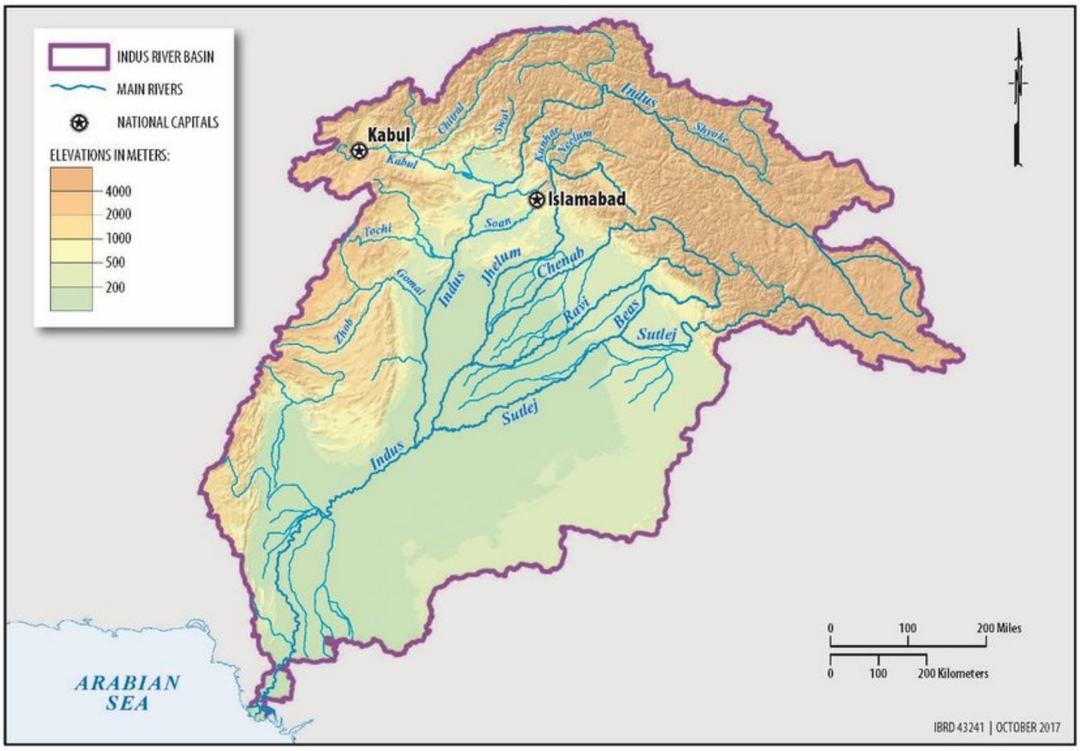

Figure 5.2: The Indus Basin of Pakistan [129]

Government of Pakistan. The main purpose of the project was to build capacity and knowledge management in water resources management with prime focus on Integrated Water Resources Management. The existing Indus River Systems IBM/IBMR and the Regional Water System Model(RWSM) have been discussed. IBMR is a hydro-economic model where as RWSM caters for only hydrology part embedded with more detailed economic model [130, 131].

The Water Resources Management in South Asia is important with reference to present and future scenarios. Some important facts related to regional per capita water availability, population growth vs per capita water availability, decreasing live storage capacity of reservoirs and province wise soil salinity status have been discussed. Mathematical Modeling of the Upper-Indus Glaciers and governing equation are discussed [43]. The latest work analyzes the impact of climate change in Indus Basin. The author along with his team, spent two years in Pakistan and studied the climate changes in the basin. They also worked on Indus

Basin Model Revision after 1992, the revision is known as Indus Basin Model Revised 2012(IBMR-2012). The research resulted in Book and covers all the aspect of Indus Basin viz Literature Review, Model Equations and results which reflect the current agro-economic conditions of the country. IBMR2012 was used to explore impact of climate change for food security and water allocation in Indus Basin. Hydro-climatic parameters sensitivity analysis for the provinces showed that Punjab would be impacted with least climate change in the future whereas Sindh would suffer the most [44].

Pakistan's water profile has changed drastically from being a water bountiful country to experiencing water stress. During the period 1990-2015, per capita water availability declined from 2,172 m^3 for every tenant, to 1,306 m^3 for each occupant. Pakistan takes out 74.3% of its freshwater yearly, subsequently applying gigantic weight on inexhaustible water resources [59]. The trans-boundary basin management is always a challenging task for policy makers and researchers. Transformative investigation encourages the understanding of techniques to avoid change, distinguishing proof of destructive collaboration, and key arrangement of chances for change. Transformative investigation obliges us to use the cooperative energy that gets from mixing disciplinary methodologies and epistemologies. All the common dangers related with such mixing apply here, including disciplinary predominance, epistemological discord, and master diaries and subsidizing streams that are intended to debilitate it [132].

Assessments of global water bargains recommend that riparian states are not paying attention to the counsel to receive Integrated Water Resources Management (IWRM). Speculations propose that the bigger the quantity of arranging states, the lower the expense (per condition) of the joint activity of arrangements. The exchange off among advantages and expenses related to the quantity of bargain signatories was modeled and applied to a worldwide settlement informational index. Discoveries affirm that the exchange expenses of arrangement and the economies of scale are significant in deciding the scarcity of bowl wide understandings, the bargains' substance, and their degree [133]. John F. Kennedy once said that the individual who can tackle the world's water issues ought to get two Nobel Prizes:

one for harmony, the other for science. Somewhere in the range of 55 years after his passing, the world is gradually valuing the propriety of his comments and the troubles and complexities of tackling the world's water issues that are presently confronting mankind, as far as both quality and quantity, on a drawn-out supportable premise. Think tanks in many advanced nations feel that their water issues were comprehended over 50 years prior, and therefore they are pertinent now just for developing nations. This is a misguided judgment [134].

In the past few decades, 'water emergency' and 'water wars' have become expanding worries of water experts, political specialists, and the media. Both beginning with the oversimplified and mistaken suspicion that the amount of water accessible on the planet for human use is restricted. The world is confronting a water emergency of a phenomenal extent, which may even bring about wars among nations. Projections as of late by significant global associations have been reliably critical. For instance, in 2009, the 2030 Water Resources Group anticipated that the world would confront 40% water deficiency under a nothing new atmosphere situation. In 2016, United Nations Environment Programme (UNEP) guaranteed that by 2030 nearly 'half of the total population will experience the ill effects of serious water pressure'. In 2017, UN Secretary-General Ban Ki-moon broadcast that by 2030 the 'world may confront 40% deficit in the water'. The World Bank has asserted that by 2050, about 1.8 billion individuals would be living under intense water shortage. In 2018, the World Bank and the UN asserted that 36% of the worldwide populace lived in water-rare regions. The World Resources Institute(WRI) asserted that 33 nations would confront 'amazingly high water pressure'. As indicated by the WRI examination, 7 nations would mutually rank as number one as far as the most water stressed nations [135]. The study [136] comprehensively reviewed the literature from January 2003 to June 2020 and identified the related gap in related areas. Water footprint is one of the key indicator of fresh water use in the world. It has social, environmental and economic impact on China. The concept of water value-flow is promising in devising tool for the integrated management of the water value within river basin management. It accounts for the new emerging fields of water accounting and socio-hydrology [137].

5.1.1 The Indus Basin and Hydro-Electric Power

The history of hydropower 1 MW construction started in 1925 at Renala Khurd. After the partition, the power capacity merely 60 MW came into share for more than 31 million electricity consumers of Pakistan [138]. The hydro power development projects 10 years after the Renala one , initiation of the 1.7 MW (Malakand-I Jaban) hydropower project then was later enhanced to 20 MW capacity. Moreover in year 1953, Dargai (Malakand-II) hydropower project was commissioned. In 1958, the creation of WAPDA increased the total hydro water capacity to 119 MW. The Indus Basin Water Treaty was signed in 1960 and entitled 142 MAF to Pakistan(Chenab 26, Jhelum 23 and Indus 93) of surface water [57]. Later the revolutionary power projects like Tarbela hydropower project of 3478 MW, Mangla hydropower project 1000 MW and 240 MW of Warsak hydropower project were introduced. 1450 MW Ghazi Barotha, 81 MW Malakand-III , 184 MW Chashma, 18 MW altar and 30 MW Jagran are the hydropower schemes that have reached completion in Pakistan.Till 2011 , 6720 MW was the total installed capacity of hydropower projects in the country out of which 1039 MW in AJK, and 133 MW in Gilgit-Baltistan, 1699 MW in Punjab and 3849 MW in Khyber Pakhtunkhwa (Private Power and Infrastructure Board, 2011).

The commissioning of Neelum Jhelum hydropower with the net installed capacity of of 969 MW, approx. 42 degree south of Muzafarabad, Azad Kashmir, on August 14, 2018 was a milestone hit in the history of Pakistan's hydropower development schemes. In 2018, it reached up to 7320 MW whereas plentiful of its potential still remained unfulfilled. Pakistan endured outrageous and perceptibly the most noticeably awful ever power lack of around 7,000 MW in the year 2015-2016 as the demand was around 20,223 MW and total production remained 13,800 MW (DAWN, 2017). Renewable energy resources like hydropoer plays an important role in sustainability and environment friendliness. According to Asian Development Bank (ADB), approx. 2-3% of GDP is cut down due to energy crisis Pakistan is suffering for last couple of years which results in circular debt, expensive fuel sources i.e. natural gas and coal and inadequate distribution and transmission network (U.S. Energy Information Administration, 2016). Most of the untapped hydropower potential lies in the mountainous north besides the Indus River in Gilgit-Baltistan and Jhelum River in the Pakistan's administered districts of Azad Jammu and Kashmir and Punjab [139].

Prosperity of any country depends upon the per capita income likewise the electricity consumption per capita is also an indicator of a country's prosperity and economic growth. The higher the electricity consumption the more economically stable country would be. Indus River also plays an important role in hydropower generation of Pakistan. The total existing installed power capacity by all means as of March, 2017 was about 29,945 MW (Pakistan Energy Yearbook 2017), thermal being the largest share (68.4% of Capacity), hydro stands at second position (23.8%), renewable about 4.1% and small share of nuclear power plants approximately 3.6%. The generated power at any specific time is considerably underneath the available generation capacity and shows up at its trough all through the winter when low water levels decline the hydro power yield. Pakistan has a huge hydropower potential of 60,000 MW and currently only about 8300 MW of power is being generated as per Energy Book of 2018. So there is a big room of expansion in the area. According to Pakistan's 2040 indicative generation mix, hydropower would take the largest share of about 40% of total generation (Source: NTDC Indicative Generation Mix Plan for year 2040). The results obtained from research reflect that by year 2040, the share of renewable and hydropower expected to be about 16% and 40% of total generation mix of Pakistan respectively. We also need to increase reliance on wind energy as started in Jhumpeer Karachi and solar energy (Quaid e Azam Solar Park, Bahawalpur) [140, 141]. The country's social and economic stability is determined by availability of energy. The prosperity index of a country is gauged by its per capita energy consumption. The world's average per capita energy consumption is about 2516 kWh which is six times higher than Pakistan's. In year 2008, the reported shortfall was 4500 MW which is 40% of the demand. The reason behind this gap is depleting local resources of oil and gas. Country has a huge estimated potential of 42 GW hydropower out of which only 6.5 GW has been exploited so far [142]. In 1990-1991, Pakistan introduced new reforms in power sector to provide incentive to catch the investment from private sector. The policy got immediate attraction from private sector and several independent power producers (IPPs) offered power plants including oil, coal and/or gas. A dynamic model has been proposed to access the electricity supply; the resource import dependency; and the evolution of CO2 emissions. Although this policy gains much attention from private sector but set asides the hydroelectric generation of huge potential [143]. There is no concept of industrialization without electricity. Electricity production has a direct impact on economic growth in Pakistan. The period of 1975-2010 exhibits a log-linear relationship between electricity production and economic growth. On the basis of many researches in power sector, Pakistan has a huge potential of hydropower. Based on this fact, hydropower plants are beneficial for two reasons. First, they produce clean energy. Second, the production cost would also decrease resulting in lower tariff rates [144]. Pakistan has a unique natural resources distribution as compared to developed countries. These resources include solar energy, wind energy, coal and hydropower [145–148].

Hydraulic energy is the cheapest and most exploited renewable energy resources for power generation in the world. Pakistan is the fortunate country having 60,000 MW potential sites for hydel power generation. Tarbela and the Mangla are the two major hydroelectric power stations using water spared from agriculture needs. These power stations coordinate with thermal generations for minimum cost of production of electrical energy subject to the satisfaction of constraints. The IBMR purely deals with optimal utilization of water for irrigation needs only. However, it cannot handle the optimal use of water for both agriculture requirements and power generation requirements. The current study presents hybrid IBMR model addressing optimal utilization of water for both agriculture and power generation needs. The philosophy of this model is that it maximizes the CPS considering the execeedance probabilities for inflows subject to the satisfaction of constraints. The objective function has been modified by incorporating control parameter alpha α and integrating the energy cost of hydel power generation. The proposed model is implemented in GAMS and has been tested for scenarios with and without hydel power generation. Rest of the chapter is organized as follows: Section 2 is dedicated to the System Modeling. Section 3 explains Methodology. Section 4 elaborates the case studies, economic analysis of the proposed system and related discussions. Section 5 concludes the study and enlists suggestions and the way forward.

5.1.2 Contributions

The summary of main contributions to the work is given below:

1. The main objective function of the IBMR is modified and impact of hydropower generation is incorporated in CPS calculation.
2. A control parameter α has been introduced to control the water allocation for agriculture and power sector.
3. Mapping of proposed model in GAMS to runon Dell Latitude Core i7 laptop with 7820HQ 2.9 GHz processor and 16 GB of RAM in order to obtain results:optimized energy generation mix for year 2040 and yearly energy generation up to year 2040.
4. Comparison of the obtained results with NTDC generation indicative plan.

5.2 System Modeling

The objective function of IBMR-2012 does not account for the hydropower contribution in CPS. In the current study, hydropower contribution is also incorporated in CPS calculation. A control parameter α has been introduced in the newly proposed objective function to control the multi-sectoral water distribution.

5.2.1 Objective Function

The IBMR functions as a hydro-agro-economic model that utilizes agro-climatic zonesas the fundamental spatial units. The primary goal of the model is to optimize the combined benefits of consumer and producer surpluses (CPS) across zones, which represent the overall economic gains within the entire Indus Basin. To achieve this, the IBMR-2012 employs a quadratic supply-demand relationship to model CPS. As CPS exhibits a nonlinear structure, the IBMR-2012 employs a method of solving this objective function through piece-wise linear programming. While the simulated prices may vary between zero and the demand curve's intercept, this scenario is unlikely in reality. Therefore, price boundaries are established to set upper and lower limits. It is assumed that, beyond these limits, trade between zones takes place. However, the model does not actively simulate such trading. Additionally, while the IBMR does not explicitly factor in international trade, it does consider the pricing of international imports and exports, making production adjustments accordingly.

The Consumer Producer Surplus (CPS) [41] calculates the basin-wide income in the following way:

$$\begin{aligned} CPS = & \sum_{Z}\sum_{G}\sum_{C} Price_{z,c} * Production_{Z,G,C} \\ & - \sum_{Z}\sum_{G} Cost_{Z,G} - \sum_{Z}\sum_{C} Import_{Z,C} \\ & - ImaginaryWater + \sum_{Z}\sum_{C} Export_{Z,C} + \\ & \sum_{M}\sum_{N} WaterValue_{M,N} \end{aligned} \tag{5.1}$$

where Z is the ACZ index, G the groundwater type index, C the crop index, M the month index, and N the node or reservoir index Price × Production is the overall gain from raising crops and livestock. Cost is the sum of all production costs. Import is the sum of all costs associated with importing crops. Export is the sum of all benefits associated with exporting crops, and WaterValue is the value of water that is used up by the system or held in reservoirs but flows to the sea. This value can be used to demonstrate the economic advantage of maintaining environmental flows to the sea. The ImaginaryWater parameter in the network flow model represents the cost of having insufficient water in the objective purpose. This newly proposed objective function includes energy cost and control parameter is given below:

$$\begin{aligned} CPS = \alpha(&\sum_Z\sum_G\sum_C Price_{z,c} * Production_{Z,G,C} \\ &+\sum_M\sum_N WaterValue_{M,N} + \sum_Z\sum_C Export_{Z,C}) \\ &+(1-\alpha)\sum_M\sum_N UnitPrice * EnergyProduced_{M,N} \\ &-\sum_Z\sum_G Cost_{Z,G} - \sum_Z\sum_C Import_{Z,C} \\ &-Slackvariables \end{aligned} \tag{5.2}$$

where α is a control parameter and it varies from 0 to 1. Zero means all water is utilized for hydropower generation whereas one shows that all water is allocated for agricultural purposes.

5.2.2 Major Constraints

Major constraints include the following:

1. Canal Commands: 42 canal commands are used to represent the whole irrigation system.

2. The Inter-Provincial Accord 1991: IRSA Rules are use for water allocation to the provinces.

3. Reservoir Operating Rule: Monthly lower and upper boundaries of reservoir capacity are used as upper and lower bounds. No complex, operating rules are defined for this purpose.

4. Turbine efficiency: 80% efficiency is used.

5.2.3 Cost Function

The basin wide cost [41] includes the cost of seed , tube well operating cost, fertilizer cost, protein cost, labor cost and misc. costs and it is given by:

$$\begin{aligned} Cost_{Z,G} = MISCCOST_{Z,C,S,M} + SEEDP_{Z,C,S,M} \\ +TW_{Z,C,S,M} + \sum_{Z}\sum_{C}\sum_{S}\sum_{W}(FERT_{Z,C,S,M} + \\ TRACTOR_{Z,C,S,M}) + \sum_{Z}\sum_{SEA} PP_{Z,SEA} + \\ \sum_{Z}\sum_{G}\sum_{A} Animal_{Z,G,A} + \sum_{Z}\sum_{G}\sum_{M} Labor_{Z,G,M} \end{aligned} \tag{5.3}$$

5.2.4 Hydro Electric Power Generation

Power generation is generated by using the potential energy of stored water in reservoir and it is given by [149]:

$$P(kW) = \frac{Q * \rho * g * H * \eta}{1000} \tag{5.4}$$

where

P = the generated power in kW

Q = water flow rate (m^3/s)

g= gravitational acceleration (m/s^2)

ρ = water density (kg/m^3)

H = height of waterfall (m)

η = the efficiency ratio (usually between 0.7 and 0.9)

The maximum available energy generated within 24 hours in (GWh) is given using the following formula:

$$E(GWh) = 24 * \frac{P(kW)}{1000 * 1000} \tag{5.5}$$

.

5.3 Methods and Materials

The proposed model is programmed in GAMS and dynamic nonlinear programming solver based on generalized reduced gradient (GRG) method is used for CPS maximization calculation. The flow chart of the GRG method is shown in figure 5.3. The real time data for Indus River System at rim stations of around 80 years have been used. Different exceedance probabilities have been used for inflows calculation and IRSA Rules for water distributions among the different provinces of Pakistan are used. Microsoft Excel and GAMS Studio have been used for calculations and optimizations.

5.3.1 Input Data

The inputs to the IBMR-2020 include (1) livestock and agronomic data; (2) resources inventory; (3) economic data; and (4) canal commands and water inflows related data.

5.3.2 Output Data

The outputs from the proposed IBMR are of great importance for policymakers and researchers. It provides a great insight to policymakers for future planning in the field of agriculture and hydropower generation. The main objective function provides the basin-wide income and net profit from agricultural production and power generation. It also provides the value of water stored in reservoirs, agricultural imports and exports, the economic benefits, and the flow of water to the sea.

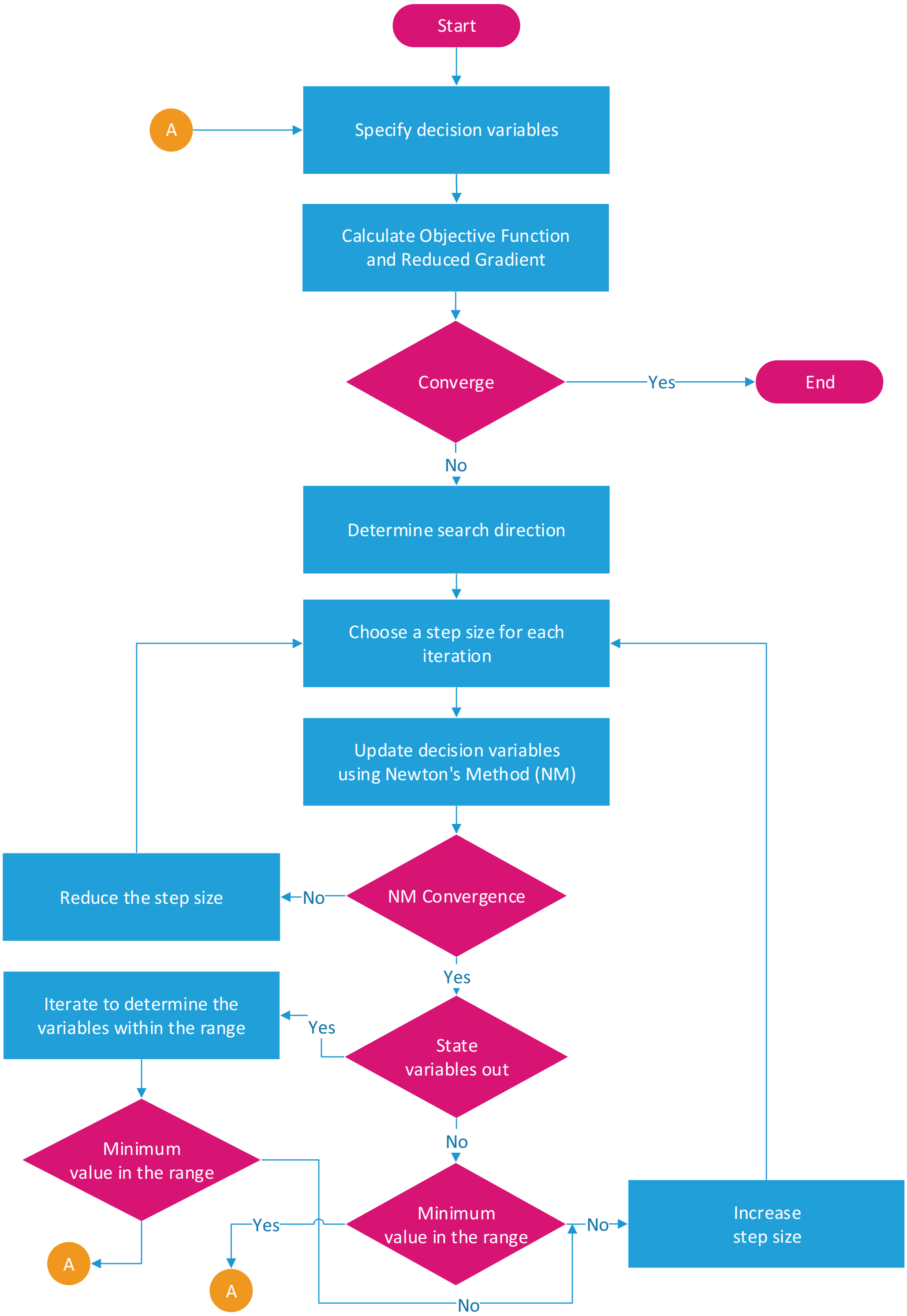

FIGURE 5.3: Flow chart of generalized reduced gradient method

5.3.3 Study Area

Different Studies on Indus basin have been performed considering upper [150] and lower indus basin [151]. In this study we have included the Pakistan's site of the whole Indus basin.

The Indus stream framework comprises of the fundamental Indus River and its significant tributaries: The Jhelum, Kabul, Ravi, Sutlej and Chenab [152, 153]. Pakistan's side of Indus basin has been included for hydropower and agricultural purposes. The study area covers all the twelve Agro Climatic Zones (ACZ). The basin includes three major reservoirs namely Mangla, Tarbela and Warsak with live storage capacity of about 14 MAF which accounts for about 10% of annual inflows. The system consists of the world's largest canal network with 42 major canals [154]. Figure 5.4 shows Indus river and its tributaries, major reservoirs and barrages.

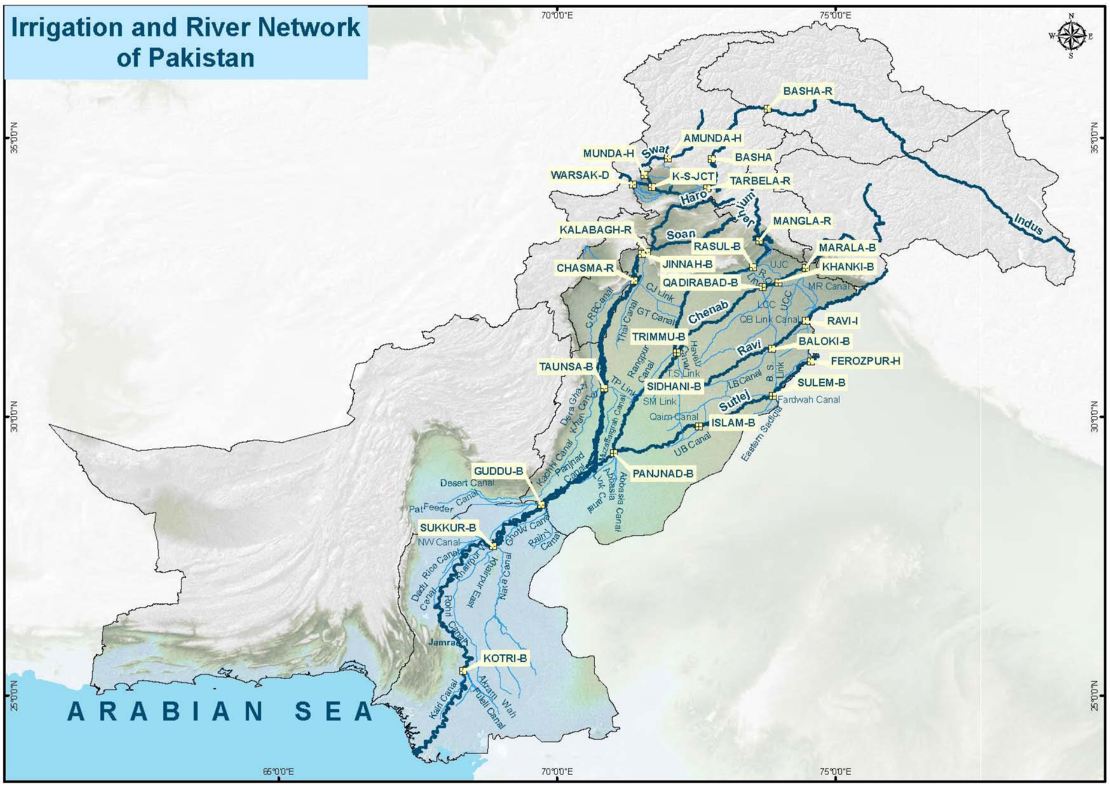

FIGURE 5.4: The Indus Basin of Pakistan Courtesy:IRSA Paksitan

5.3.4 Scenarios Development

The following three scenarios have been designed and analyzed using proposed model:

1. Scenario1: Whole water is utilized for agriculture
2. Scenario2: Whole water is utilized for power generation
3. Scenario3: Water is utilized both for power generation and agricultural purposes

5.4 Government Initiatives Under SGD7 for Hydropower Generation

In 2015, the 2030 Agenda for Sustainable Development Goals [155] was conceived and Pakistan committed to it [156]. Through a National Assembly Resolution in 2016,Pakistan adopted the Sustainable Development Goals (SDGs) as part of its national development agenda becoming the first country in the world to do so. For this purpose, specific SDG Task forces were formed by the national and provincial assemblies of the countries. The experience from the Millennium Development Goals (MDGs) facilitated the task forces. The conversations surrounding the Agenda started Pakistan in 2013, it was due to the timely prioritization of Pakistan's national development interests. Such developments are a reflection of Pakistan's commitment to the SDGs. In the current years, it is to be noted that the medium-term development strategies by provincial assemblies along with the 12th Five Year Plan seemed to be in alignment with the 2030 agenda. Few of the many areas Pakistan is advancing in are promotion of gender equality, lowering the poverty rate and creating an environment of accountability and transparency. The commitment to these priorities by the Pakistani politics favors the 2030 Agenda.

It is said, “a megawatt saved is better than a megawatt produced.” Pakistan’s foremost priority is to improve energy efficiency and conservation. National Energy Efficiency and Conservation Authority(NEECA) has been formed to pinpoint energy efficiency and conservation opportunities. Attempts are being made to enhance the share of renewable in Pakistan’s energy supply mix to 20 per cent in 2025, and 30 per cent by 2030. The private sector’s installation of several renewable energy plants have been assisted by the Alternative Energy Development Board(AEBD) including wind and solar power plants. Bagasse-based co-generation projects under the Framework for Power Co-generation (Bagasse/Biomass) 2013 are also being supported by AEDB. Their efforts have made Pakistan able to stand up through the ranks of countries considered attractive for renewable energy investments- from 38th to 26th in 2016. A major step towards adopting clean energy was taken by national parliament when the building was turned into a sustainable, green building in 2016. The “Green Parliament of Pakistan” is distinguishable as “world’s largest solar-powered legislative building”. It sets a standard for other government departments and private buildings too.

Energy integration is essential for ensuring uninterrupted energy supplies. Pakistan is improving its renewable energy strategy in order to attract investment in a dependable, sustainable, and economical energy mix. Simultaneously, the country is looking for ways to tap into its unconventional gas resource potential in order to alleviate the gas shortfall. Natural gas import projects, such as the Turkmenistan Afghanistan Pakistan-India (TAPI) gas pipeline project, would be vigorously pursued in the context of regional energy cooperation to complement the indigenous gas supply. Electric vehicles are being developed to reduce high levels of fuel usage in the transportation industry. Associated policy measures are also being introduced, with fiscal incentives being used to address the strengths, opportunities, and constraints of such projects.

Pakistan wants to lessen its reliance on energy imports during the coming five years. To move the industry toward sustainability, it will gradually and significantly raise the proportion of domestic, clean resources in the country’s energy supply mix. Additionally, a freshly developed road map for an open power market will be put into practice. With a focus on distant locations, the government has chosen to solarize 20,000 schools in Punjab province. 10,800 schools in South Punjab will be illuminated during the first phase of the ”Ujala” program via the installation of solar panels. Public buildings are currently being ”energy benchmarked” in an effort to promote energy efficiency, solar energy adoption, and energy productivity.

In order to attain universal access to energy while tripling the pace of improvement in energy efficiency and the amount of renewable energy in the supply mix, the Sustainable Energy for All (SE4All) initiative has been created. Through a collaborative process, a related National Action Plan 2018–30 was finalized and launched in 2019. In order to bring energy to off-grid villages in the province using renewable technology, the ”Bright Balochistan” initiative will also be started. Additionally, a thorough program for converting the farm tube wells in Balochistan to solar electricity would be implemented.
The government of Pakistan is committed to pursue the work and monitored continuous progress since the inception of the SDGs. The government and their designated institutions are putting their best to attain 2030 goals of the SDGs. The SDG 7 emphasizes on affordable and clean energy. The major hydopower projects under this initiative are tabulated below in 5.1:

5.4.1 Indicators of SDG 7: Striving Towards Affordable and Clean Energy

5.4.1.1 Indicator 7.1.1: Proportion of the Population with Access to Energy

Development of the human race and the economy is hampered by lack of access to energy sources and transformation systems. The environment offers a variety of both renewable and non-renewable energy sources, including uranium, sun, wind, hydropower, geothermal, and bio fuels. According to SDG 7, everyone should have

TABLE 5.1: Government Initiatives Under SDG7 for Hydropower Generation

Power Plant	**Capacity (MW)**	**Year**	**Installed Cost ($/KW)**	**Annual Energy (GWh)**	**Cost (c/KWh)**
Harigel	40.00	2022	2,697.00	223.00	5.06
Jagran-II	35.00	2022	2,068.00	154.00	4.97
Dasu Hydel	2,160.00	2023	1,888.00	11,176.00	3.87
Gumat Nar HPP	49.50	2023	3,253.00	218.00	7.68
Harpo	34.50	2024	2,947.00	173.00	6.13
Lower Palas	665.00	2024	1,901.00	2,568.00	5.22
Lower Spat Gah	496.00	2024	2,060.00	2,084.00	5.18
Phander	80.00	2024	1,824.00	365.00	4.25
Mohmand Dam	800.00	2024	2,244.00	2,859.00	6.61
Ashkot HPP	300.00	2024	2,301.00	1,376.00	5.28
Tarbela	1,410.00	2025	586.00	1,401.00	6.95
Pattan	2,400.00	2026	1,904.00	12,544.00	3.87
Kohala	1,124.00	2028	2,456.00	6,608.00	4.38
Azad Pattan	700.00	2028	2,164.00	3,192.00	5.01
Thakot HPP	4,000.00	2028	3,205.00	19,947.00	6.68
Shyok HPP	640.00	2028	2,793.00	3,740.00	4.99
Diamer Basha	4,500.00	2029	1,711.00	18,071.00	5.00
Chakothi	500.00	2029	2,353.00	2,440.00	5.07
Mhl	640.00	2030	2,266.00	3,720.00	4.10
Bunji Hydel	3,600.00	2030	1,901.00	12,078.00	6.00

access to clean and affordable energy by 2030.

Access to electricity is one of the main pillars of development strategy of the government particularly rural electrification. An increase of three percent was recorded in 2019-20 with 96% of the population having access to electricity as compared to 93% in 2014-15 (indicator 7.1.1 is the proportion of the population with access to electricity). Except for the Sindh province that recoded an increase of almost 6%, all other provinces and regions recorded a decrease in access to electricity between 2015-15 and 2017-18. In the Khyber Pakhtunkhwa province, the access to electricity decreased to 92% in 2018-19 from 96.2% in 2014-15 [157]. Table 5.2 shows the percentages of population w.r.t. the access of affordable and clean energy for years 2014-15 as a base line and years 2019-20 as latest.

Region	Baseline	Latest
National	**2014-15**	**2019-20**
	93%	96.00%
Punjab	**2014-15**	**2018-19**
Overall	95.00%	95.00%
Urban	99.00%	99.00%
Rural	93.00%	93.00%
Sindh	**2014-15**	**2018-19**
Overall	91.71%	97.50%
Urban	98.90%	87.50%
Rural	82.18%	97.50%
KPK	**2014-15**	**2018-19**
Overall	96.20%	92.00%
Urban	99.00%	99.00%
Rural	96.00%	90.00%
Balochistan	**2014-15**	**2018-19**
Overall	80.73%	75.00%
Urban	98.00%	05.00%
Rural	74.00%	96.00%
AJK	**2014-15**	**2018-19**
Overall	97.60%	97.00%
Urban	96.20%	100.00%
Rural	97.80%	96.00%
GB	**2014-15**	**2018-19**
Overall	98.73%	96.00%
Urban	100.00%	19.00%
Rural	98.53%	96.00%

TABLE 5.2: Indicator 7.1.1: Proportion of the Population with Access to Energy [157]

5.4.1.2 Indicator7.1.2: Proportion of the Population with Primary Reliance on Clean Fuel and Technology

Pakistan saw an improvement of 6% between 2015 and 2019 in its primary reliance on clean fuels and technology (indicator 7.1.2). At the national level, the use of clean fuel climbed to 47% in 2018–19 from 41.3% in 2014–15. Table 5.3 shows the percentages of Proportion of the population with primary reliance on clean fuel and technology for years 2018-19 as a base line and years 2019-20 as latest. From the table 5.3 there is an increase of 2% overall as countrywide on the reliance of proportion of the population with primary reliance on clean fuel and technology.

Region	**Baseline**	**Latest**
National	**2018-19**	**2018-19**
	35%	37%
Punjab	**2014-15**	**2019-20**
Gas (cooking)	39.00%	50%
Electricity	96.00%	97%
Sindh	**2014-15**	**2019-20**
Gas (cooking)	56.00%	55%
Electricity	91.28%	86%
KP	**2014-15**	**2019-20**
Gas (cooking)	26.00%	32%
Electricity	96.00%	92%
Balochistan	**2014-15**	**2019-20**
Gas (cooking)	24.71%	37%
Electricity	80.73%	24%

Table 5.3: Indicator 7.1.2: Proportion of the Population with Primary Reliance on Clean Fuel and Technology [157]

5.4.2 Public Sector Hydropower Generation

Hydropower has a lion share in total energy mix of Pakistan. Public sector hydropower generation plants contribute about 8066 MW. Plantwise generation is given below in the table 5.4:

5.4.3 Cost Comparison of Hydro Energy with Other Energy Source

The table 5.5 shows price comparison among different sources of energy. From the table it is evident that hydropower has the lowest Per Kilowatt Hour cost as compared to other sources [158, 159].

Table 5.4: Public Sector Hydropower Generation

Power Plant	**Source**	**Installed Capacity**	**Derated Capacity**
Tarbela	hydro	3948	3948
Mangla	hydro	1000	1000
Ghazi Brotha	hydro	1450	1450
Chashma	hydro	184	184
Jinnah Hydel	hydro	96	96
Allah Khwar	hydro	121	121
Khan Khwar	hydro	72	72
Dubair Khwar	hydro	130	130
Nelum Jhelum	hydro	969	969
Small Hydel	hydro	96	96

Table 5.5: Cost Comparison of Hydro Energy with Other Energy Sources

Sr.No	**Energy Source**	**Cost of Per kWh in $**
1	Hydro	0.01
2	Coal	0.08
3	Furnace Oil	0.11
4	Wind	0.07
5	Solar	0.13

5.5 Results and Discussions

This section contains case studies dealing the analysis of the proposed scenarios, their results with discussion.

5.5.0.1 Scenario1:Whole Water is Allocated for Agriculture

If the whole water is used for agriculture purpose, the net basin-wide economic benefit calculated by using IBMR-2020 is Rs 3495008.856 Millions. This number is very close to economic benefit of agriculture income calculated using IBMR 2012.

5.5.0.2 Scenario2: Whole Water is Utilized for Power Generation

If the whole water is used for electricity generation purpose, the net basin-wide economic benefit calculated by using IBMR-2020 is Rs 1435141000.000 Millions. This number is very large and gives rise to a huge economic benefit apparently but is not practical. Reason being, if there is no agriculture then there is no concept of life.

5.5.0.3 Scenario3: Water is Utilized for Both Agricultural Purposes and Power Generation

The option to use water for both agriculture and power generation fulfills both food and power needs. This can be achieved using the parameter α introduced in equation 2. If 50% water is used for agriculture and rest of the 50% is used for power generation, about 2.73 billion dollars benefit is increased. Please note that all the calculations are performed using updated Indus basin Model Revised 2020 (IBMR-2020) with 50% inflow exceedance probability.

5.5.1 Pakistan's Energy Mix by Year 2040

The energy mix composition calculated by proposed IBMR model is shown in figure 5.5. The energy mix has been calculated using NTDC data. A linear program was used to get the optimal energy mix using the above mentioned data. The pie chart shows that the hydro power will take a major share of about 40% followed by 25% local coal and renewable being the third largest contributor of about 16%. By year 2040 we would have around 56% of the hydro and renewable energy share in accordance with SDG 7 initiative by government of Pakistan. The obtained results are in close agreement with results given in indicative generation plan 2040 by NTDC. This indicates the promise of the approach.

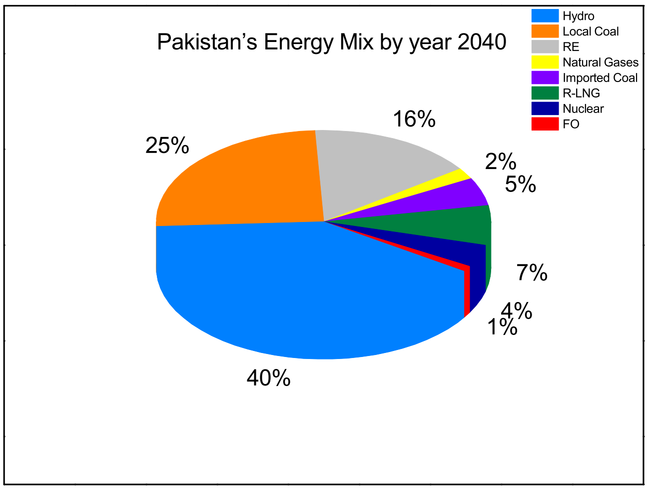

Figure 5.5: Pakistan's Energy Mix by Year 2040

5.5.2 Impact of α on Agriculture and Power Generation

The parameter α controls the usage of water for both agriculture and power generation in IBMR. The value of $\alpha = 1$ means the whole water is used for agriculture purpose where as value of $\alpha = 0$ shows the total water potential for hydropower generation. The figure 5.6 shows the impact of α on agriculture and power generation: The variation of CPS for different values of α is shown n figure 5.7. The bar graph indicates CPS with hydropower has marked increase when compared with CPS for agriculture alone for all values of α. Trend line shows that the CPS increases linearly for different values of α.

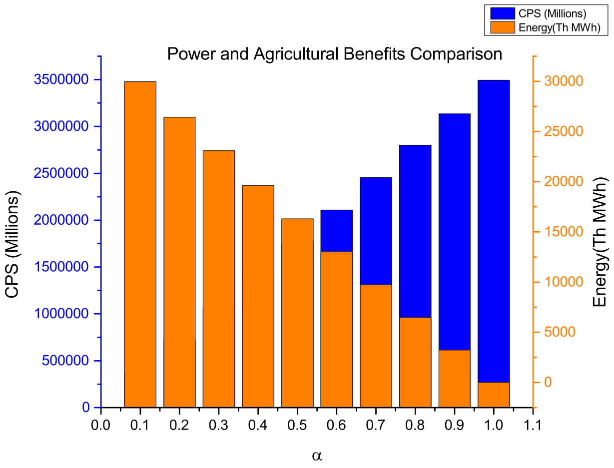

FIGURE 5.6: Impact of α on Agriculture and Energy

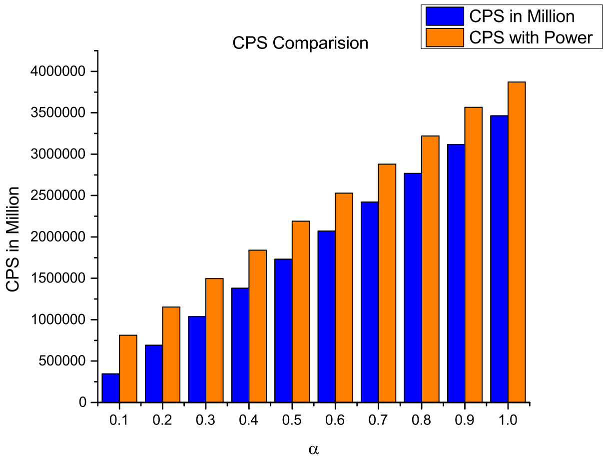

FIGURE 5.7: Impact of α on Agriculture, Energy and CPS

5.5.3 Indicative Generation Plan for Year 2040

An exponential model has been derived using the data from NTDC to obtain yearly indicative generation plan. The table 5.6 shows the comparison between Indicative Generation Plan for year 2040 by NTDC [160] and that of calculated using the proposed IBMR2. The estimated values from both NTDC and IBMR2020 are 370,348.00 GWh 367,549.8405 GWh respectively and in good agreement with the reference energy estimated by NTDC.

Table 5.6: Indicative Generation Plan for Year 2040

Year	NTDC Energy Estimated	IBMR Energy Estimated
2017-18	120,791.00	134,782.04
2018-19	144,665.00	141,070.38
2019-20	151,062.00	147,652.12
2020-21	158,842.00	154,540.92
2021-22	166,267.00	161,751.13
2022-23	173,178.00	169,297.74
2023-24	181,051.00	177,196.44
2024-25	188,749.00	185,463.65
2025-26	193,948.00	194,116.59
2026-27	202,763.00	203,173.22
2027-28	211,718.00	212,652.40
2028-29	220,940.00	222,573.84
2029-30	231,142.00	232,958.18
2030-31	241,889.00	243,826.99
2031-32	253,101.00	255,202.90
2032-33	265,289.00	267,109.57
2033-34	278,069.00	279,571.74
2034-35	291,403.00	292,615.35
2035-36	305,685.00	306,267.51
2036-37	320,652.00	320,556.62
2037-38	336,293.00	335,512.41
2038-39	352,917.00	351,165.96
2039-40	370,348.00	367,549.84

5.5.4 Impact of Hydropower on Basin Wide Income

Using the proposed formulation for CPS and hydropower generation, basin wide income (CPS) has been calculated using IBMR-2020 model. Results are shown in the table below: Please note that we have used 50% and 80% exceedance probabilities for these calculation. It is observed that basin wide income increases about 11.5% with inclusion of power generation in CPS. For details, please see the tables 5.7 and 5.8:

TABLE 5.7: Impact of Hydropower on Basin Wide Income with 50% Exceedance Probability

α	**Energy Income in Million Rs**	**Agri Income Million Rs**	**CPS Million Rs**	**% increase in CPS**
0.00	456,387.806	3,492,930.765	3,949,318.571	11.556
0.100	413,155.764	3,491,496.749	3,904,652.513	10.581
0.200	365,046.080	3,491,298.061	3,856,344.141	9.466
0.300	319,386.620	3,492,938.116	3,812,324.736	8.378
0.400	274,931.608	3,492,952.126	3,767,883.734	7.297
0.500	227,788.652	3,492,971.482	3,720,760.134	6.122
0.600	181,296.416	3,493,045.561	3,674,341.977	4.934
0.700	135,843.498	3,493,115.142	3,628,958.640	3.743
0.800	90,500.256	3,491,657.044	3,582,157.300	2.526
0.900	45,162.782	3,493,129.807	3,538,292.589	1.276
1.000	0.000	3,495,008.856	3,495,008.856	0.000

TABLE 5.8: Impact of Hydropower on Basin Wide Income with 80% Exceedance Probability

α	**Energy Income in Million Rs**	**Agri Income Million Rs**	**CPS Million Rs**	**% increase in CPS**
0.000	322,566.592	3,252,438.722	3,575,005.314	9.023
0.100	289,642.857	3,250,850.477	3,540,493.334	8.181
0.200	257,435.765	3,252,490.249	3,509,926.014	7.335
0.300	225,239.596	3,244,082.846	3,469,322.442	6.492
0.400	192,941.479	3,250,862.374	3,443,803.853	5.603
0.500	160,783.730	3,252,500.194	3,413,283.924	4.711
0.600	128,619.027	3,252,270.465	3,380,889.492	3.804
0.700	96,423.046	3,244,326.030	3,340,749.076	2.886
0.800	64,161.919	3,252,285.338	3,316,447.257	1.935
0.900	31,956.792	3,234,092.533	3,266,049.325	0.978
1.000	0.000	0.000	3,253,137.467	0.000

5.6 Summary

This chapter in detail describes that how an agriculture model IBMR can be used for the evaluation of economic benefits of hydropower generation by incorporation in the cost of hydropower generated in the objective function of Indus basin model revised. Also, an additional parameter impact has been studied on the water distribution for agriculture and power generation and observed that the basin wide income or CPS improves up to 6.10% under real world constraints ($\alpha = 0.5$). Finally, the energy mix has been calculated and it is evident that the hydropower will have the largest share of about 40% by year 2040.

Chapter 6

Conclusion and Future work

”Every genuine friendship and love story has an unanticipated turning point. We haven’t loved enough if we continue to be the same person we were before and after a relationship.”

Elif Shafak

6.1 Overview

Chapter 6 concludes the thesis. It mainly describes the contributions of the Ph.D. research work and future work directions in the fields of Indus Basin of Pakistan.

6.2 Main Contribution of Research Work

The contribution of this research work can be summarized as:

- In the current research, the main objective function of IBMR-2012 that calculates Consumer Producer Surplus(CPS) has been modified with the addition of power share. The basin-wide income increases by around 11% with the inclusion of power generation.

- Indicative Generation Plan for year 2040 has been calculated using IBMR and results are in good agreement with NTDC results.
- Energy Mix for year 2040 has been calculated results reveals that hydropower will take a lion share of about 40%.
- New water distribution schemes using several bankruptcy rules have been investigated as an alternative to water distribution as compared to IRSA rules. It has been observed from the results that bankruptcy rule not only provides the fair distribution of water among the provinces of Pakistan. Four Bankruptcy rules have been studied and results are compared with IRSA rule. According to results obtained from Proportional Rule, smaller provinces get better allocation of water which minimizes the trust deficit among the provinces. The Constraint Equal Award Rule favors all three provinces except Punjab. Smaller provinces get better award and increases Confidence Building Measures (CBM) among the provinces. The Constraint Equal Loss Rule favors the larger province and distribution according to this rule will increase trust deficit. Hojjat Mainabadi Rule is based on provincial contribution. Every province will get reward as per its contribution.
- Bankruptcy rules can be an alternate option for water allocation problem for trans-boundary basins. Water distribution using bankruptcy rule could be an alternate step towards confidence building among stakeholders. We may introduce some economic shocks like province productivity (ROI) other than population and area to be irrigated. Crop selection can be another parameter and we may associate some weighting function. Along with economic factor, we may take confidence building measure to increase inter-provincial trust and create awareness to use scientific knowledge in this regard.

6.3 Conclusion

The updated IBMR ensures that water is used as efficiently as possible for both agriculture and the production of electricity. This strategy strengthens the government's commitment to the SDGs and is a useful addition for both IRSA and

NTDC. The optimal proportion of water for the production of electrical power has been incorporated into the primary objective function of IBMR-2012 that calculates CPS. An improved version of IBMR that takes into consideration both agriculture and hydropower generation has been proposed in the current research. Using a modified version of IBMR, hydropower generation was added with the intention of examining the effect of hydropower on basin-wide income. The analysis of the following three case studies is presented together with the findings. The current study expands the application of IBMR beyond agriculture to include hydropower planning and generation with the goal of lowering energy costs and improving water use:

- Scenario 1: Presently, the IBMR takes this scenario into account, which states that all of the water is used for agriculture and that all income for the basin is dependent only on that income.
- Scenario 2: describes an extreme case in which all water is used to generate electricity. Although the net basin income in this situation is very large, we cannot actually reserve all of the water for hydropower.
- Scenario 3: This scenario combines the income from hydropower production and agriculture into a single goal function. A gain in benefits of around 2.73 billion dollars results from allocating 50% of water for agriculture and the remaining 50% for power production.

The investigation of these case studies reveals that the inclusion of power generation boosts basin-wide income by 11.83% considering a 50% exceedance probability. In comparison to NTDC's estimated power generation, the results are consistent. Due to advancements in technology, green energy has received a lot of attention and offers affordable solutions for power needs. Both the NTDC year 2040 plan and government initiatives for a hydroelectric project place an emphasis on hydropower, which is a clean and reasonably priced energy source. Thus, it is important to promote and guarantee the effective implementation of SDG 7. The inclusion of the hydrothermal coordination feature in this improved version may provide another fascinating and cutting-edge facet to future study in order to fully use the Indus River System's hydropower potential. WAPDA and other decision-makers have traditionally used IBMR for planning purposes including irrigation and agriculture.

6.4 Future Recommendations

The following researches are suggested for enhancing the Indus Basin irrigation system's long-term viability:

i. Additional crops, such as olives, should be included in the model as they are one of the fastest-growing in the area and will increase basin income.

ii. For more precise modeling of under-water storage, aquifer dynamics must be taken into account.

iii. It could be a good idea for future research to coordinate hydro and other renewable energy sources at the basin level. The most effective way to generate power from various sources must be researched in order to lower the cost of fuel generation overall.

iv. Increase water availability through building more storage and upgrading water infrastructure.

v. Improve agricultural water productivity to grow more food with less water.

vi. Grow more food with less water: improve agricultural water productivity.

vii. Manage groundwater supplies by adjusting agricultural patterns and aquifer management.

viii. Manage salinity in the fields and basin to maintain the resource base.

ix. Strengthen institutions for change to speed up the reform process.

x. Development of Systematic Asset Management Plan should be of high priority.

x1. It is necessary to explore climate change scenarios for the upper and lower Indus basins, such as Representative Concentration Pathways.

x11. Economic evaluation of new dams like Diamer Basha and Mohmend dams can be performed using IBMR.

x111. Indian part of indus basin can be included in the model.

xiv. Can be integrated with climate change models.

xv. Integration with MESSAGEix model which provides Energy, Climate, and Environment program modeling framework.

xvi. Around 27 MAF of water is sent into the sea every year. A detailed assessment of the impact of this water on the Indus delta, agroclimatic zones of Sindh, salinity, impact on aquatic life, mangrove forest growth, and survival of blind dolphins, one the rarest species is required.

For clean and affordable energy, we need to increase our reliance on renewable energy like (solar, wind, hydro, etc) along with reduced carbon emission and noxious gases emission. We need to enhance electricity generation from other than coal and furnace oil. Renewable energy resources such as hydropower, solar electricity, and wind power must be planned and implemented. Small and medium size reservoirs throughout the country need to be built in future along with maintenance of existing major reservoirs like Mangla, Tarbela, Warsak and Chasma. Micro turbines on run of canal need to be installed in small villages for cheaper and energy sustainable Pakistan. In pursuance of SDG goals, initiatives by government of Pakistan towards clean, cheaper and access to all have been highlighted. The government is committed to complete all the planned hydro, solar and wind power plants in due course of time. The expected share of hydro and other renewable forms of energy is anticipated around 56% by year 2040.

There is a lot of room for research in the area of climate change impact on Indus basin of Pakistan and its integration with existing IBMR. Use of Machine learning techniques for forecasting of rainfall, flood and inflow and drought and consequently their environmental, agricultural and hydropower generation impacts on basinwide income could be a good candidate for future research.

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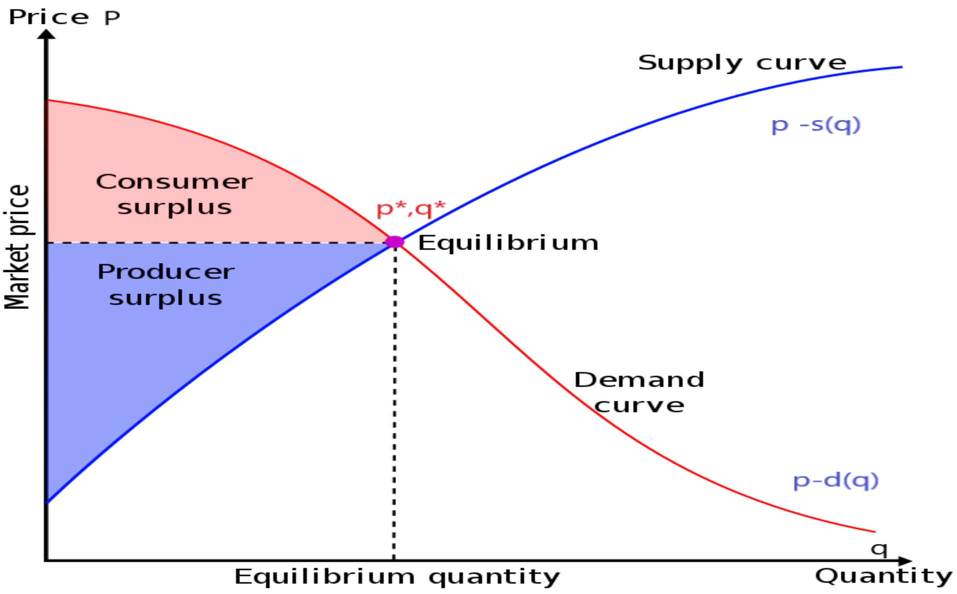
Appendix A

Consumer Producer Surplus is an indicator of economic activity. It is also known as economic surplus, total welfare, total social welfare, or Marshallian surplus in economics (after Alfred Marshall). The producer surplus and the consumer surplus are the two major quantities and collectively known as Consumer Producer Surplus.

Suppose we have a demand function p = f(q) and a supply function p = g(q) at the equilibrium point (q*, p*), then the consumer and producer surpluses can be defined as follows:



The Consumer Producer Surplus

A.0.1 Producer Surplus

The consumer surplus $= \int_0^{q*} f(q)dq - p * q*$

A.0.2 Consumer Surplus

The producer surplus $=p * q * - \int_0^{q*} g(q)dq$

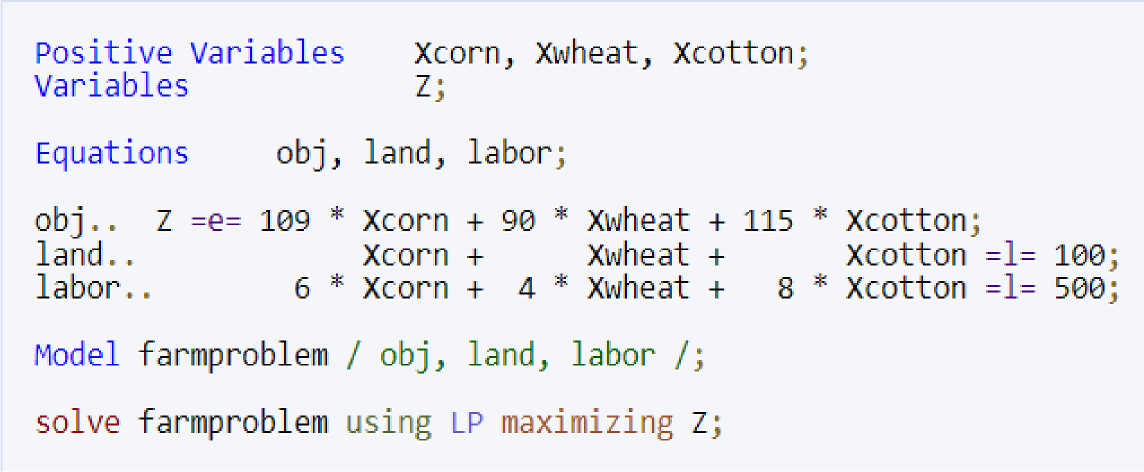
Appendix B

B.1 Solving a Linear Programming Problem (LP) using GAMS

$$
\begin{array}{rrcrcrcll}
\max & 109X_{corn} & + & 90X_{wheat} & + & 115X_{corn} & & & \\
s.t. & X_{corn} & + & X_{wheat} & + & X_{cotton} & \leq & 100 & \text{(land)} \\
 & 6X_{corn} & + & 4X_{wheat} & + & 8X_{cotton} & \leq & 500 & \text{(labor)} \\
 & & & & & X_{corn} & \geq & 0 & \text{(nonnegativity)} \\
 & & & & & X_{wheat} & \geq & 0 & \text{(nonnegativity)} \\
 & & & & & X_{cotton} & \geq & 0 & \text{(nonnegativity)}
\end{array}
$$

Linear Programming Problem with constraints

An LP is the simplest constrained optimization problem. Assume we want to solve the LP below, which depicts a simple farm model with maximum profit: There are three decision variables to consider: The land assigned to producing corn is $Xcorn$, the land assigned to growing wheat is $Xwheat$, and the land assigned to growing cotton is $Xcotton$. The total profit is expressed as a function of the acreage given to the three crops in the first line, and the multipliers show the predicted profit per acre based on the crop type. The first inequality sets a restriction on the amount of land that may be used, the second inequality sets a limit on the amount of labor that can be used, and the last three lines limit the choice variables to nonnegative values.



```
Positive Variables    Xcorn, Xwheat, Xcotton;
Variables             Z;

Equations     obj, land, labor;

obj..  Z =e= 109 * Xcorn + 90 * Xwheat + 115 * Xcotton;
land..             Xcorn +      Xwheat +       Xcotton =l= 100;
labor..          6 * Xcorn +  4 * Xwheat +   8 * Xcotton =l= 500;

Model farmproblem / obj, land, labor /;

solve farmproblem using LP maximizing Z;
```

Solving LP problem using GAMS

B.2 Bankruptcy Rules implementation in GAMS

B.2.1 Proportional Rule

$Title Bankruptcy Rules Optimization: Proportional Rule

Positive Variable lpi1,lpi2,lpi3,lpi4,ci1,ci2,ci3,ci4,si1,si2,si3,si4;

Free Variable J;

scalar Et,D,lpt;

Et=132.02;

D=149.71;

lpt=Et/D;

ci1.L= 0.10;

ci2.L= 0.10;

ci3.L= 0.10;

```
ci4.L= 0.10;


ci1.UP= 10.73;
ci2.UP= 69.03;
ci3.UP= 61.84;
ci4.UP= 08.11;


Equations
Con1,Con2,Con3,
Con4,Con5,Con6,
Con7,Con8,Con9,
Con10,Con11,Con12,
Con13,Con14,Obj;


*********** Constraint Definition ****************
Con1.. lpi1 =E= si1/ci1;
Con2.. lpi2 =E= si2/ci2;
Con3.. lpi3 =E= si3/ci3;
Con4.. lpi4 =E= si4/ci4;


Con5.. si1 + si2 + si3 + si4 =E= Et;
Con6.. ci1 + ci2 + ci3 + ci4 =E= D;


Con7.. si1 =L= ci1;
Con8.. si2 =L= ci2;
Con9.. si3 =L= ci3;
Con10.. si4 =L= ci4;
```

```
Con11.. lpt=L=lpi1;
Con12.. lpt=L=lpi2;
Con13.. lpt=L=lpi3;
Con14.. lpt=L=lpi4;
*********** Cost function ****************
Obj.. J =E= lpt -lpi1 * lpi2 * lpi3 * lpi4 ;


Model Model1 /All/;


solve Model1 using NLP minimizing J;


Display ”************** Results ****************”;
Display ”************** Lambda Values ****************”;
Display lpi1.L, lpi2.L, lpi3.L,lpi4.L,lpt;


Display ”************** Claim Values ****************”;
Display ci1.L,ci2.L,ci3.L,ci4.L; Display ”*** Allocations using Proportional Rule ***”;


Display si1.L,si2.L,si3.L,si4.L;


Display ”*** Cost Function Optimized Value ***”;
Display J.L;
```

B.2.2 Constraint Equal Award Rule

```
$Title Bankruptcy Rules Optimization
```

```
Set PVV /KPK, Baloch, Punjab, Sindh / ;


Positive Variable lceai(PVV),cci(PVV),si(PVV),lcea;


Free Variable J;
scalar Et,D;


Et=132.02;
D=149.71;
lcea.L=1;


cci.L(PVV)$(ord(PVV) eq 1)= 8.25;
cci.L(PVV)$(ord(PVV) eq 2)= 05.99;
cci.L(PVV)$(ord(PVV) eq 3)= 62.48;
cci.L(PVV)$(ord(PVV) eq 4)= 55.30;


cci.UP(PVV)$(ord(PVV) eq 1)= 10.73;
cci.UP(PVV)$(ord(PVV) eq 2)= 08.11;
cci.UP(PVV)$(ord(PVV) eq 3)= 69.03;
cci.UP(PVV)$(ord(PVV) eq 4)= 61.84;


Equations
Con1(PVV),
Con2,
Con3,
Con4(PVV),
Con5(PVV),
Con6,
```

```
Objj;


*********** Constraint Definition ****************
Con1(PVV).. lceai(PVV) =E= si(PVV);
Con2.. Sum(PVV,si(PVV)) =E= Et;
Con3.. Sum(PVV,cci(PVV)) =E= D;
Con4(PVV).. cci(PVV) =L= si(PVV);
Con5(PVV).. lceai(PVV)=L=lcea;
Con6.. sum(PVV,min(lcea,cci(PVV)))=E= Et;
*********** Cost function ****************


Objj.. J =E= lcea -((prod(PVV,lceai(PVV))/(lcea)**3));


Model Model1 /All/;
solve Model1 using DNLP minimizing J ;


Display ”************** Results ****************”;
Display ”************** Lambda Values ****************”;
Display lceai.L;


Display ”************** Claim Values ****************”;
Display cci.L;
Display ”*** Allocation using Constraint Equal Award Rule ******”;


Display si.L;
```

```
Display ”*** Cost Function Optimized Value ***”;
Display J.L;
```

B.2.3 Constraint Equal Loss Rule

```
$Title Bankruptcy Rules Optimization


Set PVV /KPK, Baloch, Punjab, Sindh / ;


Positive Variable lceli(PVV),ci(PVV),si(PVV);


Free Variable J;
scalar Et,D,L,lcel;


Et=132.02;
D=149.71;
L=D-Et;
lcel=L/4;


ci.L(PVV)$(ord(PVV) eq 1)= 8.25;
ci.L(PVV)$(ord(PVV) eq 2)= 05.99;
ci.L(PVV)$(ord(PVV) eq 3)= 62.48;
ci.L(PVV)$(ord(PVV) eq 4)= 55.30;


ci.UP(PVV)$(ord(PVV) eq 1)= 10.73;
ci.UP(PVV)$(ord(PVV) eq 2)= 08.11;
ci.UP(PVV)$(ord(PVV) eq 3)= 69.03;
```

```
ci.UP(PVV)$(ord(PVV) eq 4)= 61.84;


Equations
Con1(PVV),
Con2,
Con3,
Con4(PVV),
Con5(PVV),
Con6(PVV),


Obj;


*********** Constraint Definition ****************
Con1(PVV).. lceli(PVV) =E= ci(PVV)-si(PVV);


Con2.. Sum(PVV,si(PVV)) =E= Et;
Con3.. Sum(PVV,ci(PVV)) =E= D;
Con4(PVV).. si(PVV) =L= ci(PVV);
Con5(PVV).. si(PVV) =E= max(0,ci(PVV)-lceli(PVV));
Con6(PVV).. lcel=L=lceli(PVV);


*********** Cost function ****************
Obj.. J =E= lcel -((prod(PVV,lceli(PVV))/(lcel)**3));


Model Model1 /All/;


solve Model1 using DNLP minimizing J;
```

```
Display ”************** Results ****************”;
Display ”************** Lambda Values ****************”;
Display lceli.L;


Display ”************** Claim Values ****************”;
Display ci.L;
Display ”**** Allocation using Constraint Equal Loss Rule ****”;


Display si.L;


Display ”**** Cost Function Optimized Value ****”;
Display J.L;
```

Appendix C

C.1 Nonlinear Programming Problem

NLP is a mathematical technique for tackling optimization issues with nonlinear constraints or objective functions. An optimization problem is the calculation of an objective function's extrema (maxima, minima, or stationary points) over a set of unknown real variables, conditional on the satisfaction of a system of equalities and inequalities, commonly known as constraints. It is a non-linear branch of mathematical optimization.

Assume that m, n, and p are positive integers, and that X is a subset of Rn, and that f, gi, and hj are real-valued functions on X for each I in 1,..., m, and each j in 1,..., p, and that at least one of f, gi, and hj is nonlinear.

$$\min f(x) \tag{1}$$

$$\text{s.t.} \quad g_i(x) \leq 0 \quad \forall \quad i \in 1, 2, 3..., m \tag{2}$$

$$h_j(x) \leq 0 \quad \forall \quad j \in 1, 2, 3..., p \tag{3}$$

$$x \in X \tag{4}$$

C.1.1 Types of constraint set

The constraint set, also known as the feasible region, can have a variety of characteristics. If no set of values for the choice variables fits all of the conditions, the problem is impossible to solve. To put it another way, the constraints are mutually contradictory, hence there is no solution; the only possible set is the empty set. A feasible problem is one in which all of the conditions are met by at least one set of values for the choice variables. The objective function of an unbounded problem can be improved to be better than any finite value. As a result, there is no such thing as an optimal solution because a feasible solution always produces a better objective function value than any proposed solution.

C.1.2 Techniques for solving the problem

If the objective function is concave (maximization problem) or convex (minimization problem) and the constraint set is convex, the program is called convex. General convex optimization methods can be applied in most scenarios. When the target function is quadratic and the restrictions are linear, quadratic programming methodologies are used. Fractional programming techniques can be used to turn the problem to a convex optimization problem if the objective function is a ratio of concave and convex functions (in the maximize scenario) and the constraints are convex.

C.2 Examples

C.2.1 2-D nonlinear problem

A simple 2-d nonlinear programing problem can be formulated as :

$$x_1 \geq 0 \tag{5}$$

$$x_2 \geq 0 \tag{6}$$

$$x_1^2 + x_2^2 \geq 1 \tag{7}$$

$$x_1^2 + x_2^2 \leq 2 \tag{8}$$

Provided to minimize the objective function

$$f(x) = x_1 + x_2 \tag{9}$$

where $x = (x_1, x_2)$.

C.2.2 3-D nonlinear problem

A simple 3-d nonlinear programing problem can be formulated as :

$$x_1^2 - x_2^2 + x_3^2 \leq 2 \tag{10}$$

$$x_1^2 + x_2^2 + x_3^2 \leq 10 \tag{11}$$

Provided to minimize the objective function

$$f(x) = x_1 x_2 + x_2 x_3 \tag{12}$$

where $x = (x_1, x_2, x_3)$.