CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Evaluation of Water Allocation System and Reservoir Ranking for Indus River Basin: A Hydro-Economic Perspective

by

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A thesis submitted in partial fulfillment for the degree of Doctor of Philosophy

in the

Faculty of Engineering
Department of Civil Engineering

2021

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2021

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Dedicated to my family

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This is to certify that the research work presented in the thesis, entitled "**Evaluation of Water Distribution System and Reservoir Ranking in Indus River Basin: A Hydro-Political Perspective**" was conducted under the supervision of **Dr. Ishtiaq Hassan**. No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the **Department of Civil Engineering, Capital University of Science and Technology** in partial fulfillment of the requirements for the degree of Doctor in Philosophy in the field of **Civil Engineering.** The open defence of the thesis was conducted on **February 12, 2021.**

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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:-

1. **S. Janjua** and I. Hassan, "Transboundary water allocation in critical scarcity conditions: A stochastic bankruptcy approach," *Journal of Water Supply: Research and Technology-AQUA*, vol. 69, no. 3, pp. 224-237, 2020.

2. **S. Janjua** and I. Hassan, "Use of bankruptcy methods for resolving interprovincial water conflicts over transboundary river: Case study of Indus River in Pakistan," *River Research and Applications*, pp. 1-11, 2020.

3. **S. Janjua** and I. Hassan, "Fuzzy AHP-Topsis multi-criteria decision analysis applied to the Indus Reservoir System in Pakistan," *Water Supply*, vol. 20, no. 5, pp. 1933-1949, 2020.

4. **S. Janjua** and I. Hassan, "Role and relevance of three enabling conditions to resolve inter-provincial water conflicts in the Indus basin within Pakistan," *Water Policy*, vol. 22, no. 5, pp. 811-824, 2020.

5. **S. Janjua**, I. Hassan, M. Zarghaami, and S. Islam, "Addressing the supply-demand gap in shared rivers using water diplomacy framework: utility of game theory in the Indus river within Pakistan," *Water Policy*, vol. 22, no. 5, pp. 789-810, 2020.

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Acknowledgement

I am thankful to Almighty Allah, who gave me strength and patience to complete my research. I would like to pay debt of gratitude to **Dr. Ishtiaq Hassan**, being advisor for this study, whose countless inspiration and guidance made it possible to complete my research work.

I would also like to thank **Prof. Shafiqul Islam** at Tufts University (USA), whose role has been instrumental in every manner. This feat was possible only because of the unconditional support provided by him. A person with an amicable and positive disposition who always made himself available to clarify my doubts despite his busy schedule. Thank you Professor for all your help and support.

Also, the respondents, working in different Water Sector of Pakistan (engaged on water projects diversify in type and location) at the level of Managers, Supervisors or workers are greatly appreciated for their concrete input to make this study successful.

In the end, I pay my earnest gratitude with sincere sense of respect to my parents and family for their unending support, encouragement, prayers and patience.

Shahmir Janjua

Abstract

The main objective of this thesis is the development of methodologies that promote development, harmony and cooperation in place of violence and conflict in transboundary rivers basin. Its objectives in particular are: (1) to understand the complexity of water systems, water conflict management and the role of three enabling conditions for resolving the interprovincial water conflicts in Pakistan's Indus Basin, (2) to investigate the problems of the water systems in Pakistan, hydro-politics in Pakistan's Indus Basin and water crisis in Pakistan, (3) development of methods which would ensure equitable water and benefit allocation in inter-provincial transboundary river basins using bankruptcy rules, proposed rules, weighted bankruptcy rules and NASH bargaining solution for the surface water allocation in Pakistan and (4) to apply a Fuzzy AHP- TOPSIS Multi-Criteria Decision Analysis for ranking Reservoir Systems in Pakistan. The above-mentioned methods have been applied for the case study of the Indus River which is the largest river of Pakistan and is shared by the four administrative units (provinces) of Pakistan namely Baluchistan, Punjab, Sindh and Khyber Pakhtunkhwa (KPK). The thesis starts (first chapter) with in-depth discussion of the three enabling conditions which represents the pattern of interactions in the negotiated resolution of conflicts in the Interprovincial water distribution amongst the provinces of Pakistan. It also presents an in-depth review of water resources situation in Pakistan (second chapter); the challenges met by the water sector and likely remedial measures to overcome this issue and guarantee sustainable irrigated agriculture in Pakistan. Among the several factors identified, the issue of equitable water allocation, the lack of environmental flows and the need for new storage reservoirs were identified as the most conflictive issues among the provinces of Pakistan.

As the thesis lays emphasis on the issues related to transboundary river basins, the second part of the thesis (fourth, fifth and sixth chapters) discusses different mechanisms for the fair water allocation among the provinces of Pakistan using the Bankruptcy rules, Weighted Bankruptcy Rules and Nash Bargaining Solution. Apart from bankruptcy rules, two new rules are also proposed for the allocation

of water among the riparian (agent). These rules are applied for the water resource allocation problem and distribution of water in Pakistan and also present a new method to compare and contrast the water allocation rules. The results show that proposed 'Groundwater based Rule' has the lowest dispersion and is the most suitable allocation rule. The UN Water courses Convention 1997, in its article 6 has various factors which are concerned with the equitable distribution of the water resources. In case of the water resources which are shared among two or more riparian (agent), we have to consider these factors. A new methodology has also been described in this thesis for the scarce water allocation using weighted bankruptcy approach under stochastic settings. In 'weighted bankruptcy' approach, the claims of the riparian (agent) can be assigned different weights as per their socio-ecological factors. Results show that the allocation of the provinces increase with the increase in agricultural productivity. A new framework for the allocation of water among the provinces of Pakistan has been proposed which synthesizes the Nash bargaining solution concept with the bankruptcy theory to resolve supply-demand conflicts in the Indus basin among four provinces within Pakistan. The water required for the environmental flows has also been considered in the process of water allocation. Results show that moving from the non-cooperative approach of Bankruptcy to the cooperative approach of Nash results in 6.2% increase in the total monetary benefit. It also shows that the water allocation approaches proposed by the authors may help in negotiations and have a great potential to help solving conflict and dispute over river resources allocation problems in transboundary river basins.

The ranking of the reservoirs in Pakistan is also an important decision and it has a vital impact on the sustainability of the region and the economic operation of the reservoir. The reservoirs ranking is a vital problem which involves multi-criteria decision-making. The framework proposed in the third part of the thesis (seventh chapter) involves Fuzzy AHP-TOPSIS method for the ranking of reservoirs in Pakistan. Potential feasible locations are identified from the Water and Power Development Authority (WAPDA), Pakistan. Weight calculation for the criteria is done by the fuzzy AHP method which is a multi-criteria decision-making method.

In order to model the fuzziness, equivocacy, incomplete knowledge and ambiguity, the fuzzy AHP is used. Furthermore, in order to rank the selected reservoirs based on their performance, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied, which is a multicriteria decision making method. We demonstrate the application of above-mentioned methods to the case study of the Indus Reservoir system in Pakistan. A decision support tool is provided for the decision makers in this thesis to manage, evaluate and rank the planned reservoirs in the Indus River. Results show that Diamer-Basha is the most feasible option and Kalabagh Dam is the least preferable option due to latter's collapse in terms of political, security and legality criteria. The analyses also show that the overall ranking of reservoirs location fluctuates when the sensitivity analysis is performed.

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Abbreviations

ACO	Agricultural Census Organization
AHP	Analytic Hierarchical Process
ANP	Analytic Network Process
BCM	Billion Cubic Meter
CCI	Council of Common Interests
CEA	Constraint Equal Award
CEL	Constraint Equal Loss
CGT	Cooperative Game Theory
FATA	Federally Administered Tribal Areas
GDM	Group Decision Making
GDP	Gross Domestic Product
HKH	Hindu Kush Himalaya
IBIS	Indus Basin Irrigation System
IRBS	Indus River Basin System
IRSA	Indus River System Authority
IWRM	Integrated Water Resource Management
IWT	Indus Water Treaty
KPK	Khyber Pakhtunkhwa
MAF	Million-acre Feet
MCDM	Multi-criteria Decision Making
PRO	Proportionate
TBW	Trans-boundary Water
TFN	Triangular Fuzzy Numbers
TOPSIS	Technique for Order Preference by Similarity of Ideal Solution
TRB	Transboundary River Basin
TWM	Transboundary Water Management

UNESCO	United Nations Educational, Scientific and Cultural Organization
WAA	Water Apportionment Accord
WAPDA	Water and Power Development Authority
WDF	Water Diplomacy Framework

Chapter 1

Introduction

1.1 Transboundary River Basins

Depleting freshwater resources and increasing demands of water due to the rise in population have resulted in various water conflicts in many counties of the world, especially in arid and semi-arid areas (Oftadeh et al. 2016). The scarcity of water, both nationally and internationally, can lead to conflict as well as co-operation between riparian countries, states or provinces (Robertson et al. 2012). The declaration of principles between the countries of Egypt, Ethiopia and Sudan on the River Nile is the recent example of water cooperation (Mianabadi 2016). The shared natural resource, which also includes transboundary rivers among the riparian countries, states or provinces can be a cause of both cooperation and conflict (Mianabadi and Sheikhmohammady 2014).

Water, being an important economic, social, cultural, political and environmental resource ignores not only the political boundaries, but also the cultural, societal and natural boundaries. Water Systems operate in multiple domains and consist of inter-connected networks. (e.g., societal, political and natural), on multiple scales (e.g., institutional, temporal, spatial), and at multiple levels (e.g., local, national, international) (Islam and Susskind, 2012). Directly or indirectly, water is also linked to national security, energy and food. As water resources are often shared by more than one country or province and there is no replacement for water, it has turned out to be a very sensitive subject. Water resources systems of the world are becoming more and more complex due to these issues.

There are around 1600 shared reservoirs and lakes, 445 international aquifers and 276 river basins internationally which occupy at least forty percent of the surface area of the land (Stefano et al. 2011) and (Allen 2001). In future, these statistics can increase.

Much of the analysis, discussions and research related to the water disputes lays emphasis on the international water disputes but there is also a growing hazard of interstate or subnational water conflict. The subnational water competition and violence has been given very less attention although it also appears to be a significant risk. The subnational water violence may also spread over the international arena. The water droughts, shortages and mismanagement of water resources in Syria due to the ongoing civil war is an example of this subnational water crisis (Gleick and Heberger 2012).

Transboundary river basins have international, national and local dimensions and are "glocal" natural resources that means, they are characterized by both local and global considerations. As discussed earlier, the water shared between two or more riparians can be a cause of cooperation or conflict among the states, national governments and local water users. The main theme of this thesis is how the transboundary water resources can promote harmony, development and cooperation instead of conflict.

1.2 The Role of Three Enabling Conditions to Resolve Inter-Provincial Water Conflicts in Pakistan's Indus Basins

The literature related to the Transboundary Water Management (TWM) shows that there lies a wide range of complexity in terms of dynamics of cooperation and competition that emerge from the feedback and interconnection among the institutions, processes, actors and variables. Changing climate, socioeconomic and demographic conditions along with competing and conflicting needs are attracting people from several communities and disciplines towards TWM issues. With the changing scenarios and the complexity of TWM, the narrative is to define those circumstances under which the conflict occurs or cooperation is endeavored (Roberts and Palmer 2012); (Wolf et al. 2003); (Zeitoun and Mirumachi 2008a).

Three enabling conditions are introduced in this thesis (Chapter 2) which represent a pattern of interactions in the negotiated resolution of conflicts in the Interprovincial water distribution amongst the provinces of Pakistan (Water Apportionment Accord, 1991).

1.3 Hydro-Political Issues of Pakistan

Majority of Pakistan's domestic as well as agricultural needs are dependent on the Indus River Basin System (IRBS) which is a main source of life in Pakistan. River water sharing between the provinces has always been a bone of contention among provinces in Pakistan. Over the past many years, a great deal of distrust has been developed amongst the provinces of Pakistan regarding the water issues. The successive federal governments of Pakistan have failed to formulate a National Water Policy which involves all the provinces of Pakistan. Along with the shortages and increasing demands of water, the system of administrative dishonesty in the water sector of Pakistan is also common. The politically influential landlords along with the small and medium farmers benefit from the current water allocation system. If not properly addressed, this problem of decreasing water resources would result in serious confrontation amongst the provinces in future.

This thesis also presents an in-depth review of water resource situation in Pakistan, the challenges being faced by the water sector and likely remedial measures to overcome these issues and suggests a sustainable irrigation system in IRBS (Chapter 3).

1.4 Equitable Water Distribution Among Riparian

Wolf (1999) states that the most important issue related to water quantity is that how shared water resources are allocated among the riparian. This is a real challenge as what methodology should be adopted to allocate the available water amongst the riparian in a "reasonable" and "equitable" way and which mechanism and criteria should be used for the said purpose. So far, there has been no internationally recognized mechanism for the equitable allocation of water (Wolf 1999). According to Article 6 of the 1997 United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses, utilization of an international watercourse in a reasonable and equitable way involves taking into account appropriate factors and circumstances, including: (a) geographic, hydrographical, hydrological, climatic, ecological and other factors of a natural character; (b) the social and economic needs of the watercourse by the states concerned; (c) the population of each state that is dependent on the watercourse; (d) the effects of the use or uses of the watercourse(s) by one state on other state(s); (e) existing and potential uses of the watercourse; (f) conservation, protection, development and economy of use of the water resources of the watercourse and the costs of measures taken to that effect; (g) the availability of alternatives, of comparable value, to a particular planned or existing use (Fitzmaurice 1997).

Regardless of all the criteria, each riparian country, state or province prefers the criteria which supports its claim the most. An example of such transboundary water dispute is the Nile basin shared among eleven riparian countries. Egypt, which is the downstream riparian claims for its water rights based on its historical uses and rights whereas Ethiopia, which is located upstream refers to the principle of equitable and reasonable water utilization to defend its claim as stated in Helsinki Rules (Ansink 2009a) and (Yihdego 2013).

A serious shortfall, or the limitation of existing water laws is that there is no allocation mechanism which is accepted generally throughout the world. Because of the complex nature of the transboundary water systems, it is very difficult to develop such method of water allocation which is acceptable worldwide. In the light of above-mentioned shortfalls and the absence of any accepted allocation mechanism among the riparian countries, states or provinces, the allocation of water becomes a critical issue.

The "Bankruptcy Theory" and "NASH bargaining solution" are the methods which can be used to allocate the water among the riparian countries, states or provinces because fair distribution of an asset "E" among the group of claimants are the main purpose of these methods, provided that the total assets "E" are inadequate to satisfy the claims (C) (Herrero and Villar 2001). The Bankruptcy Rules, Proposed Rules, Weighted Bankruptcy Rules and NASH bargaining solution have been applied in thesis (Chapter 4, 5, and 6) for the water allocation among the provinces of Pakistan.

1.5 The Use of Multi-Criteria Decision Techniques for the Evaluation of Water Resources Alternatives

The Multi-Criteria Decision Making (MCDM) approach, in the recent years, has been used considerably in environment modelling (Zhou 2006). Apart from the economic criteria, it is also essential to consider the social, technical, environmental and political implications of water resource projects for ensuring the favourable and sustainable decisions. For this purpose, the stakeholders must be engaged at every step of the process which involves decision making. This requires the use of both MCDM and the Group Decision Making GDM methods (Zarghami et al. 2008). The significant advantages of such techniques for the water resources management are that they allow to:

- deal with the limited quantity of water, human and financial resources;
- lower the costs of delays in decision making;
- do multi-criteria decision making;
- avoid disputes amongst stakeholders; and

- manage and administer the projects in a better and efficient way.

The Multi-Criteria Aid has become an important tool for the water resources management problems due to the reason that the policy of water is not defined by "one" objective. The Multi-Criteria Decision Analysis (MCDA) has been applied in this thesis (chapter 7) to rank the water resource projects which are planned or ready for construction in the IRBS, Pakistan. Ranking of the selected projects on the defined criteria is also main aim of this thesis as this has not be done earlier that which project is to be executed in what sequence out of a number of planned projects by WAPDA (Water and Power Development Authority) Pakistan. It will be proposed that the projects which are ranked high should be given priority in construction.

1.6 Objectives of the Thesis

The objective of this thesis is the development of methodologies which would promote peace and cooperation in transboundary water resources instead of war (even cold war at international level) or conflict (at both national and international levels). The objectives of this thesis, in particular, are the following:

- Establishing the needs and role of three enabling conditions required to act as a basis for the resolution of interprovincial water conflicts.
- Development of methods to support ensure equitable water and benefit allocation in inter-provincial transboundary river basins using:
    - Bankruptcy rules and Proposed rules,
    - Weighted bankruptcy rules and
    - NASH bargaining solution for the surface water allocation in Pakistan.
- To Rank the reservoir systems in Pakistan using Fuzzy AHP-TOPSIS Multi-Criteria Decision Analysis.
- To apply the above-mentioned methods for the case study of the Indus River which is the largest river of Pakistan and shared among four administrative units (provinces) of Pakistan.

1.7 General Methodology

Figure 1.1 shows General Methodology for our Study. An extensive literature review was first conducted related to Hydro-politics in Pakistan's Indus Basin. Data was collected from various departments like IRSA, Planning Division WAPDA and Agricultural Census of Pakistan. The crop water requirements were also worked out and compared from various Independent reports and official reports.

The problems in Pakistan's Water sector were identified and several recommendations were given to resolve these problems in the light of three enabling conditions.

After this, Water allocation was done using the Bankruptcy Rules, Weighted Bankruptcy Rules and NASH Bargaining Solution. The results were finally compared and finally some important conclusions were drawn from this. Also, in parallel, reservoir ranking was done using Fuzzy AHP Topsis, followed by some conclusions. Finally, recommendations were made for the decision makers and stakeholders for sustainable water management in Pakistan.

1.8 Research Gap

The water issues have been discussed in this thesis at provincial level. There exists no systematic method to find the proportional quantity of irrigation canal water to the provinces of Pakistan. At international level, Hojjat Mianabadi applied the concept of the Bankruptcy rules for the water resource distribution between Turkey, Iraq, and Syria. In this study, in addition to the three rules used by Mianabadi, two additional rules of bankruptcy and two proposed rules are used which differentiate this study from the above one. Also, a new methodology for the selection of best rule has been applied. NASH bargaining solution has also been applied to allocate water and benefits to the provinces of Pakistan.

Second novelty of this study is that Fuzzy-AHP TOPSIS has been applied for the first time to rank execution of reservoir projects in Pakistan. A sensitivity analysis has also been performed.

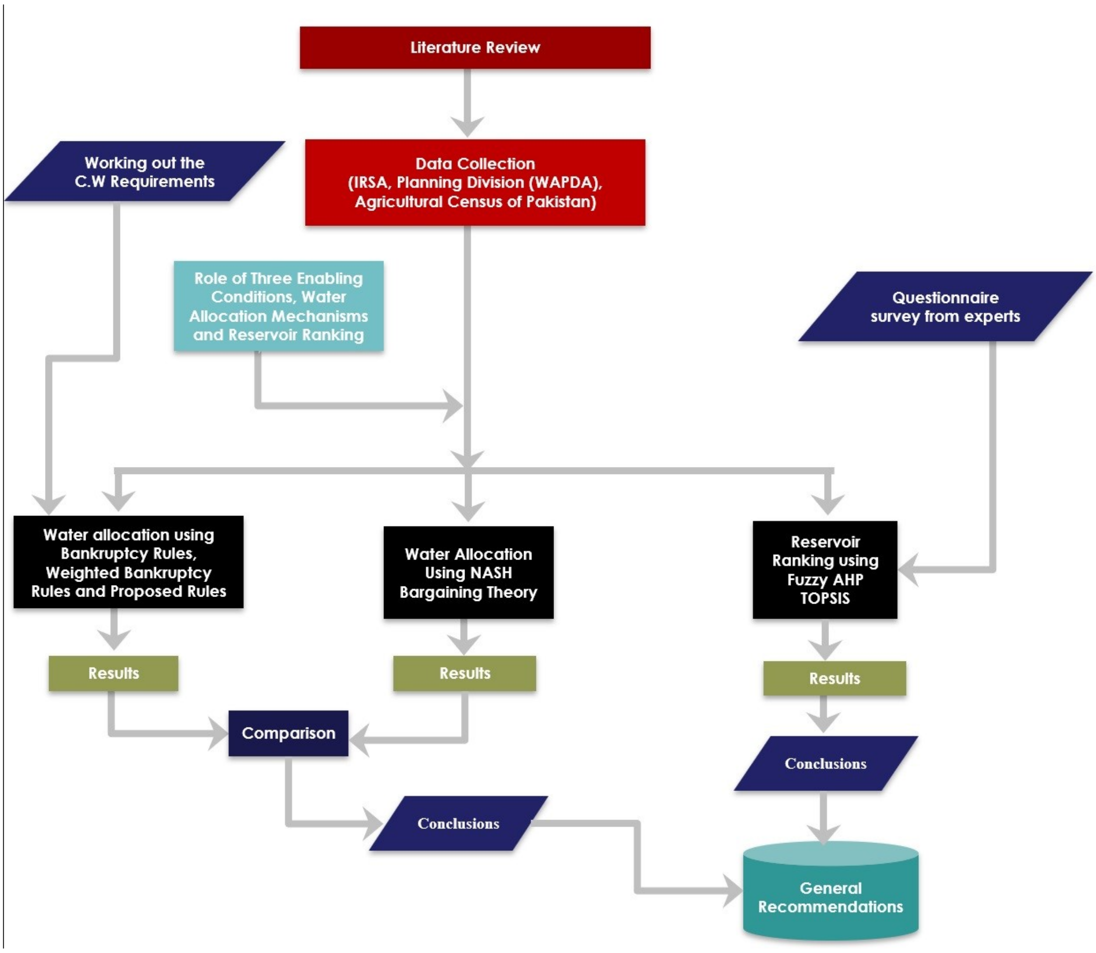

FIGURE 1.1: General methodology.

These techniques have been applied in the Indus River System of Pakistan for resolving the interprovincial water conflicts. It is, therefore, expected that these techniques would help in resolving the water disputes among the provinces of Pakistan.

1.9 Outline of the Thesis

The thesis, according to the objectives listed above, is organized as follows.

The second chapter of this thesis identifies three enabling conditions applicable in the Pakistan's IRBS that underline the cooperation required. The chapter emphasizes that effective resolution of complex Trans-Boundary Water (TBW) problems is rooted in the nature of the negotiation process, the provisions in the negotiated agreement and the establishment of institutional means to solve emergent problems that are related to the original agreement.

The hydro-politics in the Pakistan's Indus Basin and water crisis in Pakistan is discussed in the third chapter. This chapter emphasizes that Pakistan, in order to deal with the increasing water demands, need to develop a fair water allocation mechanism among its provinces, increase its water storage capacity by constructing new reservoirs, allocate the water for environmental flows, improve the water use efficiency and manage its groundwater and surface water resources in a sustainable way.

As the thesis lays emphasis on the issues related to transboundary river basins, the fourth, fifth and sixth chapters discuss the different mechanisms for the fair water allocation among the provinces of Pakistan using the Bankruptcy rules, Weighted Bankruptcy Rules and Nash Bargaining Solution. In chapter 4, apart from bankruptcy rules, two new rules are also proposed for the allocation of water among the riparian. These rules are applied for the water resource allocation problem and distribution of water in Pakistan. The chapter also presents a new method to compare and contrast the water allocation rules.

The UN Water courses Convention 1997, in its article 6 has various factors which are related to equitable and reasonable distribution of water resources. In case of the water resources, which are shared among two or more riparian, one has to consider these factors. These factors have been stated in Section 1.4. Also, a common problem in water resource allocation is to design a stable and feasible mechanism of water sharing in critical scarcity conditions. A new methodology has been described in the fifth chapter for the scarce water allocation using the weighted bankruptcy rules. The weighted bankruptcy rules have been applied under the stochastic settings. In "weighted bankruptcy" approach, the claims of the riparian are assigned different weights as per socio-ecological factors as stated in Section 1.4. These weighted bankruptcy rules have been applied under different water scarce scenarios and the available water is allocated under the simple and weighted bankruptcy rules.

In the sixth chapter, a new framework for the allocation of water among the provinces of Pakistan has been proposed which synthesizes the Nash bargaining solution concept with the bankruptcy theory to resolve supply-demand conflicts in the Indus basin among four provinces within Pakistan. In this chapter, five commonly used Bankruptcy Rules and Successive linear programming (based on Nash bargaining theory) are used to distribute the water and benefits among the four provinces.

The seventh chapter of the dissertation examines negotiation methods and ranking of reservoirs in Pakistan's Indus Basin using Fuzzy AHP-TOPSIS. A decision support tool is provided for the decision makers in this chapter to manage, evaluate and rank the planned reservoirs in the Indus River.

Results of the above-mentioned methods, along with the conclusions and recommendations are summarized in the Chapter 8. Some recommendations for the future studies are also presented as well.

Chapter 2

Bridging Complexity and Contingency: Role of Three Enabling Conditions in Resolving Inter-Provincial Water Conflits in Pakistan's Indus Basin

2.1 Introduction

Despite repeated calls and efforts to develop a comprehensive approach to resolve TWM problems, search for causal mechanisms for cooperation has yet to yield any reliable theory (Choudhury and Islam 2015). For example, two envoys were sent by the United States in 1950s in order to address the water conflicts: one in the Middle East and the other one in South Asia. The Indus Water Treaty (IWT) was signed in 1960 and despite several wars between Pakistan and India, the treaty has survived the last 60 years. On the other hand, the Jordan, Israel peace treaty took several decades and was signed in 1994. Choudhury and Islam (2015) looked at the similarities and differences for these two as well as several other TWM cases and provided a re-framing of TWM issues. In particular, they have used the notion of complexity science, contingency, and enabling conditions to understand, explain, and resolve TWM issues.

The Indus Water Treaty (IWT) resulted in the partitioning of the rivers between Pakistan and India. The 1960 IWT has also created a decision vacuum regarding the allocation of the Indus water among the provinces within Pakistan. Before IWT, allocation of water within the provinces of Pakistan – primarily Sindh and Punjab – was dictated by the Sindh-Punjab agreement of 1945 (Ahmad 2011; Wescoat Jr et al. 2000 and Mustafa 2010). Several high-level committees and commissions were appointed by the Federal Government of Pakistan between the enactment of the IWT and Water Apportionment Accord of 1991. Yet, no formal water allocation agreement materialized on how to allocate water among the provinces. This thesis has examined the evolution of inter-provincial water conflicts in the Indus basin within Pakistan to show why over 30 years of dialogue and discourse could not create any formal water allocation agreement. It also shows why the Water Apportionment Accord of 1991 was a game-changer and how the notion of enabling conditions suggested by Choudhury and Islam (2015) can help to explain the evolution and dynamics of inter-provincial water conflicts within Pakistan.

The question of how to govern and manage transboundary water for human consumption, irrigation, hydropower, urban and industrial development, socio-cultural needs and sustainability of ecosystems continue to be an issue of concern, conflict, and cooperation. Despite its increasing sophistication, most of this literature and discourse remains wedded to implicit assumptions about values (e.g., that cooperation is desirable and is more cost-effective than conflicts; yet, no formal agreements exist to most shared transboundary basins) and that engaging an array of methods, tools, governance structures, and institutions will yield a universal cure. These assumptions are rarely challenged, and the search for a general theory (e.g., a general method of TWM cooperation) continues.

The TWM literature shows a wide range of complexity in terms of competition and cooperation that arise from the interactions and feedbacks among variables, processes, actors, and institutions. These interactions and feedback are attributed to allocation, access, and use of water related to a variety of natural, societal, and political elements. Given the complexity of TWM and its contingent manifestations, the discussion goes on to specify the conditions under which conflict arises or cooperation is attempted (Falkenmark and Suprapto, 1992; Frey, 1993; Lowi, 1995; Wolf and Hamner, 2000; Wolf et al., 2000; Zeitoun and Mirumachi, 2008; Priscoli and Wolf, 2009; De Stefano et al., 2010; Schmeier, 2013; Zawahri et al., 2016; Dinar, S., & Dinar, 2017).

Despite repeated calls and efforts to develop a comprehensive approach for resolving transboundary water conflicts (Swain, 1999; Uitto and Duda, 2002; Dinar, 2004; De Stefano et al., 2012; Dinar, S., & Dinar, 2017) using the conventional notion of causality is yet to yield any reliable framework of theory, as many scholars in the field have pointed out (Dinar, 2004; Yoffe et al., 2003; Pahl-Wostl, 2007; Zawahri et al., 2016b).

Why have some negotiated mechanisms been successful and resilient despite the shortcomings in the agreements reached? (Choudhury and Islam 2015) suggest that a critical reason for such a shortcoming is that, while the necessary conditions of certain aspects of causality can be agreed to (e.g., issues of scarcity, need for cooperation), even then the sufficient conditions cannot be easily identified and agreed upon by all parties involved. Among different modes of cooperation, direct and mediated negotiations have shown resilience in initiating, affecting and sustaining institutional interactions among riparian, even when they remain hostile to each other on other issues (Elhance, 2000; Biswas, 2008; (Susskind 2015). Choudhury and Islam (2015) suggested that the reason for such successful outcomes are contingent. More importantly, they argued that reasons for success were not easily identifiable through the conventional notion of causal conditions but to the presence of enabling conditions.

Choudhury and Islam (2015) introduced three enabling conditions that constitute a pattern of interactions in the negotiated resolution of conflicts in the IRBS between Pakistan and India and the Jordan river between Israel and Jordan. In advancing the notion of enabling conditions, they made the point that resiliency of these three enabling conditions rest on operationalizing the values of equity and sustainability in context-specific ways. Here, this thesis examines the role and relevance of these three enabling conditions to resolve inter-provincial water conflicts in the Indus basin within Pakistan. Following (Choudhury and Islam 2015), paragraphs highlight the key attributes of these three enabling conditions:

Enabling Condition #1: Active Recognition of Interdependence

Active recognition of interdependence is a critical enabling condition, because, "active" form of recognition is what transforms a mere desire or policy intent to a declared commitment to make it happen.

Enabling Condition #2: Mutual Value Creation

This enabling condition expands the scope and meaning of interdependence (enabling condition # 1) by encouraging involved parties to explore options that create mutual value. Value creation rests on what each party can add to different options to satisfy their respective needs.

Enabling Condition #3: Adaptive Regime of Governance

This enabling condition deals with developing a governance structure and institutional capacity to act on operationalizing the mutual values created in Enabling Condition #2. It requires the governance regime to be adaptive to uncertain and changing future scenarios.

One may argue that these enabling conditions are already known in terms of cooperation, negotiation, and institution building. Thus, conceptualizing them as enabling is nothing more than another jargon that creates mere semantic variation. Against such argument, Choudhury and Islam (2015) suggest that the notion of "active recognition," "mutual value" and "adaptive governance" introduce a different framing to the conventional meaning of cooperation as conflict prevention, negotiation as mutual gain strategy, and institution building as flexible design. What follows is a brief description of the Indus basin history, water inter-provincial water conflicts, and an examination of the relevance of the three enabling conditions in resolving inter-provincial water conflicts in the IRBS.

2.2 The Indus Basin Within Pakistan

The Indus Basin Irrigation System (IBIS) is the largest contiguous irrigation system in the world (Shahid et al. 2018). Constitutionally, in Pakistan, water is a federal subject and provinces are in charge for domestic water supply, sanitation as well as irrigation and drainage. The constitutional provisions ensure that the critical decisions are administered jointly through the Council of Common Interests (CCI), Pakistan (Mustafa 2010).

Indus Basin Irrigation System (IBIS) comprises networks of canals, headworks, and hydropower dams (Figure 2.1). Pakistan is an arid country with a mean annual rainfall of less than 100 mm in parts of Baluchistan and Sindh to more than 1500 millimeters in the mountains. Physical and hydrological variability makes the management of IBIS very difficult. It contributes over 20% of Pakistan's GDP and plays a vital role in the livelihood of millions of people (Ahmad et al. 2014).

2.2.1 History of Interprovincial Water Conflicts in the Indus Basin within Pakistan

There are four major administrative units in Pakistan i.e. Punjab, Sindh, Baluchistan and Khyber Pakhtunkhwa (KPK) and few minor units which consist of small areas of Gilgit-Baltistan, Federally Administered Tribal Areas (FATA) and Kashmir. Main water crises exist among major administrative units that have been focused and addressed in this thesis. In Pakistan, the principal natural resources are water, and arable land and agriculture contribute significantly towards the country's economy, accounting to almost 19.8% of the gross domestic product (GDP) (Anwar and Bhatti 2017). Out of the 27% of the cultivated land in Pakistan, Punjab has the highest proportion (63%), followed by Sindh (18%), and the remainder is equally divided between the provinces of Baluchistan and Khyber Pakhtunkhwa (ACO, Agricultural Census Organization 2010).

Beginning with the construction of canal construction projects by the British, the issue of water allocation and conflicts among provinces rose from time to time. The first significant treaty between the downstream Sindh and upper riparian Punjab

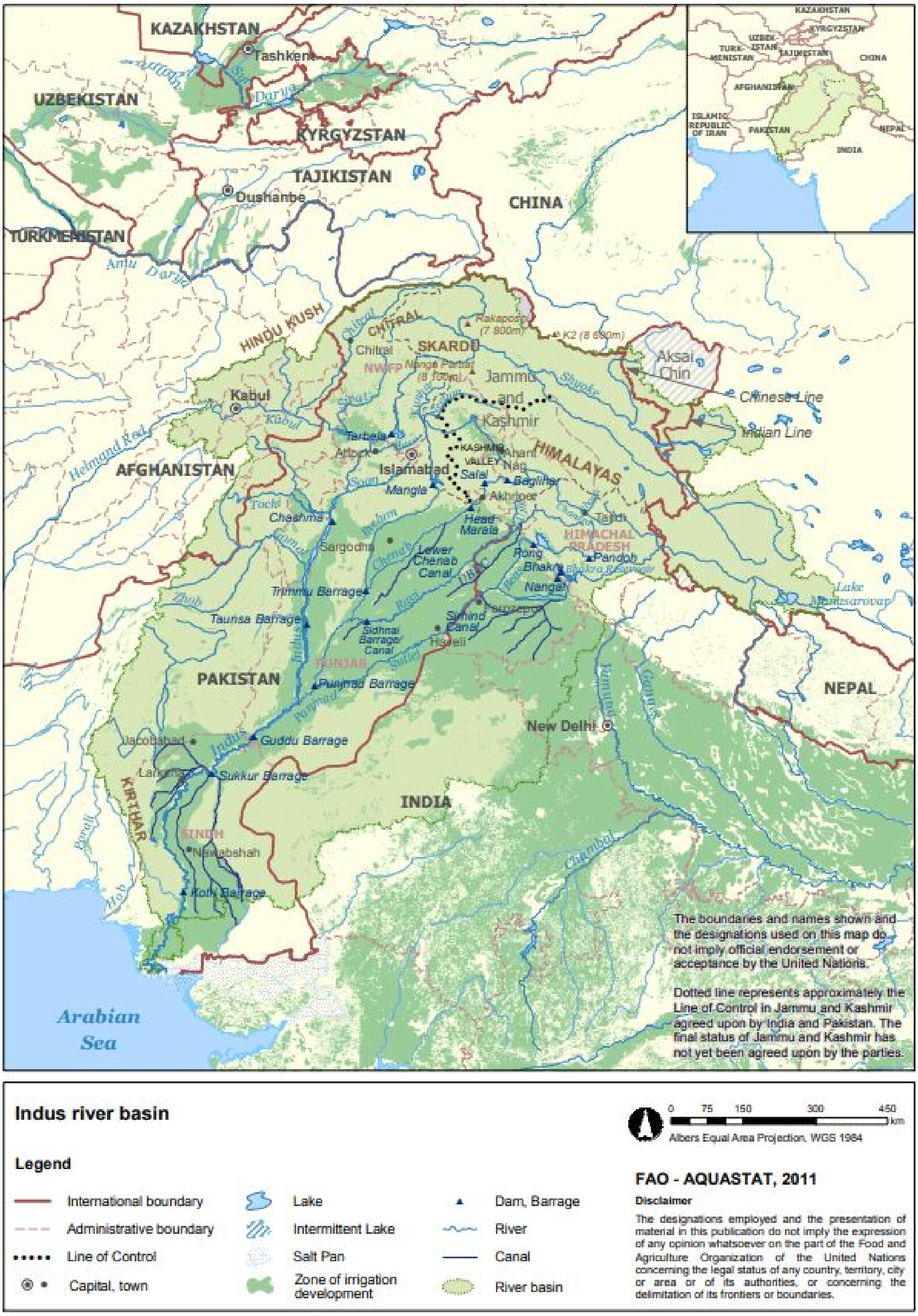

FIGURE 2.1: Irrigation and river network of Pakistan's Indus Basin.

regarding the interprovincial water allocation dates back to 1945. According to this treaty, 25% of the water of the main part of the Indus River was allocated to

Punjab, and the remaining 75% was allocated to Sindh. Punjab was given 94% of the water from the five eastern tributaries of the Indus, and the remaining 6 percent was allocated to Sindh (Michel 1967).

After the emergence of Pakistan and India as independent nations, the Indus Water Treaty (IWT) between Pakistan and India was signed in 1960. The IWT allocated most of Punjab's share of the Indus River (according to the 1945 agreement between Punjab and Sindh) to India. It also made provisions for the construction of the link canals and storages from the western half of the Indus Basin to the eastern half, which was done to compensate for the water lost to India. The allocation of water and storage provisions created with the IWT was widely perceived by the Sindh to be favorable to Punjab (Mir and Muhammad 2001). To resolve these inter-provincial water conflicts, several commissions and committees were formed.

2.2.2 History of Committees and Commissions to Address Inter-Provincial Water Conflicts

The IWT brought drastic changes to water allocation among provinces within Pakistan. The IWT made the 1945 agreement between Punjab and Sindh irrelevant. In the absence of any formal agreement among the provinces, water allocation was done by the Water and Power Development Authority (WAPDA) on an ad-hoc basis (Syed et al. 2021). To address the contentious inter-provincial water issues, several commissions were appointed by the Government of Pakistan as outlined below.

2.2.2.1 Akhtar Hussain Committee (1968)

The Water Allocation and Rates Committee was formed by the Government of Pakistan in 1968. The chairman of this committee was Mr. Akhtar Hussain. The Commission was tasked to recommend reservoir release patterns, barrage apportionments, and drawdown levels. It was also tasked to examine the use of groundwater with surface water. The major disputed parties were Punjab and Sindh (Khalid and Begum 2013). The water demands of Khyber Pakhtunkhwa and Baluchistan were small. On 30 June 1970, the Committee submitted its report to the Governor of West Pakistan. Unfortunately, the next day (1 July 1970) constitutionality of four provinces was dissolved, and entire West Pakistan was made into one unit to be administratively consistent with East Pakistan (now Bangladesh). Consequently, this report did not get any attention (Khalid and Begum 2013).

2.2.2.2 Fazl-e-Akbar Committee (1970)

Another committee was set up on 15 October 1970 - chaired by the former judge of Supreme Court of Pakistan, Mr. Justice Fazl-e-Akbar - for the water apportionment of the Indus River System within West Pakistan. In addition to surface water allocation and storage provision considerations, the Committee was asked to examine the role of groundwater as well. The Committee could not come to a consensus. And the Justice Fazl-e-Akbar formulated his recommendations and submitted his report. Recommendations of this report were discussed in October 1972 at the Governor's Conference, but no result was finalized, and the ad-hoc allocation of water by the WAPDA continued (Syed and Choudhury 2018).

2.2.2.3 Indus Water Commission (Anwar-ul-Haq Commission of 1981)

On the recommendation of the Council of Common Interests (CCI), the President of Pakistan constituted the Indus Water Commission in 1981. The chairman of this Committee was the Chief Justice of Pakistan and chief justices from four High Courts as its members. The commission was given nine months to prepare a report, but it could not conclude its recommendations. In June 1982, the commission suggested to the President that the distribution of waters from the Indus and its tributaries could be based on the Fazl-e-Akbar Committee report with provisions for modifications and adjustments as needed (Khalid and Begum 2013) and (Bhatti and Farooq 2014).

2.2.2.4 Haleem Committee (1983)

In March 1983, the President of Pakistan directed Chief Justice Haleem to re-examine the problem of apportionment of waters on an equitable basis with the assistance of Chief Justices of High Courts of the four provinces. On 15th April 1983, the committee submitted its report to the President with a dissent note of the Chief Justice of Peshawar High Court. Recommendations from the Committee remained pending, and the ad-hoc allocation of water by the WAPDA continued until 1991 (PILDAT 2011).

Despite the formation of several committees and commissions from the initiation of the 1960 IWT to the establishment of the 1991 Water Apportionment Act, it appears that no tangible outcome emerged to resolve inter-provincial water issues. One may speculate about several causal reasons for this outcome. For example, the supply-demand gap from the Indus was not considered to be a severe issue because provinces were addressing water shortage through overexploitation of groundwater. The Federal Government - with the military rule was preoccupied with external conflicts and threats – did not pay much attention to water issues (Anwar et al. 2018).

We make a distinction between causes and conditions to address TWM issues. In such situations, conventional causal reasoning based on specifying the effects of exogenous or antecedent factors that cause cooperation – argument commonly used in TWM literature; for example, in Song and Whittington (2004); Tir and Ackerman, (2009); Zawahri and Mitchell (2011); (Zawahri et al. 2016) – loses its primacy. In contrast to searching for causal conditions, following Choudhury and Islam (2015), we examine the efficacy of three enabling conditions that constitute a pattern of interactions to address inter-provincial water conflicts in the Indus river within Pakistan.

2.3 Role and Relevance of Three Enabling Conditions for Conflict Resolution

2.3.1 Enabling Condition #1: Active Recognition of Interdependence among the Provinces

Active recognition of interdependence means that the parties (four provinces) in the governance process agree to resolve a focal conflict(s) and cooperate on a set of agreed-upon operating rules. Such recognition can happen when parties in a conflict recognize their mutual water needs, constraints, and capacity. Although several committees and commissions were formed as discussed above, none of them played an active role in resolving the Inter-Provincial water conflict. In 1990, when the Federal government took the initiative to address inter-provincial water issues, a sense of urgency was created, which encouraged four provinces to engage in a dialogue making the role of active recognition of interdependence relevant (Khan, A., & Awan 2020).

The four provinces were recognized in the 1973 constitution, and a new system of federal administration was created. Water management was considered a provincial matter, and the constitution did neither establish nor define the provincial water allocation rules. However, the doors for active participation for the provinces in the decision-making process were kept open in the constitution. A new institution called the Council of Common Interests (CCI) was formed, which enabled active participation from the provinces related to water management issues. The CCI was the first to initiate discussion around water disputes among the four provinces. The CCI would hold meetings upon the request of one or more stakeholders (provinces of Pakistan). Its functioning was similar to that of the 'Indus Water Commission' of the IWT. However, the CCI had no legal basis or a water treaty to refer to, unlike the IWT. Thus, any water-related issues were addressed by the CCI primarily through negotiation (Paukert 2015).

After assuming the office in November 1990, the new government of Pakistan took the initiative to address provincial water disputes. A subcommittee was appointed under the supervision of the cabinet. The primary purpose of this Committee was to explore different options to resolve water disputes among the provinces (Indus River System Authority (IRSA) 1991) . The CCI acted upon the recommendations from the cabinet, and the "Inter-Provincial Committee on the Apportionment of Indus Rivers" was set up in 1991. This Committee first met on 30 January 1991. It held several other meetings throughout February in which the stakeholders of the provinces discussed technical and legal aspects. The Committee presented its recommendations to the provincial governments. On 3rd March 1991, the Chief Ministers of all the provinces met again (Yang et al. 2014).

Finally, the four Chief Ministers, with the support of CCI and the federal government, agreed on the water apportionment on 16th March 1991. The Water Apportionment Accord protected existing uses of canal water in each province, with recognition of the need for escape below Kotri for environmental purposes, and apportioned the "balance of river supplies", including "flood surpluses" and "additional supplies" from future storages. It defined provincial water entitlements based on water availability of 141 cubic kilometers, assuming that new water storages would provide additional water of around 12.33 cubic kilometers for the environmental flows (Garrick et al. 2014).

It took thirty years for this pivotal breakthrough – the Water Apportionment Accord of 1991- to happen. The mediating role of the Prime Minister was critical for this enabling condition to become a reality (Indus River System Authority (IRSA) 1991). Mediation as the means of dispute resolution functioned here as enabling because the advisement and facilitation process of mediation allows both parties to remain engaged and negotiate their own needs and concerns. Active involvement of a mediator increased familiarity, reduced mutual vulnerability, and hence buffered the perceived risks of cooperation among all four provinces of Pakistan. The above set of actions emerged from recognizing that if provinces acknowledge their interdependence, combine their efforts and understand each other's needs, only then can they achieve sustainable development of the Indus waters for the benefit of all stakeholders.

2.3.2 Enabling Condition #2: Mutual Value Creation through Cooperation

Mutual value creation builds on the notion of exploration of options without commitment. This enabling condition allows parties to be creative in exploring options that are mutually beneficial to parties involved. The mutual value creation is an exploratory phase of cooperation and does not require anyone to commit to any particular option. It demystifies the notion of the zero-sum situation by allowing parties to explore what each side can gain from cooperation by connecting issues and resources from multiple sectors and by going beyond the traditional notion of allocating existing water as the only resource (Choudhury and Islam 2015).

One way to explore mutual value creation is to have a professionally facilitated discussion among the parties to identify and agree on mutual benefits and costs of cooperation, as well as to devise instruments to secure them (Chazournes et al. 2013). For the interprovincial water sharing in Pakistan, this involved exploring the benefits of allocating and sharing water for agriculture and environmental needs. Through the Water Apportionment Accord, each of the four provinces achieved more gains than they initially expected. Punjab received 69 cubic kilometers of water per annum, Sindh 60.14 cubic kilometer per annum, KPK 7.12 cubic kilometer, and Baluchistan received 4.77 cubic kilometers of water per year. Another 3.7 cubic kilometers per year of water from the local canals above the rim stations was further allocated to the province of KPK. The "balance river supplies" which included future storages and flood flows were apportioned to Punjab and Sindh at 37% each, Baluchistan at 12% and KPK at 14% (Bhatti and Farooq 2014).

Several other mutual gains' options were discussed and included in operationalizing the Accord. It was decided to set aside 12.33 cubic kilometers per year for environmental flows downstream of Kotri to combat seawater intrusions and protect mangrove forests. The provinces were also allowed to plan new projects. No restrictions were placed on small schemes not exceeding 20 square kilometers above the elevation of 366 meters. It was agreed that concerted efforts be made by the provinces to minimize wastage of water (Ranjan 2012). If a province can't make full use of its allocated water, the other province may be allowed to use it without acquiring a right on it. It was decided that allocation will be done based on ten daily usages. The operation of the existing reservoirs will give priority to provincial irrigation uses and provisions are included to address future scenarios like the construction of new dams and storage reservoirs (Indus River System Authority (IRSA) 1991).

The Water Apportionment Accord provided flexibility to each province to use their allocated water most effectively by recognizing their context, capacity, and constraints. For example, over 20234 square kilometers (5 million acres) of additional land was expected to be brought under cultivation. The production of wheat was expected to increase by 2 million tons per year. The province of Sindh got an additional 5.55 cubic kilometer per year from this Accord which was 13% more than its previous share. The province of KPK got 50% more water than it demanded in 1983. This increased allocation boosted the sugarcane production in KPK. The province of Baluchistan also came out to be a major beneficiary from the Accord, and it was hoped that 0.6 to 1.6-million-acre additional land would be brought under cultivation under the new allocation. Punjab also benefitted significantly by increasing its irrigated area by 3 million acres (Rajput 2011 and Paukert 2016).

2.3.3 Enabling Condition #3: Adaptive Regime of Governance through Creating the Indus River System Authority (IRSA)

This enabling condition deals with developing institutional capacity to act on the negotiated agreement in an adaptive way. As a result of the Water Accord signing between the provinces, an independent entity known as the Indus River System Authority (IRSA) was created. Within 20 months after the signing of the Water Apportionment Accord, the IRSA came into being with the IRSA Act as a federal law (XXII, 6 December 1992) passed by the parliament. According to this law, the IRSA would implement and oversee the implementation of the agreement between the provinces. It would also work towards just and equitable allocation of water (Ranjan 2012). The IRSA was primarily tasked to:

- Provide the basis for the distribution and regulation of surface waters amongst the provinces according to the policies and allocations discussed in the Water Accord;
- Review and specify reservoir and river operation patterns on a regular basis;
- Coordinate and regulate the activities of the Water and Power Development Authority (WAPDA) in exchange of data sharing between the Provinces;
- Address any dispute that may arise between the provinces related to the distribution of river flows and reservoir levels;
- Evaluate water availability against the provinces allocated shares and make appropriate recommendations;
- Resolve questions related to the implementation of Water Accord by the majority vote of members.

IRSA's main task is the distribution of water among the provinces based on the 1991 Accord. Regular monthly meetings are held by IRSA with all relevant stakeholders. About planning and allocation of water supplies for the provinces, especially during the crop seasons, two committees support the decision-making process of IRSA (Wescoat Jr et al. 2000). The Technical Committee provides the data and support on the operation of reservoirs and the irrigation system while the Advisory Committee represents the institutional link between the affiliated bodies and IRSA and is composed of the representatives of provinces, federal government, WAPDA and representatives of IRSA (Ahmad 2009).

How adaptive governance helped IRSA to be effective?

The IRSA did not have the data or access to the monitoring stations. The WAPDA was responsible for the operation of barrages and the collection of data. To make allocation decisions, IRSA was dependent on WAPDA to provide the necessary data. This impeded IRSA's decision making on a real-time and transparent basis (Anwar et al. 2018). It prompted IRSA to work with the Federal government in modernizing the data collection by installing telemetry systems. This move proved very beneficial as it provided IRSA an opportunity to independently determine the exact flows rather than relying on data provided by the WAPDA and provincial irrigation departments. This also provided IRSA a state-of-the-art facility for assessing the water availability and evaluating allocation patterns on a real-time basis (Paukert 2016).

Some concerns were raised by the downstream provinces of Baluchistan and Sindh regarding the reliability and accuracy of the telemetry system. A neutral consultant was appointed to assess the accuracy and reliability of the telemetry system. In 2008, the consultant reported that only minor adjustments are required in the telemetry system, and the system is working as intended (Garrick et al. 2014). To sum, the implementation of the Water Apportionment Accord through the IRSA shows how an adaptive governance regime can act as an enabling condition to resolve contentious transboundary water issues.

2.4 Discussion and Concluding Remarks

Choudhury and Islam (2015) introduced three enabling conditions and examined seven cases in Indus, Jordan, Nile, Danube, Colorado, Brahmaputra, and Ganges to illustrate the utility of three enabling conditions for effective resolution of complex TWM issues. These three enabling conditions are: (a) active recognition of interdependence; (b) mutual value creation; and (c) adaptive regime and rules of governance. Together, these provide a focal set of conditions to initiate, design, and implement a resilient negotiated process to resolve TWM water issues.

There is a growing consensus that the complexity of issues as well as the competing and often conflicting values and priorities call for a reframing of TWM problems. The politics of water demand answers: Who decides? Who benefits? Who bears the burden? At what scale? At what price? These difficulties are amplified by practical questions like, in the Nile, how can one reconcile the building of the dam to support Ethiopia's economic development with the need for adequate water for a growing population in Egypt? Questions for the Ganges may include: How can future management meet the previous agreements on the Ganges that allocate water between India and Bangladesh? How does any water agreement among the Himalayan basin countries relate to larger regional concerns beyond water?

Over the last several decades, integrated water resources management (IWRM) has been strongly endorsed as a guiding principle to coordinate and manage water, land and related resources to maximize economic and social benefits. In a critical assessment of IWRM, Biswas (2004) argued for a focus on operational ("what will be") concerns and suggested deemphasizing normative ("what ought to be") dimensions. The WDF does not endorse either normative or operational perspective; rather, it emphasizes both normative and operational aspects through explicit conversation about facts and values need to be integral to any sustainable and resilient water treaty framing, formulation, and implementation.

The WDF recognizes that solution space for many of these complex TWM problems are intertwined with facts and values that can't be pre-stated without understanding contextual nuances. Consequently, the goal is not to search and satisfy the necessary and jointly sufficient conditions for securing predictable outcomes (Islam and Susskind 2018). We need to look for and identify situational conditions for effective intervention and desirable outcomes. Identifying and implementing these successfully is a craft, and this craft is dependent on engaging in continual adaptive learning. In March 2016, for example, after decades of hostility and stalemate, Egypt, Ethiopia and Sudan signed a Declaration of Principles on the Grand Ethiopian Renaissance Dam, signaling a concrete expression of the three parties' desire to move beyond political posturing and rhetoric. Now, moving forward from satisfying this first enabling condition, there are opportunities to seek lasting water security for the Nile. Similarly, as the time for the 1996 Ganges Treaty renewal nears, this is an opportune time to think about enabling and situational conditions for effective TWM of the Himalayan rivers (Choudhury and Islam, 2018; Islam, 2019). Using the negotiated agreements of the 1991 Water Apportionment Act to resolve inter-provincial water conflicts in the Indus basin within Pakistan as an example, we have illustrated the presence and applicability of three enabling conditions that led to negotiated cooperation among four provinces. The resolution of conflicts happened due to the willingness of the affected parties to recognize their interdependencies and to settle their differences through the mediating role played by the Federal Government. Favorable political regime in the center and provinces at that time was a major reason for the Water Apportionment Accord of 1991. The enabling conditions emerged not only for pragmatic reason (i.e., the emergence of political opportunity and active involvement of the Federal Government) but also from the operationalizing the contingent meaning of equity and sustainability by creating flexible and adaptive processes to address uncertainties in physical (e.g., inter-annual variability) and institutional (e.g., changing roles of WAPDA and IRSA) settings.

The effectiveness of the interaction among provinces is also reflected in the options explored and adopted to realize the mutual gains. These gains formed the foundation for creating mutual values that were absent before the negotiation. The 1991 Accord allowed each of the four provinces to achieve more benefits than they originally expected. Also, the Accord provided flexibility to each province to use their allocated water most effectively by recognizing their context, capacity, and constraints. In other words, exploration related to finding mutual gains led to the emergence of interactions on creating mutual values. We suggest that sustained interaction among provinces will make this Accord more resilient by being adaptive to changing circumstances.

Given the changing nature of TWM issues, continued interactions among provinces will sustain these enabling conditions and provide stability to institutional processes to address emerging issues on an incremental and case by case basis. The implementation of the Accord needs to remain flexible to address the contingent needs of the IBIS as they arise, for instance, issues like adapting to climate change, relying more on virtual waters, and using conservation technologies more effectively to gain water efficiency and improve water quality.

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These three enabling conditions constitute a focal set of minimums – neither exhaustively sufficient nor a guaranteed prescription for the predictable outcome – conditions to initiate, design and implement a negotiated process to resolve TWM issues. Recall, solution space for complex TWM problems can't be pre-stated. Consequently, in resolving TWM conflicts and challenges, the goal is not to seek and satisfy the necessary and jointly sufficient conditions for securing reliable and predictable outcomes. The ingenuity and creativity need to focus on identifying the situational conditions for effective intervention within an emergent pattern of interactions as exemplified by the effectiveness of the 1991 Water Apportionment Act.

Chapter 3

Challenges and Response in Pakistan's Indus Basin

3.1 Introduction

Being the sixth most populous country in the world, Pakistan is predicted to reach 220 million by the year 2025. The Indus Basin occupies a total area of 566,000 square kilometers (km^2). Eighty percent of the Pakistan's total population lives in the Indus Basin. Over the last ten years, Pakistan has become a water stressed country. The United Nations (UN) has estimated that the per capita water availability of Pakistan has reached 1090 cubic meters (Condon et al. 2014). The economic development of Pakistan has always been dependent on the irrigated agriculture and consequently, water. Seventy-five percent of Pakistan's total population is dependent on agriculture and it accounts 60% of the foreign exchange earnings, employs 44% of the labor force and accounts for almost 20% of the country's GDP (Qureshi 2011a).

However, Pakistan's water resources are under immense pressure due to the rapidly growing population. An increase in population means that there is a requirement of more food, but no new resources of water are there for its production. The water shortage is identified as the most challenging task by the Government of Pakistan because the water required for agriculture is vital for the growth of agriculture sector and consequently for the poverty reduction (Syed et al. 2021).

Due to the deficiency in the surface water supplies, farmers are meeting their needs through over exploitation of ground water which is unregulated in Pakistan. The simultaneous use of both ground water and surface water is taking place on almost 70% of the irrigated lands (Qureshi et al. 2004). However, poor quality of groundwater has resulted in the salinization which is a significant threat to the sustainable irrigated agriculture in Pakistan. Today, Pakistan is one of those countries which are worst affected by salinity (Briscoe J 2006). Successful conjunctive management of both groundwater and surface water is essential for the successful irrigation in Pakistan (Qureshi and Mccornick 2010). With the passage of time, contract farming in Pakistan is increasing rapidly resulting in more advanced and commercial farmers, food grains are being displaced by high-value crops and more people are being attracted to agriculture because of increasing prices of agriculture commodities. A paradigm shift in the water management strategies and water-resource development is required as a solution.

Irrigation is the leading user of both the groundwater and surface water in Pakistan and is expected to do so in future. With the passage of time, as the population and the economy of the country grow, the management and distribution of the water resources will be a more serious concern. Currently, the water usage for the industrial and municipal supplies in the urban sector is about 5.3 km^3 which is expected to increase to 14 km^3 by 2025 (Condon et al. 2014). The irrigation sector will therefore face a tough competition from the industrial and municipal sectors for the use of water. The current per-capita water availability of 1090 m^3 will be decreased considerably by the year 2025, which would mean that the shortfall in the water requirement will be around 32% that will result in a 70 million tons of food shortage in Pakistan (USAID 2009). In order to cover the large areas in the canal commands, the Indus Basin was designed to provide low intensity irrigation. However, the increased cropping intensities and the demand for more water has put more pressure on the surface irrigation systems (Bhutta and Smedema 2007). The over exploitation of groundwater and reduction the surface water supplies are having a serious effect on the agriculture sector in Pakistan which accounts for almost 20% of the country's GDP and is consequently affecting the food security of the people living in Pakistan.

Pakistan's water disputes with Afghanistan and India are always focused and given more preference, but in an already fragile nation like Pakistan, it is the intrastate or inter-provincial water disputes which are a threat to environmental, domestic and political security in an already weak nation. Intrastate or inter-provincial water disputes can cause more violence and damage than intrastate or international conflicts. Mostly, the level of attention gained by the international water disputes is much more than the intrastate water disputes (Mustafa et al. 2013). The growing demand supply gap as a result of climate change and the growing population is making the water resource as a source of conflict between the provinces and among the communities. Pakistan, being an agriculture dominated country, having deep regional and ethnic fissures which have led to the disputes amongst the four provinces (Ranjan 2012). The management of both surface water and ground water is very important for the future of Pakistan. There exist various opportunities for an improved management of water in Pakistan. The supply-demand gap is increasing and is creating unrest among the provinces of Pakistan. The increase in droughts specially in Sindh have made the problems worst. Therefore, there is an urgent need of water conservation measures, new water reservoirs and better management and allocation of water resources. This chapter presents an in-depth review of water resource situation on Pakistan, the challenges confronted by the water sector and likely remedial measures to overcome these issues and ensure sustainable irrigated agriculture in Pakistan's Indus Basin.

3.2 Features of the Indus Basin

About 566,000 square kilometers (km^2) of the area, which is about 70 percent of the country is drained by the Indus Basin. It spreads over parts of four provinces namely Punjab, Sindh Baluchistan and Khyber Pakhtunkhwa (KPK) (Yu et al. 2013). As shown in Figure 2.1, the Basin is fed by the eastern rivers (Rave and Sutlej) and western river (Jhelum, Chenab and Kabul). The total length of the basin is about 2,900 km and an altitude of 18,000ft from the top of Himalayas to the low-lying areas of Sindh, where it flows into the Arabian Sea.

The Indus Basin has the largest contiguous irrigation system in the world. About 150,000 km^2 of the cropland, out of 190,000 km^2 are irrigated by the Indus Basin

Irrigation System (Ahmad 2005a). The Indus Basin is the home to seventh largest mangrove system and the fifth largest delta in the world. The deterioration of delta's ecosystem in the recent years has occurred due to the lack of sustained minimum river flows. The average precipitation in the basin is around 230 millimeters per year, which is very low. Sub-tropical climate exists in the basin with transpiration rates of 2,112 millimeters per year (Ullah, M. Kaleem, Zaigham Habib 2001). Most of the flow of Indus River (around 40-70 percent) is from glacier melt and snow off the Himalayas. Most of the flow (about 85 Percent) in the Basin's catchment occur from the months of May to September (National Research Council. 2012). The Indus Basin in Pakistan has a mean annual flow of 176 billion cubic meter of which almost 90 percent is supplied for the irrigation purposes. Despite this, there are high variations in demand and supply: for example, during the droughts of 2000-2002 the difference between supply and demand was 20 percent (Briscoe, J. 2006). Due to the factors such as urbanization and high population growth aggravated by evapotranspiration, canal and water course seepage, field application losses and field level irrigation inefficiency, the future deficits would be around 20 percent by 2025 (Briscoe, J. 2006).

The underlying unconfined aquifer in the Indus Basin covers 0.16 million square kilometers of the surface area. A total of 63 billion cubic meter is considered as the safe groundwater yield for the aquifer, whereas the extractions from the industrial, domestic and agriculture sector is 52 billion cubic meters. However, the increase in salinity due to the decline in the groundwater levels and redistribution of the salts in the aquifer, further exploitation of the groundwater is very limited. In Pakistan, the concept of uncertain and low crop yields has been transformed into more assured crop production due to the availability of groundwater. Due the on-demand groundwater availability in this Indus Basin, the crop yields have increased which has resulted in the improved rural livelihoods and increased food security. This growth has led to various other problems like degradation of groundwater quality, falling water tables and groundwater overdraft (Qureshi and Mccornick 2010).

3.3 Water Management Challenges in Pakistan's Indus Basin

3.3.1 Availability, Variability and Future Water Demand in Pakistan

Pakistan's population is increasing at the rate of 2.8% and by 2025, it is expected to reach 250 million. The percentage increase in urban population will be from 35 to 52% by 2025. Due to this increase in population, the water demand for industrial, domestic and non- agricultural uses will increase by 8% (Bhutta and Smedema 2007). In 1951, Pakistan had a per-capita water availability of 5000 cubic meter in 1951 which fell to 11,00 cubic meter per capita in 2005 and by 2025, it is expected to fall to 800 cubic meter (W. W. F. Pakistan 2007). The United Nations estimates that the Pakistan's water demand is increasing at the rate of ten percent every year (UNESCO 2015). The estimates suggest that water demand will increase to 338 km^3 by 2025 but the total water available will not be changed from 240-258 km^3 (Akhtar 2010).

The total current water withdrawals in Pakistan are175 Cubic Kilometer. Out of this, almost 29% of the withdrawals (about 50.75 km^3) are from groundwater and about 71% (124.25 km^3) are from the surface water. Out of the overall surface water available, 74% is extracted, while 83 % of the total available groundwater is extracted, which is extremely high (Laghari et al. 2012). The demand-supply gap is also increasing due to increase in the population (Figure 3.1) and since there is no proper mechanism for water allocation, the disputes between the provinces is also increasing (Bakhsh et al. 2011).

3.3.2 Vulnerability due to Climate Change

The effect of climate change on the water supply in the Indus Basin is still uncertain. There are many uncertainties associated with respect to the local impacts of glacial melt, snowmelt, glacial retreat and precipitation patterns (National Research Council 2012). Glacial melt and snow from the Himalayas contribute about

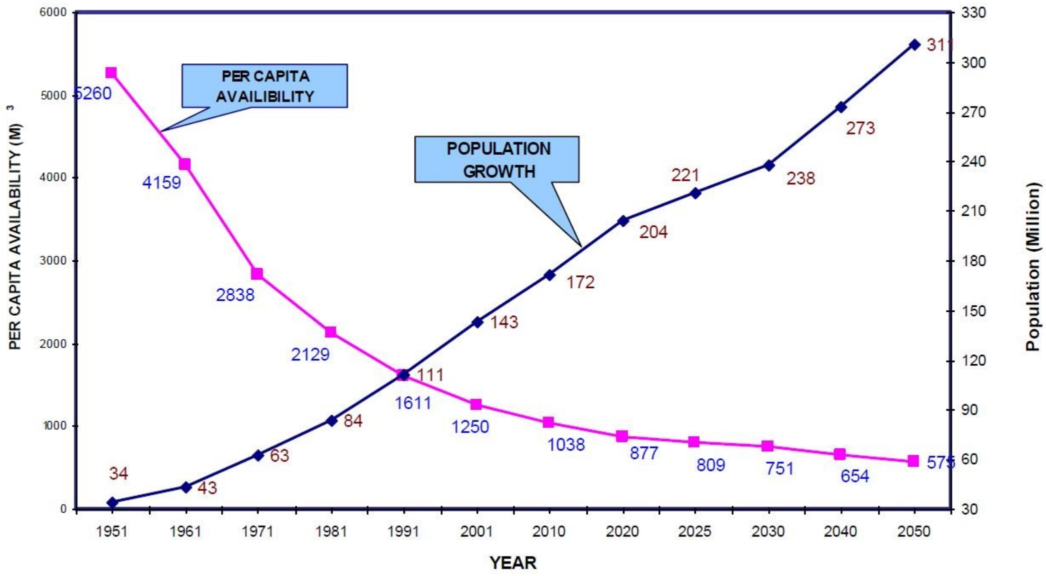

FIGURE 3.1: Water availability per Capita.

45 percent of the flow to the basin which suggests that the vulnerability to climate change and glacial melt is very high. The Hindu Kush Himalaya (HKH) range is stretched 2000 km across the Asian continent, spanning Pakistan, Nepal, India, China, Bhutan and Bangladesh. This region comprises of large rivers which include Indus, Brahmaputra and Ganges. These rivers provide water source to almost one billion people in these regions. According to the latest research, the rate of glacial retreat in the local glaciers can be compared to those in the other parts of the world, confirming that the glacial retreat has accelerated in the past century (National Research Council 2012).

Some recent estimate indicates that in the coming years, the glacial melt due to the rise in temperature will increase which will cause a 40 percent surge in the flow. However, the average flows of the Indus River in the long run would be lowered by almost 60 percent (Briscoe J 2006). Although, with the climate warming, the evapotranspiration rates across the irrigated Indus Basin are likely to increase which will result in increased irrigation water demands resulting in more competition of surface and groundwater among the provinces (National Research Council 2012).

Almost 85 percent of the annual discharge in the Indus Basin occurs between the months of May and September from monsoon rainfall, glacier and snowmelt.

During the next decade or two, some large changes due to hydrological system could be there due to the change in intensity, location and timing of the monsoon activity (National Research Council 2012). The flooding of 2010 in Pakistan is an example of this change in hydrological system (Lau and Kim 2011). No role was played by the glacial melting in this case.

3.3.3 Groundwater Overdraft

In Pakistan, the surface water has always been a main focus related to subnational hydro-politics but the groundwater in the Indus Basin and the problems related to it such as groundwater overdraft, salinity and water logging are expected to have more serious effects on the efficiency of agriculture, water use and hence the hydro-politics in the long run. Due to the surface water scarcity, the farmers have taken this problem in their own hands during the past three decades by abstracting more groundwater. According to survey, 0.8 million water pumps are operating in Pakistan, most of them in Punjab and almost 50% of the agricultural water requirements are met by them (Qureshi et al. 2008).

Due to the increasing number of water pumps and over extraction of Groundwater, almost 4.5 million hectares of land has become salinized, half of which lies in the irrigated lands of Indus Basin. Due to inappropriate practices of irrigation and water logging from the canal seepage, nearly 1 million hectares of the irrigated land is also affected. In Sindh, the problem of salinity is more serious. The remedies and measures taken to counter the problems water logging and salinity have been proved futile and the degradation of land is having a damaging effect on the agricultural productivity of Pakistan (Qureshi et al. 2008). In view of the above-mentioned groundwater problems, the surface water conflict between the two large provinces, that is, Sindh and Punjab also arise. The land degradation and salinity in the province of Sindh is more as compared to other provinces, therefore, according to Sindh, its requirement for surface water supplies are much more obvious. In both the canal command areas of Sindh and Punjab, there is a severe decline in the water table due to the overexploitation of groundwater (Bhutta and Smedema 2007).

3.3.4 Lack of Storage Capacity

Pakistan has a very less storage capacity relative to other arid countries which is only 15 percent of the annual river flow. Pakistan has a per capita water storage capacity of only 150 m^3 which is very less considering that United States and Australia have storage capacity of above 5000 m^3 and China has 2200 m^3. In Pakistan, the river flows are highly uneven all around the year, therefore the agricultural requirements depend on storage capacity. However, Pakistan has a storage capacity for only 30 days. If we compare this capacity with the other countries, it is considered extremely low given that Egypt has the storage capacity of about 700 days, United States has the storage capacity of about 900 days and India has the storage capacity of about 120 to 220 days (Monheit 2011).

Currently, Pakistan has only two major reservoirs, Tarbela and Mangla, which are plagued with siltation problem. Due to the sediment deposition, both the reservoirs have lost between thirty-two and twenty percent of their storage capacity, respectively (Sattar, Robison, and McCool 2017. Agriculture was also recognized as the center of long-term development plan of Pakistan according to the Lieftinck Report of 1968. In the report, insufficient irrigation development was the main cause of the limiting growth of agriculture sector between 1950 and 1960. In this report, it was concluded that in order to meet the increasing demands for agriculture, at least one reservoir, of the size of Tarbela should be constructed after every ten years. The report also stated that a yield of a million-acre feet would be created by million acre-feet of storage available for agriculture. The storage yield curve (Figure 3.2) also shows that the Indus River has significant storage potential remaining. It was also stated that due to high silt load of rivers, the storage capacity of existing reservoirs would decrease (Hassan 2016).

Another reason was also put forward by the Lieftinck Report for the construction of new storage reservoirs which was hydropower potential of the Indus River. The report also calculated that in order to meet the growth targets, the electricity production in Pakistan should increase by 13 percent every year. Cheap, clean and abundant hydro power was expected to be generated from large dams, if they were built according to the proposed schedule (Lieftinck et al. 1968).

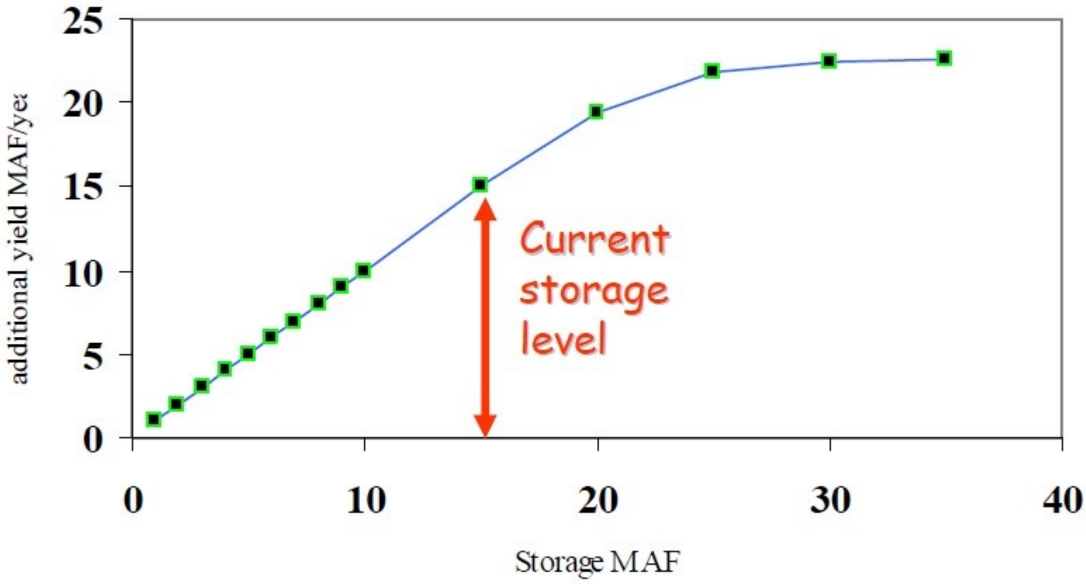

FIGURE 3.2: Additional storage yield curve for River Indus (Briscoe, J. 2006).

3.3.5 Lack of Environmental Flows

The writing of Water Apportionment Accord in 1991 recognized the need of environmental flows in the Indus Basin for the first time. Amount necessary for the environment was not agreed by the provinces at that time and further studies were planned to determine the environmental flows. It was decided in the report by the international experts in 2005 that in order to maintain the necessary sustainable flows which were required to sustain the coastal fisheries, prevent salinity accumulation and to check the sea water intrusion, a flow of 5000 cubic feet per second is necessary from the Kotri Barrage to the sea (González et al. 2005). Due to the extensive Indus Basin Irrigation System canal network which diverted most of the water of Indus River for irrigation, the sediment supply to the delta was also reduced considerably. Therefore, in order to meet the sediment demands, it was decided for a cumulative flow of 30 cubic kilometre in a five year period (González et al. 2005).

Despite the recognition of environmental flows by the Water Apportionment Accord of 1991, these flows are not allocated separately. Although while making the calculations for the allocation to provinces in each 10-day period, these environmental flows are included but they are the first ones to be compromised whenever the system's supply is insufficient. With the increasing claim of provinces in the water allocations, the federal government must take a strong stance to make the environmental flows necessary which will be very beneficial for the long-term sustainability of the basin.

3.3.6 Transboundary Water Issues (International)

The Indus Basin Treaty was signed between Pakistan and India in 1960 which entitled the three eastern rivers (Beas, Sutlej and Ravi) to India and the use of three western rivers (Indus, Chenab and Jhelum) was exclusively given to Pakistan. The construction of dams, link canals and barrages on the Indus River and its two tributaries was also a part of this treaty. Being the largest contiguous irrigation system in the world, the IRBS consists of 4 storage reservoirs (Tarbela, Chashma, Mangla and Warsak), 16 barrages, 12 inter-river link canals, 2 siphons, 44 command canals (23 in Punjab, 14 in Sindh, 5 in Khyber Pakhtunkhwa, and 2 in Baluchistan), 59,000-km-long irrigation canals, and 107,000-km long watercourses. The last few years have witnessed serious differences between Pakistan and India over the water sharing. The construction of series of dams on the rivers by India has created serious concerns for Pakistan. These issues need to be resolved to avoid any damage to the irrigated agriculture in Pakistan (Qureshi 2011a).

Apart from the rivers flowing from India, the Kabul River from Afghanistan is also a major contributor to the flows of River Indus. It contributes twenty-five billion cubic meter to the River Indus annually (IUCN. 2011). Afghanistan's short-term water usage are around ten billion cubic meters. Much of the water contribution form the Kabul River can be lost once Afghanistan begins to establish water storage projects on the River Kabul. In order to make mew dams, the feasibility studies are already being conducted by Afghanistan. It is important that Pakistan should reach an agreement with Afghanistan regarding the sharing of water before the disputes become more serious (Qureshi et al. 2010a).

3.3.7 Transboundary Water Issues (National)

In order to resolve the chronic issue of the water disputes between the provinces, the then (1990) government of Pakistan took a positive step in the form of Water Apportionment Accord. The Water Apportionment Accord 1991 was signed by all the four provinces of Pakistan but serious differences between the provinces arose shortly after the signing of the accord, specially between Punjab and Sindh and between Sindh and Baluchistan. The Indus River System Authority (IRSA), an independent body was established according to the provisions of the Water Accord by an act of parliament in 1991. The member board of Indus River System Authority (IRSA) comprised of five members, one from the federal government and one from each province. The chairman was to be from selected 5 members in alphabetical order for period of one year in rotation. The term of the office of members is 3 years. Implementation of the Accord is the main function of IRSA. Share of the available water supplies for each season is determined by IRSA for each province. These supplies are released by Water and Power Development Authority (WAPDA) from the reservoirs accordingly (Bhatti and Farooq 2014).

The operation of IRSA was smooth and satisfactory for about a decade, but due to the sedimentation problem in Mangla and Tarbela and drought conditions, the water fell short of the requirements. Severe criticism was faced by IRSA, as it failed to satisfy all the provinces due to the shortage of water. The provinces, mainly Sindh and Baluchistan objected to the Accord and with this the Sub-national hydro-politics also came into play. The Indus Water Accord 1991 also became controversial as Punjab was blamed by the then Sindh government for not releasing its agreed quantity of Water. The Baluchistan government also alleged Sindh for not releasing water to Baluchistan (Kanwal 2014).

The reservoirs of Mangla and Tarbela were the main causes of dispute among the provincial governments of KPK, Punjab and Sindh provinces. The irrigation water for the agriculture is mainly used by these three provinces. Sindh Government accused Punjab for stealing its share of water from these reservoirs. Punjab's provincial government was of the view that in order to accommodate the provincial governments of the KPK and Sindh, it has been using less water than its requirements. Table 3.1 shows the water distribution for the four provinces of Pakistan as per the Indus Water Accord of 1991.

3.4 Limitations of the Inter-Provincial Water Accord

A minimum flow of water was allowed by the Indus Water Accord into the sea and the remaining water was shared among the provinces. An erratic flow was ensured by the accord. The accord made sure that all provinces lost from the shortages or gained from the surpluses. The share of water for the provinces were: a) Punjab 69.03 km^3; b) Sindh 60.17 km^3; c) NWFP 7.13 km^3; and d) Baluchistan 4.78 km^3. The future storages and flood waters were to be distributed as: a) Punjab and Sindh each of 37%; b) NWFP 14%; and c) Baluchistan 12%. 141.11 km^3 was the total surface water which was distributed among the provinces. (+3.70 km^3 above the Rim Stations).

Until 1999, the distribution of water was done on the ad-hoc basis. As ample amount of water was available, therefore, there was no controversy over the distribution of water and all four provinces received their shares as defined in the Water Apportionment Accord of 1991. However, the declining availability of water after 1999 led to the implementation of ministerial decision that led to the water allocation as per historical uses of 1977-82 (Condon et al. 2014). The proportional sharing of the shortages and surpluses among the provinces is accounted for by the accord. However, the two small provinces, Baluchistan and Khyber Pakhtunkhwa (KPK) were exempted by the water shortages by an act of 2003. Thus, whenever the total volume falls, the deficiencies are shared by Sindh and Punjab (Condon et al. 2014). Therefore, there is no proper mechanism of water distribution when the total volume falls short or when the demands of the provinces exceed the total available water. Also, Khyber Pakhtunkhwa (KPK) and Baluchistan have not yet developed their irrigation system properly, therefore, they always get more water than they can use. The flows of the western rivers vary from 112.5 to 231.6 km^3 annually during 1937-2007. The mean annual river flows at 50% probability came out to be 168 km^3. When the river flows are less than allocated water based on canal diversions as given in the Accord of 141.11 km^3 by about 17% of probability of exceedance, it creates disputes amongst the provinces (Iucn 2010).

3.4.1 Problem of Improper Distribution and Non-Utilization

Out of the total water available in the country, only 3% is used in domestic and industry, therefore, the main problem of water sharing is in environmental and agricultural areas. The main problems of the water conflict lie between the province of Sindh (lower riparian) and Punjab (upper riparian) and between Sindh (upper riparian) and Baluchistan (lower riparian). Punjab has its certain grievances regarding the water sharing, which are as follows (Hassan 2016).

Punjab has more than double cropped areas as compared to Sindh, but the water allocation of Punjab is only slightly higher than Sindh (Table 3.1). Almost 66 % of the total wheat, 73% of the total cotton, and 68% of the total rice in Pakistan is produced in Punjab, while Sindh produces 17% of wheat, 27% of cotton and 26% of rice. So, the crop productivity of Punjab is higher than that of Sindh. On the other hand, Baluchistan also accuses Sindh of stealing its water which it is not able to utilize. The Baluchistan government had filed a case against the Sindh government for payment of Pakistani Rupees (PKR) 7 billion. The Baluchistan government was of the view that Sindh had used its share of water which it could not utilize because of the lack of carrying capacity (Laghari et al. 2012).

3.4.1.1 Water Sharing and Distribution in Islam

Ensuring equity and social justice is the cornerstone of Islam. The Prophet Muhammad (pbuh) also set an example of equity in this regard. There are also various examples of equity in hadith. As per Islam, a Muslim cannot hoard excess water. The recognition of water as a vital resource, of which everyone has the right to a fair share, is emphasized by the following hadith, which effectively makes water a community resource to which all, rich or poor, have a right: “Muslims have common share in three things: grass (pasture), water and fire (fuel)”. On the Prophet's advice, one of his companions, Usman (RA), who later became the third Muslim caliph, bought the well of Ruma (a settlement in Arabia) and made its water available free to the Muslim community – the well was actually made into a waqf, a collective property for religious purposes and public utility.

3.5 Recommendations

The IRBS is encountered by several problems which include improper management of groundwater, increasing water logging and salinity, seepage from unlined canals, poor irrigation practices, improper water distribution, transboundary water issues (national and international) and insufficient surface water supplies. Studies suggest that forty percent additional food would be required by 2025 to feed the increasing population. The ecological and environmental threats along with the decreased investments in the water sector can further aggravate the problem of water management in Pakistan. Development of the new storage reservoirs, development of new water sharing mechanisms among the provinces, improvement of existing irrigation structures and removal of mistrust among the provinces of Pakistan are some of the ways forward. To boost the sustainability and productivity of the irrigation system in Pakistan and to avoid the conflicts among the provinces, the following potential solutions are suggested.

3.5.1 Improvement of Water Infrastructure and Development of New Storage Reservoirs

Pakistan has invested heavily on the water infrastructure and is extraordinarily dependent on it. Much of the irrigation infrastructure in Pakistan is in decay due to negligence and mismanagement. No fund allocation or asset management plan is there for the existing irrigation infrastructure. The funds allocated by the government for the irrigation infrastructure are very less. More fund allocation and investments are needed in irrigation sector to ensure the food security for more than 20 million people of Pakistan. A policy should be formulated by the federal government for the development of the hydropower and water storage projects on urgent basis. No major water project could have been started in Pakistan since the construction of Tarbela 1976 as a result famine conditions have resulted, particularly in Sindh. The major reservoirs should be constructed by developing the consensus among all the provinces.

Pakistan is dependent on the import of expensive oil to generate electricity despite its access to hydropower. Oil purchase are a huge strain on the economy as they raise external current account deficit and aggravate the countries balance of payment options (Trimble et al. 2011). Construction of hydropower dams would not only help in flood control and irrigation storage, but it would also lessen the burden of importing oil which puts a considerable strain on our economy.

3.5.2 Developing Mathematical Models for the Water Allocation Among the Provinces

A serious problem with the Water Apportionment Accord is that the water allocations are fixed, which creates a quantified entitlement. Fixed water allocation mechanisms can lead to water allocations that are unacceptable for the provinces, especially under uncertainty, droughts and the stochastic nature of river flows. The Water Apportionment Accord between the provinces of Pakistan was signed almost 28 years ago. Since then, the water demands of the provinces have changed due to the increase in the population and the irrigated area. Therefore, in Pakistan, the gap between the water supply and water demand has considerably increased. As the provincial water entitlements stated in the water apportionment are fixed, mathematical models (Bankruptcy Methods and Nash Bargaining Solution) are needed for the water allocation among the provinces of Pakistan in order to cope up with the changing supply and demand.

3.5.3 Addressing Inequitable Distribution and Inefficient Water Use

Inefficient use and inequitable distribution of water leads to wastage and socio-political disorder respectively. This is particularly relevant in the case of irrigation sector and provincial water distribution where unjust distribution creates a feeling of dissatisfaction and deprivation in particular segments of society and leads to inefficient use of water. Pakistan one of the lowest agricultural productivity in the world. For wheat, agricultural productivity is 1 kg/m^3 in India and 1.5 kg/m^3 in California whereas is it is only 0.5 kg/m^3 in Pakistan. Pakistan has an enormous potential of increasing the crop water productivity and improving low system efficiency which will bring more income and jobs - per drop of water.

Equitable distribution of water should be ensured among all water users to overcome this problem. The farmers should be educated and encouraged to use efficient technology for the irrigation like sprinkler and drip irrigation, which would help to save large amount of water. Out of all the modern irrigation technologies which are available at present, Drip Irrigation the most efficient. The water can be conserved, and yield can be expanded for the farmers with the help of this technology, specifically for those who are cultivating their crops in the semi-arid regions. It has exceptionally attractive characteristics among all the alternatives considered by the experts and policy makers to address the issue of water availability. Water use efficiency is greatly increased by this method (when compared with the conventional irrigation methods the yield increase is from 20 to 100 % while the water savings range from 40 to 70%). Introduction of other water conservation technologies such as bed and furrow planting, precision land levelling, zero tillage (ZT) can also help in improving water productivity.

3.5.4 Ensuring Controlled Pumpage of Groundwater

In order to ensure a sustained supply of water in the areas where the water level is going down due to increased and unchecked pumping of groundwater, controlled pumpage is essential. There is no particular check or regulation for the installation of tube wells or the groundwater extraction at present. The over-extraction of groundwater has resulted in the scarcity of water in the certain areas of Punjab. The groundwater consumers with better technology are going deeper for the extraction of groundwater but with depleting groundwater, it will not be possible in the future to get further water even with the powerful pumps. In order to maintain a certain level of groundwater, restrictions need be imposed on the pumping of groundwater to allow the groundwater recharge. Also, instead of individual water extraction, community-based water supply should be encouraged to conserve fast depleting groundwater resources.

3.5.5 Mass Public Awareness about Water Management

It is essential that the people should be taken along with the campaigns at the government level. In general, radio and television are the most effective instruments for comparatively less educated people and print media should focus on the educated segments of the society. One aspect of the issue is the motivation and awareness at the national level and the other segment of the campaign is also very important which pertains to making the people realize through their payment/ contribution for the services which they utilize. The people generally become careful when they know that whatever they are consuming requires payment, may it be very small amount. The severity of the issue is sometimes not conveyed through free services and mere motivation is not enough.

3.5.6 Improve Water Availability Predictions and Establish Independent Monitoring

The federal water agencies of the country, WAPDA and IRSA should work along with the provincial departments of the country to set up a modern, reliable and independent methodology of water prediction. Some large multi-state basins around the world should be consulted and the technology best suited for the Indus River should be adopted along with the investment in existing infrastructure. Along with the improvement in the water availability prediction, a reliable method of flow monitoring should be implemented by the federal government through audit of conveyance losses. The provincial irrigation departments should be involved and asked where the conveyance losses have increased, and compensation should be made to those who have suffered from these losses. To achieve this, an appropriate compensatory mechanism should also be implemented.

3.5.7 Marketing of Unutilized Water Share

Presently, the smaller provinces, KPK and Baluchistan are not able to utilize their share of water. As per functional decision of IRSA, their unutilized share is used by the provinces of Sindh and Punjab. The provinces of Baluchistan and KPK have sought compensation from Sindh and Punjab on several occasions for using their unutilized share.

The functional decision of IRSA to exempt these provinces from sharing of shortages means that their "unused" water is used by the larger provinces of Punjab and Sindh. In the past, the Baluchistan, for example, is presently not able to fully exploit its allocated water share, therefore as stated in the Water Apportionment Accord of 1991, the provinces should be allowed to market their unutilized water share to the other provinces.

3.5.8 Rationalize Cropping Patterns

The misuse and overuse of groundwater water in the past was the main reason of the survival of Pakistan's agricultural economy as unmanaged groundwater was used by the millions of farmers. This era of the misuse and overuse of groundwater is mow coming to an end as the water table is now falling in many areas. A policy should be formulated to develop a balance between water withdrawals and groundwater recharge. There is a need to develop appropriated policy to replace water intensive crops such as sugarcane and rice with high-value crops like pulses, vegetables, sunflower which can also increase farm incomes. Pakistan is currently importing US $1 billion worth of edible oil (Qureshi and Mccornick 2010). Restricting the rice and sugarcane production to domestic needs could reduce a considerable pressure on both the surface and groundwater.

3.5.9 Separate Allocation for Environmental Flows

Pakistan's agriculture primarily relies on the Indus River and in the long term, the cost of neglecting the environmental flows will be very high. These environmental flows must be allocated separately and should be a part of Pakistan's national water strategy. With the construction of new dams, there is an opportunity to recognize the environmental flows, revise the allocations and make separate allocation for them. It must be recognized that the window of opportunity for allocating and recognizing these flows will be very narrow as with the passage of time, the provinces will also claim their increase in shares. The federal government must take a strong stance to recognize and prioritize the environmental flows for the long-term benefit of the Indus Basin.

Chapter 4

Use of Bankruptcy Methods for Resolving Inter-Provincial Water Conflicts Over Transboundary River: Case Study of Indus River in Pakistan

4.1 Introduction

Chapter 3 gave several recommendations which are necessary for sustainable water management in Pakistan. Out of this, improper water distribution of water, increase in future water demands, variability due to change in climate and lack of environmental flows and were stated as the most important ones. Chapter 4, 5 and 6 addresses these problems and proposes mathematical models for water allocation. Several political disputes have been caused throughout the world due to the non-equitable distribution of water resources, the increasing consumption of resources and the scarcity of water resources (Homer-Dixon 1994). There are a total of 276 transboundary river basins that are shared among 148 countries (De Stefano et al. 2012). During the past 50 years, forty-three political or military acts related to shared water resources have taken place around the world (Wolf

2007). Due to factors such as climate change, growing crop production, increasing populations, and soil degradation, freshwater has become a source of conflict among riparian states. Hence, one of the key tasks in transboundary river management concerns how we can apportion the limited and shared available water amongst riparian states when it is not adequate to satisfy the claims of all riparian states. Therefore, "reasonable" and "equitable" water resource reallocation faces the question of which standards and mechanisms should be considered for this "reasonable" and "equitable" reallocation (Mianabadi et al. 2012). A variety of climatic, socioeconomic, environmental, geographical, historical and political factors and conditions can affect water resources and, consequently, different types of water conflicts (Priscoli and Wolf 2009). In one category, there are two different approaches to addressing water conflicts: first, conflicts over international water resources (Yoffe et al. 2003) such as aquifers, lakes, and rivers that are shared between two or more countries; second, conflicts over internal water resources shared between states, provinces, cities, or different groups within a specific country (Toset et al. 2000). Two different types of water conflicts are there in another category: conflicts over the availability of water (Ping and Ping 2010) and conflicts over the quality (Perry and Vanderklein 2009) of water resources. In terms of the seriousness and intensity, these conflicts can have different degrees. The complication of water conflicts calls for precise investigations so that these conflicts can be resolved efficiently. Shared water can be a cause of both cooperation and conflict among riparians. The main problem arises when the total demand of riparian countries or provinces is more than the total available water. In quantitative conflict resolution, the equitable distribution of water among riparian is a complex process at both the national and international scales (Jarkeh et al. 2016).

To manage conflicts and allocate resources, the bankruptcy method is widely used. This method is applicable when the total claims exceed the total resources or assets. Bankruptcy theory has been applied to problems related to the allocation of resources. Grundel et al. (2013) used this method for multipurpose resource allocation situations. Ansink and Marchiori (2015) used it for water resource management. In addition, Beard (2011) provided a detailed review of the connection between river sharing and the bankruptcy literature. The frequent application of the bankruptcy method reveals that it is a popular tool for resolving conflicts and for achieving agreement on water resource allocation problems. Bankruptcy theory can be used in resource allocation and dispute resolution when the total available resources are less than the total demand or claims of riparian (agent) countries or provinces (Ansink and Marchiori 2015). Auman and Maschler (1985) and O'Neill (1982) introduced bankruptcy theory, and it was later studied by various researchers e.g. by Alcalde et al. (2014), Hendrickx et al. (2005), Lorenzo-Freire et al. (2010), and Thomson (2012). Bankruptcy theory has also been used by several researchers for water allocation among riparian (agent) countries e.g. by Mianabadi and Sheikhmohammady (2014), Mianabadi et al. (2015), Madani et al. (2014) and Li et al. (2018). Bozorg-Haddad et al. (2018) used bankruptcy theory for water allocation in Iran. Degefu et al. (2018) applied the cooperative game theory allocation by combining the Nash bargaining theory and bankruptcy games for the water allocation among Syria, Iraq and Turkey. In this research, the Shapely value and two new water allocation rules are proposed along with the bankruptcy rules. These new rules are (i) the groundwater-based rule and (ii) the proposed rule. In the first rule, two factors are considered: the rate of groundwater usage and the rate of claims. In this rule, the deficit is divided not only with respect to the claims but also according to the claimants' groundwater usage. It is assumed that agents who claim less water and use less groundwater will have a lower deficit. In the second rule, water is allocated according to the "land lost or affected by salinity in each province" and the "amount of GDP generated by each province". In this rule, the total deficit is shared in inverse proportion to the land of provinces affected by salinity and in direct proportion to the amount of GDP generated by them. These rules are proposed because bankruptcy rules distribute water only according to the claims of riparian (agent). They do not take into consideration other factors that are mentioned in these two proposed rules.

Another reason for proposing these rules is that the water deficit in any river basin that is facing a water shortage should be distributed and measured in a way that reduces the asymmetries that exist between riparian provinces or countries in terms of their groundwater usage, their gross domestic product (GDP) and their area of land affected by salinity. Hence, these two allocation rules reduce the asymmetries between riparian by considering these factors. Due to the different definitions of fairness, there is no documented method for determining the most appropriate rule. In this chapter, we introduce a new methodology for selecting the best rule. Five classical bankruptcy rules, the Shapely Value and the two proposed rules are applied to allocate water among the four provinces of Pakistan, and then, this new proposed method is applied for the "selection of the best rule".

4.2 Current Water Distribution Mechanism in Pakistan and its Shortcomings

The Islamic Republic of Pakistan is home to the sixth largest population in the world. There are four administrative units in the country or four provinces, namely, Punjab, Sindh, Baluchistan and Khyber Pakhtunkhwa. It also consists of small areas of Federally Administered Tribal Areas (FATA) and Gilgit-Baltistan. The principal natural resources of Pakistan are water and arable land, and agriculture significantly contributes to the country's economy. It accounts for almost 19.8 percent of the country's gross domestic product (GDP) (Anwar and Bhatti 2017). Of the 27 percent of cultivated land in Pakistan, Punjab has the highest proportion (63 percent), followed by Sindh (18 percent), and the remainder is equally divided between the provinces of Baluchistan and Khyber Pakhtunkhwa (ACO (Agricultural Census Organization) 2010); (Priscoli and Wolf 2009).

The interprovincial water sharing of surface waters in Pakistan is currently governed by the Water Apportionment Accord of 1991. The main aim of the Accord was to build trust among the provinces of Pakistan. Unfortunately, this accord does not adapt to changing conditions over time; hence, it can be considered "a glass that is half empty and half full". The current water distributions among the provinces of Pakistan according to the Water Apportionment Accord are given in Table 4.1. The Indus River System Authority (IRSA) is responsible for the distribution of water among the provinces. The main shortcomings of the Water Apportionment Accord of 1991 are highlighted below.

The average canal diversions in the post-Tarbela periods have been only 127 km^3, which is less than the Accord's entitlements of 144.87 km^3, as shown in Table 4.1. This creates problems among the provinces of Pakistan when they have to

Table 4.1: Surface water allocation among Provinces.
(Source: Indus Water Accord 1991)

Province	**Water Share (km^3)**	**Supply Shares* in %**
Punjab	69.03	37
Sindh**	60.17	37
Baluchistan	4.78	12
KPK	7.13	14
Ungauged Canals***	3.70	
Total	144.87	100

*Including future storage and flood flows

**Including already sanctioned urban and industrial uses for Karachi

***Ungauged civil canals above rim stations in KPK

share shortages, as there is no defined mechanism for sharing water shortages (Condon et al. 2014). Currently, the two smallest provinces by their irrigated areas, Baluchistan and Khyber Pakhtunkhwa (KPK), are exempted from water shortages by an act passed in 2003. Thus, whenever the total volume falls, the deficits are shared by Sindh and Punjab (Condon et al. 2014). Therefore, there is no proper mechanism for water distribution when the total volume falls short or when the demands of the provinces exceed the total available water. Additionally, Khyber Pakhtunkhwa (KPK) and Baluchistan have not yet properly developed their irrigation systems; therefore, they always obtain more water than they can use.

Another serious problem with the Water Apportionment Accord is that the water allocations are fixed, which creates a quantified entitlement. Fixed water allocation mechanisms can lead to water allocations that are unacceptable for the provinces, especially under uncertainty, droughts and the stochastic nature of river flows. The Water Apportionment Accord between the provinces of Pakistan was signed almost twenty-eight years ago. Since then, the water demands of the provinces have changed due to the increase in the population and the irrigated area. Therefore, in Pakistan, the gap between the water supply and water demand has considerably increased. Several features and attributes of the Indus River disputes are described below:

4.2.1 Surface Water Diversions

The Indus River, which is composed of six major tributaries, namely, the Indus, Chenab, Jhelum, Ravi, Beas, and Sutlej tributaries, is a major source of water supply for Pakistan. The water of the Indus River is shared among all four provinces of Pakistan. River flows are mainly supplied by rainfall, snowmelt, glacier melt and runoff. According to the Indus River System Authority, the median canal diversions from 1975 to 2013 were 125.61 km^3.

4.2.2 Groundwater Availability

The total groundwater potential in Pakistan is approximately 68 km^3, of which 60.5 km^3 is extracted. Punjab extracts 54 km^3 of groundwater, Sindh 3.1 km^3, KPK 2.5 km^3 and Baluchistan 1.2 km^3 (Ghazanfar 2009).

4.2.3 Agricultural Water Requirements for Pakistan

The water requirements (in ft) for various crops were taken from the Planning Commission Report (Commission 2012), whereas the cropped area was taken from the Agricultural Statistics of Pakistan (Government of Pakistan 2011).

The total agricultural water requirements or demands for Pakistan for 2002-2003 were estimated to be 109.7 km^3. Punjab had the highest irrigation water requirements, 78.4 km^3, followed by Sindh (20.1 km^3), KPK (6.2 km^3) and Baluchistan (5 km^3) (Ahmad 2005b). For this particular study, the total water requirements (in ft) of the various crops of Pakistan were taken from the Planning Commission Report of the Government of Pakistan (Commission 2012). The total area under various crops in the provinces of Pakistan was taken from the Agriculture Census of Pakistan 2010. The total water required for various crops in cubic kilometers (km^3) was calculated as follows.

The total water required for crop "X" was calculated as follows:

Total water required for crop "X" = net crop water requirement (ft) × area under crop "X"

According to the Agricultural Census of Pakistan, of the four provinces of Pakistan, Punjab has the largest cultivated area, accounting for approximately 56.6 percent, followed by Sindh, KPK and Baluchistan. According to this study, the agricultural water requirements for Pakistan were 157.25 km^3. Punjab had the highest water requirements (109.48 km^3), followed by Sindh (30.07 km^3), Baluchistan (9.41 km^3) and KPK (8.27 km^3), as shown in Table 4.2. To check the reliability of our estimated water demands for agriculture, we compared our calculated water demands with other studies. According to the report published by the Ministry of Food, Agriculture and Livestock, Islamabad, Pakistan, in 2004, the total agricultural water requirements in Pakistan would be approximately 150 km^3 (Hanif et al. 2004). According to (Ahmad 2012), "the demand of water to meet net crop needs would be 154.5 km^3 by 2025". The estimates in these two reports suggest that our calculation of the agricultural water requirements, 157.25 km^3, is reliable.

4.2.4 Land Affected by Salinity and Gross Domestic Product (GDP) of Each Province

According to the estimates by the WAPDA, approximately 21 percent of the irrigated land in Pakistan is affected by salinity. Table 4.3 shows the provincial distribution of salt-affected areas (Qureshi and Mccornick 2008).

As of 2017, Punjab had a GDP of $173 billion, followed by Sindh's GDP of $83 billion. KPK and Baluchistan had a GDP of $27 billion and $9 billion, respectively.

Table 4.2: Water requirements of various crops.
Source: Agricultural Census and Planning Commission Report

Water Requirements for Various Crops	**Punjab** km^3	**Sindh** km^3	**KPK** km^3	**Baluchistan** km^3	**Total** km^3
Water Requirements for Wheat	26.72	5.17	3.05	1.20	36.12
Water Requirements for Rice	17.66	3.97	0.41	2.10	24.16
Water Requirements for Cotton	14.29	2.97	0.00	0.20	17.46
Water Requirements for Sugarcane	8.07	2.72	0.88	0.01	11.68
Water Requirements for Maize	2.04	0.01	1.69	0.02	3.76
Water Requirements for Barley	0.10	0.04	0.10	0.04	0.28
Water Requirements for Other Crops	40.62	15.20	2.14	5.85	63.80
Water Requirement for All Crops (Claims)	109.49	30.07	8.28	9.42	157.25

Table 4.3: Cultivated areas and salt-affected areas of Pakistan, in million hectares (Mha).

	Provinces				
	Punjab (Mha)	Sindh (Mha)	Baluchistan (Mha)	KPK (Mha)	Pakistan (Mha)
Cultivated Area (Mha)	12.27	5.65	1.84	2.11	21.87
Salt-Affected Area (Mha)	1.234	3.04	0.11	0.12	4.50

4.2.5 Water Diversions of the Indus River and Water Deficit in the Indus River Basin

Various researchers have different views regarding the flows of the Indus River and its tributaries. According to the Water and Power Development Authority (WAPDA), the average annual river flow is approximately 175 km^{3,} of which 128 km^3 is diverted for irrigation (Bakhsh et al. 2011). (Qureshi 2011b) stated that the average flow of the Indus River and its tributaries is 175 km^3 of water. Of this amount, 165 km^3 is from the western rivers (Jhelum, Chenab and Indus), whereas 10 km^3 is from the eastern rivers (Beas, Ravi and Sutlej). Most of this amount, 128 km^3, is diverted for irrigation. According to (Hussain et al. 2011), the total water supply for the agriculture sector is 130 km^3. According to another report by the Ministry of Food, Agriculture and Livestock, Islamabad, Pakistan, the total surface water diversions for Pakistan are 130 km^3 (Hanif et al. 2004). From the above figures, if we take 130 km^3 as the total surface water diversions for agriculture, the total deficit, that is, the difference between the water demand and water availability, is 27.25 km^3.

One might argue that the total surface water diversions for agriculture are 130 km^3 and that the ground water extractions are almost 60.1 km^3, summing to a total of 190.1 km^3. The total agricultural water requirements are calculated as 157.25 km^3 (Table 2); therefore, there is no deficit. The reason for the water shortage and, hence, the deficit is the low canal water efficiency in the river system, which leads to the overexploitation of groundwater.

According to (Ahmad 2009), "about 124 km^3 of water is provided by the canal diversions, out of which 54.5 km^3 is lost through water conveyance. The water available at the farm head is, therefore, only 69.5 km^3, with an additional 62 km^3 from groundwater pumpage, tallying a net water amount of 129.5 km^3". Therefore, our available water remains almost 130 km^3; hence, the water deficit still exists. According to another report published in 2014, "out of an average 128.3 km^3 of river flows diverted for canal irrigation about 54 km^3 is lost in conveyance and only 74 km^3 reaches the farm head (International Union for Conservation of Nature and Natural Resources 2014)". The analysis of these two reports suggests that a water deficit of almost 27 km^3 exists even with the overexploitation of groundwater.

4.3 Bankruptcy Rules: A Method for Managing the Allocation of Resources

In regard to the allocation of water resources, there are no mathematical rules for allocation that are accepted internationally; therefore, issues arise in regard to the water sharing among riparians (Wolf 1999). According to the international rules of shared water resources, the term "equitable and reasonable utilization" of water does not mean that water has to be shared equally (Rahaman 2012a). Regarding the principle of the equitable utilization of water, several conventions and rules have been adopted. The important conventions and rules are the United Nations Convention on the Law of the Non-Navigational Uses of International Watercourses from 1997 (UN Watercourses Convention, 1997), the Helsinki Rules on the Uses of the Waters of International Rivers and the Berlin Rules. Several factors, as mentioned in the Article 6 of the UN water convention must be considered for the reasonable and equitable sharing of watercourse. These factors have been discussed in Section 1.4.

Several factors, such as the minimization of environmental harm, sustainability and various other factors, are included in the Berlin Rules. In water resource allocation, equity is generally the key (Van der Zaag 2002). The "reasonable and equitable utilization" of water resources has several meanings, and several studies have been conducted to reach a conclusion regarding the "reasonable and equitable utilization" of water resources. Several conflicts between countries have occurred due to this issue, e.g., the conflict over the Nile River Basin among Sudan, Egypt and Ethiopia (Mianabadi et al. 2014) and (Ansink 2009b). Turkmenistan, Afghanistan, Tajikistan, Uzbekistan and Kyrgyzstan have a conflict over the Amu Darya River Basin that was studied by (Rahaman 2012b). Mexico and the USA have had a long dispute over three shared rivers that was studied by (Drieschova et al 2008). (Zarezadeh et al. 2013) used bankruptcy methods to resolve the water sharing dispute among the eight provinces of Iran.

Five classical bankruptcy rules are applied in this study: constrained equal losses (CEL), constrained equal awards (CEA), proportional (Pro), Piniles and Talmud. Apart from this, the water allocation between provinces is also been carried out through the Shapely value. Two new bankruptcy rules are proposed to address the equitable and reasonable utilization and distribution of water.

4.3.1 Classical Bankruptcy Rules

Five classical bankruptcy rules are used for the allocation of resources (also known as assets) among creditors (also known as stakeholders) when the total resources are not enough to satisfy the needs of all stakeholders. Several factors, such as economic and social needs, geography, and population, are considered during the negotiation process to ascertain the meaning of "equitable"(Gleick 1993).

The bankruptcy rules are used in this study for the water allocation between the administrative units (provinces) of Pakistan for two reasons. First, because of their simplicity, these rules can be used by policy makers and agents for problems related to river sharing. Second, the claims in real bankruptcy problems are also exceeded by the total assets (Ansink and Weikard 2012).

Bankruptcy methods are used in economics when the available stock is not adequate to satisfy the claims of creditors. Based on this, the assumption can be made that the total water resources are not enough to satisfy the demands of recipients; therefore, these bankruptcy rules can be used for the fair allocation of water resources to satisfy all beneficiaries (Kaveh Madani 2012).

Let 'n' be the number of claimants. The claimants are $n \geq 2$, and their claims are $C_i \geq 0; C = (C_1, \cdots, C_n)$. In river systems, a bankruptcy problem is defined as $F(N, E, C_i, a_i)$; $i = 1, 2, \cdots, n$, where N = number of agents, E = total resources, c_i = claim of agent i, and a_i = contribution of agent i. The objective of the bankruptcy method is to determine the apportionment to each agent, denoted by $F(N, E, C_i, a_i) = x_i$ where $x_i \geq 0; x = (x_i, \cdots, x_n)$. For a resource allocation problem, we have following Equations (4.1) to (4.4):

$$\mathrm{E} = \sum_{i=1}^{n} a_i \tag{4.1}$$

$$\mathrm{C} = \sum_{i=1}^{n} C_i \tag{4.2}$$

$$\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} x_i \tag{4.3}$$

$$0 \leq x_i \leq C_i \tag{4.4}$$

where Equations (4.1) and (4.2) are the contributions and claims of the agents, respectively. Equation (4.3) states that the assets are fully allocated. Equation (4.4) states that the allocation cannot exceed its claims, which can never be negative.

4.3.1.1 Proportional Rule (PRO)

The proportional rule (PRO) is given by Equation (4.5):

$$\mathrm{p_i^{pro}}{=}\rho \mathrm{C_i} \text{ where } \rho{=}\frac{\mathrm{E}}{\mathrm{C}} \tag{4.5}$$

where C is the total amount of claims and E is total assets.

4.3.1.2 The Constrained Equal Award (CEA) Rule

This rule is given by Equation (4.6):

$$\mathrm{x_i^{CEA}}{=}\min(\lambda, \mathrm{C_i}) \text{ where } \sum_{i \in N} \min(\lambda, \mathrm{C_i}){=}\ \mathrm{E} \tag{4.6}$$

CEA allocates each agent an equal share λ of E, except that no creditor receives more than his or her claim.

4.3.1.3 The Constrained Equal Losses (CEL) Rule

This rule is defined as Equation (4.7):

$$\mathrm{x_i^{CEL}}{=}\max(0, \mathrm{C_i}{-}\lambda) \text{ where } \sum_{i \in N} \max(0, \mathrm{C_i}{-}\lambda){=}\ \mathrm{E} \tag{4.7}$$

CEL allocates each claimant a share of the asset, such that compared with their claims (C), the losses of all claimants are equal, constrained to no claimant receiving a negative allocation. Here λ is the loss shared by each agent which is calculated by dividing the total deficit by the number of riparians.

4.3.1.4 The Talmud Rule

The Talmud Rule is derived by combining the CEL and CEA rules and is given by Equation (4.8):

$$x_i^{TAL} = \begin{cases} CEA\left\{\frac{1}{2}C_i, E\right\} & if\ E \leq \frac{C}{2} \\ \\ \frac{1}{2}C_i + CEL\left\{\frac{1}{2}C_i, E - \frac{1}{2}C\right\} & \text{otherwise} \end{cases} \tag{4.8}$$

In this rule, if the total assets (E) are less than or equal to half of claims (C), then CEA rule is used. If not, then half of the claims are distributed first and the remaining by CEL rule.

4.3.1.5 The Piniles Rule

For each C_i, ${x_i}^{Pin}$ is calculated as follows (Bosmans and Lauwers 2011), i.e. Equation (4.9):

$$x_i^{Pin} = \begin{cases} x_i^{CEA}\left\{\frac{1}{2}\underline{c}, E\right\} & if\ E \leq \frac{D}{2} \\ \\ \frac{1}{2}\underline{c} + x_i^{CEA}\left\{\frac{1}{2}\underline{c}, E - \frac{D}{2}\right\} & if\ E \geq \frac{D}{2} \end{cases} \tag{4.9}$$

In this rule, if the total assets (E) are less than or equal to half of claims (C), then CEA rule is used. If not, then half of the claims are distributed first and the remaining by CEA rule.

4.3.2 The Shapely Value

In the Shapely value, a payoff is allocated to each participant; the payoff is the average marginal worth of that player to all the coalitions in which that player can participate. All the core conditions, which are efficiency, group rationality and individual rationality, are satisfied by this method (Mianabadi 2016) using Equation (4.10).

$$\Psi i\,(S,v) = \sum_{\substack{0 \leq \ i \ \leq \ m \\ 0 < j < n}} \frac{(|s|-1)!\ \ (n-\ \ |s|)}{n!} \left[v\,(s) - v\,\left(\frac{s}{i}\right)\right] for\ all\ i = 1,\ldots,n \tag{4.10}$$

The Shapely allocation or allotment to player 'i' is given by $\Psi i\,(S,v)$, the number of players in the coalition is given by 'n', the set of all possible coalitions that contain the player is given by 'S', the characteristic function of the coalition is given by v(s), the number of elements in 's' is given by$|s|$, and the characteristic function of coalition s without 'i' is given by $v\ \left(\frac{s}{i}\right)$. The following procedure is adopted to compute the Shapely value for the bankruptcy games.

The agents are lined up in a random order, starting with the first agent, and each agent is allotted his or her entire claim until the total assets are finished or exhausted. All such possible orders are considered, and the allocation is performed using the Shapely value.

4.3.3 Two Proposed Rules

4.3.3.1 Groundwater-Based Rule

One problem with the classical bankruptcy rules is that they distribute the total assets E among agents N using some mathematical criteria without considering other factors, such as the contribution of the agents and groundwater usage. Here, we introduce a new rule to distribute the total deficit - the difference between the total claims and total assets – among the agents in such a way that the larger the groundwater usage of the agent, the larger the difference between his or her claim and the allocation that he or she obtains. Two factors are considered: the rate of groundwater usage and the rate of claims. A lower allocation to agents who use more groundwater is made, and they receive a lower proportion of their claims. The total deficit (D) is estimated by Equation (4.11):

$$D = C - E \tag{4.11}$$

Agents with more groundwater usage will receive a lower share of surface water. Thus, the d_i (deficit) of each agent is calculated as follows (Equation 4.12):

$$d_i = \frac{\left(\frac{c_i}{\sum c_i}\right) + 1 + \left(\frac{G_i}{\sum G_i}\right)}{n+2} \ . \ D \tag{4.12}$$

In the above equation, $c_i$and $G_i$are the claims and current groundwater usage of agents, respectively. D is the total deficit, that is, the difference between the total claims and total assets and n is the number of agents. In the denominator of Equation (4.12), 'n' is the number of riparian (agent) and '+2' indicates that both the parameters are directly proportional to the deficit, that is, the higher the value of the parameters, the more will be the deficit. According to this Rule, agents with more groundwater usage and more claims will have a higher deficit.

The equation proposed by (Kaveh Madani 2012) is used for the allocation of each agent:Therefore, the allocation (x_i) to each agent is given by Equation (4.13) or (4.14):

$$x_i = c_i - d_i \ ; \ 0 \leq x_i \leq C_i \tag{4.13}$$

or

$$x_i = c_i - \left[\frac{\left(\frac{c_i}{\sum c_i}\right) + 1 + \left(\frac{G_i}{\sum G_i}\right)}{n+2} \ . \ D\right] ; \ 0 \leq x_i \leq C_i \tag{4.14}$$

A key advantage of this proposed method is that the deficit is divided with respect to the usage of groundwater and the claims of the agents instead of any arbitrary mathematical criteria (for example, the deficit is divided equally in the CEL rule).

4.3.3.2 Proposed Rule

Article 6 of the UN Water Convention suggests considering several factors to ensure the equitable and reasonable utilization and distribution of water. These factors have been stated in Section 1.4. Here, a new rule accounting for the “land lost or affected by salinity in each province” and the “amount of GDP generated by each province” is proposed. With this rule, the total deficit is shared in inverse proportion to the land of provinces affected by salinity and in direct proportion to the amount of GDP generated by them.

The condition of every riparian (agent) varies according to the geographic, economic and environmental differences that exist between them. Riparian (agent) provinces, states or countries have different adaptive capacities and levels of risk exposure to water scarcity. With these factors in mind, a new method is proposed that takes into account riparian (agent)'s relative exposure or vulnerability to water shortage (in this case, the area affected by salinity). The water deficits allotted to riparian (agent) will be made based on their exposure to salinity. The amount of water shortage for each riparian (agent) is inversely proportional to the extent of salinity and directly proportional to the gross domestic product (GDP) of each province. An agent or riparian (agent) is excluded from the allocation problem if its claim is smaller than the average water deficit since its relative contribution is lower than 1/ n. If such a case occurs, the bankruptcy problem is rearranged again with the remaining riparian (agent) (Herrero and Villar, 2001; 2002). If the water is surplus, it is equally divided among the claimants. The total deficit for this rule is given by Equation (4.15):

$$d_i = \frac{1 - \left(\frac{S_i}{\sum S_i}\right) + \left(\frac{I_i}{\sum I_i}\right)}{n} \,.\, D \tag{4.15}$$

In the above equation, $S_i$and $I_i$are the “land affected by salinity” and “GDP” of each province or agent, respectively. D is the total deficit, that is, the difference between the total claims and total assets and n is the number of agents. Here, in the denominator, only 'n' is there. This is because one parameter is inversely proportional to deficit and the other parameter is directly proportional to the deficit. Hence the denominator becomes $(n + 1 - 1) = n$.

The equation proposed by (Kaveh Madani 2012) is used for the allocation of each agent.Therefore, the allocation (x_i) to each agent is given by Equation (4.16) or (4.17):

$$x_i = C_i - d_i \; ; \; 0 \leq x_i \leq \mathrm{C}_i \tag{4.16}$$

or

$$x_i = c_i - \left[\frac{1 - \left(\frac{S_i}{\sum S_i} \right) + \left(\frac{I_i}{\sum I_i} \right)}{n} \right] . \, D; \quad 0 \leq x_i \leq c_i \tag{4.17}$$

The advantage of both the "groundwater-based rule" and the "proposed rule" is that both these rules take into account other important factors such as claims, groundwater usage, land affected by salinity and the GDP of each riparian while distributing the deficit, whereas typical bankruptcy rules do not take into account these factors.

4.4 Results and Discussion

4.4.1 Results of the Bankruptcy Rules

The reallocation of the water of these rivers is first performed using the five bankruptcy rules. Figure 4.1 represents the water allocation of the Indus River among the four riparians (provinces) by the five classical bankruptcy rules. Table 4.4 shows the results and compares them. Results show that the agents with the smaller claims are favored by the CEA rule whereas the agents with the larger claims are favored by the CEL rule and higher priority is given to them in the reallocation. PRO is positioned between CEA and CEL. It is also evident from the results that Punjab, being the largest province of Pakistan by population and irrigated area, receives the highest allocation, followed by Sindh, Baluchistan and KPK.

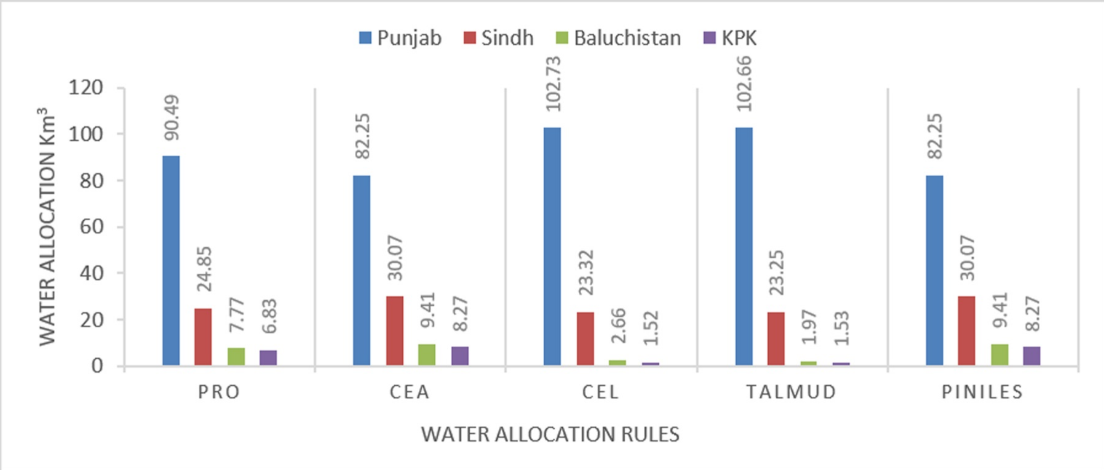

FIGURE 4.1: Water allocation under different bankruptcy rules.

TABLE 4.4: Water allocation under different "bankruptcy rules".

Riparian	**PRO (km^3)**	**CEA (km^3)**	**CEL (km^3)**	**Talmud (km^3)**	**Piniles (km^3)**
Punjab	90.49	82.25	102.73	102.66	82.25
Sindh	24.85	30.07	23.32	23.25	30.07
Baluchistan	7.77	9.41	2.66	2.60	9.41
KPK	6.83	8.27	1.52	1.46	8.27

4.4.2 Results of the Shapely Value and Two Proposed Rules

The results of the Shapely value are given in Table 4.5, whereas the combined results of the Shapely value, the groundwater-based rule and the proposed rule are shown in Table 4.6. The reallocation suggests that the "groundwater-based rule" favors riparians that have lower groundwater usage, whereas the "proposed rule" favors agents who are more affected by salinity and have a lower gross domestic product (GDP). Figure 4.2 shows the results for the Shapely value and two proposed rules. Table 4.7 shows the allocated water of the Indus River among the riparian provinces as a percentage of water demand under all rules.

Table 4.5: Water distribution according to the Shapely value.

Ordering	Punjab (km^3)	Sindh (km^3)	Baluchistan (km^3)	KPK (km^3)
PSBK	109.49	18	0	0
PBKS	109.49	0.30	8.28	9.42
PKSB	109.49	9.72	0	9.42
SPBK	97.42	30.07	0	0
SBKP	79.72	30.07	8.28	9.42
SKPB	88	30.07	0	9.42
BPSK	109.49	9.72	8.28	0
BKPS	109.49	0.3	8.28	9.42
BSKP	79.72	30.07	8.28	9.42
KPSB	109.49	8.58	0	9.42
KBPS	109.49	0.3	8.28	9.42
KSBP	79.72	30.07	8.28	9.42
TOTAL	1191.01	197.27	57.96	84.78
AVERAGE	**99.25**	**16.43**	**4.83**	**7.06**
Sum		**127.585**		

Table 4.6: Water allocation under the Shapely value, groundwater-based rule and proposed rule.

Riparian	Shapely Value (km^3)	Groundwater-Based Rule (km^3)	Proposed Rule (km^3)
Punjab	99.25	98	100.6
Sindh	16.43	24.50	25.96
Baluchistan	4.83	4.40	2.65
KPK	7.06	3.50	1.38

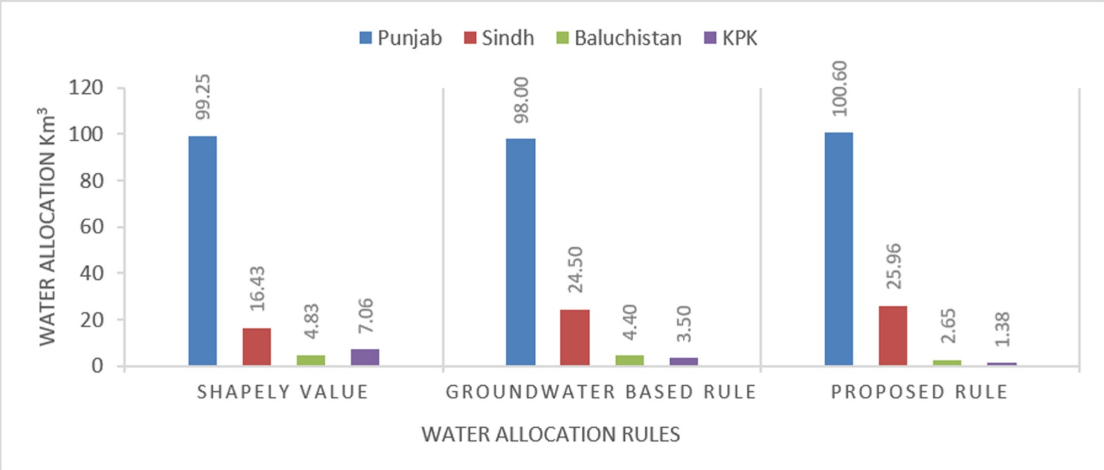

FIGURE 4.2: Water allocation under the Shapely value, groundwater-based rule and proposed rule.

4.5 Selection of the Most Appropriate Rule

Regarding the distribution of water resources, the definition of "equity" is still not clear, and for this reason, it is difficult to choose the most appropriate rule. In most cases, the doctrine of absolute territorial sovereignty (ATS) is preferred by upstream countries, while the doctrine of absolute territorial integrity (ATI) is preferred by downstream countries (Moynihan 2012). To select the most suitable allocation rule, a new method is proposed. To use this method, three assumptions are considered. The first assumption is that the stakeholders have equal power. The second assumption is that all countries choose the highest allocation rate. The third assumption is that there is no other method for the allocation of water. This method selects a rule which all participants or stakeholders have the lowest dispersion about their total preferences on that rule. For this reason, for each stakeholder, the allocations are ranked in ascending order separately. The priority vectors Ω are set for this reason with the elements of w_i. Here, wi is a vector that has elements of θ^i_j, where w_i are the preference vectors, i is the number of rules, and j is the number of stakeholders. In the current study, $1 \leq i \leq 8$ and $1 \leq j \leq 4$.

The priority vector set for our study is $\Omega = \{w_1, w_2 \ldots\ldots w_n\}$ in which w_1= (5, 3, 2, 2), w_2= (6, 1, 1, 1), w_3 = (1, 5, 6, 4), w_4 = (1, 4, 5, 6), w_5 = (6, 1, 1, 1), w_6= (3, 6, 3, 3), w_7= (4, 4, 4, 3) and w_8= (2, 2, 5, 5). Accordingly, each bankruptcy rule corresponds to a priority vector w_i. The priority vector with the lowest distance from the intermediate value is the best one, which in this chapter is $\overline{w}$. The dispersion around the mean of vector i, δ_i, is calculated by Equation 4.18:

$$\delta\mathrm{i} = \frac{\sum_{j=1}^{n} (\theta_{ji} - \overline{w})^2}{n} = \frac{\sum_{j=1}^{n} \left(\theta_{ji} - \frac{\sum_{j=1}^{n} \theta_{ji}}{n} \right)^2}{n} \tag{4.18}$$

As an example, for the Talmud rule, we have:

$$\overline{w}_4 = \frac{1+4+5+6}{4} = 4$$

$$\delta_4 = \frac{(1-4)^2 + (5-4)^2 + (6-4)^2 + (4-4)^2}{4}$$

$$\delta_4 = 3.5$$

Table 4.8 presents the δ_i for all rules. The most suitable allocation rule will be that which has the lowest δ_i. The allocated water of the Indus River among the provinces as a percentage of their water demands is presented in Table 4.7. According to Table 4.8, the groundwater-based rule ranks first, and the Piniles and CEA rules are ranked last. Different provinces may prefer different rules for themselves, but the most appropriate and equitable rule is that which satisfies riparian or provinces in the most suitable way.

TABLE 4.7: The allocated water of the Indus river among the Riparian provinces as a percentage of water demand under the "bankruptcy rules, Shapely value, groundwater-based rule and proposed rule".

Riparian	**PRO** (%)	**CEA** (%)	**CEL** (%)	**Talmud** (%)	**Piniles** (%)	**Shapely Value** (%)	**Groundwater Based Rule** (%)	**Proposed Rule** (%)
Punjab	82.65	75	94	94	75	90.60	89.50	91.80
Sindh	82.65	100	77	77	100	54.60	81.40	86.30
Baluchistan	82.65	100	28	28	100	51.20	46.70	28.10
KPK	82.65	100	18	18	100	42.20	42.20	16.60

Table 4.8: Priority vectors, priority index and ranking of the five bankruptcy rules, the Shapely value, the groundwater-based rule and the proposed rule.

Province	**PRO**	**CEA**	**CEL**	**Talmud**	**Piniles**	**Shapely Value**	**Groundwater Based Rule**	**Proposed Rule**
$\boldsymbol{\delta}_i$	1.25	4.68	3.00	3.50	4.68	1.68	0.18	2.25
Rank	**2**	**7**	**5**	**6**	**7**	**3**	**1**	**4**

4.6 Concluding Remarks

This chapter examined the utility of bankruptcy rules in addressing the supply-demand gap in shared rivers. Five bankruptcy rules, the Shapely value and two other proposed rules were used in this study to resolve the conflict between the provinces of Pakistan over the allocation of water. The water allocations are different for different bankruptcy rules; therefore, different parties may prefer different rules. Additionally, the bankruptcy rules do not take into account various factors, and they have certain shortfalls. Since riparian have different adaptive capacities and risks of exposure, water sharing rules should also take all these factors into account. Hence, there is a need for allocation rules that take into account all these issues, which are required for "reasonable and equitable utilization". Two new rules are proposed in this study, namely, the "groundwater-based rule" and the "proposed rule". The groundwater-based rule takes into account "groundwater usage" and favors agents who have lower groundwater usage, whereas the "proposed rule" considers the land affected by salinity and the gross domestic product (GDP) of each province and favors agents who have a lower GDP and more land affected by salinity. Additionally, in this study, a method is applied that enables us to establish the most appropriate rule to satisfy the four provinces of Pakistan. The results reveal that the CEL rule seems to favor agents with larger claims, and higher priority is given to them in the reallocation. CEA rule seems to prefer the agents with smaller claims, and they get a relatively higher portion of their claims. PRO rule is located between CEA and CEL rules. The selection of the most appropriate rule show that the groundwater-based rule has the lowest dispersion and is the most appropriate water sharing rule. Although appropriate vision is provided by the allocation rules for the conflict management of transboundary water resources, the distribution of water among riparian can be a complex problem that cannot be solved only by mathematical methods; therefore, water diplomacy and negotiation between the provinces of Pakistan are suggested, which would help them to develop a consensus and reach an agreement. The method applied above for the 'selection of the best rule' can help the provinces reach an agreement. It is expected that the findings of this research will be very helpful in resolving the longstanding disputes between the provinces of Pakistan.

Chapter 5

Transboundary Water Allocation in Pakistan's Indus Basin in Critical Scarcity Condition: A Stochastic Bankruptcy Approach

5.1 Introduction

Management and allocation of water in scarce conditions is a common problem in water resource management (Kanakoudis et al. 2016); (Kanakoudis et al. 2017) and (Kanakoudis 2002). This problem of water allocation can be analyzed using Bankruptcy Game (BG) techniques, which is a branch of Cooperative Games Theory (CGT) (Young 1994). The problem of bankruptcy arises when some riparians or agents have claims on the available assets, but the sum of their claim is greater than the total available assets. The total assets must be divided among the claimants in such a way that each claimant is awarded a non-negative amount that cannot be greater than its claim. Bankruptcy problems have numerous applications which include numerous real-life problems and the bankruptcy approach has proved very useful for those problems. In this literature, several bankruptcy rules and their extensions have been introduced for the solution of bankruptcy problem (O'Neill 1982); (Thomson 2003); (Auman and Maschler 1985); (Herrero and Villar 2001).

Several political disputes have been caused throughout the world because of the non-equitable allocation of water resources, the increasing consumption of water resources and their scarcity (Homer-Dixon 1994). There are a total of 148 transboundary river basins shared among 148 countries (De Stefano et al. 2012). During the past 50 years, forty-three political or military acts related to shared water resources have taken place around the world (Wolf 2007). Due to factors such as change in climate, growing crop production, increasing populations, and soil degradation, freshwater has become a source of conflict among riparian states. Hence, one of the basic challenges in transboundary river management concerns the allocation the limited available water among riparian countries, states or provinces when it is not enough to satisfy the claims of all riparian countries, states, or provinces. Therefore, "reasonable" and "equitable" water resource reallocation faces the question of which criteria and mechanisms should be considered for this "reasonable" and "equitable" reallocation (Mianabadi et al. 2012). The main problem arises when the total demand of riparian countries or provinces is more than the total available water. In quantitative conflict resolution, the equitable water allocation among riparian is a complex process at both the national and international scales (Jarkeh et al. 2016).

To manage conflicts and allocate resources, the bankruptcy method is widely used. This method is applicable when the total claims (C) exceed the total resources or assets (E). Bankruptcy theory has been applied to problems related to the allocation of resources. (Grundel et al. 2013) used this method for multipurpose resource allocation situations. (Ansink and Marchiori 2015) used it for water resource management. Beard (2011) provided a detailed review of the association between river sharing and the bankruptcy literature. These application of the bankruptcy method shows that it is an essential tool for resolving conflicts and for achieving agreement on water resource allocation problems. Bankruptcy theory can be used in resource allocation and dispute resolution when the total available resources are less than the total demand or claims of riparian countries or provinces (Ansink and Marchiori 2015). (Auman and Maschler 1985) and (O'Neill 1982) introduced bankruptcy theory, and it was later studied by various researchers

(Alcalde et al. 2014); (Hendrickx et al. 2005); (Lorenzo-Freire et al. 2010); (Thomson 2012). Bankruptcy theory has been used by several researchers for water allocation among riparian countries (Mianabadi and Sheikhmohammady 2014); (Mianabadi et al. 2015); (Madani et al. 2014) and (Li et al. 2018). (Bozorg-Haddad et al. 2018) used bankruptcy theory for water allocation in Iran. (Degefu et al. 2018) applied the cooperative game theory allocation by combining the Nash bargaining theory and bankruptcy games for the water allocation among Syria, Iraq and Turkey. Water Management Using System Dynamics Modeling in Semi-arid Regions was done by (Reza et al. 2017). (Sedghamiz et al. 2018) used a Game Theory Approach for Conjunctive Use Optimization Model Based on Virtual Water Concept.

A methodology for the water allocation using the Bankruptcy Games is described in this article for the water resources under scarcity. A new methodology is also developed which considers the priorities in the allocation of water. This novelty is presented by the consideration of user's priorities, which are settled by 'high agricultural productivity': the user with high agricultural productivity will be given preference in water allocation. First, the water distribution among the provinces of Pakistan is done under 'four" different scenarios using the Bankruptcy Rules. Secondly, a novel allocation procedure is applied which includes claimants' priority by taking into account the 'agricultural productivity' of the users.

5.2 Bankruptcy Problem and Cooperative Game Theory

The rules of bankruptcy are used in economics when the total available asset (resource) is not sufficient to satisfy the claim of creditors (stakeholders). When total available resources are less than the aggregate demand, the share of each user need to be lessened by some amount. This share can be calculated using different bankruptcy methods (Curiel et al. 1987), (Dagan and Volij 1993) and (Madani and Dinar 2011). The fundamentals of these bankruptcy models are set in the works of (O'Neill 1982) and (Auman and Maschler 1985). The links between the Bankruptcy Games (BG) and Cooperative Game Theory (CGT) were consolidated by (Curiel et al. 1987) in which they studied the class of division rules for bankruptcy as corresponding to a CGT approach to those problems.

Cooperative Game Theory (CGT) by (Neummann and Morgenstern 1944) and (Young 1985) offers the essential instruments to analyze division problems and to research an allocation mechanism which is considered efficient, impartial, and fair by users. A cooperative game can be perceived as a kind of a game where it is essential to determine the impartial allocation of "goods" among different players (Lemaire 1984). The distribution can consider "positive" or "negative" goods according to a "benefit game" or a "cost game" solution for the users. In the first case, users cooperate with each other in order to attain the biggest fair benefit; in the subsequent case, users cooperate to share the smallest cost system (Young 1994).

Various allocation problems have been addressed in the literature by means of the Cooperative Game Theory (CGT). Different research fields have been considered in the approaches including the water resources (Deidda et al. 2009); (Zucca 2011).

To state a cooperative game problem, the following definitions are required:

$N = (1, 2, \cdots, n)$ is the set of players take part in the game

$S \in N$ is a "coalition" or "alliance", and for $S = N$ we have the so-called "Grand Alliance"

$v(i)$ denotes the least cost or maximum benefit associated with the user i

$v(S)$ is the least cost or maximum benefit associated to the alliance S

$v(N)$ therefore, denotes the cost or benefit related to the Grand Alliance.

An allocation or apportionment is a vector $[x_1, x_2, \cdots, x_n]$, where x_i is the quantity of the good allocated to the i^{th} player.

Regarding a benefit-sharing game, to obtain a fair solution, CGT exploits three fundamental principles (in the case of a cost game the inequality signs are the opposite):

The *efficiency principle*, which assures the over-all sharing of the Grand Coalition profit among all the members of the game, is signified by Equation (5.1):

$$\sum_{i \in N} x\ (i)\ =\ v(N) \tag{5.1}$$

The *rationality principle*, for which no user (or coalition) can be allocated less than its standalone benefit (i.e., opportunity benefit), is represented by Equation (5.2):

$$\sum_{i \in S} x\ (i)\ \geq\ v(S) \tag{5.2}$$

The *marginality principle*, which states no user should be charged more than its marginal benefit from being counted in an alliance, is represented by Equation (5.3):

$$\sum_{i \in S} x\ (i)\ \leq\ v(N)\ -\ v(N - S)) \tag{5.3}$$

The sharing of total available goods is ensured by the statement 5.1; the incentives for the voluntary cooperation is ensured by the statement 5.2 while the statement 5.3 provides the consideration for equity. Conditions 5.2 and 5.3 become equivalent as the condition 5.1 is ensured.

Two different definitions are given in CGT for the 'game problem solution'. The first is given by the set of permissible solutions: the so-called "core" that is the set of all allocations $x \in R^N$, such that 5.1 and 5.2, or equivalently 5.3, hold for all S of N (Young and Okada 1982). The second sort is given by a single allocation, which individuates only one solution, and this is more analogous to the classic idea of the solution to a problem.

5.3 Bankruptcy Rules

As described above, the bankruptcy methods are used in economics when the available stock is not adequate to gratify the claim of the claimants. Based on this, the assumption can be made that the total water resources are not adequate to satisfy the demand of the claimants, therefore these rules of bankruptcy can be used for the fair distribution of water resources to satisfy all the beneficiaries (Kaveh Madani 2012). The literature related to the bankruptcy problems can be found in the works of (Gallastegui, Inarra 2002) ; (O'Neill 1982); (Ansink 2009a) and (Mianabadi et al. 2015). More literature related to the bankruptcy rules have already been discussed in the introduction.

The set N of claimants is of the form $\{1, 2, \ldots, n\}$. Each claimant i ∈ N advances one claims d_i on the estate E with $E < \Sigma_{i \in N}\ d_i$.

A division rule f (E, d) linked with the bankruptcy problem gives a solution, Equation (5.4), as a vector $x = (x_1, x_2, \ldots, x_n)$, such that:

$$\begin{cases} \sum_{i \in N} x(i) = E \\ 0 \leq Xi \leq di \end{cases} \tag{5.4}$$

In Equation (5.4), x_i denotes the quantity of the estate E allocated to the i^{th} claimant.

The cooperative game, associated with the bankruptcy problem, is defined by the characteristic function as given in Equation (5.5):

$$v_{E,d}(S) = max \left\{ \left(E - \sum_{i \in (N-S)} d_i \right), 0 \right\} \quad S \in N \tag{5.5}$$

where $v_{E,D}(S)$ in Equation 5.5 represents the nominal amount that the alliance $S \subset N$ will obtain once the claims of the creditors outside 'S' has been fully rewarded.

In this state, the solution to the bankruptcy problem and the related cooperative game is the same. Henceforth we consider division rules described by (Branzei et al. 2008) considering a flow approach to bankruptcy problems: the proportional rule (PROP), the constrained equal award rule (CEA), the constrained equal loss rule (CEL), the Talmudic rule (TAL), and the Piniles rule (Pin) which are explained below:

Let 'n' be the number of claimants. The claimants are $n \geq 2$ and their claims are $c_i \geq 0$; $C = (C_1, \ldots, C_n)$. A bankruptcy problem in river systems is defined as

F (N, E, c_i, a_i); i = 1, 2,...,n, where N = no. of agents, E = total resources, C_i = claim of the agent i and a_i = contribution of the agent i. The purpose of bankruptcy method is to determine the apportionment to each agent, symbolized by F $(N, E, C_i, a_i) = x_i$ where $x_i \geq 0$; $x = (x_i, \ldots, x_n)$. For a resource sharing problem, we have Equations (5.6) to (5.9):

$$\mathrm{E} = \sum_{i=1}^{n} a_i \tag{5.6}$$

$$\mathrm{C} = \sum_{i=1}^{n} C_i \tag{5.7}$$

$$\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} x_i \tag{5.8}$$

$$0 \leq x_i \leq C_i \tag{5.9}$$

Where Equation (5.6) and (5.7) are the contribution and claims of the agents respectively. Equation (5.8) states that the assets are fully allocated. Equation (5.9) states that the allocation cannot exceed its claims can never be negative.

5.4 Weighted Bankruptcy Rule: Methodology Development

A novel 'Weighted Bankruptcy' mechanism has also been developed and the above defined Bankruptcy Rules have also been applied that included the riparians priority considering 'agricultural productivity' of each riparian: higher agricultural productivity produces higher user priority. The method will encourage the riparians to increase their agricultural productivity, which is very essential considering the scarcity of water in future. A simple method to define 'agricultural productivity' is given by Crop Production Per Acre Feet of Water (US$). Therefore, the claimants 'weights' are included, and the BG allocation has been revised. These weights are assessed considering the agricultural productivity: higher weight w_i is given to the riparian with high crop productivity; the weighted demands will be consequently defined as:

$$w_i = f(p_i,\ u_i) \quad ; \quad d_i^* = d_i w_i$$

All the bankruptcy rules defined above will then be applied again considering the 'Weighted Water Demands'. The 'crop production per acre feet of water', 'weights' and 'weighted demands' are given in Table 5.3. The weighted water requests are considered as the claims of the agents or riparians. If any riparian or claimant receives a bigger water allocation than its original request, the assignment will be equal to its original demand and available left-over will be shared among the other riparians using the same rule.

5.5 Solution Framework

After defining the objective, the fundamental principles of water sharing as stated in the Equations (5.1), (5.2) and (5.3) are defined. The disagreement points as well as the quantity of water available for consumption is then determined. The allocation of water among the riparians is then done using the Bankruptcy Rules. The method for water apportionment problem under water bankruptcy using the bankruptcy rules is described below in Figure 5.1.

When the claim and the available water in the river basin fluctuates with time, the bankruptcy rules are applied again by updating the disagreement points and the water allocation is done again using the bankruptcy rules.

5.6 Current Water Distribution Mechanism in Pakistan and its Shortcoming

As discussed in Chapter 4, the interprovincial water sharing of surface waters in Pakistan is currently governed by the Water Apportionment Accord of 1991. The main aim of the Accord was to build trust amongst the provinces of Pakistan.

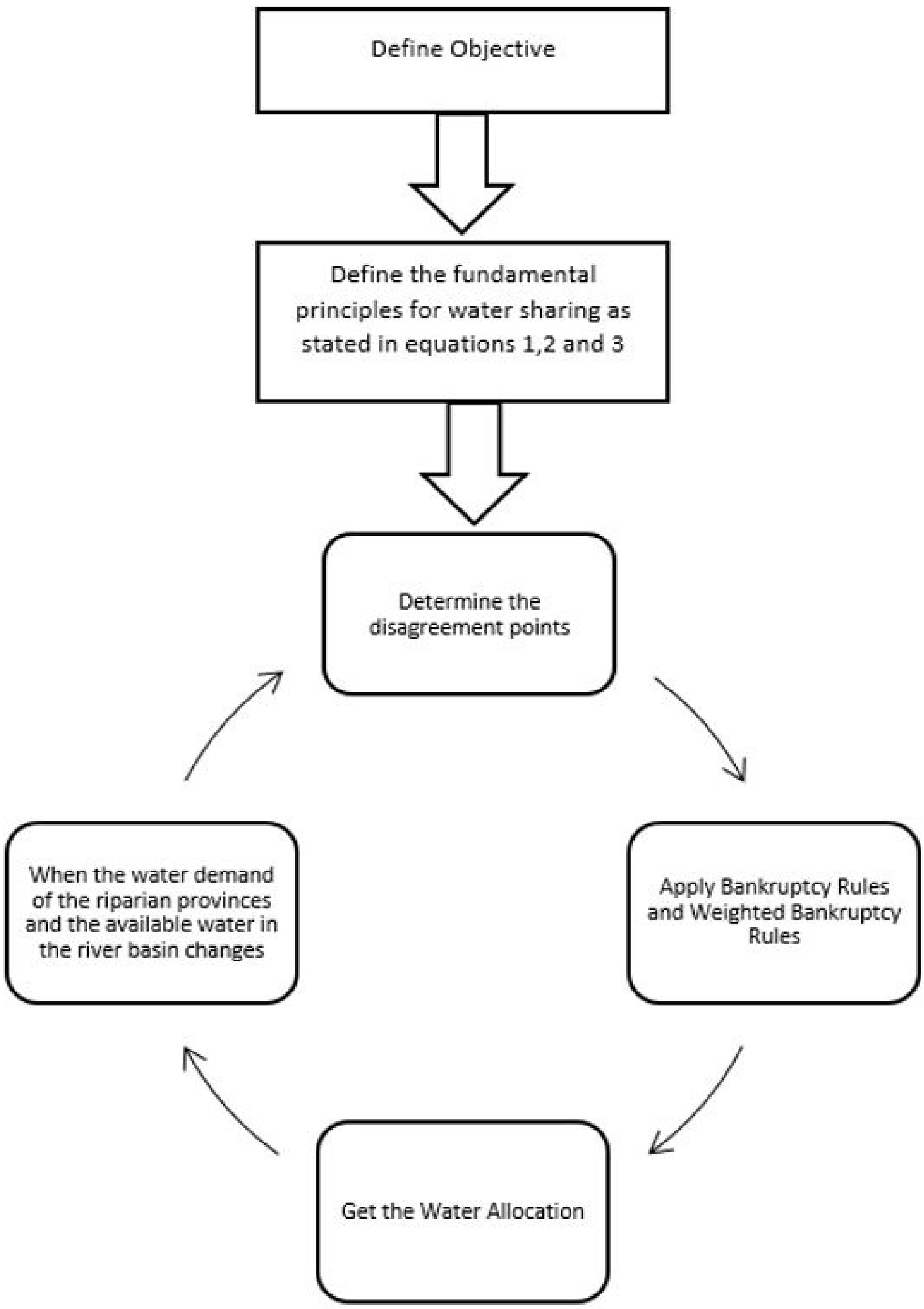

FIGURE 5.1: Flow chart for water allocation under bankruptcy.

Unfortunately, this accord does not adapt to changing conditions over time; hence, it can be considered "a glass that is half empty and half full". The current water distributions among the provinces of Pakistan as per the Water Apportionment Accord are given in Table 4.1. IRSA is mainly responsible for water allocation among the provinces. The main shortcomings of the Water Apportionment Accord of 1991 are highlighted below.

The average canal diversions in post-Tarbela periods have only been 127 Km^3 which is less than the accord's entitlements of 144.87 Km^3. This creates problems among the Provinces of Pakistan when they have to share shortages as there is no defined mechanism to share the water shortages (Condon et al. 2014). Currently, the two small provinces, Baluchistan and Khyber Pakhtunkhwa (KPK) are exempted by the water shortages by an act of 2003. Thus, whenever the total volume falls, the deficiencies are shared by Sindh and Punjab (Condon et al. 2014). Thus, there is no proper mechanism of water distribution when the total volume falls short or when the demands of the provinces exceed the total available water. Also, Khyber Pakhtunkhwa (KPK) and Baluchistan have not yet developed their irrigation system properly, therefore, they always get more water than they can use.

Another serious problem in the Water Apportionment Accord is that the water allocations are fixed which create a quantified entitlement. Fixed water allocations mechanisms can lead to the water allocations which are unacceptable for the provinces, especially in the uncertainty, draughts and the stochastic nature of River flow. The Water Apportionment Accord between the provinces of Pakistan was signed almost twenty-eight years ago. Since then, the water demands of the provinces have changed due to the rise in the population and the irrigated area. Therefore, the gap between the water supply and water demand has increased considerably in Pakistan. Several features and attributes of the Indus river disputes are described below:

5.6.1 Surface Water Diversions

As shown in Figure 2.1, the Indus River comprising of six main tributaries, namely, the Indus, Chenab, Sutlej, Ravi, Jhelum and Beas tributaries, is a main source of water supply for Pakistan. The water of the Indus River is shared amongst all four provinces of Pakistan. River flows are primarily supplied by rainfall, snowmelt, glacier melt and runoff. According to the Indus River System Authority, the median canal diversions from 1975 to 2013 were 125.61 km^3 (Hassan 2016).

5.6.2 Agricultural Water Requirements for Pakistan

In this study, the water requirements (in ft) for various crops were taken from the planning commission report (Commission 2012) whereas the cropped area was taken from the Agricultural Statistics of Pakistan (Government of Pakistan 2011).

According to (Ahmad 2005), the total agriculture water requirements or demands for Pakistan for the year 2002-2003 were estimated to be 109.7 MAF. Punjab had the highest Irrigation water requirements at 78.4 Km^3, followed by Sindh (20.1 Km^3), KPK (6.2 Km^3) and Baluchistan (5 Km^3). For this particular study, the total water requirements (in feet) of the various crops of Pakistan was taken from the Planning Commission Report of the Government of Pakistan (Commission 2012). The total area under various crops in the Provinces of Pakistan was taken from the Agriculture Census of Pakistan 2010 (Government of Pakistan 2011). The total water required for various crops in cubic kilometers (Km^3) was calculated as follows:

Total water required for crop "X" = Net crop water requirement (ft) $\times$ Area under crop "X"

As per the Agricultural Census of Pakistan, Punjab has the largest cultivated area among the four Provinces of Pakistan which accounts for about 56.6 Percent, followed by Sindh, KPK and Baluchistan. According to this study, the agriculture water requirements for Pakistan came out to be 157.25 Km^3 (excluding the environmental flows). The water required downstream of Kotri as 'Environmental flows' for the province of Sindh is 12.3 Km^3. The 1991 Water Accord amongst the provinces also recognized the necessity for a residual flow to the delta of 12.3 Km^3 but no official policy or established mechanism has yet been implemented to make environmental water apportionments. There is a strong need for such environmental apportionments to be made not only for a minimum residual flow but also to provide a measure of flow variability that mimics the natural river regime (Archer et al. 2010). The total water requirement including the environmental flows, therefore, came out to be 170.56 Km^3, which also included 12.3 Km^3 as environmental flows for the province of Sindh. Punjab had the highest water requirements (109.48 Km^3) followed by Sindh (43.07 Km^3), Baluchistan (9.41 Km^3)

and KPK (8.27 Km^3) as shown in Table 5.1. In order to check the reliability of our estimated water demands for agriculture, we compared our calculated water demands with other studies. According to the report published by the Ministry of Food, Agriculture and Livestock Islamabad, in 2004, the total agricultural water requirements in Pakistan would be around 150 Km^3 by 2020 (Hanif et al. 2004). According to (Ahmad 2012), "the water demand to meet net crop requirements would be 154.5 Km^3 by 2020". The estimates in these two reports suggest that our calculation of the agricultural water requirements of 157.25 Km^3 is reliable.

TABLE 5.1: Water Requirements of Various Crops.
Source: Agricultural Census and Planning Commission Report 2010

Water Requirements for Various Crops	**Punjab km^3**	**Sindh km^3**	**KPK km^3**	**Baluchistan km^3**	**Total km^3**
Wheat	26.72	5.17	3.05	1.20	36.12
Rice	17.66	3.97	0.41	2.10	24.16
Cotton	14.29	2.97	0.00	0.20	17.46
Sugarcane	8.07	2.72	0.88	0.01	11.68
Maize	2.04	0.01	1.69	0.02	3.76
Barley	0.10	0.04	0.10	0.04	0.28
Other Crops	40.62	15.20	2.14	5.85	63.80
All Crops	109.49	31.07	8.28	9.42	157.25
All Crops after Sindh's requirement for environmental flows	109.49	43.37	8.28	9.42	170.56

Note: The Requirements for Sindh includes an additional 12.3 Km^3 as Environmental Flows

5.6.3 The Canal/Irrigation Water Supplies for Indus River

Various Researchers have different views regarding the flows of Indus River and its tributaries. According to WAPDA, the average annual river flows is approximately 138 MAF or 170 Km^3 out of which 128 Km^3 is diverted for irrigation.(Bakhsh et al. 2011). (Qureshi 2011b) stated that the average flow of the Indus River and its tributaries is 175 Km^3 of water. Out of this, 165 Km^3 is from the western rivers (Jhelum Chenab and Indus) whereas 10 Km^3 is from the eastern rivers (Beas, Ravi and Sutlej). Most of this, 128 Km^3, is diverted for irrigation; According to (Hussain et al. 2011), the total water supply for the agriculture sector is 130 km^3. According to another report by the Ministry of Food, Agriculture and Livestock, Islamabad, Pakistan, the total surface water diversions for Pakistan are 130 Km^3 (Hanif et al. 2004).

Indus river supplies and consequently, the canal water diversions for agriculture in Pakistan are highly variable as shown in Figure 5.2. The canal diversions vary from 137 km^3 (111.1 MAF) to 94 km^3 (76.2 MAF). Thus, the variability between the highest and lowest canal diversion comes out to be 43 km^3 (34.9 MAF) due to the stochastic nature of river flows. The canal diversions are also affected due to less storage capacity. From the year 1975-2013, the lowest canal diversion was 94 km^3 (76.2 MAF) which severely affected the agricultural sector in Pakistan. The 141 km^3 (114.32 MAF) of the canal water supplies was allocated to the provinces according to the Water Accord (Table 4.1) on the condition that more dams will be constructed, and additional storage will be created. Since the signing of the Water Accord in 1991, the agricultural water demands have increased but no new storage reservoir has been constructed. The median canal diversion from 1975-2013, was 125.61 km^3 (101.84 MAF) which is less than 141 km^3 (114.32 MAF), as decided by the Water Accord.

5.7 Bankruptcy Games Method Applied in Water Resource Distribution in the Provinces of Pakistan

This chapter aims in the distribution of limited quantity of water available to satisfy the riparian or claimants using the BG procedures. The case of Indus River system is considered. Four different scenarios are developed for the water allocation as shown in Table 5.2. First the distribution of water for all the four

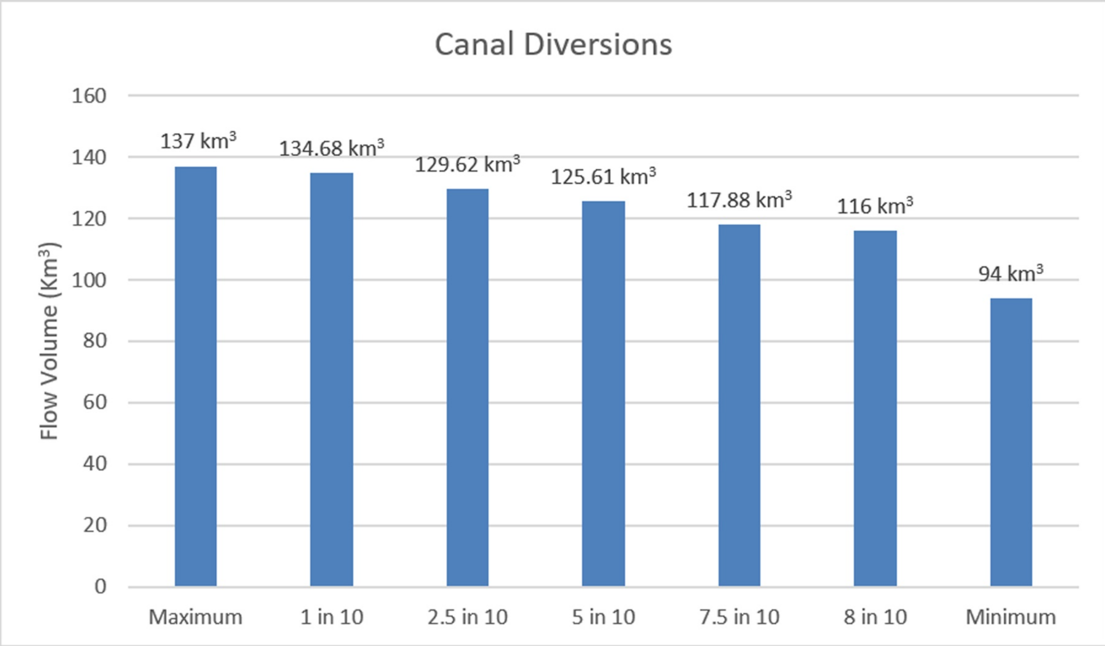

FIGURE 5.2: Canal diversions (Km^3) during 1975-2013.

scenarios is done using the five Bankruptcy Rules given above, then, a novel allocation procedure is applied which includes claimants 'agricultural productivity'. More agricultural productivity would result in higher priority in water allocation.

The core solutions of the cooperative game are defined by the principles of efficiency, rationality and marginality as defined in Equations 5.1, 5.2 and 5.3. The lower bound for each user is given by the rationality principle and the upper bound is given by the marginality principle. Table 5.3 summarizes the results, x(i) denotes the water apportionment for the i^{th} user stated in Mm^3/year; the parenthesis value denotes the allocated percentage in the four water scarce scenarios with respect to the existing resource. In Table 5.3, the upper and lower bounds of water apportionment inside the core can be considered as limits of "feasible values" that could be accepted by each user.

Figure 5.3 summarizes the results of five bankruptcy rules under different scenarios. These results are expressed as percentage values. These values are therefore not compared to the over-all assets but to the user's claims. For example, in Scenario 1, according to Proportionate Rule, all the four provinces are awarded 73 percent of their claims. Similarly, in Scenario 1, according to Piniles Rule, Punjab is awarded 58 percent of its claims whereas Sindh, Baluchistan and KPK are awarded 100 percent of their claims. It is evident form Figure 5.3 that a fixed proportional

TABLE 5.2: Water availability, claims and deficit under different scenarios.

Reference Scenarios	**Water Availability (Km^3)**	**Claims (Km^3)**	**Deficit (Total) (Km^3)**
Scenario-1 (5 in 10)	125.61 Km^3	Punjab (P)= 109.49 Km^3 Sindh (S)= 43.37 Km^3 Baluchistan (B)= 9.42 Km^3 KPK (K)= 8.28 Km^3 **Total= 170.56 Km^3**	44.95
Scenario-2 (8 in 10)	116.00 Km^3	Punjab (P)= 109.49 Km^3 Sindh (S)= 43.37 Km^3 Baluchistan (B)= 9.42 Km^3 KPK (K)= 8.28 Km^3 **Total= 170.56 Km^3**	54.56
Scenario-3 (Minimum)	94.00 Km^3	Punjab (P)= 109.49 Km^3 Sindh (S)= 43.37 Km^3 Baluchistan (B)= 9.42 Km^3 KPK (K)= 8.28 Km^3 **Total= 170.56 Km^3**	76.56
Scenario-4 (5 in 10) (15% increase in water demands under future scenario)	125.61 Km^3	Punjab (P)= 126 Km^3 Sindh (S)= 49.87 Km^3 Baluchistan (B)= 10.83 Km^3 KPK (K)= 9.52 Km^3 **Total= 196.12 Km^3**	70.51

apportionment that shares the shortage among users is given by the PROP rule. CEA favors the agents having small claims whereas the CEL favors the agents having large claims. Talmud and Piniles rules have somewhat similar results and their results fall in between CEL and PROP rules.

The weighted water demands are shown in the Table 5.4. The Bankruptcy rules are then applied considering the weighted water demands and the results are shown in Figure 5.4. A comparison between Figures 5.3 and 5.4 highlight how weighted water requests modify BG assignments including priorities. From Figure 5.4, it is evident that due to their higher weights, KPK and Baluchistan are given more preference and hence their satisfaction level is more than Punjab and Sindh in

TABLE 5.3: Indus river basin core solutions (Km^3/ year and percentage with respect to existing resources).

Scenario-1 (Canal Diversion: 5 in 10)	**Scenario-2 (Canal Diversion: 8 in 10)**
x(P)+ x (S)+ x(B)+ x(K) = 125.61 64.54(51%) ≤ x(P) ≤ 109.49 (87%) 0(0%) ≤ x(S) ≤ 43.37 (34.5%) 0(0%) ≤ x(B) ≤ 9.42 (7.5%) 0(0%) ≤ x(P) ≤ 8.28 (6.6%)	x(P)+ x (S)+ x(B)+ x(K) = 116 54.93(44%) ≤ x(P) ≤ 109.49 (87%) 0(0%) ≤ x(S) ≤ 43.37 (34.5%) 0(0%) ≤ x(B) ≤ 9.42 (7.5%) 0(0%) ≤ x(P) ≤ 8.28 (6.6%)
Scenario-3 (Canal Diversion: Minimum)	**Scenario-4 (Canal Diversion: 5 in 10) (15% increase in water demands)**
x(P)+ x (S)+ x(B)+ x(K) = 94 33(35%) ≤ x(P) ≤ 94 (100%) 0(0%) ≤ x(S) ≤ 43.37 (34.5%) 0(0%) ≤ x(B) ≤ 9.42 (7.5%) 0(0%) ≤ x(P) ≤ 8.28 (6.6%)	x(P)+ x (S)+ x(B)+ x(K) = 125.61 55.28(44%) ≤ x(P) ≤ 125.61 (100%) 0(0%) ≤ x(S) ≤ 43.37 (34.5%) 0(0%) ≤ x(B) ≤ 9.42 (7.5%) 0(0%) ≤ x(P) ≤ 8.28 (6.6%)

almost all the Bankruptcy Rules, even when considering the minimum canal water diversions (Scenario 3). Moreover, the distribution rules used here give results that are still inside the core boundaries (Table 5.3) and they belong to the set of acceptable solutions satisfying efficiency, rationality, and marginality principles. The main advantage of the weighted bankruptcy rules is that it permits to consider the 'agricultural productivity' of provinces as a vital factor which may facilitate negotiations among riparian (agent) countries or provinces. Other factors such as 'groundwater usage' (discussed in chapter 4) and climate change can have undesirable effects on the basin. Therefore, the impact of climate change and groundwater usage can be considered in water allocation as well. This can potentially decrease future conflict over the negative aspects of climate change and increased groundwater usage. As shown in figure 5.4, the combined effect of "Agricultural Productivity" and "Groundwater Usage" can also be considered and weighted water demands of the provinces can be calculated. However, other measures will be required as well, such as increasing water use efficiency, improving water resource management.

Due to the complex nature of transboundary water allocation, we cannot be certain

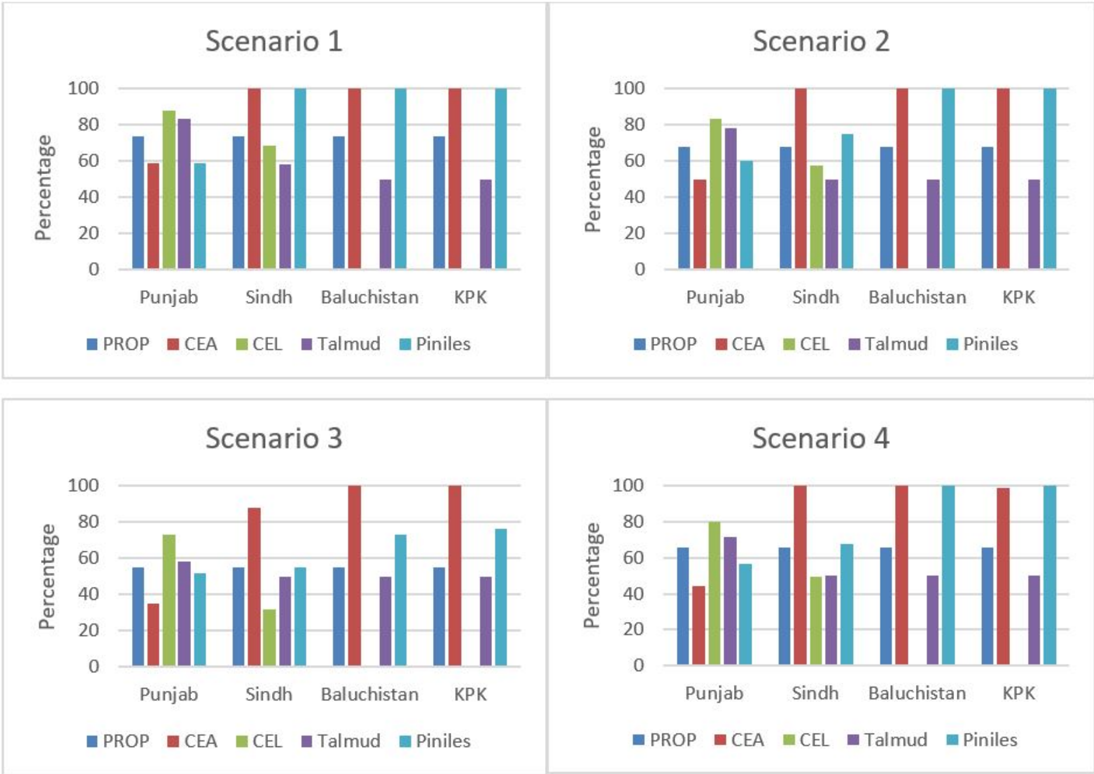

FIGURE 5.3: Division rule results (percentage with respect to individual water demand).

that the simple bankruptcy rules and the weighted bankruptcy rules will be able to solve all the problems related to shared water resource distribution. Water sharing is viewed differently by the people living in different regions, so their appreciation of the resource and the values attributed to the several functions of the water as a result of climatic, cultural and economic circumstances are different.

5.8 Conclusions

The water shortage issue can be a source of conflict among the riparian countries, states or provinces. This chapter examined the utility of bankruptcy rules in addressing the supply-demand gap in shared rivers. Five bankruptcy rules were used in this study to resolve the conflict amongst the provinces of Pakistan over the allocation of water. Apart from water scarcity, the uncertain and stochastic nature of river and the increasing water demands due to climate change makes the water

TABLE 5.4: Weighted water requests using priorities.

	Punjab (P)	**Sindh (S)**	**Baluchistan (B)**	**KPK (K)**	**Total**
Crop Production Per Acre Feet of Water (US$)	189	80	277	307	-
Weight	1.89	0.80	2.77	3.07	-
Actual Water Demand (Km^3/ year) **Scenario 1,2 and 3**	109.49	43.37	9.42	8.28	**170.56**
Weighted water Demand (Km^3/ year) **Scenario 1,2 and 3**	207.0	34.7	26.0	25.4	**293.1**
Actual Water Demand (Km^3/ year) **Scenario 4**	126	49.87	10.83	9.52	**196.12**
Weighted water Demand (Km^3/ year) **Scenario 4**	238.1	40	30	29.2	**337.3**

sharing mechanism more complex and challenging. The water allocation mechanism described in this study uses the Bankruptcy Game (BG) technique, which is a branch of cooperative game theory. The decision makers can use this approach for decision making under water scarce conditions. Using the five bankruptcy rules, the water allocation was done among the four provinces of Pakistan under four different critical scenarios. Also, the Bankruptcy Rules were applied again which included the water allocation priorities favoring the users which have a 'higher agricultural productivity'. From the results obtained, it can be seen that the 'Simple Bankruptcy Rules' and 'Weighted Bankruptcy Rules' can be an important tool for the decision makers to allocate the water in critical scarcity and uncertain conditions between the different water users. Although appropriate vision is provided by the allocation rules for the conflict management of transboundary water resources, the distribution of water among riparian can be a complex task that cannot be resolved only by mathematical approaches; therefore, water diplomacy and negotiation between the provinces of Pakistan are suggested, which would help them to develop a consensus and reach an agreement. This method can facilitate

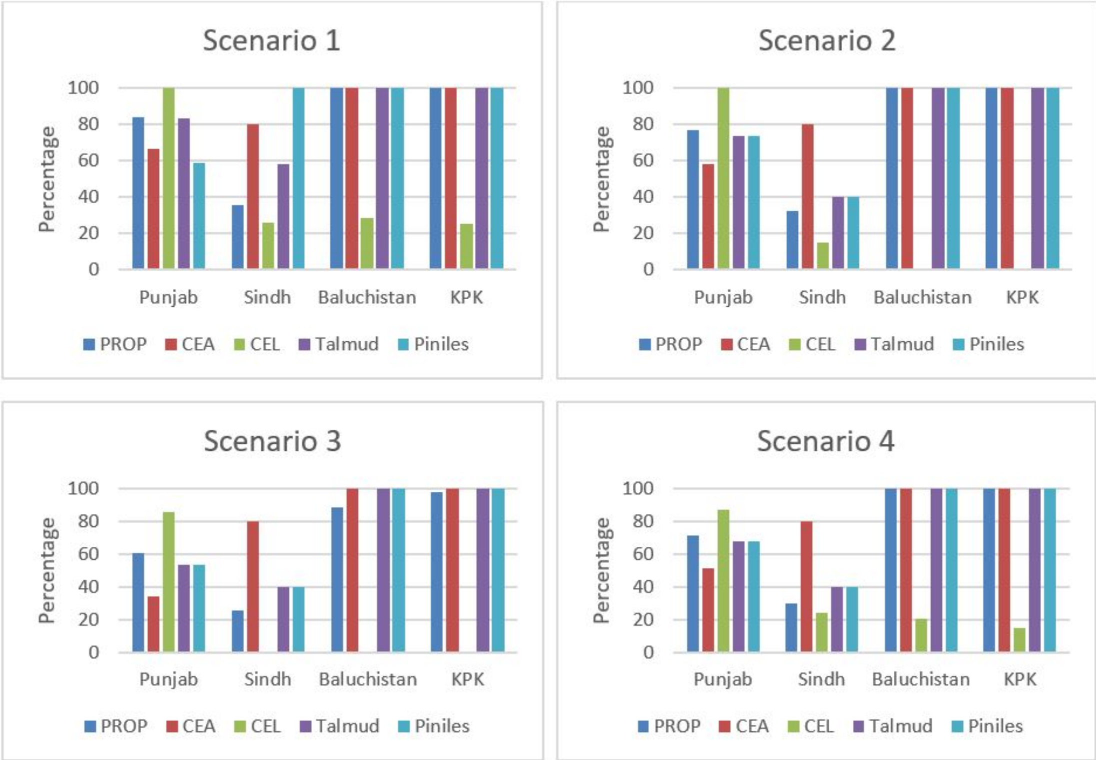

FIGURE 5.4: Division rule results using priorities (percentage with respect to individual water demand.

the negotiations and help the policy makers in managing the conflict and clash over water resources distribution problems.

Chapter 6

Addressing Supply-Demand Gap in Shared Rivers Using Water Diplomacy Framework: Utility of Game Theory in the Indus River Within Pakistan

6.1 Introduction

Conflicts related to the transboundary river basins (TRBs) are not new. The question of how to govern and manage TRB for human consumption, irrigation, hydropower, urban and industrial development, socio-cultural needs, and sustainability of ecosystems continues to be an issue of concern, conflict, and cooperation. Academic literature and policy practice suggest interactions of many natural, societal, and political elements (hereafter, elements will be used to mean variables, processes, actors and institutions within a TRB system) shape the nature and evolution of TRB dynamics. Challenges and opportunities associated with understanding, explaining, and managing the TRB issues are many. Context, complexity and contingency are terms that are now in frequent use in addressing TRB issues; yet, these terms are often vaguely defined and used in a colloquial sense. There are multiple schools of thought and scholarship (Wolf 1999); (Swain 2001); (Salman M A 2007); (Islam and Choudhury 2019); however, there appears to be a void of actionable ideas on *what to do and how.*

With the rise to prominence of TRB challenges on the global stage, concerns over water security and regional stability have become inextricably associated with many national and international agendas and initiatives supported by a wealth of academic literature and policy practice. In spite of its increasing sophistication, most of this literature remains wedded to implicit assumptions about values (e.g. that cooperation is desirable and is more cost effective than conflicts; yet, no formal agreements exist to most shared TRBs) and that engaging an array of methods, tools, governance structures, and institutions will yield a universal cure. These assumptions are rarely challenged; when faced with failure, it has become commonplace to assert that '*context matters',* but less has been done to show *why, when and how it matters and what can be done about it.*

This chapter will look at the supply-demand mismatch as a key attribute leading to complexity of TRB management. Although many technical solutions are discussed and debated to address this aspect of TRB management using a range of methods; yet, there appears to be no general consensus on how to effectively address this key aspect of TRB conflicts: supply-demand mismatch.

In order to deal with the Transboundary river basin water allocation problems, an efficient and effective way is to reframe them as joint decision-making problems - from identifying and defining the problem to innovating and implementing mutual gains options for resolutions - tasks that can generate politically legitimate policies and projects based on objective facts with the active participation of different stakeholders . An alternative to the traditional techno-focused approach to water management is provided by the Water Diplomacy Framework (WDF) (Islam and Susskind 2012). The WDF diagnoses water problems, identifies intervention points, and proposes sustainable and equitable resolutions that are sensitive to diverse viewpoints and uncertainty as well as changing and competing demands.

In addressing these types of multi-criteria multi-decision maker water problems where variables, processes, actors and institutions interact in complex ways one needs to look for optimal space – not universal optimal solutions – where solutions are not generalizable but contingent upon the constraints imposed by the context and capacity of the system. We use water allocation among four provinces within Pakistan to show how innovative game theoretic approaches along with the water diplomacy framework can be used as an effective tool to address supply-demand mismatch in the Indus basin.

A variety of frameworks, models and tools - from systems engineering, game theory, negotiation, and social choice methods – were used to address supply-demand mismatch of TRB conflicts. Game Theoretic approaches can be useful in situations when the market mechanism fails, and traditional systems optimization are not effective (Madani 2010); (Dinar and Hogarth 2015). The game theoretic approaches have been increasingly used to address TRB water allocation problems beginning with the pioneering work of Ransmeier, 1942 for the Tennessee Valley Authority investment project; yet, there appears to be no general consensus regarding which game theoretic approach works best for what type of TRB conflict and why. A key reason is that there is no prototypical TRB conflict as briefly discussed in highlighting different faces of TRB complexity. In this chapter, we will look at the utility of game theoretic approaches to address supply-demand gaps in TRBs using the Water Diplomacy Framework building on complexity science and negotiation theory (Islam and Susskind 2012).

An elegant mathematical formulation of cooperation and competition is provided by the game theory. Games can be classified as non-cooperative or cooperative. In the non-cooperative games, independent decisions are made by the players when they cannot or do not want to coordinate their bargaining plans or strategies. Players in the cooperative games cooperate in bargaining or by coalition forming and coordinating strategies to increase their benefits benefits (Tisdell and Harrison 1992). The cooperative game approach can define fair and efficient solutions that provide the appropriate incentives among the parties involved (Sechi et al. 2013). Several studies have been carried out in the past decades for the development of cooperative game models for water resource allocation problems.

A cooperative game theoretic framework was proposed (Wang 2003) in order to obtain a sustainable, efficient, and equitable scheme for water allocation among different agents in a river basin. A linear programming model was presented (Kucukmehmetoglu, Mehmet 2004) using the cooperative game theory framework for the water allocation among Turkey, Iran and Syria. A negotiation procedure and companion modelling approach were combined (Dinar and Farolfi 2006) to address the water allocation problem in Kat watershed in South Africa. Several cooperative game theoretic solutions like nucleolus, Nash-Haryansi, Shapley and the core were applied to the groundwater problem by Kaveh Madani and Dinar (2011). The water allocation problem in Southern Iran was addressed (Mahjouri and Ardestani 2011) by developing two non-cooperative and cooperative methodologies.

Fuzzy Cooperative games were developed for the fair and efficient water allocation among the user in Iran (Abed-Elmdoust and Kerachian 2012). In order to model the fuzzy cooperative games, Jafarzadegan, Abed-Elmdoust, and Kerachian (2013) developed a Fuzzy Variable Least Core method and applied it to inter-basin water transfer project in Iran. In order to maximize the net benefits to maximize the net benefits in Zarrinehrud River basin Iran, a two-level leader–follower model was applied (Safari et al. 2014). (Zomorodian et al. 2017) developed a cooperative game model for the optimum water allocation in the Langat River basin in Malaysia. (Degefu et al. 2018) applied the cooperative game theory allocation by combining the Nash bargaining theory and bankruptcy games for the water allocation among Syria, Iraq and Turkey.

Mianabadi et al. 2015 applied the Weighted Bankruptcy Rules for the water allocation in water bankrupt Tigris and Euphrates Basin. Different weights were assigned to the countries of Turkey, Syria and Iraq which are three main agents in this basin. (Degefu, Dagmawi Mulugeta 2016) considered the disagreement points and the bargaining weights of the agents to incorporate the concept of sustainability and fairness. But the main objective of many of these studies was to allocate water among the agents. Recently, TRB water management has also relied upon cooperative decision making through bargaining (Sgobbi 2011). The increase in water scarcity also increases the probability of the water sharing agreements being broken and this can be mitigated by the design of water allocation mechanisms which are flexible, realistic and self-enforcing (Degefu et al. 2018).

A synthesis of the bargaining solution process with the bankruptcy rules may provide a flexible framework to address TRB supply-demand mismatch in an effective way. The bargaining problems can be solved by various methods; but, much desired properties such as flexibility, invariance under change of scale, unanimity and Pareto optimality can be satisfied by the Nash bargaining solution (Nash Z 1950) (Nash 1953). Here, in addition to providing water allocation using Bankruptcy Rules and Nash bargaining solution, key ideas from water diplomacy framework is incorporated to emphasize the complexity of TRB problems and inadequacies of applying technical solutions without considering contextual conditions.

Each stakeholder usually competes to have a bigger share of available transboundary water resources. This creates a supply-demand mismatch and necessitates to model competitive and non-cooperative scenarios to guide the allocation of the limited resource. The Bankruptcy Rules are chosen to model this allocation problem for the Indus basin. The most important advantage in selecting these rules in comparison to the non-linear optimization problem modeled by Nash bargaining problem is their simplicity to understand and implement. If the stakeholders do not understand the model; usually, they will not participate in the problem solving and joint fact-finding process.

Consequently, the acceptance and implementation of the findings will not materialize. As WDF suggests joint fact-finding then co-creation of models to explore different options is the effective way to resolve conflicting needs and competing demands. Therefore, we will use the Nash Bargaining problem as a prototypical cooperative problem-solving tool. As the relation of these two different approaches, the results of the Nash Bargaining problem- as a cooperative game-could be a stable outcome of a non-cooperative game. It means that Bankruptcy rules provide "what could be at least-bottlenecks" in water allocation problem while Nash Bargaining provide "what could be-dreams" in the case of WDF if implemented.

The chapter is organized as follows: Section II discusses the methodology followed by a description of the Indus basin case study (Section III). Section IV discusses the results and Section V provides a summary of findings and concluding remarks.

6.2 Methodology

6.2.1 Water Diplomacy Framework

Due to the crossing of multiple boundaries and involvement of various stakeholders with conflicting and competing needs, the TRB issues are complex. If one views water as a limited resource, it may create damaging conflicts over its access and allocation; proper knowledge and information of water allocation and its use, however, can convert a finite water quantity into a flexible resource. A framework to synthesize scientific (explicit) and contextual (tacit) water knowledge is needed to generate such a transformative knowledge base for water. Such a framework needs to build on the objectivity of science and be cognizant of contextual differences inherent to water issues - Water Diplomacy Framework (WDF) initially proposed in (Islam and Susskind 2012) is a step in that direction. An evolving version of the WDF (Islam and Smith 2019) is based on the following premise:

- Water is not a fixed resource.
- Complexity of water problems arises from the coupling of natural and human systems.
- Solution space for these complex problems – with interdependent variables, processes, actors, and institutions - can't be pre-stated. The use of dualistic representations (numbers or narratives; facts or values; objective or subjective) for these problems is inadequate.
- Differentiate complexity from deterministic certainty and statistical uncertainty; instead, identify the conditions (rather than the cause) for emergent patterns.
- Use the rigor of scientific methods as the principle to derive facts with an adherence to a negotiated application of sustainability and equity as guiding values to design and implement pragmatic interventions.
- Focus on identifying and implementing societally relevant technological solutions given the context, constraints, and capacity of a given system.

To operationalize the WDF, in this chapter we will examine the utility of innovative cooperative and non-cooperative game theoretic approaches to address supply-demand mismatch to develop effective TRB management strategies.

6.2.2 Water Allocation Using Simple Bankruptcy Rules

The bankruptcy methods are used in economics when the available asset (resource) is not adequate to satisfy the claim of creditors (stakeholders) (Curiel et al. 1987), (Dagan and Volij 1993), (Kaveh 2013). For its relative simplicity and wide applications, we will begin with the bankruptcy rules to allocate water in shared Indus River within Pakistan. Here, five classical rules of Bankruptcy are used for the allocation of the resource among the stakeholders when the total assets are not enough to satisfy the needs of all stakeholders. It will be followed by water allocation strategies using asymmetric Nash bargaining theory combined with water Bankruptcy Concept.

Let 'n' be the number of claimants. The claimants are n $\geq$ 2 and their claims are $C_i \geq 0$; $C = (C_1,\ldots,C_n)$. In river systems, a bankruptcy problem is defined as F (N, E, C_i, a_i); $i = 1, 2,\ldots, n$, where N = no of agents, E = total resources, C_i = claim of the agent i and a_i = contribution of the agent i. The bankruptcy method aims to determine the allocation of each agent, denoted by F (N, E, C_i, a_i) = x_i where $x_i \geq 0$; $x = (x_i,\ldots, x_n)$. In case of a resource allocation problem, we have relationships in the form of Equations (6.1) to (6.4):

$$\text{E}= \sum_{i=1}^{n} a_i \tag{6.1}$$

$$\text{C} = \sum_{i=1}^{n} C_i \tag{6.2}$$

$$\sum_{i=1}^{n} a_i = \sum_{i=1}^{n} x_i \tag{6.3}$$

$$0 \leq x_i \leq C_i \tag{6.4}$$

Where Equation (6.1) and (6.2) are the contribution and claims of the agents respectively. Equation (6.3) states that the assets are fully allocated. Equation (6.4) states that the allocation cannot exceed its claims can never be negative. The bankruptcy rules are given below which have also been discussed previously in Chapter 4 and 5.

These Bankruptcy rules are primarily based on mathematical formulation of the strategic behavior of the stakeholders, in circumstances where one stakeholder's decisions may affect other stakeholders. It consists of a modeling part and a solution part. Mathematical description of cooperation and conflict provide strategic behavioral patterns, and the resulting payoffs to the players are determined according to certain solution concepts. These rules work well when TRB conflicts are only about allocation outcomes. When TRB conflicts are rooted the allocation outcomes along with the allocation processes also matter and we need more than an elegant mathematical solution. For example: Who decides what criteria to choose among the competing bankruptcy rules? Is agricultural productivity more important than ecological sustainability of the Indus basin while allocating water? Can (and how much) groundwater be used to supplant the supply-demand mismatch of available surface water for the Indus basin within Pakistan? These questions cannot be addressed by pure technical solutions like the bankruptcy rules. We need an allocation process with certain desirable properties like equity and sustainability as discussed in the water diplomacy framework.

6.2.3 Water Allocation Using a Combination of Asymmetric Nash Bargaining Theory Water Bankruptcy Concept

Building on earlier work (Safari et al. 2014); (Houba 2013); (Sgobbi 2011); (Degefu, Dagmawi Mulugeta 2016)(Degefu, Dagmawi Mulugeta 2016); and (Qin et al. 2019),) and using equity and sustainability as guiding principles from the water diplomacy framework, we plan to use a water allocation framework which combines the asymmetric Nash bargaining solution concept with the bankruptcy theory for solving the water sharing problem among four provinces within Pakistan.

During the water bankruptcy situations, the water allocation problem can be formulated as (N, E, C, x^-), here, N is the number of agents involved in a water dispute, E is the total amount of water available for sharing among the agents, C is the amount of water claimed by the agents and x^- is the amount of water allocated to the agents. In this step, Asymmetric Nash bargaining theory is combined with the bankruptcy concept and applied in the transboundary river basin for the allocation of water under scarcity. While applying this methodology, the disagreement allocation points (m_1, m_2, m_3,..., m_n) and the bargaining weights ($w_i = w_1, w_2, w_3, \ldots, w_n$) of the agents were also considered to ensure equity and self-enforceability in a closed and bounded space. Apart from having a unique solution, such optimization solution also satisfies a set of desirable properties. The area between the disagreement point (m_i) and pareto-optimal frontier (x^-) is satisfied by the solution.

The disagreement points can be determined by the Nash equilibrium point, the minimum benefit of each agent, the maximum and the minimum point and by other methods. In our case, vector of disagreement points (d_1, d_2,... di, ...d_n) are defined as the benefits of minimum water allocation (I_1, I_2,..., I_n) to the agents. This represents the minimum benefits that the agents can accept. It is therefore necessary that the individual rationality requirements are reflected before the cooperation of the followers so that the maximal and minimal solutions are satisfied. For each agent, the disagreement point formula is defined as:

$$d_i = u_i(m_i) \tag{6.5}$$

In order to solve the problem of minimal water allocation to each agent, the bankruptcy theory can be used when the total available water is less than the total water demands. The minimal water allocation formula for each agent is given by:

$$m_i = \max(0,\ E - \sum_{k\ \neq i} (C_i)) \tag{6.6}$$

Subject to:

$$E < \sum_{i=1}^{n} C_i \tag{6.7}$$

The minimum water allocation to any agent, especially to the agents with smaller claims may become zero if we use the above method of Bankruptcy Theory for the minimum water allocation. However, each agent will demand a minimum amount of water λ_i in the process of water resource allocation. The minimum water required by each agent may be more than the minimum water allocation if we use the above theory of bankruptcy. Therefore, we propose a new formula to avoid the case of unreasonable minimum water allocation by bankruptcy theory. This formula determines the minimum water allocation and considers the minimum requirement for each agent and is given by:

$$I_i = \max(\ \lambda_i,\ \text{E}- \sum_{k\ \neq i} c_i) \tag{6.8}$$

Where λ_i is the minimum water requirement of each agent which in our study is taken as half of the claim of any agent.

For the optimization problem, the respective water claims of the agents serve as the upper bound core. According to (Harsanyi 1982), the optimization problem for the allocation of water under bankruptcy scenario is given by:

$$\begin{aligned} maximize N^{wi} = & \left(x_1^- - \left(E - \sum_{i \in N/1} C_i\right)\right)^{w_1} \left(x_2^- - \left(E - \sum_{i \in N/2} C_i\right)\right)^{w_2} \\ & \left(x_3^- - \left(E - \sum_{i \in N/3} C_i\right)\right)^{w_3} \cdots \left(x_n^- - \left(E - \sum_{i \in N/n} C_i\right)\right)^{w_n} \end{aligned} \tag{6.9}$$

The above model is constraint by feasibility and individual rationality. The claims and the disagreement points serve as the upper and the lower bounds respectively. The river sharing optimization problem in Pakistan's Indus Basin can be formulated as below:

$$\begin{aligned} maximize N^{wi} = & \left(x_p^- - \left(E - \sum_{i \in N/P} C_i\right)\right)^{w_p} \left(x_S^- - \left(E - \sum_{i \in N/S} C_i\right)\right)^{w_S} \\ & \left(x_B^- - \left(E - \sum_{i \in N/B} C_i\right)\right)^{w_B} \left(x_K^- - \left(E - \sum_{i \in N/K} C_i\right)\right)^{w_K} \end{aligned} \tag{6.10}$$

$$Maximize N^{wi} = \left(x_1^- - \left(E - \sum_{i \in N/1} C_i\right)\right)^{w_1} \left(x_2^- - \left(E - \sum_{i \in N/2} C_i\right)\right)^{w_2} \left(x_3^- - \left(E - \sum_{i \in N/3} C_i\right)\right)^{w_3} \cdots \left(x_n^- - \left(E - \sum_{i \in N/n} C_i\right)\right)^{w_n} \tag{6.11}$$

The above model is constraint by feasibility and individual rationality. The claims and the disagreement points serve as the upper and the lower bounds respectively. The river sharing optimization problem in Pakistan's Indus Basin can be formulated as below:

$$Maximize N^{wi} = \left(x_p^- - \left(E - \sum_{i \in N/P} C_i\right)\right)^{w_p} \left(x_S^- - \left(E - \sum_{i \in N/S} C_i\right)\right)^{w_S} \left(x_B^- - \left(E - \sum_{i \in N/B} C_i\right)\right)^{w_B} \left(x_K^- - \left(E - \sum_{i \in N/K} C_i\right)\right)^{w_K} \tag{6.12}$$

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

In Equation (6.17)

x_P^- is the optimized water allocation for Punjab.

I_P is the lower core bound for Punjab.

x_S^- is the optimized water allocation for Sindh.

I_S is the lower core bound for Sindh.

x_B^- is the optimized water allocation for Baluchistan.

I_B is the lower core bound for Baluchistan.

x_K^- is the optimized water allocation for Khyber Pakhtunkhwa (KPK).

I_K is the lower core bound for Khyber Pakhtunkhwa (KPK).

The following constraints should be set for this allocation model;

1. The allocation of water to each agent (province) should be more than or equal to its lower core bound.

$$x_i^- \leq I_i \; i \; = \; 1, 2, \cdots, n \tag{6.13}$$

2. The water allocation to each agent (province) should be more than its lower core bound and less than its claim.

$$I_i \leq x_i^- \leq c_i \tag{6.14}$$

3. The total water allocation in the basin should be equal to or less than the total available water.

$$\sum_{i \, = \, 1}^{n} x_i^- \; \leq \; E \tag{6.15}$$

6.2.3.1 Determination of Bargaining Weights

The optimization model in Equation (6.17) is applied to the Indus River Basin in Pakistan. In this article three cases were analyzed. The bargaining weights of all the provinces in the first case were assumed to be equal. According to (Kalai 1977), asymmetric Nash solutions induce symmetric Nash solutions and the converse is also true. All the agents provinces in reality are different in terms of their environmental and socio-economic status and hence they have a different groundwater usage, therefore in the second case, the bargaining weights of the agent provinces were taken according to their groundwater usage to show the importance of using different bargaining weights. The total groundwater potential in Pakistan is about 68 km^3 out of which 60.5 km^3 is being extracted. Punjab is extracting 54 km^3 of groundwater, Sindh 3.1 km^3, KPK 2.5 km^3 and Baluchistan 1.2 km^3 (Ghazanfar 2009). According to these usages of groundwater, the bargaining weights for the provinces of Punjab, Sindh, Baluchistan and KPK come out to be 0.05, 0.20, 0.25, 0.50 respectively. These bargaining weights are inversely proportional to their rate of groundwater usage, that is, the greater the groundwater usage, the lesser will be the bargaining weight of the province. In the third case, the bargaining weights of the agents were taken in terms of their crop productivity. Higher crop productivity will lead to higher weight and hence, more allocation. The groundwater usage of the provinces in cubic kilometers, their crop production benefits Per Cubic Kilometer of Water (Billion US $) and their population (in Millions) are shown in Table 6.1.

TABLE 6.1: Groundwater usage of the four Provinces, water benefits (in millions), per cubic kilometer of water and population (in Millions).

	Punjab (P)	**Sindh (S)**	**Baluchistan (B)**	**KPK (K)**
Groundwater Usage of the Provinces (Cubic Kilometers)	54.0	3.1	2.5	1.2
Crop Production Benefits, Per Cubic Kilometer of Water (Billion US $)	153	65	224	249
Population (in Millions)	110	48	12	30

6.2.4 Sharing of Mutual Benefits Using Nash Bargaining Theory

After the water resources to each agent are allocated, the next stage is to distribute the maximum monetary benefits among the agents (provinces). Asymmetric Nash bargaining theory was once again applied, this time, for the allocation of the monetary benefits among the agents. The minimum benefits or welfare allocation for each agent are given by:

$$I_i = \max(\ \lambda_i,\ \mathrm{T}-\sum_{k\ \neq i} B_i) \tag{6.16}$$

where

I_i is the minimum benefit which the agent is willing to accept

T is the total benefits,

B_i is the benefit claimed by the agent i

λ_i is the minimum benefit for each agent which in our study is taken as half of the benefit claim of agent i.

The maximum benefit a agent can secure if it is rewarded with its full water claim, that is, ($w_{Max_i} = \propto_i c_i$) is the upper bound. Here $\propto_i$ is the benefit per Km^3 of water in million (US$). The economic bankruptcy problem arises in these cases when the total benefit claims of the agent provinces or countries are more than the total maximized welfare. During these bankruptcy situations, the welfare allocation problem can be written as ($N,\ W_T,\ w_{Max},\ w_i$). Here, N is the number of agent provinces or countries, W_T is the total welfare that can be divided among the agents, w_{Max} is the benefit of the agent province or the country i and w_i is the optimized welfare or benefit variable to agent province or country i. For the basin sharing provinces or countries, the utility function can be defined as linear interval function. Hence, the function can be formulated as follows considering their welfare claims, disagreement welfare apportionments and optimized welfare assignments of agent states.

$$f_i\ (w_i) \ = \ \frac{w_i \ - \ w_i^-}{w_{Maxi} - w_i^-} \tag{6.17}$$

The below equation is used for the value of disagreement utility:

$$d_i \ = \ f_i\ (w_i^-) \tag{6.18}$$

The Nash optimization solution (Fu et al. 2018) is again applied for the for the allocation of total water benefits. The optimization problem can be modified according to (Harsanyi 1982) and the bargaining weights of the agents can also be considered. In this allocation, the bargaining weights are taken are different from the bargaining weights assigned to the agent states when allocating the scarce water resource. These weights are based on the population of each province (Table 6.1). The reason for assigning the weights on the basis of population was that every province has different population dependent on it and the allocation of the benefits by assigning equal weights to each province might not be accepted by every province. The weighted welfare distribution problem for the case considered in this study can be written as the following.

$$
\begin{aligned}
Maximize N^{w_i} = & (f_P(w_P) - d_{w_P})^{w_P} (f_S(w_S) - d_{w_S})^{w_S} (f_B(w_B) - d_{w_B})^{w_B} \\
& (f_K(w_K) - d_{w_K})^{w_K}
\end{aligned} \tag{6.19}
$$

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

where

$f_P(w_P)$ is the functional utility of Punjab.

d_{w_P} is the lower core bound for Punjab.

$f_S(w_S)$ is the functional utility of Sindh.

d_{w_S} is the lower core bound for Sindh.

$f_B(w_B)$ is the functional utility of Baluchistan.

d_{w_B} is the lower core bound for Baluchistan.

$f_K(w_k)$ is the functional utility of KPK.

d_{w_K} is the lower core bound for KPK.

The feasibility space of this optimization problem is assumed to be closed, convex and bounded. Both the feasibility and individual rationality should be satisfied by this optimization problem.

$$\sum_{i \in N} w_i = W_{Total} \tag{6.20}$$

And

$$w_i^- \ \leq \ w_i \leq \ w_{Maxi} \tag{6.21}$$

6.3 Case Study

Pakistan is a home to sixth largest population in the world. There exist four administrative units in the country or the four provinces namely Punjab, Sindh, Baluchistan and Khyber Pakhtunkhwa. It also consists of small areas of Gilgit-Baltistan and Federally Administered Tribal Areas. Agriculture contributes significantly towards the country's economy and accounts for almost 19.8% of the gross domestic product (GDP) (Anwar and Bhatti 2017). Out of the 27% of the cultivated land in Pakistan, Punjab has the highest proportion (63%), followed by Sindh (18%) and the remainder is equally divided between the provinces of Baluchistan and Khyber Pakhtunkhwa (ACO (Agricultural Census Organization) 2010).

The interprovincial water sharing of the surface waters in Pakistan is currently governed by the Water Apportionment Accord of 1991. The main aim of the Accord was to build the trust among the provinces of Pakistan. Unfortunately, this accord does not adapt to the changing conditions over the time and hence it can be considered as "a glass half empty and half full". The current water distributions among the provinces of Pakistan as per the water apportionment accord are given in Table 3.1. IRSA is mainly responsible for the water allocation among the provinces. The main shortcomings of the Water Apportionment Accord of 1991 are highlighted below.

The average canal diversions in post-Tarbela periods have only been 127 Km^3 which is less than the accord's entitlements of 144.87 Km^3 as shown in Table 3.1. This creates problems among the Provinces of Pakistan when they have to share shortages as there is no defined mechanism to share the water shortages (Condon et al. 2014). Currently, the two small provinces, Baluchistan and Khyber Pakhtunkhwa (KPK) are exempted by the water shortages by an act of 2003. Thus, whenever the total volume falls, the deficiencies are shared by Sindh and Punjab (Condon et al. 2014). Thus, there is no proper mechanism of water distribution when the total volume falls short or when the demands of the provinces exceed the total available water. Also, Khyber Pakhtunkhwa (KPK) and Baluchistan have not yet developed their irrigation system properly, therefore, they always get more water than they can use.

Another serious problem in the Water Apportionment Accord is that the water allocations are fixed which create a quantified entitlement. Fixed water allocations mechanisms can lead to the water allocations which are unacceptable for the provinces, especially in the uncertainty, draughts and the stochastic nature of River flow. The Water Apportionment Accord between the provinces of Pakistan was signed almost twenty-eight years ago. Since then, the water demands of the provinces have changed due to the increase in the population and the irrigated area. Therefore, the gap between the water supply and water demand has increased considerably in Pakistan. Several features and attributes of the Indus river disputes are described below:

6.3.1 Surface Water Diversions

The water of Indus River and its tributaries is shared among all the four provinces of Pakistan. River flows are mainly supplied by rainfall, snowmelt, glacier melt and runoff. According to Indus River System Authority, the median canal diversions from 1975 to 2013 were 130 Km^3, (Hassan 2016).

6.3.2 Groundwater Availability

The total groundwater potential in Pakistan is about 68 km^3 out of which 60.5 km^3 is being extracted. Punjab is extracting 54 km^3 of groundwater, Sindh 3.1 km^3, KPK 2.5 km^3 and Baluchistan 1.2 km^3 (Ghazanfar 2009).

6.3.3 Agricultural Water Requirements for Pakistan

According to the study as stated in Chapter 4, the agriculture water requirements for Pakistan are 157.25 Km^3 (excluding the environmental flows). The water required downstream of Kotri as 'Environmental flows' for the province of Sindh is 12.3 Km^3. The 1991 Water Accord between the provinces also recognized the requirement for a residual flow to the delta of 12.3 Km^3, no institutional mechanism or policy has yet been adopted to make the allocations for environmental flow(Archer et al. 2010). The total water requirement for Pakistan is 170.56 Km^3, which also includes 12.3 Km^3 as environmental flows for the province of Sindh. Punjab had the highest water requirements (109.48 Km^3) followed by Sindh (43.07

Km^3), Baluchistan (9.41 Km^3) and KPK (8.27 Km^3) as shown in Table 6.2. According to the report published by the Ministry of Food, Agriculture and Livestock Islamabad, in 2004, the total agricultural water requirements in Pakistan would be around 150 Km^3 by 2020 (Hanif et al. 2004). According to (Ahmad 2012), "The crop water requirements would be 154.5 Km^3 by 2020". The estimates in these two reports suggest that the agricultural water requirements of 157.25 Km^3 is reliable.

TABLE 6.2: Water Requirements of Various Crops.

Water Requirements for Various Crops	**Punjab km^3**	**Sindh km^3**	**KPK km^3**	**Baluchistan km^3**	**Total km^3**
Wheat	26.72	5.17	3.05	1.20	36.12
Rice	17.66	3.97	0.41	2.10	24.16
Cotton	14.29	2.97	0.00	0.20	17.46
Sugarcane	8.07	2.72	0.88	0.01	11.68
Maize	2.04	0.01	1.69	0.02	3.76
Barley	0.10	0.04	0.10	0.04	0.28
Other Crops	40.62	15.20	2.14	5.85	63.80
All Crops	109.49	31.07	8.28	9.42	157.25
All Crops after Sindh's requirement for environmental flows	109.49	43.37	8.28	9.42	170.56

Note: The Requirements for Sindh includes an additional 12.3 Km^3 as Environmental Flows

6.3.4 Water Diversions of Indus River and Water Deficit in Indus Basin

Qureshi (2011) stated that 128 Km^3 of water is diverted for irrigation; According to (Hussain et al. 2011), the total water supply for the agriculture sector is 130 km^3. From the above figures, if we take the total surface water diversions for agriculture to be 130 Km^3 the total deficit, that is, the difference between the Water demand and Water availability comes out to be 40.56 Km^3.

One might argue that the total surface water diversions for agriculture are 130 Km^3 and ground water extractions are almost 60.1 Km^3, which, in total comes out to be 190.1 Km^3 and the total agricultural water requirements are calculated as 170.56 Km^3 (Table 6.2), therefore there is no deficit. The reason of water shortage, and hence, the deficit is the low canal water efficiency in the River System which leads to the overexploitation of the groundwater. According to (Ahmad 2009), "approximately 124 Km^3 is provided by the canal diversions out of which 54.5 Km^3 is lost through water conveyance. Therefore, only 69.5 Km^3, is available at the farm head, with an additional 62 Km^3, from groundwater pumpage, totaling a net water amount of 129.5 Km^3". Therefore, our available water remains almost 130 Km^3, hence, the water deficit still exists. According to another report of "International Union for Conservation of Nature and Natural Resources" published in 2014, "out of an average 128.3 Km^3 of river flows diverted for canal irrigation about 54 Km^3 is lost in conveyance and only 74 Km^3 reaches the farm head (International Union for Conservation of Nature and Natural Resources 2014). The study of these two reports suggests that the water deficit of almost 40 Km^3 exists even with the over-exploitation of groundwater.

6.4 Results

Table 6.3 shows the results when the water allocation is done among the provinces of Pakistan using the five commonly used bankruptcy rules. The water demands or claims of the provinces of Pakistan are 170.56 Km^3, whereas the total available surface water is 130 Km^3 due to which river sharing problem arises. The results of these bankruptcy rules suggest that different provinces might prefer different rules based on their preference. As these bankruptcy rules do not consider other factors such as population in each province, water use efficiency and amount of groundwater usage for each province; these rules might not be acceptable for some provinces. For the consideration of these factors, Nash bargaining method was used for the allocation of water which incorporates these factors for water allocation among the provinces. Table 6.4 shows the distribution of water among the Provinces of Pakistan in the Indus Basin by applying the Nash bargaining method. The Nash bargaining method is applied under three scenarios. In the first scenario, the provinces are assigned equal weights. In the second scenario, the provinces are assigned weights as per their groundwater usage (more groundwater usage leads to less weight) whereas in the third scenario, the provinces are assigned weights according to their agricultural productivity (more agricultural productivity leads to high weight). The Groundwater Usage of the four Provinces (Ghazanfar 2009) and their agricultural productivity in the form of Water benefits (in millions) Per Cubic Kilometer of Water (PWP 2001) are shown in Table 6.1. The water allocation among the riparians at this stage is done by using the water allocation framework as proposed by (Degefu, Dagmawi Mulugeta 2016), which is a combination of asymmetric Nash bargaining solution method and Bankruptcy theory. The Nash bargaining solution allocates 73%, 83%, 100% and 100% of the water claims to Punjab, Sindh, Baluchistan and KPK respectively under the homogenous weights, whereas the allocation percentage for the second scenario under the heterogenous weights (bases on groundwater use) comes out to be 66%, 100%, 100% and 100% respectively. This is due to the fact that the province of Punjab uses a majority portion of the groundwater in Pakistan. In the third scenario, when the provinces are assigned the weights as per their increasing agricultural productivity, the water claims of the provinces come out to be 77%, 71%, 100% and 100% respectively. This is due to the fact that the provinces of Baluchistan and KPK and Punjab have high agricultural productivity whereas Sindh has the lowest, therefore the water allocation for Sindh is reduced. As discussed, these weights are based on the Groundwater usage and the Agricultural Productivity of the provinces. More equity is ensured by accommodating these weights in the allocation process as it enables us to account other aspects and sources of asymmetries among the provinces or riparians other than just their water claims and their disagreement points. The water allocation using the Nash bargaining concept with the results shown in the Table 6.4 considers important variables such as the bargaining weights and the minimum acceptable water demands which are needed for the to ensure the principles of efficiency, sustainability and equity (Degefu, Dagmawi Mulugeta 2016).

TABLE 6.3: Water allocation for the provinces of Pakistan's Indus Basin using bankruptcy rules.

Total Available Water = 130 Km^3				
Total Water Claims of the Riparians (Provinces of Pakistan) = 170.56 Km^3				
	Riparian Province (n)	**Water Demand (Km^3)**	**Water Allocation x_i (Km^3)**	**Allocation Percentage ($p\%$)**
Proportionate Rule (PRO)	Punjab	109.49	83.45	76
	Sindh	43.37	33	76
	Baluchistan	9.42	7.17	76
	KPK	8.28	6.31	76
Constraint Equal Award Rule (CEA)	Punjab	109.49	68.93	63
	Sindh	43.37	43.37	100
	Baluchistan	9.42	9.42	100
	KPK	8.28	8.28	100
Constraint Equal Loss Rule (CEL)	Punjab	109.49	98.06	89
	Sindh	43.37	31.94	77
	Baluchistan	9.42	0	0
	KPK	8.28	0	0
Talmud Rule (TAL)	Punjab	109.49	93.635	85
	Sindh	43.37	27.515	63
	Baluchistan	9.42	4.71	50
	KPK	8.28	4.14	50
Piniles Rule (PIN)	Punjab	109.49	72.68	66
	Sindh	43.37	39.62	84
	Baluchistan	9.42	9.42	100
	KPK	8.28	8.28	100

Table 6.5 shows the total monetary benefits generated when the distribution of water is done using Bankruptcy Rules and Water Apportionment Accord (1991). As per IRSA act, the provinces of Baluchistan and Khyber Pakhtunkhwa (KPK) were exempted by the water shortages. Whenever the total volume falls, the deficiencies are shared by Sindh and Punjab. Table 6.6 shows the monetary benefits

TABLE 6.4: Water allocation for the Provinces of Pakistan's Indus Basin using Nash bargaining theory.

Total Available Water = 130 Km^3						
Total Water Claims of the Riparians (Provinces of Pakistan) = 170.56 Km^3						
	Riparian Province (n)	**Water Demand (Km3)**	**Bargaining Weights (wi)**	**Disagreement Point mi (Km3)**	**Optimization Results xi (Km3)**	**Allocation Percentage (p %)**
Water Allocation Using Homogeneous Weights	Punjab	109.49	0.25	68.93	80.36	73
	Sindh	43.37	0.25	21.68	35.83	83
	Baluchistan	9.42	0.25	4.71	9.42	100
	KPK	8.28	0.25	4.14	8.28	100
Water Allocation Using Heterogenous Weights (Based on Groundwater Use)	Punjab	109.49	0.05	68.93	72.82	66
	Sindh	43.37	0.2	21.68	43.37	100
	Baluchistan	9.42	0.25	4.71	9.42	100
	KPK	8.28	0.5	4.14	8.28	100
Water Allocation Using Heterogenous Weights (Based on Crop Productivity)	Punjab	109.49	0.22	68.93	85.14	77
	Sindh	43.37	0.10	21.68	31.05	71
	Baluchistan	9.42	0.32	4.71	9.42	100
	KPK	8.28	0.36	4.14	8.28	100

generated when the water is distributed using Nash bargaining solution under the three scenarios. It can be seen from these results that the total monetary benefits are the highest when the water distribution is done using the Nash bargaining theory under the third scenario (based on crop productivity).

After the allocation of water using the Bankruptcy Rules and Nash bargaining theory and the extraction of the maximum benefits out of the water resource, this benefit is distributed among the provinces of Pakistan by again applying the Nash bargaining procedure. The maximum welfare a riparian state can secure with its full water claim is the benefit demand of the province or the upper bound. Variables such as upper core bound, lower core bound, and the bargaining weights are taken into account for the welfare allocation procedure which distributes the benefits by utilizing the water efficiently. Hence, the benefits distribution is constrained by the fairness and sustainability principles.

The results for the allocation of benefits are shown in Table 6.7 using homogenous and heterogenous weights. The heterogenous weights are taken based on the population living in each province, as this will ensure the principle of equity among the riparians. As shown in the Table 6.7, when the optimization is done using the homogenous weights, the three provinces of Sindh, Baluchistan and KPK get 100 percent of their claimed benefits, whereas the Punjab gets 73 percent of its

Table 6.5: Total water benefits from water allocation by Bankruptcy rules.

Total Available Water = 130 Km^3						
Total Water Claims of the Riparian (agent) (Provinces of Pakistan) = 170.56 Km^3						
	Riparian (agent) Province (n)	**Water Demand (Km^3)**	**Crop Production Benefits, Per Cubic Kilometer of Water (Million US$)**	**Water Allocation (x_i), in Km^3**	**Water Allocation Percentage**	**Total Benefits from Water Allocation (Million US$)**
Proportionate Rule (PRO)	Punjab	109.49	153	83.45	76	12768
	Sindh	43.37	65	33	76	2145
	Baluchistan	9.42	224	7.17	76	1606
	KPK	8.28	249	6.31	76	1571
	Total					**18090**
Constraint Equal Award Rule (CEA)	Punjab	109.49	153	68.93	63	10546
	Sindh	43.37	65	43.37	100	2816
	Baluchistan	9.42	224	9.42	100	2110
	KPK	8.28	249	8.28	100	2062
	Total					**17534**
Constraint Equal Loss Rule (CEL)	Punjab	109.49	153	98.06	89	15003
	Sindh	43.37	65	31.94	77	2459
	Baluchistan	9.42	224	0	0	0
	KPK	8.28	249	0	0	0
	Total					**17462**
Talmud Rule (TAL)	Punjab	109.49	153	93.635	85	14326
	Sindh	43.37	65	27.515	63	1789
	Baluchistan	9.42	224	4.71	50	1055
	KPK	8.28	249	4.14	50	1031
	Total					**18201**
Piniles Rule (PIN)	Punjab	109.49	153	72.68	66	11120
	Sindh	43.37	65	39.62	84	2575
	Baluchistan	9.42	224	9.42	100	2110
	KPK	8.28	249	8.28	100	2062
	Total					**17867**
WAA, 1991	Punjab	109.49	153	59	53	9027
	Sindh	43.37	65	59	100	3835
	Baluchistan	9.42	224	4.78	51	1071
	KPK	8.28	249	7.13	86	1775
	Total					**15708**

claimed benefits. The allocation of water using the heterogenous weights, which were based on the population of each province, gave Sindh and KPK 100 and 96 percent of their benefit claims respectively, while Punjab's allocation was increased to 77 percent and Baluchistan's allocation was reduced to 68 percent. The decrease in the benefit allocation to Baluchistan using heterogenous weights was due to the fact that Baluchistan has a very small population as compared to the other three provinces which is also shown in Table 6.1.

The maximum total benefit made by using different Bankruptcy methods and WAA of 1991, based on Table 6.5 is 18090 million US$ while the benefit made

Table 6.6: Total water benefits from water allocation by Nash bargaining solution.

Total Available Water = 130 Km^3						
Total Water Claims of the Riparians (Provinces of Pakistan) = 170.56 Km^3						
	Riparian Province (n)	**Water Demand (Km^3)**	**Crop Production Benefits, Per Cubic Kilometer of Water (Million US $)**	**Water Allocation (x_i), in Km^3**	**Water Allocation in %**	**Total Benefits from Water Allocation (Million US$)**
(Scenario 1) Water Allocation Using Homogeneous Weights	Punjab	109.49	153	80.36	73	12336
	Sindh	43.37	65	35.83	83	2329
	Baluchistan	9.42	224	9.42	100	2110
	KPK	8.28	249	8.28	100	2062
	Total					**18,837**
(Scenario 2) Water Allocation Using Heterogenous Weights (Based on Groundwater Use)	Punjab	109.49	153	72.82	66	11141
	Sindh	43.37	65	43.37	100	2819
	Baluchistan	9.42	224	9.42	100	2110
	KPK	8.28	249	8.28	100	2062
	Total					**18132**
(Scenario 3) Water Allocation Using Heterogenous Weights (Based on Crop Productivity)	Punjab	109.49	153	85.14	77	13026
	Sindh	43.37	65	31.05	71	2018
	Baluchistan	9.42	224	9.42	100	2110
	KPK	8.28	249	8.28	100	2062
	Total					**19216**

by using the Nash bargaining approach is 19216 million US$ based on Table 6.6. Then moving from the non-cooperative approach of Bankruptcy to the cooperative approach of Nash, results in 6.2% increase in the total monetary benefit.

In the allocation of benefits using the Nash bargaining theory, the reason for assigning the weights based on the population was that each provinces have different populations dependent on it and the distribution of benefits using homogenous weights might not be acceptable for some provinces, especially for the provinces which have more population. From Table 6.1, it can be seen that the province of Punjab has a population of almost 110 million, Sindh 48 million, Baluchistan 12 million and KPK 30 million. The Nash bargaining theory using homogenous weights allocates almost equal benefits to Sindh, Baluchistan and KPK (Table 6.7). The results might not be acceptable for Punjab as it has the largest population among the four provinces, therefore, water allocation using heterogenous weights (based on population) would ensure equity among all the provinces as it allocates the benefits among the provinces as per population as shown in Table 6.7.

Table 6.7: Sharing of benefits among the Provinces using optimization.

Total Benefits = 19216 Million US$								
Total Benefit Claims of the Riparians (Provinces of Pakistan) = 23743 Million US$								
	Riparian Province (n)	**Maximum Value (c_i), in Million dollars**	**Population in millions**	**Bargaining Weights (w_i)**	**Disagreement Point (m_i)**	**Optimization Results (x_i)**	**Benefit Allocation Percentage (p %)**
Water Allocation Using Homogeneous Weights	Punjab	16752	110	0.25	9455.28	12225	73
	Sindh	2819	47	0.25	1409.5	2819	100
	Baluchistan	2110	12	0.25	1055	2110	100
	KPK	2062	30	0.25	1030.86	2062	100
Water Allocation Using Heterogenous Weights (Based on Population)	Punjab	16752	110	0.55	9455.28	12969	77
	Sindh	2819	47	0.24	1409.5	2819	100
	Baluchistan	2110	12	0.06	1055	1438	68
	KPK	2062	30	0.15	1030.86	1989	96

6.5 Concluding Remarks

This chapter addresses the question of how to govern and manage transboundary river basin for competing and often conflicting demands in the midst of limited supplies. It builds on innovative applications of game theoretic approaches and uses equity and sustainability as guiding principles to propose a new framework that has the potential to resolve supply-demand mismatch in boundary crossing river basins.

The initial allocation of water among the provinces is done using five commonly used Bankruptcy rules. Findings from these bankruptcy rules suggest that different provinces might prefer different rules based on their allocated demands. As these bankruptcy rules are primarily mathematical and do not consider other factors such as population in each province, water use efficiency and amount of groundwater usage for each province; these rules might not be acceptable for all provinces. The Nash bargaining theory along with the Bankruptcy rules are then used for water distribution in the Indus river among four provinces within Pakistan.

The findings suggest that moving from the non-cooperative approach of Bankruptcy to the cooperative approach of Nash, results in increase in the total monetary benefit. The total monetary benefits generated by the allocation of water using the Nash bargaining theory gives the highest monetary benefits. Reallocation of these total benefits among the four provinces of Pakistan is done by applying the Nash bargaining theory under homogenous and heterogenous weights.

Findings also suggest that the basic water demands among the provinces can be satisfied by proposed disagreement points and the bargaining weights can highlight the role of different level of groundwater usage, irrigation efficiencies and variations in population among the provinces. Such a framework of creating and sharing of mutual benefits among the provinces highlight the efficacy of water diplomacy framework to encourage and enhance cooperation when water demand exceeds supply. We hope this proposed work will find more innovative applications for other transboundary river basins across the world.

Chapter 7

Fuzzy AHP TOPSIS Multicriteria Decision Analysis Applied to the Indus Reservoir System in Pakistan

7.1 Introduction

Chapter 3 of the thesis gave some recommendations which are necessary to address the water shortage and resolve interprovincial water conflicts in Pakistan's Indus Basin. One of these recommendations included the improvement of water infrastructure and development of new reservoirs, which are addressed in this chapter.

Conflicts arise over the water resource projects and systems if they have diverse purposes and resource values. The main reason of the conflict is that the water resource projects are managed to optimize conflicting benefits for flood control, recreation, water supply and hydropower. The measurement of these benefits is usually easy because they are quantified in monetary values but the other resources like environmental and natural resources are very difficult to be measured and quantified in terms of economics. However, while analyzing the systems, specifically in optimization, it is most suitable if one quantitative measure is used to describe all the objectives for resource management (Flug et al. 2000).

The Multi-Criteria Decision Making (MCDM) methods, in the recent years, have been used considerably in environmental modelling (Zhou 2006). Apart from the economic criteria, as stated above, it is also essential to consider social, technical, environmental and political implications of water resource projects for ensuring the favourable and sustainable decisions. For this purpose, the stakeholders must be engaged at every step of the process which are necessary for decision making. This requires the use of both MCDM techniques and the Group Decision Making GDM (Zarghami et al. 2008). The significant advantages of such MCDM techniques for the water resources management are that these help to:

- deal with the limited quantity of water, manpower and financial resources;
- lower the costs of delays in decision making;
- allow for making decision by considering different prominent criteria;
- provide information to resolve disputes among stakeholders;
- manage and administer the projects in a better and efficient way.

In order to construct an MCDM model, there is need to establish the relative importance of criteria, their attributes as well as their hierarchy. In order to rank the water projects in Pakistan, a hierarchy of criteria and sub-criteria have been developed.

Due to their multi-objective, multi-layer and multi-period features, the management of the water resource projects becomes very difficult and a complicated task. Each stakeholder and decision maker may have a different level of satisfaction because for a given goal, many choices may exist, therefore, it is very difficult to point out which project is the best amongst them (Afshar et al. 2011).

The Multi-Criteria Decision Analysis (MCDA) has become an important tool for managing water resource projects because the policies of water are rarely defined by one objective. MCDA is a decision model which contains (Greco and Ehrgott 2008)::

- ranking of the decision options by the decision makers,
- different units of criteria, and
- a set of performance measures

When conflicting criteria are involved, MCDM is used for the ranking of alternatives (Larichev and Moshkovich 1995). Some works related to MCDM are as follows: For River Basin Planning, multi-objective optimization was done by Gershon et al. (1982). The best wastewater management option was selected by using MCDA by Tecle (1988). Ranking of national water projects in Canada was done using MCDM by Simonovic (1989). Conflict management in water resource management and planning was done by Cai et al. (2004). Waste management problems were solved by using fuzzy approach by Tan et al. (2010).

There is a need for a reliable methodology for the ranking of water resource projects (Afshar et al. 2011). A framework is provided by the MCDA which helps the decision makers to find the main issues. These issues are assigned with the relative priorities and then an alternative is selected. This process facilitates a communication among the stakeholders and helps them to reach a decision (Hajkowicz and Collins 2007).

The 'Technique for Order Preference by similarity of Ideal Solution (TOPSIS)' was proposed by (Hwang and Yoon 1981) for solving the multi attribute decision making problems. Fuzzy TOPSIS just like the fuzzy AHP has been used in several studies for the location selection problems. Ertuğrul and Karakaşoğlu (2008) applied fuzzy-AHP and fuzzy TOPSIS for a facility location selection problem of a textile company. A fuzzy version of the TOPSIS method, based on fuzzy arithmetic operations, was proposed by Triantaphyllou and Chi-Tun (1996). Chen (2000) applied the fuzzy TOPSIS for engineer's selection for a software company. A fuzzy TOPSIS model was also presented by Chu (2002) under group decisions for solving the facility location selection problem. The problems related to MCDM, with a given reference point, can be solved by defining the options or decisions which are nearest to the ideal point or reference point.

The pros and cons of MCDM approaches are shown in Table 7.1. Before setting up a large hydropower or energy project, its detriments and benefits to the society must be kept in view. According to Lior (2012), all large scale projects must be implemented and designed sustainably keeping in view social, environmental and economic impacts.

TABLE 7.1: Comparison of multi-criteria decision-making methods.

MCDM methods	**Pros**	**Cons**
ANP	Interdependencies and feedbacks can be handled by this method. It shows the influence and dependence of the aspects involved to the goal or higher-level performance objective.	The pairwise comparisons in ANP are more than the AHP, hence, its solution is difficult. It can only be solved using specific software.
Multi-objective programming	Model comprises non-linear or linear objective function and constraints. Large number of alternatives can be considered by this method	Complex computational procedure makes it difficult to solve. It can only be solved using meta-heuristic approach or specific software. It only considers quantitative attributes. Only applicable when the data available is precise and exact.
TOPSIS	Distance from the ideal solution can be measured by this method. Well understandable and easy to use. A simple spreadsheet can be used for the solution.	The process of normalization is required for the solution of multidimensional problem. No possibility of consistency check.

AHP	Both qualitative and quantitative attributed can be considered using this method. Complex decision problem can be presented using hierarchical structure. A simple spreadsheet can be used for the solution of the problem. Consistency measurement is possible.	As the number of alternatives increase, a large number of pairwise comparisons are required. Compensation between bad scores on some criteria and good scores on other criteria can occur due to aggregation

The aim of this chapter is to rank the water resource projects which are planned or ready for construction in Pakistan. The ranking of the reservoirs is among the decisions that are of importance in water supply management. The dam construction is very expensive, particularly for an underdeveloped country like Pakistan and it also has long-term environmental impacts. A large amount of Pakistan's national budget will be invested in the construction of these reservoirs. Therefore, to achieve greater efficiency in the allocation of water resources and funds, it is necessary to rank the projects and it is proposed that high ranked projects should be supported first in their construction. The low ranked projects will be constructed later due to the increasing stakeholders' conflicts and limited financial budget in Pakistan.

An integrated multicriteria decision making framework has been proposed in this study for ranking the water projects in Pakistan in the presence of vague information and multiple factors. The ranking of water resource projects involves several conflicting criteria. The available literature and expert opinion are used for the identification of main criteria and sub-criteria (Afshar et al. 2011); (Zarghaami et al. 2007) and (Minatour et al. 2015). The weights of the criteria are determined using the fuzzy AHP. In order to decide the importance and preference of one criterion over another, the linguistic preferences of the experts are mapped with triangular fuzzy numbers. The water projects are ranked based on their overall performance by applying TOPSIS. The decision framework is proposed in this chapter which provides useful insights for the water managers and the decision makers in selecting and evaluation water projects.

There are several reasons for choosing the fuzzy AHP-TOPSIS framework in this study which are:

The choice for an integrated fuzzy AHP-TOPSIS based framework proposed in this chapter is justified by several reasons:

- The incomplete knowledge and linguistic preferences of various interest groups are mapped to decide the preferences for both qualitative and quantitative criteria and to compare different alternatives. This is necessary for the evaluation of large-scale water projects, and fuzzy AHP allows it.
- Based on their overall performance, TOPSIS can rank the locations as it identifies the best solution which is furthest from the negative ideal solution and closest to positive ideal solution.
- The framework proposed above can be easily solved using a spreadsheet.

7.1.1 History of the Indus Basin

The Indus river (Figure 2.1) is a major source of life for Pakistan. It provides water for the 90% of the food production in Pakistan and contributes towards 20 % of the country's gross domestic product. Pakistan being an agricultural country could soon face a serious food and water shortage. It is projected that there will be 32% shortfall of water requirements and 70 million tons of food shortage in the country by 2025 (Qureshi 2011b).

About 566,000 square kilometers (km^2) of the area, which is about 70 percent of the country, is drained by the Indus Basin, comprising of the four provinces namely Punjab, Sindh Baluchistan and Khyber Pakhtunkhwa (KPK) (Yu et al. 2013). The Basin is fed by the eastern rivers (Ravi and Sutlej) and western rivers

(Jhelum, Chenab and Kabul). The total length of the basin is about 2,900 km and an altitude of 18,000 ft from the top of Himalayas to the low-lying areas of Sindh, where it flows into the Arabian Sea.

Although Indus Basin is the twelfth largest drainage basin in the world, yet it has the largest contiguous irrigation system in the world. About 150,000 km^2 of the cropland, out of 190,000 km^2 is irrigated by the Indus Basin Irrigation System (Ahmad 2005a). The Indus Basin is the home to seventh largest mangrove system and the fifth largest delta in the world. Due to lack of sustained minimum river flows, the delta ecosystem has deteriorated in recent years. The average precipitation in the basin is around 230 millimeters per year, which is very low. Sub-tropical climate exists in the basin with transpiration rates of 2,112 millimeters per year (Ullah, M. Kaleem, Zaigham Habib 2001). Most of the flow of Indus River (around 40-70 percent) is from glaciers' melt and snow off the Himalayas. Most of the flow (about 85 Percent) in the basin's catchment occurs from the months of May to September (National Research Council. 2012). The Indus Basin in Pakistan has a mean annual flow of 176 billion cubic meter of which almost 90 percent is supplied for the irrigation purposes. Despite this, there are high variations in demand and supply: for example, during the droughts of 2000-2002 the difference between supply and demand was 20 percent (Briscoe J 2006). Due to the factors such as urbanization and high population growth (Shahid et al. 2018), aggravated by evapotranspiration, canal and water course seepage, field application losses and field level irrigation inefficiency, the future deficits would be around 20.

7.1.2 Problem Statement

7.1.2.1 Storage Capacity

The storage capacity of Pakistan's Indus Basin is only about thirty days which is very low. This storage capacity is thirty times less than that of Colorado and Murray Darling Basin. As the majority of the river flow in Pakistan occurs during three to four-month period, such low storage puts immense constraints on assuring that the supply will meet demand. Due to this limited storage, the minimum flows required for the Indus delta are now met which are required to maintain healthy ecosystem of fisheries and mangroves. No new large reservoir has been constructed in Pakistan since 1976. Both the major reservoirs of Pakistan, Tarbela and Mangla are plagued with siltation problem. Due to the sediment deposition, both the reservoirs have lost thirty-two and twenty percent of their storage capacity respectively (Sattar et al. 2017). The storage capacity of Pakistan must be raised by 22 BCM by 2025 to meet the water requirements of 165 BCM (Rajput 2011).

7.1.2.2 Energy Security: Hydropower Capacity

The electricity generation in Pakistan by hydropower is about 36,500 megawatts hour (MWh) a year. This is far below the total hydropower generating potential of 60,000 MWh (Trimble et al. 2011). The total electricity generation capacity in Pakistan was about 21,600 MW in the year 2010. This included all forms of power including hydropower, fossil fuel and nuclear. With the growing industry and population, the electricity demand of Pakistan is increasing by almost 7 percent annually, the supply of electricity falls short of demand by 2,000 to 4,000 MW (Trimble et al. 2011). Due to poor transmission capability, generation deficits and increasing demands of electricity, the country is facing extreme power shortages in the form of daily power rationing, also known as load shedding. Blackouts are frequent in the cities, which last about 8 to 10 hours a day during summer season. In rural areas, these power outages are often double (Trimble et al. 2011).

Pakistan heavily relies on the expensive imported oil for the electricity generation despite its abundant access to hydropower. The oil-fired thermal generating plants produce about 39 percent of all the electricity in Pakistan (Trimble et al. 2011). The oil import puts a considerable burden on the economy as it worsens the balance of payments position of the country and increases the external current account deficit (Trimble et al. 2011).

Building of additional dams would help in the development of the nation's available hydropower and would lessen this financial burden while simultaneously providing much-needed supplementary capacity for flood control and irrigation storage.

7.1.2.3 Flood Security: Peak Reduction and Containment of Floodwaters

For the millions of people living in the Indus Basin, flooding is a tragic fact of life. Floods in Pakistan have caused long term disruption of economic development and productive agriculture. More than seventeen major floods have occurred in Pakistan since 1950 which resulted in a cumulative damage exceeding $15 billion in the form of direct economic losses, 9,000 loss of lives, and millions of acres of flooded land (Briscoe J 2006). The 2010 flood was the worst in the history of Pakistan which resulted in almost 2,000 deaths and 20 million displaced people. The economic damage done to the agricultural sector due to the flood was $2.9 billion (Condon et al. 2014). Although, the threat of flooding is impossible to eliminate, it is important that more storage infrastructure should be built to attenuate dangerous high flows and harness water during times of excess to provide during times of drought.

7.2 Methodology

In order to evaluate, manage and rank the planned reservoirs in the Indus River, a three-phase methodology has been proposed (Figure 7.1).

7.2.1 Stage I: Identification of Potential Locations

The water projects planned by WAPDA on the Indus River System have been considered in this study. Due to the high demand for irrigation water and high hydropower potential, numerous water projects have been planned by WAPDA. In this study, only large projects have been selected which have a high-water storage potential and high-power generation capacity. After study and discussion with various experts, five projects were selected for the ranking **(Appendix-A).**

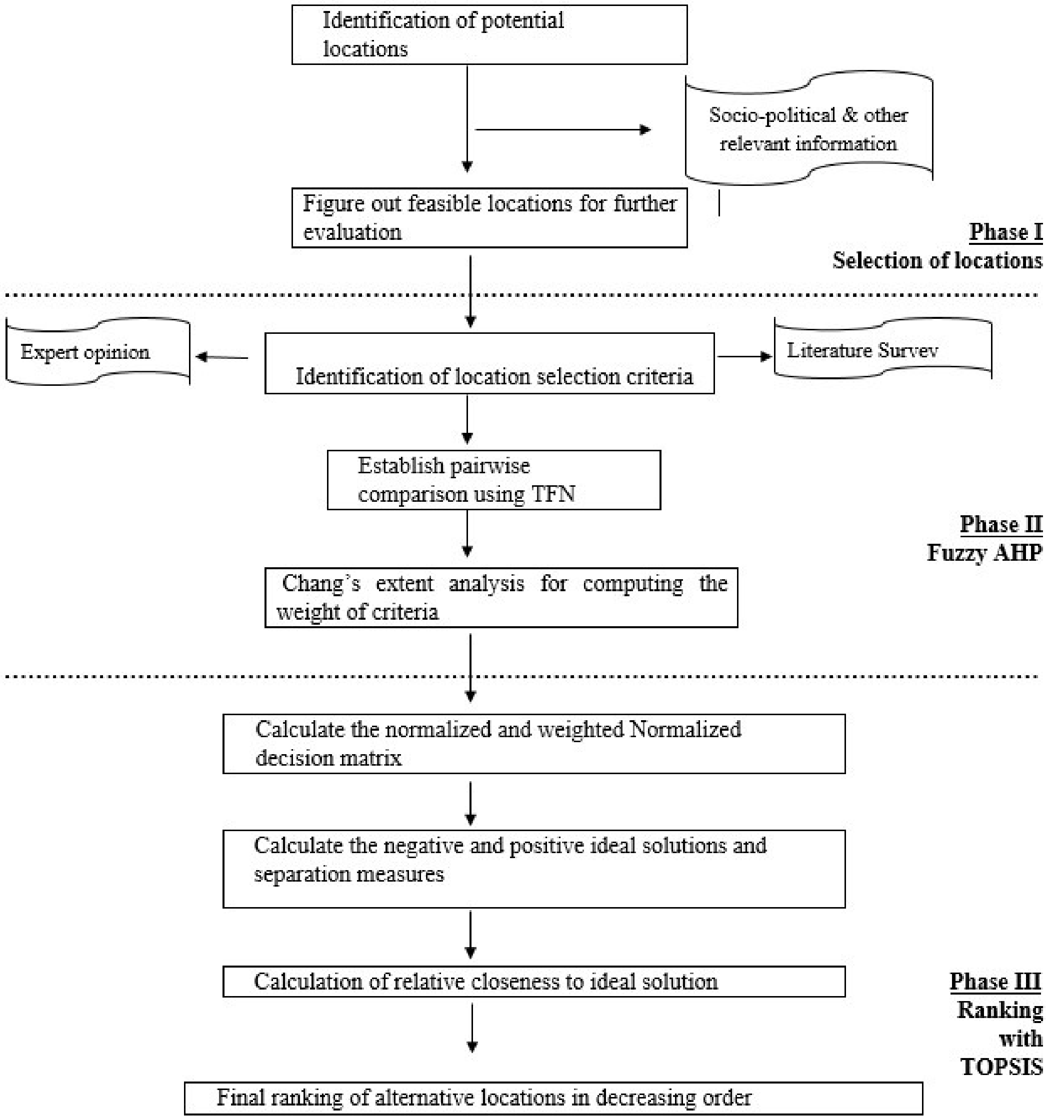

FIGURE 7.1: The three-phase research methodology.

7.2.2 Stage II: Fuzzy AHP

Saaty proposed the Analytic Hierarchy Process (AHP) in 1990. In the decision-making process, both the quantitative and qualitative factors are incorporated in AHP. As the discrete scale of 1 to 9 is used in AHP, therefore, this process is generally criticized as it does not incorporate the uncertainty in the process of decision-making.

In order to solve the multicriteria problems, the method of fuzzy-AHP has been used in other fields as well. Haq and Kannan (2006) used this method to select the best vendor in supply chain. Huang et al. (2008) used this for the selection of R & D projects. Pan (2008) used this methodology for selecting appropriate method of bridge construction. Güngör et al. (2009) applied this methodology for the personnel selection problem.

As proposed by Zadeh, fuzzy set theory is a general form of classical set theory. It is a membership function and it allocates a grade between one and ten. If the letter represents a fuzzy set, a tilde '∼' is placed over it. A fuzzy event is denoted by *(l, m, u),* where *'l'* is the smallest value, *'m'* is the most likely value and '*u'* is the highest value. Some of the definitions related to Fuzzy AHP are discussed below.

Def 1. For a triangular fuzzy number Ĩ, the membership function is given by *(l, m, u)* and is defined as (Equation 7.1):

$$\mu\widetilde{I}(x) = \begin{cases} \frac{x-1}{m-1} \; l \geq x \geq m, \\ \frac{u-x}{u-m} \; m \geq x \geq u, \\ 0, \quad otherwise. \end{cases} \tag{7.1}$$

For the left and right-side representation, the degree of membership of a fuzzy number is given by Equation (7.2):

$$\widetilde{I} = \; (I^{L(y)}, \; I^{R(y)})$$

$$\widetilde{I} = (l \; + \; (m-l) \; y, \; u + \; (u-m) \; y), \; Y \in \; [0,1] \tag{7.2}$$

Def 2. Suppose that the two triangular fuzzy numbers are $\tilde{I}_{1} = (l_1, m_1, u_1)$ and $\tilde{I}_{2} = (l_2, m_2, u_2)$. The operational laws of addition, multiplication, subtraction, division and reciprocal are expressed as follows:

Their addition is given by Equation (7.3):

$$\widetilde{I}_1 + \widetilde{I}_2 = \; (l_1, m_1, \; u_1) + (l_2, m_2, \; u_2) \; = \; (l_1 + l_2 \; , \; m_1 + m_2 \; , \; u_1 + u_2) \tag{7.3}$$

Their multiplication is given by Equations (7.4) and (7.5):

$$\widetilde{I}_1 \times \widetilde{I}_2 = \; (l_1, m_1, \; u_1) \times (l_2, m_2, \; u_2) \; = \; (l_1 l_2 \; , \; m_1 m_2 \; , \; u_1 u_2) \tag{7.4}$$

$$\alpha \times \widetilde{I}_2 = \ (\alpha\ l_2\ ,\ \alpha\ m_2\ ,\ \alpha\ u_2) \qquad \text{where} \quad \alpha\ >\ 0 \tag{7.5}$$

Their subtraction is given by Equation (7.6):

$$\widetilde{I}_1 - \widetilde{I}_2 = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \tag{7.6}$$

Their division is given by Equation (7.7):

$$\widetilde{I}_1\ /\ \widetilde{I}_2 = (l_1, m_1, u_1)\ /\ (l_2, m_2, u_2) = (l_1/u_2, m_1/m_2, u_1\ /l_2) \tag{7.7}$$

Inverse is given by Equation (7.8):

$$\tilde{\mathrm{I}}_1^{-1} = \ (\ l_1,\ m_1,\ u_1)\ ^{-1} = (\frac{1}{u_1} + \frac{1}{m_1} + \frac{1}{l_1}) \tag{7.8}$$

For the interval judgements, the triangular fuzzy numbers are used to give preference of one criterion over the other. The pairwise comparison is then done using the extent analysis and finally the weights of the criteria are calculated. The general steps for this method are as follows:

7.2.2.1 Phase 1: Synthetic Extent Calculation

Let X = {x$_1$, x$_{2,}$,., x$_n$} be an object set and U = {u$_1$, u$_2$,.,u$_m$} be the goal set. Extent analysis is performed using Chang's extent analysis (Chang 1996a) which is given below:

$I^1_{g,}\ I^2_{g,\ldots\ldots,} I^m_{gi}$, i = 1, 2, . . . , n, where all the I^j_{gi} $(j = 1, 2, \ldots, m)$ are triangular

fuzzy numbers. The fuzzy synthetic extent values with respect to i$_{th}$ object is given by Equation (7.9):

$$S_i = \sum_{j=1}^{m} I^j_{gi} \times \left[\sum_{i=1}^{n}\sum_{j=1}^{m} I^j_{gi}\right]^{-1} \tag{7.9}$$

7.2.2.2 Phase 2: Fuzzy Values Comparison: (Chang 1992, 1996b)

The degree of possibility of $I_2 = (l_2,\ m_2,\ n_2) \geq I_1 = (l_1,\ m_1,\ n_1)$ is defined as, Equation (7.10):

$$\mathrm{V}\ (I_2 \geq I_1) = \underbrace{SUP}_{X \geq y} [min\,(\mu_{I_1}(x), \mu_{I_2}(y))] \tag{7.10}$$

When a pair (x, y) exists such that $x \geq y$ and $\mu_{\tilde{I}\,1}(x) = \mu_{\tilde{I}\,2}(y) = 1$, then we have $V\ (I_2 \geq I_1) = 1.$ Since I_1 and I_2 are convex fuzzy numbers so they are expressed as follows (Equation 7.11):

$$V\ (I_2\ \geq\ I_1)\ =\ hgt\ (I_1 \cap\ I_2)\ =\ \mu_{I2}(d) \tag{7.11}$$

Where 'd' is the ordinate of the highest intersection point 'D' between μ_{A1} and μ_{A2}. When $\mathrm{I}_1=(l_1, m_1, u_1)$ and $\mathrm{I}_2=(l_2, m_2, u_2)$ then μ_{I2} (d) is computed by (Equation 7.12):

$$\mu_{12}\ (\mathrm{d}) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & l_1 \geq\ l_2 \\ \frac{l_1 -\ u_2}{(m_2 -\ u_2) - ((m_1 -\ l_1)}, & otherwise \end{cases} \tag{7.12}$$

Both the values of $V\ (I_2 \geq I_1)$ and $V\ (I_1 \geq I_2)$ are required for comparing I_1 and I_2.

7.2.2.3 Phase 3: Calculation of Priority Eeight: (Chang 1992, 1996b; Gumus 2009)

The degree possibility of convex fuzzy number to be greater than k convex fuzzy numbers $\mathrm{I}_i = (i = 1, 2, \cdots, k)$ can be defined by Equations (7.13) to (7.15):

$$V(I\ \geq\ I_1, I_2, ..., I_k)\ =\ V\ (\ I\ \geq\ I_2)\ and\ .....\ (I\ \geq\ I_k) \tag{7.13}$$

$$V(I\ \geq\ I_1, I_2, ..., I_k)\ = min\ V\ (\ I\ \geq\ I_i) \qquad i\ =\ 1, 2, ..., k \tag{7.14}$$

If

$$m\ (P_i)\ =\ min\ V\ (S_i\ \geq\ S_k)\ \ for\ k\ =\ 1,\ 2\ldots,\ n;\ k \neq\ i. \tag{7.15}$$

Then, the weight vector is given by Equation (7.16):

$$W_p = (m(P_1),\ m(P_2),\ \ldots,\ m\ (P_n))^T \tag{7.16}$$

Here P_i *(i = 1, 2, . . . , n)* are n elements.

7.2.2.4 Phase 4: Calculation of Normalized Weight Vector

After normalization of W_p, the normalized weight vectors are given by Equation (7.17):

$$W_p = (w(P_1),\ w(P_2),\ \ldots,\ w\ (P_n))^T \tag{7.17}$$

Here, W gives the priority weights of one alternative over another and it is a non-fuzzy number.

7.2.3 Stage III: TOPSIS

Based on their performance, the projects are ranked using TOPSIS. Following three types of criteria or attributes are considered in this method:

- Cost criteria / attribute
- Qualitative benefit criteria / attribute
- Quantitative benefit

Two types of alternatives are considered in this study, as given below:

- Negative ideal solution
- Positive ideal solution

TOPSIS is based on the selection of best alternative or project which is farthest from the negative ideal solution and closest to the positive ideal solution. The positive and the negative ideal solutions are the ones which have highest benefits and lowest benefits, respectively. The final ranking of the projects is done on the basis of relative closeness form the ideal solution (Ilangkumaran and Kumanan 2009).

Following steps are involved in TOPSIS process (Gumus 2009) and (Joshi et al. 2011). In these steps, 'm' represents alternatives, 'n' represents the attributes, x_{ij} represents the score of alternative i w.r.t criterion j. Also, let J' represents the cost criteria and J represents the benefits criteria.

7.2.3.1 Step 1

Construct normalized decision matrix. The calculation of normalized value r_{ij} is done by Equation (7.18):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \ i = 1, \ \ldots.., \ m; j = 1, \ \ldots.., \ n \tag{7.18}$$

7.2.3.2 Step 2

Construct the weighted normalized decision matrix. Assume, we have a set of weights for each criteria w_j for j =1..., n and $\sum_{j=1}^{n} w_j = 1$. Each column of the normalized decision matrix is then multiplied by its weight. An element of the new matrix is Equation (7.19):

$$\eta_{ij} = w_i \, r_{ij} \, , \qquad i = 1, \ \ldots., \ m; \ j = 1 \, , \ \ldots., \ n \tag{7.19}$$

7.2.3.3 Step 3

Determination of positive ideal and negative ideal solutions.

For positive ideal solution (Equations 7.20 & 7.21):

$$A^{+} = \left\{ \eta_1^{+} \, , \ldots.., \eta_n^{+} \right\} \tag{7.20}$$

where

$$\eta_j^+ = \{max(\eta_{ij})\ if\ j \in J; min(\eta_{ij})\ if\ j \in J'\},\ j = 1, \cdots, n \tag{7.21}$$

and for negative ideal solution (Equations 7.22 & 7.23):

$$A^- = \{\eta_1^-\ , \ldots.., \eta_n^-\} \tag{7.22}$$

where

$$\eta_j^- = \{max(\eta_{ij})\ if\ j \in J; min(\eta_{ij})\ if\ j \in J'\},\ j = 1, \cdots, n \tag{7.23}$$

7.2.3.4 Step 4

Separation measures calculation:

From the positive ideal alternative, the separation measure is (Equation 7.24):

$$S_i^+ = \left\{\sum_{j=1}^{n} \left(\eta_{ij} - \ \eta_j^+\right)^2\right\}^{1/2} \quad i = 1,\ \ldots,\ m \tag{7.24}$$

and from the negative ideal alternative, the separation measure is (Equation 7.25):

$$S_i^- = \left\{\sum_{j=1}^{n} \left(\eta_{ij} - \ \eta_j^-\right)^2\right\}^{1/2} \quad i = 1,\ \ldots,\ m \tag{7.25}$$

7.2.3.5 Step 5

Calculation of relative closeness from the ideal solution (Equation 7.26):

$$C_i = \frac{S_i^-}{\left(S_i^+ + \ S_i^-\right)},\ i = 1.\ \ldots,\ m.\ C_i \in\ \{0.\ 1\} \tag{7.26}$$

In TOPSIS method, C_i will denote final score.

7.2.3.6 Step 6

The alternatives should be ranked using the C_i value in increasing or decreasing order. The largest index value (C_i) will indicate that its distance from the positive ideal solution is the shortest whereas the lowest index value (C_i) will indicate the shortest distance from the negative ideal solution.

7.3 Case Study

7.3.1 Selection of Feasible Locations

There are numerous water resource projects which are planned by WAPDA. The stakeholders, that is, the provinces of Pakistan would greatly be benefitting from the construction of these reservoirs. Ranking of the selected projects on the defined criteria is main aim of this study. It will be proposed that the projects which are ranked high should be given priority in construction. The low ranked projects will be constructed later due to the increasing stakeholders' conflicts and limited financial budget in Pakistan.

The three-phase methodology is adopted to rank the water projects in Pakistan. The five feasible locations were selected which are given below. For the details of each alternative location, see Appendix A.

- Bunji Hydropower Project (P_1): Gilgit
- Diamer Basha Dam (P_2): Gilgit
- Dasu (P_3): Kohistan District, KPK
- Kalabagh Dam (P_4): Mianwali District, Punjab
- Akhori Dam (P_5): Attock District, Punjab

7.3.2 Determination of the Criteria Weights Using Fuzzy AHP

Keeney and Raiffa (1993) stated that the hierarchy of criteria should meet the following: completeness, non-redundancy, decomposable and minimum size. Certain compromises for some cases can be made. The "time of construction' for example can be combined with the calculation of financial attributes as the 'benefit to cost' ratio.

Criteria are defined in the Fuzzy-AHP to evaluate the alternative locations. To achieve this, the available literature was explored, and an intensive discussion was done with the experts to determine the criteria and sub-criteria effecting the selection and ranking of the projects in Pakistan. The defined sub-criteria are further classified into six (as shown in **Figure 7.2)** criteria which are:

- Cultural and Social,
- Political, Legal and Security,
- Technical and Executive,
- Environmental,
- Economic and financial,
- Comprehensive Management.

The Triangular Fuzzy Numbers (TFN), as defined by Gumus (2009) are used to compute the priority weights for each criteria. These TFN and their reciprocals are shown in Table 7.2. The questionnaires are used to prepare the fuzzy comparison matrices. The questionnaire form is shown in **Appendix-A.** Description of potential locations for projects and criteria are shown in **Table A-1 (Appendix-A).** Questionnaire form to calculate the weight of each criteria is given in **Table A-2 (Appendix-A).**

Twelve experts form WAPDA were contacted to give their valuable input for further data analysis. They were asked to give their valuable opinion and input as

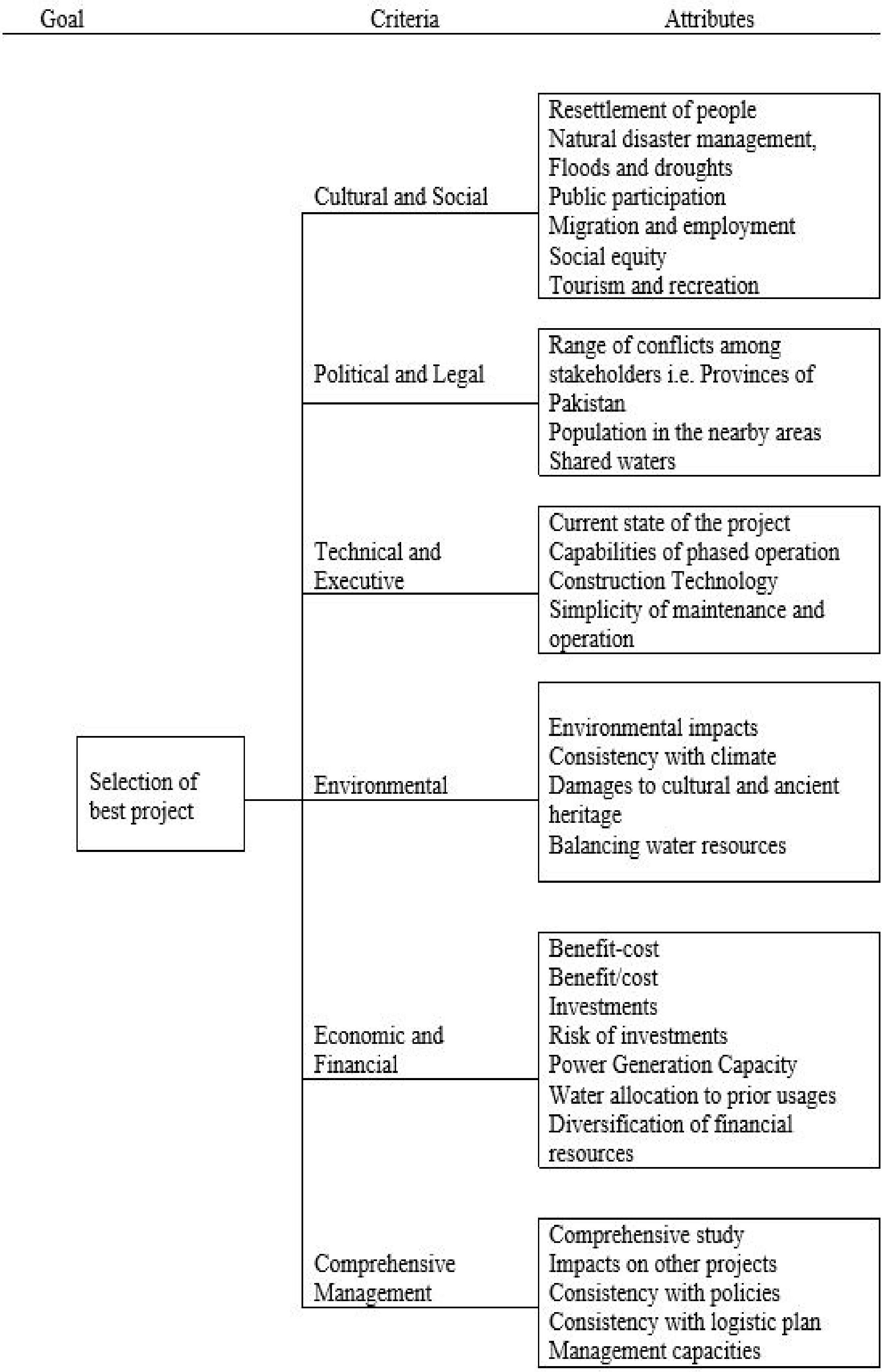

FIGURE 7.2: The criteria and sub-criteria for Water Projects ranking in Pakistan.

TABLE 7.2: Triangular fuzzy numbers and their reciprocals.

Linguistic Terms	**Triangular Fuzzy Numbers (TFN)**	**Reciprocal of Triangular Fuzzy Numbers (TFN Reciprocal)**
Perfect	(8,9,10)	(0.1, 0.111, 0.125)
Absolute	(7,8,9)	(0.11, 0.125, 0.142)
Very good	(6,7,8)	(0.125, 0.142, 0.166)
Fairly good	(5,6,7)	(0.142, 0.166, 0.2)
Good	(4,5,6)	(0.166, 0.2, 0.25)
Preferable	(3,4,5)	(0.2, 0.25, 0.333)
Not Bad	(2,3,4)	(0.25, 0.333, 0.5)
Weak Advantage	(1,2,3)	(0.333, 0.5, 1)
Equal	(1,1,1)	(1, 1, 1)

per the questionnaire given in **Appendix A**. Out of twelve, only ten agreed to give their expert input and remaining two excused to give their valuable input. These experts were those who were related to these projects in the capacity of the execution and design team. As input/opinion of other people who had no detailed knowledge of these project could have hampered both input and input-based output, therefore, only those experts were selected and contacted in this study who belonged to the planning department of WAPDA as they had all the relevant information related to these projects. Also, the feasibility reports of these projects were not available to anyone other than the personals working in the planning department of WAPDA. Extensive literature reviews and the interviews of various experts were conducted to define the criteria and sub-criteria keeping in view the conditions of Pakistan. The importance rate of the criteria was determined by the experts using linguistic variables.

The linguistic variables were then adjusted with the triangular fuzzy numbers in the next step. The data is then inserted in the excel software. The first question of the questionnaire is shown in Table 7.3 as a sample which compares the Social and Cultural criteria with the criteria of Political, Security and Legality.

TABLE 7.3: Social and cultural criteria in comparison with the criteria of political, security and legality.

Social and Cultural criteria compared with the criteria of Political, Security and Legality				
Triangular Fuzzy Number			**Linguistic Variables**	**Expert**
l	**m**	**u**		
1	1	1	Equal Advantage	1
1	1	1	Equal Advantage	2
0.33	0.5	1	Weak Advantage (Reciprocal)	3
0.111	0.125	0.142	Absolute (Reciprocal)	4
1	1	1	Equal Advantage	5
0.2	0.25	0.333	Preferable (Reciprocal)	6
1	1	1	Equal Advantage	7
0.166	0.2	0.25	Good (Reciprocal)	8
0.142	0.166	0.2	Fairly Good (Reciprocal)	9
0.25	0.333	0.5	Not Bad (Reciprocal)	10
0.5199	**0.5574**	**0.6425**	**Average**	

Table 7.4: Paired comparison matrices of criteria.

Criteria	**Social and Cultural**			**Legality, Political and Security**			**Executive and Technical**			**Environmental**			**Economic and Financial**			**Demand Management**			**Comprehensive Management**		
	l	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**
Social and Cultural	1.0000	1.0000	1.0000	0.5199	0.5574	0.6425	0.1738	0.2202	0.3191	0.7500	0.8974	1.1032	0.4403	0.4833	0.5783	0.8290	1.0581	1.3384	0.9026	1.2458	1.6642
Political, Security and Legality	1.5560	1.7940	1.9234	1.0000	1.0000	1.0000	2.5000	3.1000	3.7000	2.6142	3.4166	4.2200	1.4342	1.6416	1.8533	3.1000	4.1000	5.1000	3.6000	4.6000	5.6000
Technical and Executive	3.1338	4.5413	5.7537	0.27027	0.3225	0.4000	1.0000	1.0000	1.0000	4.6000	5.6000	6.6000	1.2250	1.4330	1.6500	1.7650	2.2833	2.8166	3.8000	4.8000	5.8000
Environmental	0.9064	1.1143	1.3333	0.2369	0.2926	0.3825	0.1515	0.1785	0.2174	1.0000	1.0000	1.0000	0.7377	0.9683	1.2173	1.1267	1.4308	1.7366	2.1250	2.6333	3.1500
Economic and Financial	1.7292	2.0691	2.2711	0.5397	0.6091	0.6972	0.606	0.6976	0.8163	0.8214	1.0327	1.3555	1.0000	1.0000	1.0000	3.4000	4.3000	5.2000	4.6000	5.6000	6.6000
Demand Management	0.7472	0.9451	1.20627	0.1960	0.2439	0.3225	0.355	0.4379	0.5665	0.5758	0.6989	0.8875	0.1923	0.2325	0.2941	1.0000	1.0000	1.0000	1.4000	1.7000	2.0000
Comprehensive Management	0.6008	0.80269	1.1079	0.1785	0.2174	0.2777	0.1724	0.2083	0.2631	0.3174	0.3797	0.4705	0.1515	0.1785	0.2174	0.5000	0.5882	0.7140	1.0000	1.0000	1.0000

In the similar manner, a total of sixteen (Equation 7.16) such tables were developed the other criteria were also compared. The dual comparison matrices are then prepared. Table 7.4 shows the fuzzy comparison matrices. Chang's extent analysis approach is used for the weight calculations. MS Excel is used for these calculations. Excel template for Ideal Solution using Chang's extent analysis approach is also shown in **Appendix B.**

Using Equation 7.9, the fuzzy synthetic extent values are:

S_1 = (0.05031004, 0.0710086, 0.10566663)

S_2 = (0.17226796, 0.2554786, 0.37200753)

S_3 = (0.172155363, 0.2597413, 0.38192277)

S_4 = (0.06849778, 0.0990314, 0.143689731)

S_5 = (0.13838967, 0.1990105, 0.28524759)

S_6 = (0.04868267, 0.0683579, 0.099802233)

S_7 = (0.03183454, 0.04387227, 0.06440454)

Equations 7.11 and 7.12 are used to calculate the values of V. After the calculation of V, Equation 7.15 is used for the calculation of the minimum degree of possibility.

$m(C_1) = 0$, $m(C_2) = 0.98$, $m(C_3) = 1.00$, $m(C_4) = 0.00$, $m(C_5) = 0.65$, $m(C_6)$ = 0.00 and $m(C_7) = 0.00$

The weight vector, W_p is given by:

$W_p = (0, 0.98, 1, 0, 0.65, 0, 0)$

The normalized weight vectors are given by:

$W = (0, 0.372, 0.38, 0, 0.247, 0, 0)$

The weight vectors clearly show that experts do not consider the criterions C_1, C_4, C_6 , and C_7 as important, therefore, the weightage of these criterions come out to be zero after applying the Equations 7.11, 7.12, and 7.15.

7.4 Ranking of Alternatives Using TOPSIS

Ranking of the alternative locations is done by using TOPSIS. As mentioned above, five locations are examined in this research, the projects are ranked by the experts using **Table A-3 (Appendix-A)**. This information is illustrated in the Table 7.5 in the form of decision matrix. The results after normalization are shown in Table 7.6. The final ranking of the projects and the evaluation of results are shown in Table 7.7.

7.5 Results and Discussion

The value of Ci closest to 1 (unity) indicates the project to be more ideal. According to this study, which is entirely based on the input recorded from the ten experts, P_2 is the most feasible option and P_5 is the least preferable option due to the collapse in terms of political, security and legality criteria. The studies conducted by various authors Khalid and Begum (2013), Ghazanfar (2008), (Nawaz Bhatti 2011) and (Khan 2014) related to the Kalabagh Dam (P_5) also confirms that this project is weak in-terms of political, security and legality criteria.

In other words, the ranking of locations according to C_i values are Kalabagh Dam – Akhori Dam – Bunji Hydropower Project – Dasu Dam – Diamer Basha Dam from the least preferable to the most preferable one. Due to its highest C_i value, the Diamer Bhasha Dam is the most preferable option. Sensitivity analysis can also be performed by the stakeholder and decision makers. To perform the sensitivity analysis, priority weights of the criteria are changed to reveal its outcome on the process of evaluation and the ranking of projects. To achieve this, the weights of the two criteria are exchanged while the others are kept constant. For example, in this study, the second criteria's weight is changed with C_1, C_3, C_4, C_5, C_6 and C_7. The TOPSIS method is used to calculate the index values (C_i).

TABLE 7.5: The priority weights of alternative locations with respect to criteria.

Criteria / Location	**Cultural and Social**			**Legality, Political and Security**			**Executive and Technical**			**Environmental**			**Economic and Financial**			**Demand Management**			**Comprehensive Management**		
Bunji Hydropower Project	0.2	1.1	2.8	6.2	8.1	9.4	5	7	8.7	2.4	4.4	6.4	5.2	7.2	8.9	7.2	8.9	9.8	6.2	8.1	9.3
Diamer-Bhasha Dam	1.7	3.4	5.4	5.8	7.8	9.3	6.8	8.6	9.6	6.6	8.3	9.5	8	9.4	9.9	5.8	7.7	9.2	4.4	6.4	8.3
Dasu Dam	4.4	6.4	8.2	7.4	9.1	9.9	4.4	6.4	8.2	5	7	8.5	4.8	6.8	8.5	4.8	6.7	8.4	3.6	5.6	7.6
Kalabagh Dam	2.8	4.5	6.3	2.1	3.2	4.6	5.6	7.5	9	5.6	7.5	9	7.6	9	9.6	5	6.9	8.6	3.6	5.6	7.5
Akhori Dam	1.9	3.5	5.4	6.2	8	9.2	5.6	7.6	9.2	5.6	7.6	9.2	4	6	7.8	5	6.9	8.6	3.6	5.6	7.4

TABLE 7.6: The weighted normalized decision matrix.

Criteria / Location	Cultural and Social			Legality, Political and Security			Executive and Technical			Environmental			Economic and Financial			Demand Management			Comprehensive Management		
Bunji Hydropower Project	0.0000	0.0000	0.0000	2.3064	3.0132	3.4968	1.9000	2.6600	3.3060	0.0000	0.0000	0.0000	1.2844	1.7784	2.1983	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diamer-Bhasha Dam	0.0000	0.0000	0.0000	2.1576	2.9016	3.4596	2.5840	3.2680	3.6480	0.0000	0.0000	0.0000	1.9760	2.3218	2.4453	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Dasu Dam	0.0000	0.0000	0.0000	2.7528	3.3852	3.6828	1.6720	2.4320	3.1160	0.0000	0.0000	0.0000	1.1856	1.6796	2.0995	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kalabagh Dam	0.0000	0.0000	0.0000	0.7812	1.1904	1.7112	2.128	2.8500	3.4200	0.0000	0.0000	0.0000	1.8772	2.223	2.3712	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Akhori Dam	0.0000	0.0000	0.0000	2.3064	2.9760	3.4224	2.1280	2.8880	3.4960	0.0000	0.0000	0.0000	0.9880	1.4820	1.9266	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE 7.7: The final ranking and evaluation of the locations.

Locations	S_i^+	Si^-	C_i	Ranking
P_1: Bunji Hydropower Project	1.4438	2.2208	0.6060	3
P_2: Diamer-Bhasha Dam	0.4611	3.2045	0.8742	1
P_3: Dasu Dam	1.3984	2.2385	0.6155	2
P_4: Kalabagh Dam	2.5206	1.1138	0.3065	5
P_5: Akhori Dam	1.541	2.10975	0.5779	4

The sensitivity analysis results are shown graphically in Figure 7.3 and are alsi given in Table 7.8. It can be seen that the index values (C_i) and the ranking of the locations change as the priority weights of the criteria are mutually changed. If the priority weights of C_1 and C_2 are exchanged, the index value of P_4 (Kalabagh Dam) jumps from 0.34 to 0.67 and the ranking of P_4 changes from 5 to 2. The C_i value of P_2 remains the highest even with all the changes which shows that this is the most feasible option. The weights can be changed in different manners and further expansion for the sensitivity analysis can be done for the decision makers.

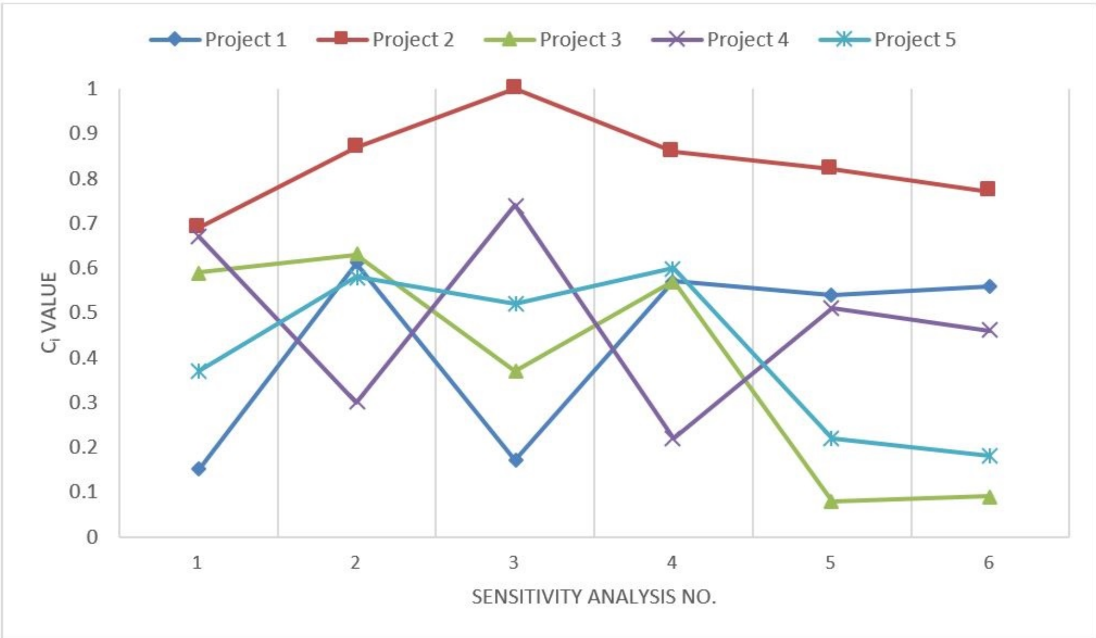

FIGURE 7.3: Sensitivity analysis and its effect on ranking.

TABLE 7.8: Sensitivity analysis.

Sensitivity Analysis	**Criteria Weights**	**Calculation of (C_i)**	**Ranking of Projects**
1	$C_1 = 0$	$P_1 = 0.61$	$P_2 \rightarrow P_3 \rightarrow P_1 \rightarrow P_5 \rightarrow P_4$
	$C_2 = 0.372$	$P_2 = 0.87$	
	$C_3 = 0.38$	$P_3 = 0.62$	
	$C_4 = 0$	$P_4 = 0.31$	
	$C_5 = 0.247$	$P_5 = 0.58$	
	$C_6 = 0$		
	$C_7 = 0$		
2	$C_1 = 0.372$	$P_1 = 0.15$	$P_2 \rightarrow P_4 \rightarrow P_3 \rightarrow P_5 \rightarrow P_1$
	$C_2 = 0$	$P_2 = 0.69$	
	$C_3 = 0.38$	$P_3 = 0.59$	
	$C_4 = 0$	$P_4 = 0.67$	
	$C_5 = 0.247$	$P_5 = 0.37$	
	$C_6 = 0$		
	$C_7 = 0$		
3	$C_1 = 0$	$P_1 = 0.61$	$P_2 \rightarrow P_3 \rightarrow P_1 \rightarrow P_5 \rightarrow P_4$
	$C_2 = 0.38$	$P_2 = 0.87$	
	$C_3 = 0.372$	$P_3 = 0.63$	
	$C_4 = 0$	$P_4 = 0.30$	
	$C_5 = 0.247$	$P_5 = 0.58$	
	$C_6 = 0$		
	$C_7 = 0$		
4	$C_1 = 0$	$P_1 = 0.17$	$P_2 \rightarrow P_4 \rightarrow P_5 \rightarrow P_3 \rightarrow P_1$
	$C_2 = 0$	$P_2 = 1.00$	
	$C_3 = 0.38$	$P_3 = 0.37$	
	$C_4 = 0.372$	$P_4 = 0.74$	
	$C_5 = 0.247$	$P_5 = 0.52$	
	$C_6 = 0$		
	$C_7 = 0$		

5	$C_1 = 0$	$P_1 = 0.57$	$P_2 \rightarrow P_5 \rightarrow P_1 \rightarrow P_3 \rightarrow P_4$
	$C_2 = 0$	$P_2 = 0.86$	
	$C_3 = 0.38$	$P_3 = 0.57$	
	$C_4 = 0$	$P_4 = 0.22$	
	$C_5 = 0.247$	$P_5 = 0.60$	
	$C_6 = 0.372$		
	$C_7 = 0$		
6	$C_1 = 0$	$P_1 = 0.54$	$P_2 \rightarrow P_3 \rightarrow P_1 \rightarrow P_4 \rightarrow P_5$
	$C_2 = 0$	$P_2 = 0.82$	
	$C_3 = 0.38$	$P_3 = 0.08$	
	$C_4 = 0$	$P_4 = 0.51$	
	$C_5 = 0.247$	$P_5 = 0.22$	
	$C_6 = 0$		
	$C_7 = 0.372$		
7	$C_1 = 0$	$P_1 = 0.56$	$P_2 \rightarrow P_1 \rightarrow P_4 \rightarrow P_5 \rightarrow P_3$
	$C_2 = 0$	$P_2 = 0.77$	
	$C_3 = 0.38$	$P_3 = 0.09$	
	$C_4 = 0$	$P_4 = 0.46$	
	$C_5 = 0.247$	$P_5 = 0.18$	
	$C_6 = 0$		
	$C_7 = 0.372$		

7.6 Conclusions

When the water resources problems are encountered with conflicting criteria, MCDM can be a powerful tool to solve these conflicts. The Fuzzy AHP is among the various methods for MCDM and is a combination of fuzzy numeric logic and AHP. The method is very appropriate for evaluating the alternatives if the linguistic vagueness is involved. The main drawback of the fuzzy AHP is that it only involves subjectivity and relies on the experience and the opinion of the decision makers. Evaluation and judgement on the alternatives and the criteria require experience and knowledge but subjectivity may be displayed by the experts in making decisions. Ranking of alternatives is done by a systematic method of TOPSIS. As compared with the other methods of multi-criteria analysis, TOPSIS and Fuzzy AHP are quite simple in application and conception.

The ranking of reservoirs is generally subjugated by the political interests or by the traditional way of making decisions. Only the resource availability and the cost are considered in the traditional way of decision making and systematic and holistic approach are not taken into consideration. The location decision is also influenced by the political interest of the political parties which results in disputes among the provinces or states of the country. The process of ranking should, therefore, not only consider the technical problems but also the political, environmental, social and economic problems. In order to protect the interest of all the stakeholders, that is, the provinces of Pakistan, a systematic approach is required for the ranking of that water resources projects.

A Fuzzy AHP-TOPSIS framework is used in this chapter for the ranking and evaluation of the reservoirs planned by WAPDA. Apart from this, few interviews were conducted, and literature was explored. After this, the criteria and sub-criteria were defined for the ranking of the projects. For the determination of criteria's relative weights and the location ranking, we integrated the fuzzy AHP and TOPSIS methods. The framework's application is exhibited by the case study of the reservoirs ranking in Pakistan. In order to explain the results and discuss them in detail, the sensitivity analysis is also performed. An integrated approach is proposed in this chapter with the main objective of ranking the water projects in Pakistan despite the conflicting criteria. An efficient way for ranking the projects under conflict is proposed in this chapter. The results show that Diamer Basha Dam (P_2) is the most favorable option whereas the Kalabagh Dam (P_4) is the least favorable option (that laps mainly due to political factor). We also observe that there are some interdependencies in the criteria which cannot be encountered by AHP method. Therefore, in order to consider, the interdependencies among the decision attributes, the analytic network process (ANP) can be used.

Chapter 8

Conclusions and Discussion

8.1 General

Water, being an important economic, social, cultural, political and environmental resource ignores not only the political boundaries, but also the cultural, societal and natural boundaries. Water Systems operate in multiple domains and consist of inter-connected networks. (e.g., societal, political and natural), on multiple scales (e.g., institutional, temporal, spatial), and at multiple levels (e.g., local, national, international). The water systems are more than the sum of their parts just like intertwined complex human-natural system. They contain various sub-systems like political, institutional, cultural, ecological, environmental and historical sub-systems. All these sub-systems have dynamic, complex and nonlinear feedback and interaction. Consequently, a large and unpredictable effect on the system's outcome can occur due to small change in the initial conditions of transboundary water system. Water resources shared between two or more riparian can be a source of cooperation as well as conflict. The relationship between these two is complicated. The hydro-political relations between two or more riparian states, countries or provinces can be affected by different socio-political and natural factors. The presence of the resilient water treaties which can cope with the changing ecological, political and societal conditions can decrease the conflicts among the riparian.

8.2 Role and Relevance of Three Enabling Conditions

The thesis identifies the role and relevance of three enabling conditions which are observed to be helpful in resolving water conflicts in Pakistan's Indus Basin. Using the inter-provincial water conflicts for the Indus basin within Pakistan as an illustrative case, it shows why over 30 years of dialogue and discourse could not create any formal water allocation agreement. Then, it suggests how the Water Apportionment Accord of 1991 created the enabling conditions that can help explain the evolution and dynamics of inter-provincial water conflicts within Pakistan.

8.3 Challenges and Response in Pakistan's Indus Basin

The thesis also discusses the water challenges faced in Pakistan's Indus Basin which is a major source of life in Pakistan. It shows that the problems of decreasing water resources would result in serious confrontation amongst the provinces in future. Pakistan, in order to harness this potential needs to increase its water storage capacity, improve its water sharing mechanism, improve the water use efficiency, allocate water for environmental flows and manage its groundwater and surface water resources in a sustainable way. Strengthening the institutions and removing mistrust between the provinces are the key elements for maintaining a sustained irrigated agriculture in the Basin.

8.4 Water Allocation Using Bankruptcy Rules

Equitable water allocation and ranking of important water projects in Pakistan are the most conflictive issues and various novel allocation mechanisms are proposed, using bankruptcy theory. Reallocation of the waters of Indus River, which is a shared river among the four provinces of Pakistan, is used as example to illustrate the application of the proposed solutions to real allocation problems (Chapter 4). The main features of the proposed rules are that they consider various factors as proposed by the UN Water Convention for the reasonable and equitable utilization of water resources. Additionally, a method is applied that enables us to establish the most appropriate rule to satisfy the four provinces of Pakistan.

8.5 Water Allocation in Critical Scarcity Conditions Using Weighted Bankruptcy Rules

Another common problem in water resource allocation is to design a stable and feasible mechanism of water sharing in critical scarcity conditions. The task becomes very challenging when the water demand exceeds the available water resources reserves. A new methodology has been described in this thesis (Chapter 5) for the water allocation in scarce conditions. The authors have also proposed "weighted bankruptcy rules" which have been applied under stochastic settings. The weighted bankruptcy approach favors agents with "high agricultural productivity". Four critical scarcity scenarios have been chosen and the bankruptcy rules and weighted bankruptcy rules have been applied in all these four scenarios. According the results, the agents having high agricultural productivity are favored by the weighted bankruptcy rules.

8.6 Water and Benefit Allocation Among the Provinces of Pakistan Using Nash Bargaining Solution (Internal Linear Programming)

A new framework for the allocation of water among the provinces of Pakistan has been proposed in this thesis (Chapter 6) which synthesizes the Nash bargaining solution concept with the bankruptcy theory to resolve supply-demand conflicts in the Indus basin among four provinces within Pakistan. Successive linear programming (based on Nash bargaining theory) are used to distribute the water and benefits among the four provinces.

The results show that the total benefit generated by using different Bankruptcy methods is US$ 18,090M while the benefits created by using the Nash bargaining approach is US$ 19,216M.

These findings suggest that moving from the non-cooperative approach of Bankruptcy to the cooperative approach of Nash, results in 6.2% increase in the total monetary benefit. Benefit reallocation among the four provinces of Pakistan is then done by applying the Nash bargaining theory under homogenous and heterogenous weights. Findings suggest that the basic water demands among the provinces can be satisfied by proposed disagreement points and the bargaining weights can highlight the role of different level of groundwater usage, irrigation efficiencies and variations in population among the provinces. Such a framework of creating and sharing of mutual benefits among the provinces highlights the efficacy of water diplomacy framework to encourage and enhance cooperation when water demand exceeds supply. The proposed formwork will find more innovative applications for other transboundary river basins across the world. Such a framework of creating and sharing of mutual benefits among the provinces also highlight the efficacy of water diplomacy framework to encourage and enhance cooperation when water demand exceeds supply.

8.7 Reservoirs Ranking in Pakistan Using Multi-Criteria Decision Making (MCDM)

Uncertainty in the selection of water resource projects is another serious problem faced in underdeveloped countries like Pakistan. A Fuzzy AHP-TOPSIS framework is used in this thesis (Chapter 7) for the ranking and evaluation of the reservoirs planned by WAPDA. The application of this framework is exhibited by the case study of the reservoirs ranking in Pakistan. The sensitivity analysis is also performed to explain the results in detail. An integrated approach is proposed with the main objective of ranking the water projects in Pakistan despite the conflicting criteria. An efficient way for ranking the projects under conflict is proposed in this chapter. The results show that Diamer Basha Dam is the most favorable option whereas the Kalabagh Dam is the least favorable option (that laps mainly due to political factor, otherwise in case of favorable political factor, it could become the second most favorable option).

In Pakistan, the majority of the river flow occurs during three to four-month period and low water storage in Pakistan puts immense constraints on assuring that the supply will meet demand. Due to this limited water storage capacity, the minimum flows required for the Indus delta are not met which are required to maintain healthy ecosystem of fisheries and mangroves. No new large reservoir has been constructed in Pakistan since 1976. Both the major reservoirs of Pakistan, i.e. Tarbela and Mangla, are plagued with siltation problem. Due to the sediment deposition, both the reservoirs have lost thirty-two and twenty percent of their storage capacity, respectively. The storage capacity of Pakistan must be raised by 22 BCM by 2025 to meet the water requirements of 165 BCM. Therefore, the construction of new reservoirs is necessary to ensure that supply is met with the provincial water demands, especially during the drought season.

8.8 Recommendations

It is notable that resilient and adaptive water governance system and conflict resolution are not "one size fits all" solutions. They should be defined with respect to cultural, social, economic and political and ecological features of the transboundary basin. It is important that the issues of water in transboundary river basins should be studied while considering the complex interactions between water, food and energy security (water-food-energy nexus). It is therefore, proposed that a nexus approach is adopted which improves food, energy and water security like addressed in this thesis.

The thesis has evaluated scientific approach to be adopted for the water allocation among the provinces of Pakistan and Reservoir ranking in Pakistan's Indus

Basin. Bankruptcy rules, Proposed Rules, Weighted Bankruptcy Rules, Nash bargaining theory and Fuzzy AHP-TOPSIS have been found the novel approaches to resolve water allocation problems and water projects construction prioritization in Pakistan. The following strategy is recommended for decision makers and stakeholders:

1. They should understand the water crisis as a national matter by having deep understanding of three enabling conditions: (i) Active recognition of interdependence, (ii) Mutual Value Creation and (iii) Adaptive Regime of Governance. This would help to initiate, design, and implement a negotiated process among stakeholders to resolve TWM issues.

2. They can use bankruptcy rules, proposed rules, weighted bankruptcy rules and NASH bargaining solution to define the scientific way of water distribution among the provinces. The thesis also recommends a new methodology for the selection of best rule which can be helpful for the decision makers and stakeholders to reach a decision.

3. Prioritization of major water resources construction projects has been done by doing AHP-TOPSIS. The thesis took several factors into account and did ranking of such projects as most feasible to less feasible (on the basis of factors considered in Chapter 7). The thesis recommends the following order of construction of major water projects studied by WAPDA:

    a. Diamer-Bhasha Dam

    b. Dasu Dam

    c. Bunji Hydropower Project

    d. Akhori Dam

    e. Kalabagh Dam

8.9 Future Recommendations

The thesis has evaluated scientific approaches to be adopted for equitable and reasonable water allocation and reservoir ranking in Pakistan's Indus Basin on the basis of data available. Following is recommended for future studies:

1. Although appropriate vision is provided by the allocation rules for the conflict management of transboundary water resources, the distribution of water among riparians can be a complex problem and mathematical models alone cannot solve these problems; therefore, water diplomacy and negotiation between the provinces of Pakistan are suggested, which would help them to develop a consensus and reach an agreement.

2. The limitations of this study may be addressed in in future studies and some additional influential factors should be considered such as the socio-political aspects of the basin , the reliable relative weights of the provinces, effects of external powers and climate change impact. It is also recommended to apply MCDA to combine all the relative weights to be considered.

3. While doing ranking of water reservoirs, ten (10) experts in WAPDA, who were aware of technical and other aspects of these projects gave their valuable input. There is need to refine this aspect further by taking more experts and relevant stakeholders on board. The author did his best to get this input from as many people as could had been possible, but due to hesitation for giving such input, few excused to give their expert opinion.

4. It is also recommended that for future studies, seasonal based water allocations should be considered.

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Appendix A

Questionnaire Form

Dear Sir/Madam,

Subject:- Evaluation of Water Allocation System and Reservoir Ranking for Indus River Basin: A Hydro-Economic Perspective

The above topic is under study for PhD Thesis at Civil Engineering Department at Capital University of Science and Technology by undersigned and the research involves the input of all the agencies/stakeholders involved in the water sector. The study involves the ranking of reservoirs in Pakistan using Fuzzy AHP TOPSIS method. As a key stakeholder, you are invited to participate in the survey for the Ranking of reservoirs in Pakistan's. Please note to return filled questionnaire within a week through return envelope already attached at the end and it is informed that all the information would be used for academic purposes only by concerned department at CUST and would be kept confidential. In advance, I wish to thank you for your kind favor, guidance and cooperation on the subject.

Thanks.

Yours Sincerely,

Shahmir Janjua Researcher	Dr. Ishtiaq Hassan Supervisor

Table A.1: Description of potential locations for projects and criteria.

Name	**Installed Capacity / Power Generation**	**Resettlement and Rehabilitation**	**Location**	**Storage Capacity**
Bunji Hydropower Project	7100 MW	A little required	The Project is located on Indus River near Gilgit. Powerhouse and dam sites are 560 km & 610 km respectively from Islamabad.	0.2 MAF
Diamer Basha Dam	4500 MW	A little required	The project is located on Indus River, about 315 km upstream of Tarbela Dam, 165 km downstream of the Northern Area capital Gilgit and 40 km downstream of Chilas.	8.1 MAF
Dasu	4320 MW	A little required	The project is located at 7 km North of Dasu Town in Kohistan District of the Khyber Pakhtunkhwa Province and 350 km North of Islamabad. The site is 74 km downstream of proposed Diamer Basha Dam Project site.	1.4 MAF

Kalabagh Dam	3600 MW	Very much required	The project is located at Kalabagh in the Mianwali District of Punjab Province in Pakistan.	7.9 MAF
Akhori Dam	600 MW	A little required	Akhori Dam site is located near Akhori Village across NandnaKas, a small tributary of Haro River in Attock District of Punjab.	7.6 MAF

Questionnaire Form

With respect to social and cultural criteria

How important is criterion Social and cultural when it is compared with criterion Political, Security and legality?

How important is criterion Social and cultural when it is compared with criterion Technical and Executive?

How important is criterion social and cultural when it is compared with criterion Environmental?

How important is criterion Social and Cultural when it is compared with criterion Economical and financial?

How important is criterion Social and Cultural when it is compared with criterion Demand Management?

How important is criterion Social and Cultural when it is compared with criterion Comprehensive Management? And so on.

Table A.2: Questionnaire form to calculate the weight of each criteria.

Pref. of Experts	Perfect	Abs.	Very Good	Fairly Good	Good	Pref.	Not Bad	Weak Adv.	Equal	Weak Adv.	Not Bad	Pref.	Good	Fairly Good	Very Good	Abs.	Perfect	Pref. of Experts
Social and Cultural																		Political, Security and Legality
Social and Cultural																		Technical and Executive
Social and Cultural																		Environmental
Social and Cultural																		Economic and Financial
Social and Cultural																		Demand Management
Social and Cultural																		Comprehensive Management
Political, Security and Legality																		Technical and Executive
Political, Security and Legality																		Environmental
Political, Security and Legality																		Economical and Financial
Political, Security and Legality																		Demand Management

Political, Security and Legality																		Comprehensive Management
Technical and Executive																		Environmental
Technical and Executive																		Economical and Financial
Technical and Executive																		Demand Management
Technical and Executive																		Comprehensive Management
Environmental																		Economical and Financial
Environmental																		Demand Management
Environmental																		Comprehensive Management
Economical and Financial																		Demand Management
Economical and Financial																		Comprehensive Management
Demand Management																		Comprehensive Management

TABLE A.3: Questionnaire form to calculate the importance index of each alternative
Verbal variables related to performance relative to benchmarks options.

Very Weak	(0,0,1)
Weak	(0,1,3)
Partly Weak	(1,3,5)
Average	(3,5,7)
Partly good	(5,7,9)
Good	(7,9,10)
Very Good	(9,10,10)

Rank Each of the alternatives with respect to the criteria, according to the fuzzy scale given above.

Criteria / Location	**Cultural and Social**	**Legality, Political and Security**	**Executive and Technical**	**Environmental**	**Economic and Financial**	**Demand Management**	**Comprehensive Management**
Bunji Hydropower Project							
Diamer-Bhasha Dam							
Dasu Dam							
Kalabagh Dam							
Akhori Dam							

Appendix B

Excel Template for Ideal Solution Using Chang's Extent Analysis Approach

Best Ideal Solution

Criteria / Location	Social and	Political, Security and Legality				Technical and				Environmental				Economic and Financial				Demand Management				Comprehensive Management					
Bunji Hydropower Project	0	0	0	0	**0**	0.4679	0.3697	0.117	**0.564**	0	0	0	0	0.4783	0.2953	0.061	**0.5274**	0	0	0	0	0.0000	0.0000	0.0000	0.0000	S1*	1.0915
Diamer-Bhasha Dam	0	0	0	0	**0**	0	0	0	**0**	0	0	0	0	0	0	0	**0**	0	0	0	0	0.4484	0.3999	0.1384	0.5735	S2*	0.5735
Dasu Dam	0	0	0	0	**0**	0.8317	0.6989	0.283	**0.778**	0	0	0	0	0.6247	0.4124	0.1196	**0.6209**	0	0	0	0	0.9355	0.8649	0.3999	0.8564	S3*	2.2549
Kalabagh Dam	0	0	0	0	**0**	0.2079	0.1747	0.052	**0.381**	0	0	0	0	0.0098	0.0098	0.0055	**0.0913**	0	0	0	0	0.9355	0.8649	0.4484	0.8658	S4*	1.3377
Akhori Dam	0	0	0	0	**0**	0.2079	0.1444	0.0231	**0.354**	0	0	0	0	0.9761	0.7053	0.269	**0.8063**	0	0	0	0	0.9355	0.8649	0.4996	0.8756	S5*	2.0357

Worst Ideal Solution

Criteria / Location	Social and	Political, Security and Legality				Technical and Executive				Environmental				Economic and Financial				Demand Management				Comprehensive Management					
Bunji Hydropower Project	0	0	0	0	**0**	0.0520	0.0520	0.0361	0.2161	0	0	0	0	0.0879	0.0879	0.0738	**0.2884**	0	0	0	0	0.9355	0.8649	0.4996	0.8756	S1-	1.3801
Diamer-Bhasha Dam	0	0	0	0	**0**	0.8317	0.6989	0.2830	0.7775	0	0	0	0	0.9761	0.7053	0.2690	**0.8063**	0	0	0	0	0.0886	0.0886	0.1121	0.3105	S2-	1.8943
Dasu Dam	0	0	0	0	**0**	0.0000	0.0000	0.0000	0.0000	0	0	0	0	0.0390	0.0390	0.0299	**0.1897**	0	0	0	0	0.0000	0.0000	0.0055	0.043	S3-	0.2327
Kalabagh Dam	0	0	0	0	**0**	0.2079	0.1747	0.0924	0.3979	0	0	0	0	0.7907	0.5491	0.1977	**0.7159**	0	0	0	0	0.0000	0.0000	0.0014	0.0215	S4-	1.1353
Akhori Dam	0	0	0	0	**0**	0.2079	0.2079	0.1444	0.4322	0	0	0	0	0.0000	0.0000	0.0000	**0.0000**	0	0	0	0	0.0000	0.0000	0.0000	3E-16	S5-	0.4322