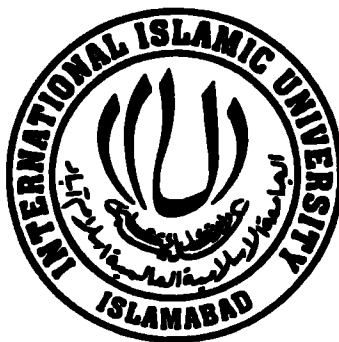


**Agriculture Water Management through Human and
Natural Systems: An Agent Based Modelling Approach**



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**A dissertation submitted in partial fulfillment of the requirements
for the PhD degree in Economics at the School of Economics,
International Institute of Islamic Economics (IIIE),
International Islamic University, Islamabad (IIUI)**

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Co-Supervisor: Dr Asad Zaman

August 2022

DECLARATION

I hereby declare that this thesis, neither as a whole nor as a part thereof, has been copied from any source. It is further declared that I have carried out this research myself and completed this thesis based on my persona under the guidance of my supervisor. If any part of this thesis is proven to be copied out or earlier submitted, I shall stand by the consequences. No portion of the work presented in this thesis has been submitted in support of any application for any other degree or qualification in International Islamic University or any other university or institute of learning.

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August, 2022.

DEDICATION

IN THE NAME OF ALLAH, THE MOST MERCIFUL AND BENEFICENT.

I dedicate my work to the seekers and preachers of ILM & Noor of Allah Subhanahu Wa Ta'ala (SWT) and my late mother Najma Jalil (may Allah elevate her ranks in Jannt-ul-Firdous) without her tireless efforts and prayers I would never have been able to complete my studies.

APPROVAL SHEET

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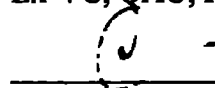
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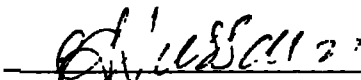
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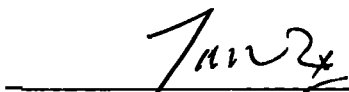
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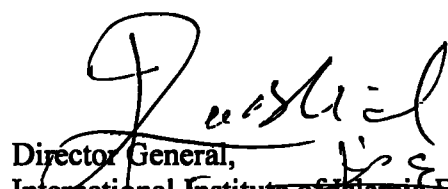
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ABSTRACT

Water demand for agriculture and other sectors in Pakistan is getting highly contested as a result of continuous mismanagement of water resources coupled with decreasing per capita water availability. Agriculture development is more endangered under climatic vulnerabilities. The traditional water management approaches in the country are detrimental to sustainable agriculture in particular and economic growth in general. The poor governance is also creating water quality and quantity imbalances in the upper, middle, and tail reaches of the Indus Basin and posing profound implications for potential spatiotemporal returns of farming. A physical water management solution wouldn't be a successful approach as it ignores water users' behaviors; their interaction with each other and the feedback effects they receive from the system. Agent-Based Modeling is a relatively new approach that provides helpful tools to simulate social behaviors in sustainable water management. The Agent-Based Modelling approach is applied to develop models to include behavioral complexities of stakeholders in water management considering uncertainties and non-convexities of the system. This study assesses policy paradigms for systematic conjunctive ground and surface water use under the physical characteristic of water resources subject to socio-economic conditions and the behaviour of farmers. Initially, the dynamics of the irrigation system with asymmetric access to irrigation water are assessed under the Business-as-Usual scenario. Climatic and physical properties of the system are varied to see water quantity-quality relation and earnings of farmers. We have found small farmers are using less both surface and groundwater irrespective of the distance from the water source. Profits and water use differences are skewed more towards the large farmers located nearest to the canal heads. It is concluded from the results that water quality

parameters logging and salinity are deteriorated if the same water use practices are adopted for an extended period. Our climate change experiment under conventional irrigation practices shows that in the season where rainfall is sufficiently high the profits based on spatial differences among farmers are not much prevalent due to less need of exchanging water turns to fulfill water demand from surface water. However, unfavorable weather conditions deteriorate water quality parameters and eventually, productivity, crop growth, and profits and have severe consequences for vulnerable small farmers located at the tails of water sources. We have developed an ABM model simulating the system by varying different agro-climatic parameters for water withdrawal behaviours of farmers as BAU, and Institutional Management Perspective(IMP) and Self-Governing Rules (SGR) to substantiate a groundwater development framework in conjunction with the management of surface water. Overtime spatially distributed farmers' caricaturized scenarios were built to include groundwater table fluctuations for better management of water resources. The model shows that SGR and IMP bring equity in water availability and prevent agriculture from worsening water quality parameters. However, consistency in the benefits may break down in extreme cases of climate change and spatio-physical conditions. Our water management perspectives provide improved outcomes of water withdrawal. SGR perspective managed to increase groundwater abstraction prices 3 times more than the existing rates for the farmers located near the water source. For the farmers located at tails, IMP appears to manage resources better than other scenarios. The results of our final conjunctive water management model show a trade-off between sustainable water management practices and farmers' benefits arising from crop production. Ground and surface water use behavior is found as a collective action problem. Farmers' benefits are always preferred over collective benefits of spatial water availability to tail-end

farmers under climatic change and critical water supply scenarios. Water costs proved a major determinant of water use behavior in less water-deficient areas. Traditionally, large farmers are found using more ground and surface water irrespective of their location. Peer pressure, local rules, or institutional management can improve the water management problem. However, all management perspectives become impotent under extreme climate change. Improved and sustainable water management requires to have area-wise surface and groundwater use policies and institutional support for the promotion of rules and norms.

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List of Symbols and Acronyms

Symbol	Description	Unit
IIP_{sub}	Allocation of subsidy for improved irrigation practices	Rs/ha/year
$S_{t:2}B$	Budget Allocation for subsidy	Rs/ha/year
$\tau_{s:2}$	Retention Land Subsidy Rate	Rs/ha/year
A^F	Total Farm Area	ha
r_{max}	Parameter for subsidy	-
$GW_{irrigsub}$	Subsidy for groundwater irrigation	Rs/unit
A_{crop}	Area under usual cropping practices	ha/year
A_{ret}	Area for retention practices	ha/year
$M_{t:3}$	Farmers Money Holding in time period 3	Rs.
$H_{t:5}$	Harvest Yield in time period 5	Maunds/ha
$Crop_{t:5}$	Realized crop yield in time period 5	Maunds/ha
$Cprice_{t:6}$	Realized Market value of famer crop	Rs/Maund
$M_{t:7}^{real}$	Realized money income at the end of cropping period 7	Rs.
$U_{t:7}^{F,total}$	Total utility received by farmer at the end of time period 7	Utils/ Money
$UOC_{t:7}$	Farmers' utility of consumption in period 7	Utils
$\bar{C}^F$	Retaining subsistence level of crop	Maunds
RT	Risk tolerance farmer retain a little more crop	Maunds
$S_{t:7}^F$	Farmer's saving in time period 7	Rs.
$S_{t:0}^F$	Farmers saving at the start of cropping period	Rs.
$TAW_{t=1:7}^F$	Total available agriculture water during cropping period	m ³ /ha
DWS	Distance from Water Source	Km ²
$Q_{gw,t=1:7}^{optFl}$	Optimal groundwater level	m ³ /ha
$D_{max,t=1:7}$	Maximum demand for irrigation water	m ³ /ha
$U_{t=1:7}^{Fl}(C \rightarrow C)$	Social Pressure	-
F_m	Modification Factor	-
$V_{t=1:7}^{n-F}(C/NC)$	Fraction of neighbor cooperative or non-cooperative	Fraction
α	fraction of training and penalty impacts on decision making of	
β	fraction of training and penalty impacts on decision making of	
UIPA	Upper Indus Basin Aquifer	
BAU	Business-As-Usual	
IMP	Institutional Management Perspective	
SGR	Self-Governing Rules	
EC	Electrical Conductivity	ds/m
SAR	Sodium Absorption Ratio	mmol/L) ^{1/2}
RSC	Residual sodium carbonate	(meq/l
WTD	Water Table Depth	Feet
DWS	Distance from Water Source	KM

CHAPTER 1. INTRODUCTION

1.1 Background of Study

Water is a necessity for all living beings on the planet. It is a crucial component of socio-economic development and environmental integrity. Sustainable development of water resources underpins all productive and liveable activities like agriculture, industry, energy, sanitation, health, and conservation of the environment (Kundzewicz et al., 2008; Xie, 2006). This means that the competition for water between agriculture and the other sectors is very high and destined to increase with population growth (Bonell & Askew, 2000). Population growth is one of the factors which primarily exacerbate pressure on water resources since the water base remains the same.

In the “Business-as-Usual” scenario, 40% of the global population is supposed to face water scarcity by the year 2050 (Garrido & Ingram, 2011).

Pakistan is an agrarian country with the world’s most extensive well-developed contagious irrigation system. Pakistan utilizes about 93% of its freshwater resources in agriculture (GoP, 2004; Mushtaq et al., 2007; Shehzad et al., 2007; Lytton et al., 2021).

Moreover, water demand for agriculture and other sectors in the country is getting more acute as a result of continual mismanagement of water resources coupled with decreasing per capita water availability. Irrigation water requirement for the year 2024-25 is projected at 255 billion m³, while it was found 163 billion m³ for the period 1994-95 under existing water management practices and policies (Ahmed et al., 2007).

Moreover, the additional supply of water for the required expansion of agriculture, industry, and the environment is estimated at 45, 7, and 2.5 m³ (Mushtaq et al., 2007).

Water resources of Pakistan are calculated at 172 billion m³ (Ahmed et al., 2007; IWASRI, 1998) which are far less than water demand and hence show a shortfall of 83

billion m³ of irrigation water for the year 2024-25(Ahmed et al., 2007, Fatima et al., 2021).

The water resource situation becomes more fragile in the context of global climate change. Global climate change is one of the most important issues faced by the world in the 21st century. It affects all sectors of the economy, but agricultural production is more sensitive in response to the disturbances in water availability. These vulnerabilities of the natural ecosystem impact the supply balances in water-scarce countries (Kaiser & Drennen, 1993; Rosenzweig & Hillel, 1998).

Agriculture is climate-dependent in both poor and rich countries (Parry & Rosenzweig, 1990; Rosenzweig & Parry, 1994; Watson et al., 1996) but poor countries are more sensitive to these changes(Kurukulasuriya & Rosenthal, 2013; Seo & Mendelsohn, 2008) due to the lack of better adaption strategies (Madzwamuse, 2011; OECD). Besides other regions of the world, water stress caused by climate change is more visible in South Asia (MoE, 2009). The resilience of water resource management strategies in response to the rising population, urbanization, industrialization, and environmental degradation is very poor. The sustainability of the system is endangered more in the presence of climate change (Laghari et al., 2012; Yu et al., 2013). Water availability in Pakistan in the climate change scenario is projected to increase or decrease by 25% or 12%, respectively (Zhu et al., 2013). Moreover, projections are also made for the production of agricultural commodities affected by climate change. UNFCCC (2007) has projected a fall in wheat production in the regions by 50 percent followed by a change in weather conditions.

Agriculture in Pakistan is also vulnerable to changes in climatic conditions. Global Climate Risk Index ranked Pakistan in the top ten countries that are prone to vagaries of climate (Kreft et al., 2014; MoE, 2009). This Sensitivity is high due to the higher

reliance of the economy on agriculture, which is vulnerable to climatic conditions (Khan, 2015). Extreme weather conditions have led Pakistan to face many losses. Increased global warming and peculiar rainfall have made arid areas more sensitive. The impacts of climate change on farmers' lives are devastating (Shakoor et al., 2011). However, climate change may boost the production of some crops in some parts of the country (IPCC, 2015).

Climate change will affect the water supplies of the country. Since most of the tributaries in Punjab are derived from Himalaya Glaciers besides monsoonal rainfalls water flow in these tributaries is majorly dependent on snowmelt in summers and spring. It is predicted that glaciers melting due to a temperature rise can reduce water flows by 40% at the end of this century as compared with the water flows in 2000 (Qureshi, 2011). An increase in water demand due to increasing agriculture, industry, and domestic needs coupled with a decrease in water flows due to climatic changes is bringing serious challenges to agriculture in general and poor and tail-end farmers in particular. Population pressure along with mismanagement of water resources exacerbates the issue. Furthermore, climate change is another factor that is anticipated to put additional stress on agriculture. Climate change and water management are closely linked, unexpected weather conditions; droughts, and floods affect the way how water is sourced and used (Ringler & Anwar, 2013). Vision 2030 recognizes the devastating impact of expected climate change on agriculture and livelihoods (PC, 2007). Extreme temperatures, the shift in the monsoon season, and the melting of glaciers have severe consequences for water consumers. Moreover, the peculiar nature of climate change along with soil and water degradation is threatening agricultural production and hence food security (Ahmed & Gautam, 2013). Yu et al. (2013) estimated a substantial fall in crop output in all regions of Pakistan. It has been

also estimated that under climate change conditions, the agriculture share of GDP is on average expected to fall by 5.1%.

The government of Pakistan has initiated water sector strategies to ensure sustainable water availability to support economic growth. Water management in Pakistan requires effective implementation of policies regarding infrastructural, financial, and institutional developments. Assessment of the socio-economic implication of these policies and their impacts are significant for their evaluation. The pressures imposed by the higher water demands, quality of water discharge, and climate change raise new water challenges, which can be handled only by coordinated efforts of multiple stakeholders through cooperation and participatory processes. Pakistan Water Sector Strategy (GoP, 2002) emphasizes the need for participatory water management at the level of planning and designing for the improved practices of irrigation water management, rural water supply, and sanitation. Moreover, switching to participatory approaches has many advantages, including easy reach to the desired outcomes, and it involves minor costs in the water sector. Implementing and increasing the extent of participatory approaches to water management are recognized as an important part of IWRM (MoE, 2011). By recognizing the need for participatory water management PIDA (Pakistan Irrigation and Drainage Authority) has initiated policies of Participatory Irrigation Management (PIM) in all provinces in anticipation of the importance associated with participatory approaches in the context of water management (Anwar et al., 2008).

1.2 Context Research Problem and Rationale

Most water crisis in the world is believed to be stemmed from misgovernance and underutilization of water resources (Pahl-Wostl et al., 2008; Winpenny & Camdessus, 2003). Similarly, inefficient use and low conservation of water are considered root

causes of water scarcity in Pakistan (Altaf et al., 2009). Moreover, water scarcity has become a major source of conflicts over water distribution among competing users (Zawahri, 2009). Pakistan is facing a continual shortfall of water as its demand is increasing to cope with the increased population's needs for food, water, and energy. Pakistan is projected to be water-stressed in 2025 as per capita water would be as low as 850 m³ while it was 1200 m³ in the year 2005 (PEPA, 2005). These water shortages and stress situations are also responsible for interprovincial conflicts regarding water distribution (IUCN, 2010). Mismanagement of water resources is responsible for a great number of water losses. As per an estimate, out of diverted water for irrigation, 30% of the water is lost through system losses (Qureshi, 2011). It is a unanimous view of all stakeholders that poor water management is responsible for persistent inequalities in water distribution at the upper, middle, and end tail of water channels (Altaf et al., 2009).

The agricultural sector has remained dominant in the provision of employment to 42.3% of the labor force in the country (GoP, 2015-16). Deployment of the sector is contingent largely on favorable water supplies. To deal with seasonal variations in water availability, conjunctive use of ground and surface water is advocated by water experts. For this purpose, the government tried to complement surface water with groundwater by installing tube wells. It increased cropping intensities by 150% (Ahmad et al., 2007). Due to these reasons, there has been a more than 3000% increase in tube wells installation since the 1960s (Watto & Muger, 2015). Pakistan appeared 4th in the world and first in South Asia for the cropped area under groundwater irrigation (Watto & Muger, 2015). Due to dwindling and uneven surface water supplies over time and space; reliance on groundwater use in Pakistan is increasing (Watto & Muger,

2015). It has been estimated that the share of groundwater in irrigation supplies has increased by more than 50% in Pakistan since the 1960s (Qureshi et al., 2010).

There exist inefficiencies in access and usage of groundwater since the potential of groundwater development is limited to large farmers. Small farmers still buy from large farmers informally from their surplus groundwater (Qureshi et al., 2010). Due to flexibility like groundwater, there has been an increasing tendency among farmers to extract groundwater. However, inefficient irrigation practices, poor drainage facilities, and canal conveyance losses cause the problem of salinity and waterlogging (Khan et al., 2008; Qureshi et al., 2010). It has been estimated that groundwater extractions are 50% greater than their annual recharge. Increasing reliance on pumped water for irrigation can endanger soil and water quality. The sustainability of the current level of agriculture production cannot be restrained under the current groundwater water withdrawal tendency. Despite the fact, groundwater water has a huge contribution to human settlements, competition among users, both agricultural and domestic, for high-quality and shallow groundwater is becoming intense. These facts have posed serious challenges for groundwater management in key areas of the country.

Surface water availability in the country is reduced by 46% from 1996- 2001. In the same period, private tube wells have observed an increase of 59%, which clearly shows the increasing importance of groundwater resources. The massive use of groundwater has created issues of salinity in large tracts of the Indus basin. And many other areas are further under threat of the issue. Farmers are conjunctively using both surface and groundwater. But current strategies are making groundwater unsustainable and exacerbating the issue of secondary salinization (Usman et al., 2016a). Excessive use of groundwater usually happens due to the seasonal or rotational availability of surface water. Fixed rotation-based irrigation system needed to be corrected to serve

the water requirement of the crop (Qureshi et al., 2010). In recent years, irrigation reliance on groundwater has increased to 70% in some parts of the Indus Basin. Greater economic returns and reliable supplies of groundwater impelled farmers to grow water-intensive crops. (Watto & Muger, 2014). This will lead to unsuitable economic returns. It has been estimated that there will be a 32% shortfall in water, which can result in a deficit of 70 million tons of food by 2025 (ADB, 2002).

There exist many kinds of negative externalities of groundwater over-abstractions. The problem of soil salinity and waterlogging is exacerbating day by day. Almost 4.5 million hectares of land are subject to salinity, half of this area is from irrigated Punjab and Sindh. Furthermore, land degradation is reducing crop potential by 25% every year (Qureshi, 2011). Moreover, it has also been found that inequities in pumping costs prevail due to the existing canal water allocations (Basharat, 2015). The farmers at the tail-end of the canal system are found to pay more than twice in pumping costs as compared to the head-end farmers. In addition to this inequity, the current surface water allocation schedule contributes to the growing waterlogging and salinity problems in areas of Punjab (Chandio et al., 2012). Moreover, water table depth and salinity are found higher in the areas away from rivers or canals. More than 1.4 million hectares of agricultural land are abandoned due to salinity in the country, and the majority of this kind of land prevails in tail-end areas (Martin et al., 2006). To manage these types of inequalities and issues, it has been suggested to utilize conjunctive surface and groundwater for sustainable groundwater abstraction in the middle Indus (MacDonald et al., 2015).

In Sindh, groundwater is 4% to 8% of the surface water as compared with canal command areas of Punjab, where the ratio of ground and surface water use is almost the same. Groundwater is an underutilized resource in surface irrigated areas of Sindh

due to high surface water allocations. Issues of logging and salinity are getting intense in some parts of Sindh and Punjab, respectively (van Steenberg et al., 2015). It has been found that groundwater abstraction in Punjab is far more than its recharge. A mechanism for parallel extraction of groundwater from tail to end can help to reduce the issue of salinity and uneven extraction of the resource (Shafeeque et al., 2016). Moreover, area-specific policies for ground and surface water conjunctive use under the physical characteristics of the resource subject to the socio-economic conditions of farmers is an urgent need of the hour (Murray-Rust & Vander, 1994).

Sustainable agriculture and food security Policies for judicious use of groundwater must be made to make surface water available for tail-enders. There is a need to motivate farmers for sustainable groundwater use and to resolve pricing entitlement and regulatory issues (Qureshi, 2011). It has been found that farmers at end tails are using 38% more groundwater water. Upstream farmers must be encouraged to use groundwater wisely to provide more canal water to tail-enders to avoid losses in agricultural production (Usman et al., 2016a). Excessive application of groundwater can cause secondary salinization at the middle and tail end of the area, and it can have serious implications in the long run. Given the enormous importance of conjunctive use of surface and groundwater, there is a need to develop systematic policy options for the head, middle, and tail end of the Indus basin for sustainable water management (MacDonald et al., 2015; Qureshi, 2011; Usman et al., 2016a). An ideal and complete model may have some sort of human behavior in response to policy initiatives (McKinney, 1999).

Ground and surface water cannot be dealt with as separate resources. Understanding the interaction of surface and groundwater is essential for policymaking for water management in agriculture. In most arid or semi-arid regions, they are

interchangeable resources. The interaction of both can have a significant impact on water quantity and quality (Brodie et al., 2007). Managing one of the components will be partly effective due to continuing interaction between them. Since shortages of surface supplies have led to the development of groundwater. Groundwater has been proved as a vital resource to deal with the vulnerabilities in surface water supplies (Bovolo et al., 2009; Taylor et al., 2013; Tsur & Graham-Tomasi, 1991). Moreover, groundwater is treated as a supplement resource where surface water is available in abundance. For sustainable use of groundwater, it is necessary to compare surface water travel cost and groundwater pumping to reflect the economic value of resource usage (Taylor et al., 2014). By comparing costs, spatial conditions can be defined to use surface water at the nearest distance from canals and groundwater at the farthest distance from headworks. The scarcity cost of both resources is also different across time. The farmer usually switches from one resource to another resource if the scarcity price of either resource changes. For instance, if groundwater becomes scarce, the farmer may switch to surface water. The surface water area will increase (Roumasset, 2007; Taylor et al., 2014). Subsidies for groundwater abstraction can be regulated by comparing the travel cost of groundwater and surface water to tail-enders and head-end farmers.

Efficient management of increasingly scarce water resources is indispensable with the continuously growing food demand, as its basic source more or less remains the same over time. Efficient management may arrive from good governance. Stakeholders' participation is one of the principles of good governance. It may prove an important factor in the improvement of water management (Harvey & Reed, 2007; Reed, 2008). It has also been emphasized in water sector strategies that conservation and management should be addressed by engaging all stakeholders for water

management in cooperation with provincial irrigation departments. Regulating rewards or penalties for farmers across space and time for expected water use strategies may prove useful for irrigation water management.

1.3. Objectives of Research

This study will aim at

- Analyzing the dynamics of the irrigation system with asymmetric access to irrigation water and highlighting farmers' potential benefits under different risks arising from uncertain hydro-climatic and economic conditions.
- Assessing how conjunctive use of ground and surface water can be managed considering spatial surface and groundwater availability of farmers through social and institutional enhancement in the forms of providing incentives, penalties, and new regulations
- Understanding policy options for groundwater regulatory framework through delineating alternative surface and groundwater use and extraction cost.

CHAPETR 2. REVIEW OF THE RELEVANT LITERATURE

Meeting the water demand of all uses is becoming an unprecedented challenge. Besides other uses, water demand for agriculture has exceeded the sustainable limits. Agricultural development has made world food secure. But there exist unmet challenges as achieving better quality food with water use efficiency, living healthy and productive lives, environmental sustainability, and value addition in GDP. Despite the availability of food at low prices, access to food remained poor around the globe. Due to ill-managed resources, agriculture development remained constrained. Groundwater is a reliable and preferred resource for agriculture is becoming polluted and depleted making access uneconomical and unsustainable.

A holistic approach to deal with the issue of increased water demand for human settlements is required. A major step to reach these goals, necessitate analysing how the water resource of the country is currently managed and affecting food supply and environmental sustainability. There is a need to see water management practices that remained successful or failed to achieve concerned goals to develop a knowledge base to have a better understanding of the current state of the resource.

2.1 Water Management Practices in Pakistan

Pakistan is highly dependent on irrigated agriculture for its agricultural produce. Irrigated agriculture in Pakistan is a major consumer of both surface and groundwater. It is mainly confined to the Indus Plains, where it has been developed by harnessing principal water resources available to the country. Without assured irrigation supplies, these arid and semi-arid areas of Pakistan cannot support any agriculture (Wescoat Jr et al., 2000). To assure water supplies for agriculture massive infrastructure projects as

link canals and large reservoirs started under the Indus Basin Development Program (IBDP) to fill the gap of the diversion of water of Sutlej, Bias, and Ravi in favor of India (Biswas, 1992). Research on water resource management in the 1960s and 1970s was primarily based upon the implementation of IBDP, which converted the Indus Basin into the largest irrigation system in the world. Engineering solutions to water management problems were regarded as the best strategic management problems of the issue at that time. Water and Power Development Authority (WAPDA) was established to regulate these megaprojects. Water governance and related issues were the main concern of policymakers (Jones, 1974).

The construction of large dams and canals fuelled the issue of waterlogging and salinity. The area under these menaces increased to over 4 million hectares. Reducing the severity of the problem was the prime concern of water sector policymaking in the country. Many corrective measures were tried, but the issue of logging intensified further due to floods in the 1950s (Rehman et al., 1997). A nationwide survey has been conducted for waterlogging assessment from 1976-79. It was found that the water table was on average at 8 feet depth in almost 50% of the area under study. The issue of salinity was found gripping due to waterlogging in these areas (Choudry, 1977). The government initiated a large-scale vertical drainage program through the Salinity Control and Reclamation Projects SCRAP program in the 1960s, which lead to the large-scale installation of tube wells (Bhutta & Smedema, 2007). A national Water Drainage plan was set to manage and coordinate regional water drainage programs (van Steenberg et al., 2015).

Initially, Soil Reclamation Board was given the responsibility to control waterlogging and salinity through the development and operation of drainage tube wells. Boards' powers were dissolved, and the Provincial Irrigation and Power

Department tried to frame licensing for groundwater extraction in 1965, but it was not ratified. In 1968 WAPDA, a federal entity was established, which is responsible for the development of all major power, irrigation, and drainage infrastructure, whereas the operation of irrigation and drainage infrastructure is usually transferred to the provincial irrigation departments. As per 1958, Act WAPDA is responsible for issuing area-specific rules; such rules have never been announced, and conflict for authorization for groundwater management between PIPD and WAPDA are neither addressed nor did they operationalize. Moreover, as part of SCARP, more than 15000 deep public tube wells in generally in Punjab and Sindh and Specifically in KP were installed till 1995.

SCARP Monitoring organization, assessed deep tube wells' groundwater quality and level for designated areas only. The government prompted private tube wells development in Punjab, Sindh, KP, and Baluchistan. This initiative was specifically taken for agricultural development drainage and food security. Subsidies were provided on power supplies up to 60%. For further development, pump sets and soft loans were provided (Johnson, 1989). Initially, the Government subsidized tube wells development, later it was recognized that through private tube wells agriculture sector has achieved sustained development in tube wells installation by the 1980s. But the Government continued subsidies in electric supply.

This program has substantially increased supplies for agriculture (Kazmi et al., 2012; Qureshi et al., 2010). This widespread development of groundwater abstraction proved more effective than any other program to deal the issue of food security. It makes groundwater a more important resource than surface water in the country. Besides knowing about water management practices it is important to see the widely developed models to understand water management problem around the world.

2.2 Water Management Models

Mainly water management models revolve around optimization and utilization of water resources to meet the competing needs of water. Usually, resource allocation decisions are guided for policymakers to make informed policies considering the relationship between the associated economic benefits of water demand and water resources. Popular optimization methods for water management are linear programming, network flow programming (Fulkerson, 1961), nonlinear programming, dynamic programming, system dynamics (Mirchi et al., 2012; Sharawat et al., 2014) and genetic algorithm (Castilla-Rho et al., 2015; Farhadi et al., 2016).

Water management models at the basin scale mainly consist of reservoir operation, groundwater management, conjunctive use of surface water and groundwater, and irrigation and drainage management (McKinney, 1999). Moreover, models for integrated water resource management (Mayer & Muñoz-Hernandez, 2009), optimization techniques for reservoir operation (Hajkowicz & Collins, 2007), and multiple criteria analysis for planning and management (Rani & Moreira, 2010) do exist in literature. Out of these models, mathematical models have been extensively used in the past to solve water quantity and quality issues. Mainly simulation and optimization are two approaches used by researchers to deal with the issue. Optimal management consists of the optimization of allocation subject to constraints in the system, and simulations are the assessment of the system behavior based on a set of rules governing water allocations and infrastructure development (McKinney, 1999). Currently, efforts are made to optimize water use to maximize monetary as well as non-monetary benefits as soil and environmental degradation (Mayer & Muñoz-Hernandez, 2009).

Ground and surface water management separately and conjunctively are dealt with simultaneously in literature. Groundwater being established as a major and viable

water resource for agriculture and municipal use (Mekonnen et al., 2016). Groundwater management, due to its complex nature, has attracted many modeling approaches from economists as compared with other physical models. Groundwater management modeling includes the valuation of groundwater use, water use efficiency, and incentivizing for policy implementation to optimal control of groundwater. Modeling focus initially was restricted towards maintaining quantities and quality of water supplies for these uses (Willis & Liu, 1984). Groundwater behavior is included in the water management framework from the approximation of finite difference and finite element methods for water quantity and quality (Gorelick, 1983). Multi-criteria and multi-objective models have been made for the problem of allocation, trading rates of freshwater, and pumping cost of the aquifer (Shafique et al., 1992; Willis & Liu, 1984).

Groundwater status is affected by the hydrological stochasticity of surface water and water management policies. The dynamic nature of groundwater resources has led researchers to develop modeling approaches accordingly. Systematic analysis methods have been used to assess the impact of quota and taxes on groundwater considering GW as a single aquifer (Feinerman & Knapp, 1983). Dynamic programming is used to have a functional equation for pumping rules to control groundwater aquifer (Burt, 1964). Optimal economic use of groundwater resources has been analyzed for optimal abstractions, and policy for cascaded pumping tax for a different level of groundwater users was advised (Brown & Deacon, 1972). A simulation model for hydrological-legal farmer decisions system was developed. Under different institutional arrangements, allocative and distributional consequences of these arrangements were made (Bromley et al., 2001). Only a few studies have included the complexity of this resource, including physical models of resources (Young et al., 1986). Conjunctive use of water is also important as one source of water cannot fulfill the future requirements of a

growing population (Harmancioglu et al., 2013). Different studies have been conducted to see the efficiency of conjunctive water use through dynamic optimization (Brown & Deacon, 1972; Noel et al., 1980). Due to the issue of dimensionality in dynamic optimization, static, steady-state optimization models for conjunctive use were developed (O'Mara & Duloy, 1984; Rogers & Smith, 1970).

Over time, conjunctive water use models have seen much development. Simulation optimization models got attention 80s and early 90s. The hydrological simulation model, along with the net benefit optimization model, is applied for conjunctive management for the Colorado River. It has been found that a centralized governed system is more effective in achieving management goals (Young, 1995). A multi-objective simulation-optimization model was developed to address the issue of water quality, water allocation, and undesirable groundwater over-abstraction (Louie et al., 1984). Simulation-optimization models have been developed for optimal irrigation to maximize crop yield (Chang et al., 2011; Lefkoff & Gorelick, 1990; Peralta et al., 1988). These studies used economic, hydrological, and agronomic components for a comprehensive assessment of water resource management at the basin level. Musharrafieh et al. (1995), have specifically used one-dimensional simulation-optimization using water flow equation for optimal control of pollution and sustainable crop yield. A multi-period conjunctive water use model with groundwater quality constraints was developed by Wong et al. (1997). The water-drawn limit has been established from the surface and groundwater for each selected time period of the study.

Recently, there has been a surge in the hydrological-economic model for maximizing economic benefits (An, 2012; Ringler & Cai, 2006). The general objective of this type of management model is to allocate water based on maximizing the annual net profits from crop or agricultural water use, water used in aquaculture production,

residential water use, industrial water use, hydroelectric power use, water allocated for ecosystem functioning, and recreational use, etc. (Cai et al., 2006; Pulido-Velázquez et al., 2006; Ringler & Cai, 2006; Rosegrant et al., 2000).

The model has also been developed to use linear programming and basin network flow programming to solve the issue of water management (Draper et al., 2003; GoA, 2002 ; Labadie, 1995).

Popular water management models as optimization through linear programming require to have linear constraint and convex objective function. Similarly, models based on nonlinear programming are much larger and usually unable to find feasible solutions for local convergence. Furthermore, models based on network flow programming will fail to give appropriate solutions for iterative updates (Islam, 2011). To capture, non-convex, and nonlinear dynamics System Dynamics and Agent-Based models are getting important. System dynamics (SD) and agent-based models (ABM) are now practiced for qualitative and quantitative causal models to see the interrelationships of the physical (e.g., water inflows, outflows) and behavioral (e.g., decision rules, perceptions) processes in the system (An et al., 2014; Janssen, 2002; Schlueter et al., 2012). It is a feedback-oriented modeling framework for learning and communicating about the inherent complexity of water management and has been widely applied in many environmental problems, including water management (Wang et al., 2011; Winz et al., 2009). All these methods have advantages and disadvantages in their applications. The nature of the study can help to use the technique most suited to solve the problem at hand. Usually, the SD approach is a top-down approach in contrast to ABM, which is a bottom-up approach (Richardson, 2003). The ABM based model will be appropriate to use due to the nature of the complexity of behaviour of agents and their interaction for water use in agriculture. Before we establish the importance of ABM models, we

will look into the need and gap in use of ABM to understand water management in Pakistan. In the following section we will review some of the important models already developed to understand water management in irrigated agriculture of Pakistan.

2.3 Water Management Models in Pakistan

Continuous struggles have been made to manage irrigated agriculture in the country. For the purpose of water management, different modeling approaches have been used by policymakers and researchers. Due to the complex nature of water allocation under multiple constraints, simulation optimization appeared as a widely used approach (Das & Datta, 1999). Since conjunctive water management increases efficiency, reliability in water supplies, and cost-effectiveness in the regional environment of the irrigation system (Chang et al., 2011; Emch & Yeh, 1998; Gorelick, 1983). Models of simulation and optimization are developed for the independent management of surface and groundwater, conjunctive water resource management is assessed by combining both approaches simultaneously. The majority of the models revolve around the optimization of water allocation, water pricing, and crop patterns. Some studies are reviewed as per changes that are evolved in simulation and optimization approaches.

Linear programming-based optimization model was developed to get optimal crop patterns, and then a simulation model was used to evaluate optimal conjunctive use surface and groundwater. Specifically, the optimal pumping rates and the regional changes in hydraulic heads caused by the optimal groundwater withdrawals from the aquifer were revealed (Garg & Ali, 2000). Linear programming models of a representative farm in Punjab Province have been used to assess the value of irrigation water. And different scenarios for economic and financial values of water-related investment were guided (Chaudhry & Young, 1989).

Indus Basin Model Revised based on mathematical programming is developed to guide optimal ground and surface water management. It was found that the Mangla dam extension can significantly reduce overexploitation of water resources (Alam & Olsthoorn, 2011).

Many studies have calibrated the physical and agro-ecological models to assess water management alternatives. A physical groundwater model for the Indus basin is developed using MODFLOW and calibrated for Punjab. Region-specific policies due to heterogeneity in groundwater conditions are recommended (Khan et al., 2016). Furthermore, MODFLOW has been used to calculate and simulate groundwater withdrawing cost and conjunctive water coming years in the Lower Indus Basin of Pakistan (Qadir et al., 2016). The impact of severe climatic conditions on groundwater depletion for upper Chaj Doab has been observed by calibrating the GIS and Feflow model (Ashraf & Ahmad, 2008).

Groundwater abstraction and depletion have been quantified by calibration Soil, and Water Assessment Tool (SWAT) with crop data and Punjab is found one of the most vulnerable provinces (Cheema et al., 2014). In Pakistan, the majority of water management studies are limited to agro-ecological and physical models. Some studies have also tried to include the economic aspect of irrigation. But the integration of agroecological studies with socio-economic aspects of irrigation is completely ignored. This study will bring a first comprehensive diagnostic framework to assess policy paradigms for systematic conjunctive ground and surface water use under the physical characteristics of water resources subject to socio-economic conditions and behavior of farmers.

2.4 Theoretical background of Economic and Social-ecological System and ABM

Water management is dealt with as an economic problem to allocate scarce resources as per the principle of maximum benefit or maximizing the present value of water use over time (Roumasset & Wada, 2012). Increased population and economic activities are mounting pressure on water resources since the last century (Esteban & Albiac, 2011). Depletable resources as water have got an important place in economic literature. Prominent authors have discussed the sustainable exploitation of resources as Solow (1974), Stiglitz (1974), and Dasgupta and Heal (1974).

The problem of water management arises due to difficulty in the recognition of property rights, which leads to having the excessive depletion of resources (Esteban & Albiac, 2011). Among others the most prominent work on management of resources is established by Pigou (1932); for efficient allocation of resources government needs to intervene in the market by imposing subsidy or tax. However, Coase (1960), established the tenet of property rights and argued that this Pigouvian concept is not satisfactory. Efficient economic outcome in presence of low or zero transaction cost parties can reach to voluntary agreement without the intervention of the government and conflicts on property rights can be resolved to bring mutually beneficial outcomes. But real world application of Coase theorem is limited as Dixit & Olson (2000) proved that efficient equilibrium is not always achievable if little transaction cost exist. In the presence of many participants as in case of irrigated agriculture not all stakeholder will voluntary agree and bargain to reach efficient outcomes. Moreover, this illustration is applied in situations where there is no asymmetric information and property rights are clearly defined along with already mentioned zero transaction costs but all these conditions are rarely achievable in agriculture water management like scenarios. Along with the

mentioned factors Galiani et al. (2014; Hesda, 2022) found commitment a crucial in conducting the bargaining process and reaching an efficient outcome.

However, water as a common pool resource creates a water use externality. There exists market failure as water extraction by one user will affect water use by others and further, they have no incentive to save water stock. So a proper institutional settlement and a balanced intertemporal allocation of water resources are required to deal with the issue (Dasgupta & Heal, 1979). Usually, there are two types of models available at hand such as econometrics and DSGE models, former successfully forecast the economy based on past data for some quarters if the world remains static, later consider the world as static so rules out chances of crisis or shocks (Farmer & Foley, 2009). Furthermore, Computable General Equilibrium (CGE) models are usually based on the assumptions of a rational representative agent with perfect and costless information and market clearing properties. Model based on these assumptions can be highly misleading. However, decentralized and bottom-up approaches in economics are complex and adaptive in nature and consist of interacting agent; their interaction create macroeconomic irregularities which in turn influence local interactions. These kinds of interactions emerge as dynamic system. But complete complexity of the system is merely measured by theoretical and econometric models (Nolan et al., 2009; Tesfatsion, 2001, 2003). In the real-world, there exist bounded rationality, adaptation, feedback, and dynamics in the system, which cannot be easily encountered through these equation-based models (Holland & Miller, 1991; Tesfatsion, 2006).

Studies in agriculture or irrigation are not dealt without the inclusion of human activities as these systems emerged as human-dominated due to extensive development of agriculture and massive use of natural resources. Besides appropriation, the issue of over-drafting of resources usually prevails. In order to examine how robust economic

decisions are made under uncertainty and how interaction typologies between agents affect the dynamics of these systems, a new approach is suggested. As far as pure analytical models are concerned, they do not consider the prospects of common-pool resources managed by stakeholders. Since there exist cases where these resources are successfully managed and resulted in reducing free-riding and building inter-personal trust (Dietz et al., 2003; Ostrom & Walker, 2003; Ruttan, 2003).

Conventionally, the management of natural resources in economics is studied as a renewable resource. Till the 1970s, models were used to consider the static state of the world (Gordon, 1954). But progress has been made to include dynamics of the system through optimization problem, which was addressed through dynamic programming, game theory, and equilibrium analysis (Dasgupta & Heal, 1979). Eventually, uncertainties and non-convexities of natural resource systems have been included in the models (Dasgupta & Mäler, 2003; Janssen et al., 2004). In mainstream economics, an agent can only maximize his utility for an infinite horizon if he has perfect knowledge, but the utility function is of limited use if we study a system similar to the social-ecological system, which consists of non-convex dynamics, structural uncertainty, and heterogeneity among agents, multi-attribute utility, and spatial heterogeneity. An analysis made on the basis of unrealistic models can lead to having misleading outcomes and governance problems (Scheffer et al., 2001). This discussion poses a question of how to analyze the management of the social-ecological systems in the presence of stakeholders with conflicting interests in spatially explicit and non-convex dynamics. ABM is considered a promising tool to analyze the complexity of social-ecological systems (Janssen, 2002). ABM can help to include spatial differences of changing social and economic conditions (Gimblett, 2002; Grimm & Railsback, 2005) which is neglected in CGE and other equations in the models. In addition,

currently, spatial models are based on the assumptions of fixed conditions, which are not a true representation of the real world. As in the case of irrigation farmers' groundwater extraction decisions can affect other farmer's decisions. Similarly, land selling, renting, water buying selling, produce selling decisions cannot be taken independently; rather, they are influenced by the decisions of other agents that exist in the system. Currently, optimization and simulation methods for farm and resource management are limited to short-run studies. However, these models have achieved sophistication due to advanced mathematical programming and computer programs. But for longer period simulations and inclusion of human-environment interaction made it analytically impossible to run these models. Computational economics encompasses these issues (Reeves, 1993) with the increasing practices of the methodology of ABM (Berry et al., 2002).

ABM is better at dealing with economic analysis of the real world. In ABM, policy makers can create an artificial economy to see the impact of different interventions quantitatively. ABM is a computerized simulation of several autonomous interacting agents. The agents can be as heterogeneous as needed e.g., individuals, social groupings, institutions, biological entities, and physical entities. Models in ABM are not built with the assumption to reach some equilibrium state, instead agents act and interact with their environment and other agents to make some emergent result. Moreover, ABM can handle a wide range of nonlinear behaviours as compared to conventional equilibrium models. It can explicitly model human behaviour, and their interaction with the environment as social dilemmas in natural resource management are better dealt with communication between different stakeholders (Ahn et al., 2003; Ostrom et al., 1994). ABM presents potentially the best solution for the understanding of the complex economic system with inclusion scale explicitly (Gibson et al., 2000).

The economic model buildt through ABM can help us to have a useful forecast of the real social-ecological system. ABM can help to build and test integrated theories which include different aspects of social and natural sciences (Farmer & Foley, 2009). The complexity of the social-ecological system provides a way forward to use ABM for studying and analysing this system. A general Framework that is required to be followed is well depicted by Anderies et al. (2004).

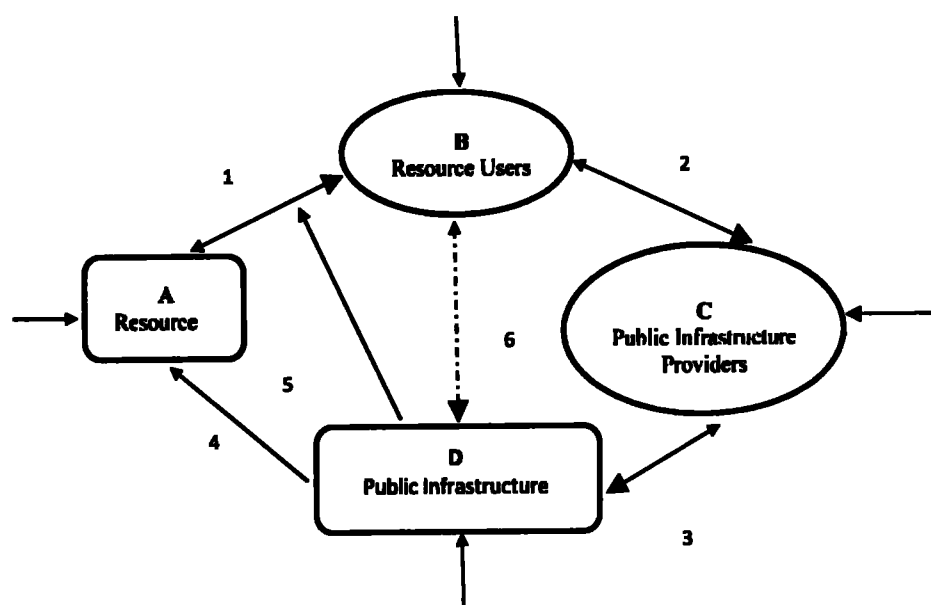


Figure 2.1: Depiction of Social-Ecological System (SES).

¹Source: Anderies et al. (2004)

Every Social Ecological System (SES, henceforth) or coupled human and natural system needs to be analysed keeping all its stakeholders into account. The system cannot be dealt with without the inclusion of social, ecological, and physical entities as far as irrigation in agriculture is concerned, the single-tiered model is given in Figure 2.1. Moreover, to see the robustness of the above system, its resilience can be examined against different types of shocks, which are represented by incoming arrows in the

¹ Anderies, J. M., Janssen, M. A., & Ostrom, E. (2004). A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecology and Society*, 9(1), 18

figure above. These can be biophysical as well as socio-economic disruptions. This system can observe changes due to fluctuations in external shocks, internal actors, and links between them. Internal disturbances can be caused through strategic interactions between B and C. Furthermore, these interactions are further complemented by links 1, 2, 3, and 6. Moreover, Linkages among ecological entities as 1, 4, and 5 can also be a significant contributor to the fluctuations in the system. External shocks may affect various components in SES. It can affect A's preference in the response of new information and inward and outward migration of people. C's abilities can also be affected by changes in high regulations and governance. D can also observe a change due to changes in regulations and natural shocks. These all changes are interdependently related to each other. And their interactions through all scales can cause SES to be less or more robust to internal or external changes.

Social dilemmas of different kinds are faced by human participants in the above system. A, face the dilemma of common-pool resources as there remain incentives of no cooperation from B to use resources. C, may also face social dilemmas of bad governance. Cooperation in social dilemmas can be obtained through repeated interaction between agents. But the issue persists with the possibility of less interaction. This kind of social dilemma can be dealt with, recognizing people's capacities to build institutions. Even though the issue of sustainably governing the resources remains unresolved. Successful governance requires creating substantial information about the availability of resources, capacity for conflict resolution among users and between resource harvesting, rule compliance between users, effective infrastructure, resilience for external shocks, and internal changes.

Including all entities of the social-ecological system can help to have optimal governance strategies that can make social dilemmas get resolved. But B and C can

have developed some set of norms that can work in some specific social-ecological settings. ABM is being intensively used for a theoretical understanding of the cooperation between agents. Since overharvesting of common-pool resources becomes more acute in the presence of uncertainty. There are different types of theoretical models available for the impact of human behaviour and resource management. Moreover, some models of mutual trust relationship also prevail where agents restrict their behaviour and set rules to prevent resource collapse.

ABM experienced its application to SES as a coordination problem that seeks to be resolved in irrigation systems of Bali (Janssen, 2007). It has also been applied to tackle the rangelands coordination problem in Cameroon (Rouchier et al., 2001). Collaborative forest management in Indonesia (Purnomo et al., 2003) and the management of livestock effluent in France have been examined through this model (Janssen, 2007).

CHAPTER 3. METHODOLOGICAL FRAMEWORK AND DATA COLLECTION

Concerning irrigation, currently, different types of models are in practice as linear programming approaches, which maximize utility and use shadow prices for the determination of water prices and quotas. Approaches from game-theory where agents try to optimize utility subject to the strategies other agents adopt for their optimizations (Le Bars et al., 2002) are also in practice. But these approaches are limited as they don't consider imperfect information, evolution, the spatiality of agriculture activities, interacting agents, and bounded rationality, which are the true characteristics of agents in the system. The explanatory power of these models is limited to answer the questions (Berger, 2001). It has been recognized that one of the crucial issues in the management of natural resources is the interaction between stakeholders (Dietz et al., 2003). Due to the reasons, currently, more comprehensive bottom-up approaches for natural resource management regarding broader stakeholder participation is becoming popular (Hare et al., 2003; Lanini et al., 2004).

3.1 ABM and Agriculture Water Management

The ABM appeared as a major bottom-up tool being extensively used in many theoretical and empirical studies based on complexity (An, 2012). ABM is defined as "An agent-based model is a computerized simulation of a number of decision-makers (agents) and institutions, which interact through prescribed rules" (Farmer & Foley, 2009). Agents in this method dynamically interact with the environment and have a capacity to learn and adapt in response to change in the environment. This method focuses on harnessing the complexity by understanding the individuality of the agents

and warns against aggregation of behaviour of agents as it may bring misleading results (An, 2012; Bousquet & Le Page, 2004).

For understanding as behaviour of farmer and their interactions, ABM starts with assumptions deduced from the real world and ends up bringing simulation-based results that can be further analysed. Some researchers have turned it into a third way of doing science (Axelrod, 1997). ABM gives promising outcomes besides certain criticism on the validation and calibration of these models (Lempert, 2002; Parker et al., 2003). In recent years many developments have been made, and the ABM model has evolved from individual-based ecological models followed by testing of conceptual and theoretical social models followed by realistic empirical models coupled with environmental, ecological models (An, 2012).

As far as natural resource management is concerned, there have been found coupling of the different agro-hydrological, eco-hydrological models (Lajiao et al., 2011; Tague & Band, 2004). Since, the coupling of ABM with the biophysical and hydrological processes is a progressively active research area (Matthews & Selman, 2006) and a powerful tool for handling the complexities of of coupled human and natural system (CHANS) (An et al., 2014). Agriculture is an example of CHANS where consistent interaction and feedback between hydrological, biophysical, and socio-economic processes takes place (Liu et al., 2007). These factors provide partial understanding if any of them are considered in isolation (Matthews & Selman, 2006). For a complete understanding of the competing interests, these three must be strongly mapped together (Berkes et al., 2008). Insights from the complexity of the system are suggested to be gained through integrating hydrological, biophysical, and socio-economic models (Liu et al., 2007) for resource management, policy implications, and designs (Schönhart et al., 2011).

Agent Based modelling is a currently widely used methodology for modelling and simulation of the complex adaptive systems which can be an effective approach for water resource management (Bandini et al., 2009). In a complex adaptive system as water; the interaction between agents can be influenced through the influence individual agents receive (Macy & Willer, 2002). ABM provides a platform for delineating interactions among individuals to include human decisions to simulate their actual behaviour (Edmonds & Barthelemy, 2002; Terna, 1998).

ABM is found advantageous as compared with other modelling approaches as it provides a detailed explicit description and emergent behaviour of the heterogeneous geographical systems with interacting agents (Bonabeau, 2002; Bousquet & Le Page, 2004; Galán et al., 2009). But it is also important to note that ABMs can't predict the exact state of the system modelled rather, it explains how the system will evolve for different possible future scenarios.

Specific ABMs for water management are available as for stakeholders' analysis; Multi-unit Auctions, Adoure Basin (Athanasiadis et al., 2005), Camargue, JOGOMAN and FIRMA Limburg models, for management of domestic demand and supply; FIRMA Thames, DAWN (Athanasiadis et al., 2004), DANUBIA, FIRMABAR models and for management of irrigated agriculture; AWARE (Farolfi, 2004), SHADOC (Barreteau & Bousquet, 2000), LAKE, BALI (Janssen, 2007; Janssen, 2001), MANGA (Le Bars et al., 2005), SINUSE (Feuillette et al., 2003) and Sao Paulo (Ducrot et al., 2004) models have been developed, widely reviewed and applied throughout the world (Tzima et al., 2006). In these models problem of appropriation of infrastructure, overexploitation of groundwater (Feuillette et al., 2003; Holtz & Pahl-Wostl, 2012), social dilemmas of cooperation and governance (Akhbari & Grigg, 2013; Janssen, 2006) are discussed. Some studies have been used to assess the dynamics of

water resource management as coupled human and natural systems (Becu et al., 2003; Tesfatsion et al., 2017). To comprehensively guide groundwater management policies recently, the coupling of ABMs have been done with physical groundwater flow modelling (Farhadi et al., 2016; Mulligan et al., 2014), where groundwater codes are updated as per stress created by ABM and then updated state of the variable is used to assess policy implication (Castilla-Rho et al., 2015).

Initially, the current study analyses the dynamics of the irrigation system using ABM. Dynamics of the irrigation system in the presence of all agents as water users, providers, ecological and physical conditions of the aquifer are assessed as per the conceptual framework given in figure 3.1. Usually, the conceptual framework for agent-based models is developed considering the properties of all agents and the way they interact with each other. After specifying their behaviour, a theoretical and conceptual formwork is developed for agent's relationship with each other and the environment. Subsequently, agent related data is developed. After delineating the appropriate relationship among agents and environment model is validated in context of real world scenarios. Some of the relevant conceptual frameworks for water management in ABMs are given in Akhbari & Grigg (2013), Becu et al., (2003), Berger, (2001) and Castilla-Rho et al. (2015).

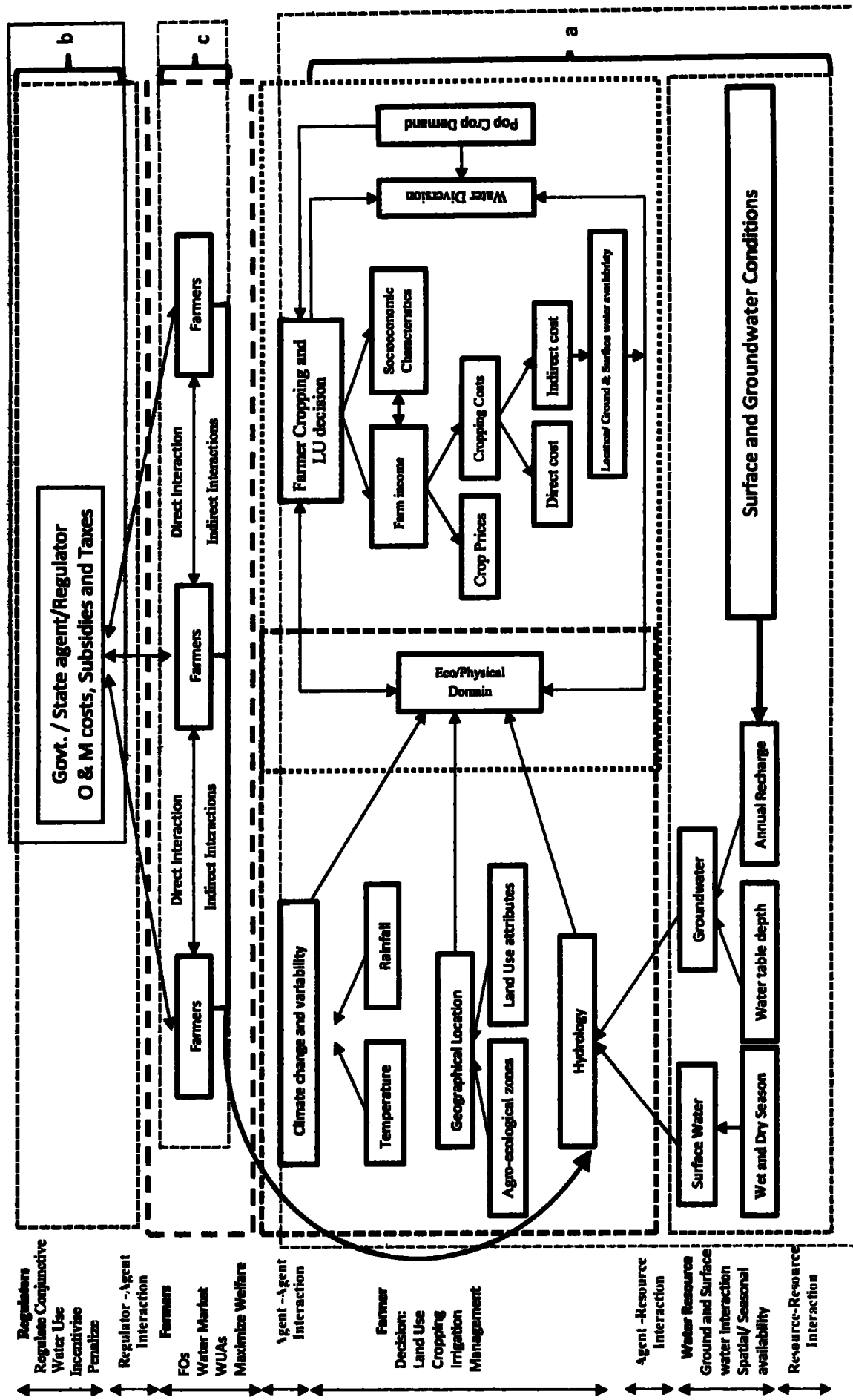


Figure 3.1 Conceptual framework, Agents and their Interaction in the Model

Source: Author's own developed

3.2 Methodology for Agent-Based Irrigation Model

A comprehensive model for dynamics of irrigation system for different management intervention under cooperation and conflict scenarios is developed, which will help to answer all objectives presented above.

3.3 Timeline of Farmers Activities

Different types of models have been used by researchers for common-pool resource management. The current study will use an agent-based model to assess feasible water management strategies for agents of conflicting and competing interests. ABM is capable of solving complex problems where human behaviour and interaction between them are included. Timeline for three crops in Rabi and Kharif seasons as per ²FAO crop calendar for Pakistan is given

Table 3.1: Crop calendar of selected crops

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Crops	t ₄			t ₅	t ₆	t ₇	t ₈	t ₉	t ₁	t ₂	t ₃	t ₄
Wheat												
Rice												
Cotton												
Sugarcane												
Key	Nursery			Sowing			Harvesting					

²Source: FAO crop calendar Pakistan

Tesfatsion et al. (2017) developed an agent-based model for watershed management that assesses the dynamics of the system by including all agents in the model. Furthermore, this model tried to cover all complexities of water use. A modified version best suited for irrigated agriculture of Pakistan is presented here. Modifications

³ <https://cropcalendar.apps.fao.org/pakistan>

are based on conjunctive water use assessment, and the kind of subsidies or concessions are available for farmers in Pakistan. Initially, the farmer will decide about crop cultivation based on his socio-economic conditions and the information about government facilitation for farming. After analyzing these variables, the farmer will grow crops and assess input costs. His money income will be updated. He will also decide on cooperation as per his perception of the system. After harvesting, his wealth or money, income is updated for next period cropping decisions.

In sub-period t_0 , farmers decide for cropping wheat subject to realization of input costs, water availability, and subsidies. There are different types of subsidies available in Pakistan; concessional prices of fertilizers, the low tariff on electricity for tube wells, and subsidy on improved irrigation practices. The Punjab Irrigated Agriculture Productivity Improvement Project (PIPIP) is subsidizing improved irrigation practices (Bell et al., 2017). This study will assess the impact of these kinds of subsidies on the system. ABM will help to see the impact of different kinds of subsidies of different amounts. Further different cases of the low, medium or high levels of subsidies on the above heads will be considered.

Through t_0 to t_1 farmer purchases inputs need for sowing the crop as seeds, fertilizers subject to socio-economic constraint, income, landholding, etc. In t_1 farmers' expected yield, water requirement, conjunctive use of surface and groundwater is determined. The government intervenes in this time period for subsidies on electricity, seeds, and fertilizers. At the beginning of t_2 support prices of wheat are realized. At the initial stage farmer will decide on cropping subject to input costs and his money holdings. Initially, input costs for farming will be realized in t_1 and it will be based on required seeds, fertilizers, labour, or water costs. The timeline will be adjusted for either

of the crops accordingly. Farmers will assess input cost as per acre requirement.

$$InputCost_{t:1} = Input\ cost\ \left(\frac{Rs}{acre}\right) \quad (3.1)$$

Government allocates its budget in the period t_2 for subsidizing electricity, seeds, fertilizers, and improved irrigation practices. $IIPsub_{t:2}Allot$ is budget allocated for improved irrigation practices and can be written as:

$$IIPsub_{t:2}Allot = S_{t:2}B_{t:1} \quad (3.2)$$

Here $S_{t:2}$ is subsidy allocated out of budget announced in period 1. Amount of budget allocated for improved irrigation practices is set aside and rate per acre is determined as below:

$$\tau_{t:2} = \tau_{s:2} = [IIPsub_{t:2}] / [r_{max}A^F] \quad (3.3)$$

$$S\&Fsub_{st:2}Allot = (S_{t:2}B_{t:1}) \quad (3.4)$$

In equation (3.3) $\tau_{s:2}$ is the retention land subsidy. Here r_{max} ranges between [0-1], is a parameter showing maximum available land for improved irrigation practices. Part of the budget is allocated for subsidy on seeds and fertilizers, as depicted in equation (3.4). The rest of the budget allocated for agriculture is allotted for subsidy on electricity. It can be written as:

$$GW_irrigsub_{st:2}Allot = [1 - IIPsub_{st:2}Allot - S\&Fsub_{st:2}Allot]B_{t:1} \quad (3.5)$$

$GW_irrigsub$ is the subsidy allocated for groundwater irrigation. At the beginning of the sub-period t_3 farmer allocates his land between usual cropping and water retention practices.

$$A_{crop}(c_{t:3}) = c_{t:3}A^F \quad (3.6)$$

Here $A_{crop}(c_{t:3})$ is the area under usual cropping practices and A^F is the total farm area.

Farmer's crop land retained for irrigation practices $A_{ret}(c_{t:3})$ in period $t:3$ can be written as

$$A_{ret}(c_{t:3}) = [1 - A_{crop}(c_{t:3})] \quad (3.7)$$

The allocation of the above land for crop and retention can help to realize retention subsidy ie.

These percentages will depict farmers land allocation for both types of cropping

$$RetSub^{real}(\tau_{t:2})(r_{t:3}) = \tau_{t:2}r_{t:3}A^F \quad (3.8)$$

Farmer's retention land subsidy for the year t is realized as in equation (3.8). Due to subsidies, farmers receive his money holding at time t: 3 will become

$$M_{t:3}(\tau_{t:2}r_{t:3}) = M_{t:1} + RetSUB^{real}(\tau_{t:2}r_{t:3}) \geq 0 \quad (3.9)$$

In sub time period t: 4 farmer purchase inputs required for cropland and input cost is needed to be subtracted to update money income of famer in time period t: 4

$$M_{t:4}(\tau_{t:2}r_{t:3}) = M_{t:3}(\tau_{t:2}r_{t:3}) - InputCost_{t:1}A_{crop}(c_{t:3}) \geq 0 \quad (3.10)$$

In sub time period t_5 total water use is realized, which is directly proportional to crop yield. $WU_{t:5}$ = total water use in time period t_5 is realized = Harvest Yield ($H_{t:5}$)

$$Crop_{t:5}(c_{t:3}) = H_{t:5} * Area^{crop}(c_{t:3}) \quad (3.11)$$

In sub-period t_6 crop price is realized.

$$Value_{t:6}^{crop}(c_{t:3}) = Cprice_{t:6} \times Crop_{t:5}(C_{t:3})$$

The market value of farmer crop is realized, and farmer update his money income as

$$M_{t:7}^{real}(c_{t:3}\tau_{t:2}r_{t:3}) = M_{t:4}(\tau_{t:2}r_{t:3}) + Value_{t:6}^{crop}(c_{t:3}) \quad (3.12)$$

Farmer sell his crop in the market at the price $Cprice_{t:6}$ and retain crop in the amount to consume for herself as $Cons_{t:7}^F$ it will determine farmers' welfare, which will be measured by utility he obtains by consuming that crop. Besides the money he receives; his utility also depends on hope the utility he obtained from cooperation during the time period of cropping. U^* the total utility received by the farmer will be obtained as:

$$U_{t:7}^{F,total} = UOC_{t:7} + U_{t=1:7}^{Fl} \quad (3.13)$$

We used additive form of utility function. In multi-agent resource allocation system for feasibly reaching the socially optimal outcome the utility functions used by agents to model their preferences over alternative bundles of resources are additive, it is sufficient to use very simple negotiation protocols that only cater for deals involving a single resource at a time. This representation is as expressive as the “standard” representation as listing the values of all possible bundles of utilities and that it often allows for a more succinct representation of utility functions (Chevaleyre et al., 2008; Nguyen et al., 2014).

Farmers Utility of consumption $UOC_{t:7}$ is measured by the following equation

$$UOC_{t:7} = u(Cons_{t:7}^F) = \ln(Cons_{t:7}^F - \bar{C}^F + RT) \quad (3.13a)$$

And $\bar{C}^F$ is a subsistence level of a crop and farmer risk tolerance parameter RT is to be maintained by the farmer. Non-concavity of the utility function is induced due to the explicit determination of the subsistence level of consumption. The standard utilitarian approach for utility maximization in the context of welfare maximization is not validated here. Furthermore, the completeness of the utilitarian approach is also challenged due to the inclusion of constraints of subsistence consumption (Tefatsion, 2006). If the farmer is unable to attain a minimum level of consumption, i.e.

$$Cprice_{t:6} * \bar{C}^F > M_{t:7}^{real}(\tau_{t:2}r_{t:3}) \quad (3.14)$$

Then the farmer's consumption will be

$$Cons_{t:7}^F = M_{t:7}^{real}(\tau_{t:2}r_{t:3}) / Cprice_{t:6} < \bar{C}^F \text{ then the farmer will exit from the market}$$

he may rent out his land. If equation (3.14) is not true, then the farmer will save and made consumption as per following saving and consumption constraints

$$\begin{aligned}
S_{t:7}^F + C_{price_{t:6}} * Cons_{t:7}^F &= M_{t:7}^{real}(\tau_{t:2}r_{t:3}) \\
Cons_{t:7}^F &> \bar{C}^F \\
S_{t:7}^F &> S_{t:9}^F
\end{aligned} \tag{3.15}$$

And possibly farmer uses his saving as next period money

$$M_{(t+1):1} = S_{t:7}^F$$

At the end of the time period, t farmer will update its state from t to $t+1$. Here the role of Government is taken as exogenous. It can be made endogenous by considering government functions as a collection of O & M costs and allocation of subsidies. The existing model will be complemented by taking the Government as endogenous if there will be a need to have an assessment of water pricing, determining O & M costs.

For general understanding, it is important to relate part of the conceptual framework with the equations of the model. Equation 3.1 and equation 3.6-3.15 can be related to farmer decision making or farmer self-interaction in a conceptual framework with the block a. Equations 3.2-3.5 include direct impact of subsidies, while the induced aspect of government intervention is depicted through equations 3.23 and 3.26 and can be related with block b in the conceptual framework. Furthermore, equations 3.19, 3.20, 3.21, 3.22 depict agent interaction with other agents in the system and can be related with block c in the conceptual framework.

3.4 Cooperation and Conflict in Water Management: Governing

3.4.1. Conjunctive Ground and Surface Water Use

Akhbari and Grigg (2013), proposed the ABM model to see cooperation between conflicting interests. ABM is calibrated with a watershed model to capture the dynamics of the system, timings of flow, allocations, the interaction between stakeholders, and resultant decision-making. A regulator is defined as a mediator between the environment and diversions. Water allocation, quantity, and quality are

determined by the environment. Water demand is supposed to be determined by the interaction of all agents.

The cooperative and non-cooperative behavior of farmers determines the gap between demand and supply of water. Farmers are allocated water after deducting it for the minimal environmental requirements as per their land area. If the water demand of agents is more than its allocated share, then the behaviour of the agent is considered non-cooperative. Afterward, willingness of a diversion for cooperative behavior is sought. The behaviour of agents to cooperate depends on social pressure, education, and neighboring agent behavior. To bring cooperative behavior legal, management, and legislative pressures are defined as per modification factor (depend on social pressure and education, etc.). If agents cooperate in case of water shortage, then demand modification will be zero. Detail of the model is given below

$$\text{Since } TAW_{t=1:7}^F = \text{Surface water} + \text{Groundwater} \quad (3.16)$$

$$\text{And } \text{Available Surface Water}_{t=1:7}^F = Q_{ln-sw} - Q_{mtn-sw} \quad (3.17)$$

Surface water is available in more quantity if the land is near to water source so available surface water will proportional to the distance from water source i.e.,

$$ASW_{t=1:7}^F = [Q_{ln-sw,1:7} - Q_{mtn-sw,1:7}] / DWS \quad (3.18)$$

Here, ASW is the available surface water, and DWS is the distance from a water source

If $ASW_{t=1:7}^F \geq D_{\max t=1:7}$ = Farmer water use is the surface water

Here $D_{\max t=1:7}$ is farmer maximum demand for irrigation water. The share of groundwater will be negligible. And if

$$ASW_{t=1:7}^F \leq D_{\max t=1:7}$$

Farmer water use will be the conjunctive surface and groundwater. There will be a cap on groundwater use as $Q_{gw,t=1:7}^{optFl}$. If surface water availability is negligible in some areas then agriculture water use will be groundwater in total. The action and

behavior of the farmers will depend on their perception of the system. Some may relate their benefits with cooperation. In contrast, some may remain consistent with cooperative or non-cooperative behavior irrespective of the benefits of cooperation they achieve. The cooperative behavior of farmers can be assessed by applying a cap on groundwater use. Two cases can be discussed as

Case1: Agents will cooperate if $ASW_{t=1:7}^F \geq D_{\max t=1:7}$ and will agree to withdraw the optimized amount of groundwater $Q_{gw,t=1:7}^{optFl}$

Case 2: Agents will not cooperate if $ASW_{t=1:7}^F \leq D_{\max t=1:7}$ and will not accept the optimized level of groundwater allocation $Q_{gw,t=1:7}^{optFl}$

The government can intervene for cooperation to exist. Water use utility can be calculated for farmers for cooperative and non-cooperative behavior as

$$U_{t=1:7}^{Fl}(C \rightarrow C) = a \times V_{t=1:7}^{n-F}(C) + F_m \quad (3.19)$$

And

$$U_{t=1:7}^{Fl}(C \rightarrow NC) = b \times V_{t=1:7}^{n-F}(NC) \quad (3.20)$$

$$U_{t=1:7}^{Fl}(NC \rightarrow C) = c \times V_{t=1:7}^{n-F}(C) + F_m \quad (3.21)$$

$$U_{t=1:7}^{Fl}(NC \rightarrow NC) = d \times V_{t=1:7}^{n-F}(NC) \quad (3.22)$$

The first term on right-hand side of these equations shows social pressure and the second term represents the effect of education and social pressure on farmers' utility. $U_{t=1:7}^{Fl}(C \rightarrow C)$ shows behaviour cooperative farmer who is willing to keep the same behaviour. And $U_{t=1:7}^{Fl}(C \rightarrow NC)$ shows a farmer's behaviour who is willing to change his behaviour from cooperative to non-cooperative behaviour. $V_{t=1:7}^{n-F}(C)$ is the proportion of neighbour of farmers having cooperative behaviour and $V_{t=1:7}^{n-F}(NC)$ is the proportion of neighbour have non-cooperative behaviour and F_m is a modification factor. And this factor can be determined through government penalties and incentives in case of non-cooperative and cooperative behaviours of farmers, respectively.

For cooperative behaviour modification factor can be estimated as

$$F_m = \underbrace{(1 - a) \times \{\alpha i_{train}\}}_{\text{Education}} + \underbrace{\left\{ (1 - a) \times \frac{[(ASW_{t=1:7}^F + Q_{gw,t=1:7}^{optFl}) - D_{max\ t=1:7}]^2}{Q_{new\ t=1:7}^{optFl}} \right\}}_{\text{Incentives}} \quad (3.23)$$

First term on right hand side shows the impact of education and training the government provides and the second term shows the incentives in the form of subsidy for the agents who cooperate, which is proportional to groundwater demand by the agent.

To update water demand after government intervention, new water demand is calculated for that agent as

$$NWD_{i=1:7}^F = [D_{max\ t=1:7} - (ASW_{t=1:7}^F + Q_{gw,t=1:7}^{optFl}) \times (1 - U_{t=1:7}^F)] \quad (3.24)$$

Non-cooperative agents use more groundwater than allocated. They will face penalties in the form of no subsidy provision. If non-cooperative agent consumes more than allocated groundwater as $\gamma \times Q_{gw,t=1:7}^{optFl}$. They will be penalized to cooperate their new maximum water demand will be

$$NWD_{i=1:7}^F = D_{max\ t=1:7} = (ASW_{t=1:7}^F + Q_{gw,t=1:7}^{optFl}) \quad (3.25)$$

Quantity of water demand γ will be calculated based on $D_{max\ t=1:7} / Q_{gw,t=1:7}^{optFl}$ and the

hydrological conditions of the agents. Impact of this encouraging impact will be added through the correction factor as F_m in the utility function of non-cooperative agents willing to cooperate. A farmer is allowed to withdraw its $D_{max\ t=1:7}$, if after intervening $D_{max\ t=1:7}$ of farmer lies between $\gamma \times Q_{gw,t=1:7}^{optFl}$ and $Q_{gw,t=1:7}^{optFl}$ then the farmer will be charged with a little tax/fine. Modification factor for non-cooperative agents can be calculated as

$$F_m = (1 - b) \times \{\beta i_{train}\} + \underbrace{\left\{ (1 - \beta) \times \frac{[D_{\max t=1:7} - (ASW_{t=1:7}^F + \gamma \times Q_{gw,t=1:7}^{optFi})]^2}{\gamma \times Q_{gw,t=1:7}^{optFi}} \right\}}_{\text{Penalties}} \quad (3.26)$$

Education

Here β and $(1 - \beta)$ coefficients are the effects of training and penalties on non-cooperative farmers, respectively. Our Agent based model reflects and approximate the methodology presented here.

3.5 Overview Design and Details (ODD) of Conjunctive Water

Every ABM is required to be reported in terms of ODD given by Grimm et al. (2010b).

The overview consists of the purpose, variable, and process of ABM. The design includes emergence, adaption and fitness stochasticity, prediction, sensitivity, collectives, and observation. Details tell us about initialization, input data, and sub-models. Explanation of all these will be added in the context of the current developed ABM model.

3.5.1 ABM for Conjunctive Ground and Surface Water

Water resource management includes human and natural agents; farmers, regulators and hydrological systems. The complexity of interaction between them requires the use of ABM to capture the feedback, adaptability, and emergent behaviour in the system. Understanding of socio-natural systems and the complexity between them can deliver policy implications for water management in irrigations systems. To develop ABM, socio-economics, natural and feedback models are to be developed (Giuliani et al., 2016; van Heerden et al., 2008). Every ABM is required to be presented through overview, design, and details (ODD) of the mode; ODD recommended by (Grimm et al., 2006). A flow chart of the model is given in Figure 6.8. Representing farmers' agents and their interaction with natural systems consisting of the canal command level

of the Lower Bari Doab Canal Command Area and the type where both ground and surface water are conjunctively used.

3.5.2 Purpose of the Model

This model will serve the purpose of surface water management and will see how farmers manage water demand from the combination of surface water allocations and groundwater extraction. Moreover, the conjunctive water used will be assessed as a source to improve water quality and crop production of the farmer. A further purpose of the model is to assess if the expenses of surface water travel cost can be approximated as of groundwater abstraction for spatial differences among farmers. Different conjunctive water management and use strategies will be observed to see if water pricing can be used for water trading and water availability at the head middle and tail reaches availability of water courses. Moreover, we are aiming to see the following outputs.

1. How dynamics of the system are affected by varying the social, economic, physical and economic variables?
2. How penalties, rewards or self-governing rules can help to maintain water quality and quantity available for farmers having spatial differences so that profits/ benefits of farmers can be improved?
3. How surfacewater use cost can be rationalized thorough groundwater use costs under spatio-temporal conditions?

Famers interact in many ways for collective action in surface water irrigation;

- i. Acquisition of more water; lobbying for an increase in discharge of canal water and illicit practices for infrastructural interventions (Tampering the Mohga)

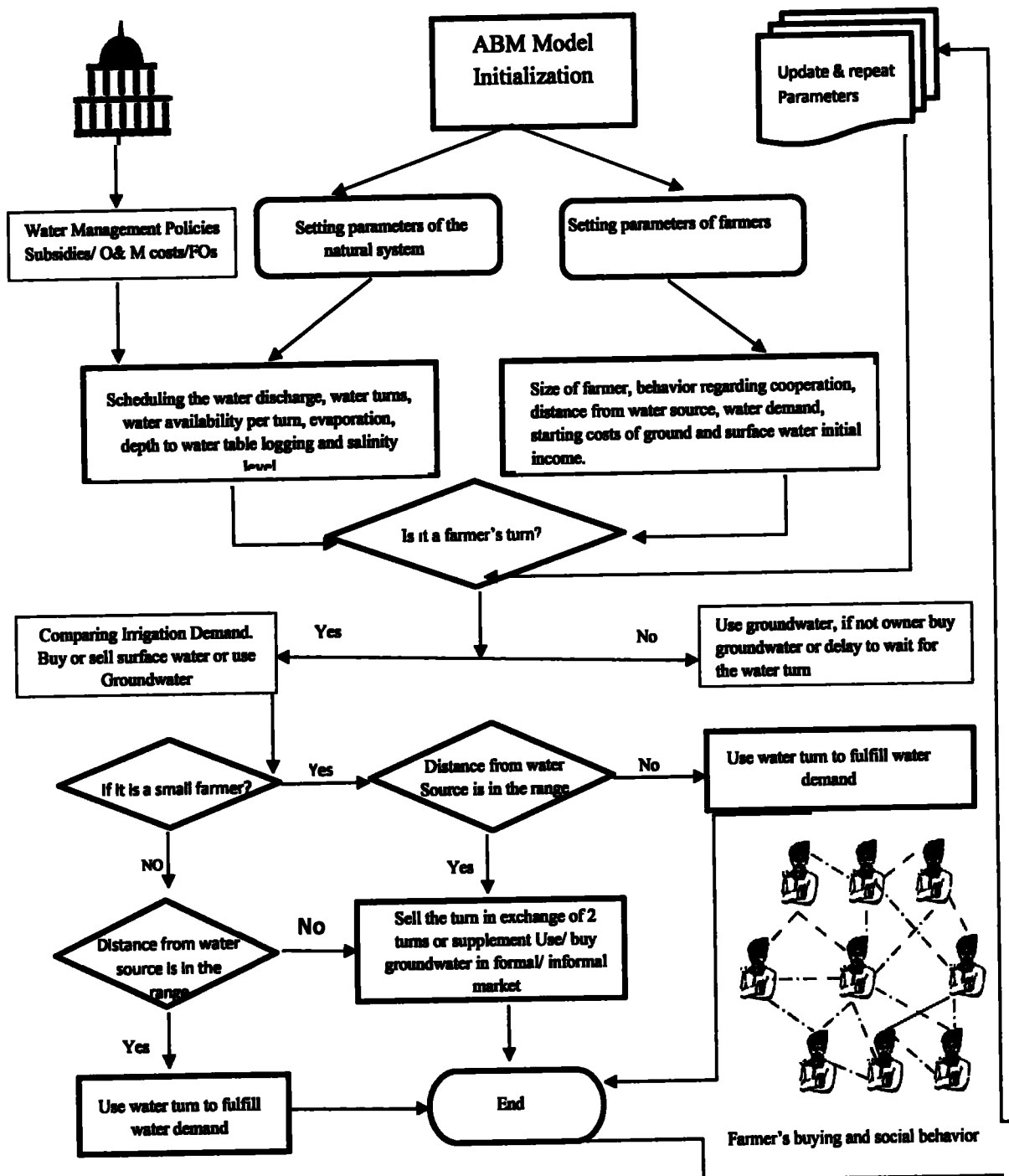


Figure 3.2: Flow chart of ABM for conjunctive water management.

Source: Author's own developed

- ii. Water courses maintenance
- iii. Relocating of infrastructure (Mohga)

- iv. The lining of main canals
- v. Groundwater markets (Buying and selling of groundwater)
- vi. Buying and selling/ exchanging of their water turn (Warabandi)

The farmer will prefer individual action if there is a lack of collective action and the possibility of getting more benefits from individual actions. Individual efforts of farmers to increase water supplies may include

- i. Conjunctive water use
- ii. Water trading (canal water is usually exchanged and groundwater is bought and sold) (Small farmer may get half an hour of water turn he may sell 2/3 days water turn to the big neighbor in order get one complete turn. This will take him to wait a long to water his crop. There is compensation of time but no compensation of the amount of water farmers gets on his exchanged turn.
- iii. Use of water allocated for government property
- iv. Physical intervention; acquisition of water, siphoning
- v. Groundwater purchase and Installation of tube wells
- vi. Refusal to spare surplus water
- vii. Cropping Pattern and Use of canal water allocated for orchards
- viii. Maintenance of the farmer channel

3.5.3 Entities, State Variables, and Scales

Farmers own farms and are spatially connected to the water courses. There are water courses in the system. Farmer chooses cropping on the basis of socioeconomic characteristics, water availability, and crop yield. Farmers own farms and farm has the following properties

- Logging and Salinity
- Water Demand
- Water allocation

Parameterization of the model is given in Appendix A3.1

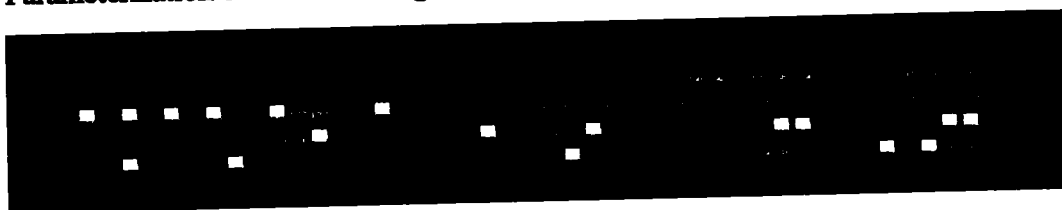


Figure 3.3: Initial view of the model.

Source: NetLogo Interface

Water is allocated as per the previous land cultivation area at the time of construction of canals. Now area under cultivation is more and so there is a need to allocate more water so that water demand can be fulfilled.

3.5.4 Initial Check of the Model

Farmers are located on the canal and they will receive water turns as per schedule every 10 days. It means that over a year a farmer will receive 47 turns approximately out of 53 weeks and total turns of the year. As rest of the days canals usually are not operated for Bhal Safaae. All his variables as yield, benefits, logging, and salinity will change accordingly. At every irrigation turn, all parameters of the farmer will change and if the farmer's demand is not met, he will use groundwater which will change his costs, benefit, and other variable scenarios. Farmer farther from canals will face water losses of seepages. The more distant a farmer from the water source more he will face water loss his fewer demand will meet through surface water rest of demand will be fulfilled through groundwater. The initial view of the model is given above.

3.5.5 Process Overview Scheduling

Water is received on the basis of rotation to every farm once every 10 days. Farmers use water they need otherwise they trade water to head or tail end farmers for money or kind. Usually, water demand is more than supply. Farmers face water deficiency and accordingly per hectare yield is less. Due to seepage and evapotranspiration water availability will be less at the turn of the farmer at the tail. Farmers can trade their water entitlements with other farmers at some agreed prices. Farmers will fulfill their deficient demand from ground water but their cost, yield, and other parameters will change accordingly.

3.5.6 Initial Model

1. A farmer will get resource as per allocation with every tick (every 10 days). It means that if there are 10 farmers with 10th tick all farmers would have received water turns and the same will be repeated 40 times. The system will complete one year in 40 ticks.
2. Farmer will change its all parameters as crop yield, logging, salinity, water table depth, and all related parameters.
3. A distant farmer from a water source which is assessed through the 'who' number of farmers will face more water seepage and evaporation problems.

3.5.7 Model with water trade

Farmer use allocated water as per his turn. There can be the following possible scenarios:

1. If the farm is at the tail and the land area is less than <7 acre, one water turn will not be sufficient to meet the water demand. The farmer will trade his turn and then combine his two to three turns to irrigate his land. Wait time may reduce

his crop productivity. He will exchange his water turn with upstream farmers.

Even this treatment may not fulfill his water demand.

2. If the farm is at the head and the farm area is < 7 acre he may sell his turn to get water exchanged with other neighboring downstream farmers.
3. If the farm is at the head and the land area is > 7 acre, water demand is fulfilled. Then farms productivity will be reasonably higher. He will not defect in his favor to acquire water through illicit arrangements. If demand is not met he may trade water or use other sources to get water. Using illicit sources will make water scarce for tail-end farmers to their allocations. And there are chances of the defect.
4. If the farm is at the tail and land area is > 7 acre. He may not be able to meet crop demand. He will exchange water right with the farmers at the head. Or he may use other sources to get more water than his allocation. Productivity may decrease or crop choice may change.
5. In the cases where demand $>$ allocation, chances of defect are higher. Farmers may not cooperate with the design principles of Warabandi. In this case, they may face social pressure and turn closure in case of complaints as a punishment. Consequently, water availability will be less.

3.5.8 Design Concepts

The design concept of conjunctive water is given below.

3.5.8.1 Basic Principles

The concept has been taken from the Indus Basin irrigation system known as Warabandi. Besides other factors water availability affects cropping decisions of

the farmers and fitness is related with the amount of benefit farmer gets out of farming.

3.5.8.2 Emergence

Spatial equity in water distribution. How cooperation for managing water is achieved?

3.5.8.3 Adaptation

The farmer will learn over time about their cropping decisions and how water availability and trading over time has an impact on crop yield. He will have a memory for the strategies which has given him the highest benefit and he will act accordingly.

3.5.8.4 Objectives

Farmer's objective is to maximize his benefit. And it will be assessed for different strategies of water use decisions. From cooperation to optimal pricing decisions.

3.5.8.5 Learning

At every time step, all farm-related variables will be updated and help for cropping and irrigation decisions of the farmers

3.5.8.6 Prediction

The farmer will predict water availability and prospective use of water and expected benefit out of the water and decide for cropping.

3.5.8.7 Sensing

Farmer will sense water prices for water trades and network with the least offered price. They may network to get the benefit of water theft etc.

3.5.8.8 Interaction

Farmers will trade their entitlements and directly interact with neighbors.

3.5.8.9 Stochasticity

Some random behaviors for cooperation are included. Farmers are supposed to compare costs and benefits of decision making.

3.5.8.10 Collectives

Farmers' water trading and defects will make some aggregate behavior emerge or their cooperation can also emerge as an aggregate behavior.

3.5.8.11 Observation

Some of the data from the literature will be used for the initialization of the model.

3.5.9 Initialization

What is the initial stage of the model of the world? At time t_0 farmer will decide cropping on the basis of expected water availability and expected gains from cropping. This model will consider the time period from sowing to harvesting the crop throughout the year. Issue of water availability becomes intense in summers for Kharif crops. The simulation will consist of 10 days rotation for 40 time steps in two seasons around the whole year. Cropping decisions at time T_0 .

3.5.10 Input Data

Input data from external sources such as data files or other models to represent processes that change over time.

- i. Distance from Water source
- ii. Water Demand

- iii. Water Trade
- iv. Farm Area
- v. Water allocation
- vi. Behaviors
- vii. Prices
- viii. Initial Benefit of cropping

3.5.11 Sub Models

The farmer will cooperate more if he needs surface water more otherwise incentive to hoard or cheat will be more. Some tenancy does exist and water is allocated as per agreement at the time of the contract between tenants. The difference in water availability at the tail and head is around 30% on average. Logging and salinity has their own dynamics. It does exist most in the areas where there is less drainage.

3.5.12 Pseudo-coding

If irrigation turn is equal =1 then surface water will be used and if demand is not fulfilled through surface water, then groundwater will be used to fulfill the excess demand.

3.6. Data Collection

Data on crop parameters, socio-economic conditions of farmers, and physical variables will be obtained through a survey from randomly selected farmers from designated sites of the upper Indus basin in Punjab and Sindh province. Data on revenues, costs and crop prices is obtained from the Agriculture Year Book of Pakistan. Data on the development of

groundwater will be taken from Punjab Development Statistics (PDS)⁴ and BoS Sindh⁵. Due to the necessity of analysis for region-specific water management policies, data from both provinces will be collected accordingly. Data on water table depth and quality will be taken from Irrigation Departments⁶, and SCARP Monitoring Organization (SMO) of the Water and Power Development Authority (WAPDA), whereas the cropping patterns and crop yield data will be collected from Agricultural Extension Services of respective provinces in Indus Basin. Data on the spatial availability of surface water will be taken from WAPDA. Data on climatic variables, water use, and crop water requirement is taken from different reports of the PCRWR and Pakistan Metrological Department. For validation purposes, data for the mentioned parameters will be taken for the recent years from literature.

3.7. Evaluation of ABM model

Evaluation of ABM is a demanding task. Verification and validation of revealed behaviour from the model are difficult to understand and relate with real-world phenomenon (Srblijinović & Škunca, 2003). However, evaluation of the ABM model is a challenging task. To assess the reliability of the developed ABM, different experiments are implemented for different parameters to observe variation in results to confirm or reject the hypothesis. Statistical analysis or test can also be run to assess the significance of the measure as in our model for logging salinity and profits. In ABM it is recommended to collect different results from multiple runs at different points in time. Data collected is used to draw charts, as summary statistics may not depict a clear picture for large data set. Graphs, which embed the full set of data in a pictorial

⁴ <http://www.bos.gov.pk/developmentstat>

⁵ <http://sindhbos.gov.pk/>

⁶ <http://irrigation.punjab.gov.pk/index.aspx>

representation, facilitate understanding while still providing all the data available. But with complex data sets, designing a useful and immediately informative graph is challenging and is the subject of an extensive body of literature (Bertin, 1983; Tufte & Graves-Morris, 1983). Graphs are not only useful to help clarify the data after a model run, but they are also useful during the running of a model. Moreover, time series analysis is very important in agent-based modeling because much of the data generated by ABMs is temporal in nature. One way to analyze a time series data is to determine if there are particular phases that data goes through during the course of a run and at multiple runs overlaid on each other. This can help to see not only the general trend of the model but the possible paths that the model usually takes. For example, time series analysis can be used to examine data that is time-dependent. The typical way this is done is by describing a relationship between time and some input parameters. The correctness of the model is measured if the model output is correct (Wilensky & Rand, 2015).

Model validation is measured if model results correspond to the real world. And the process by which agents and environment interact matches with the real world. Verification of the model entails if implemented model relates the conceptual model. Due to the stochastic nature of ABM, multiple runs depicting the output corresponds to the real world will validate the model (Galán et al., 2009). Experiment details of the model are given in appendix A 3.2 and appendix A 3.3 Further evaluation of the model requires real-world data and expert assessment of the process involved in the construction of the model. Conceptual accuracy is also one of the important factors to build ABM which further advances our theoretical understanding of the system. This highlights the importance of ABM in advancing the understanding and the development

of new formal theories and empirical corroboration (Henrickson & McKelvey, 2002). In our models we have followed the same path for evaluation and validation of the models such as if results are in accordance with real-world. Moreover, model is also built upon strong relationship among variables based on available literature. To have better understanding of the system we have simultaneously arranged our output for individual variables across management perspectives and system level results of time series.

CHAPTER 4. AVAILABILITY AND QUALITY OF IRRIGATION WATER IN PAKISTAN

This section discusses irrigation water quality and quantity status in major irrigated areas of Pakistan and links with the importance of water availability for farmers through agent-based modelling.

The Indus Basin Irrigation System (IBIS) is one of the largest irrigation system in the world, which contains area of 17.2 Mha. The IBIS comprises the Indus River, falling ultimately into the Arabian Sea, and its tributaries include the Kabul River, the Jhelum River, the Chenab River, the Ravi River, the Beas River, and the Sutlej River (Figure 4.1). (PCRWR, 2016). As per the Indus Water Treaty (IWT) (Biswas, 1992) of 1960, Pakistan has the right to use water of the former three rivers the Kabul, Jhelum, and Chenab. Furthermore, for river diversion, the IBIS comprises 12 inter river link canals, and 44 major canal and command areas are given in the diagram below canal irrigation systems (normally called canal commands), of which 23 are in Punjab Province, 14 in Sindh Province, 5 in Khyber Pakhtunkhwa (KP) Province, and 2 in Baluchistan Province. The existing canal system in Pakistan is a century-old continuous system designed to fulfill the demand of arable land required to be irrigated at that time. Although, it was not designed to fulfill the crop water requirement, which is more than 3-8 mm/day as compared with the 2 mm/day water capacity of canals (Qureshi, 2014). Primarily, the canal system was designed for crop intensities of 60 to 80%, but now the crop intensities have increased up to 172% (Mirza & Latif, 2012). Due to irrigation intensity and multiple cropping, the existing irrigation system is providing deficient water supplies

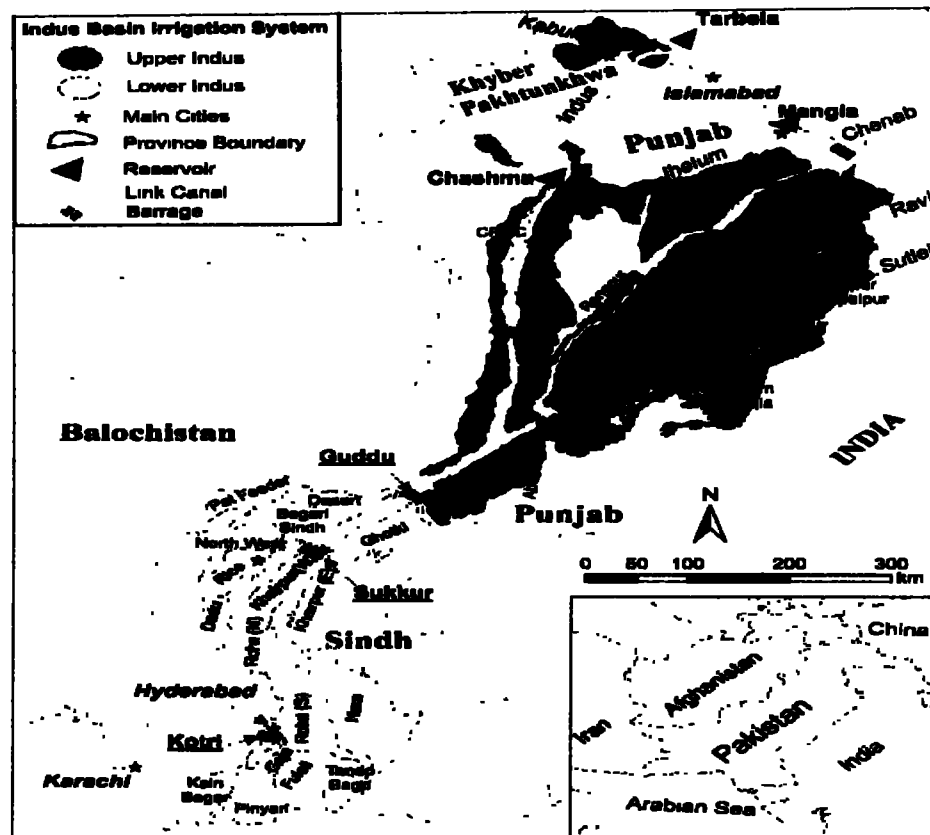


Figure 4.1: Map of the Indus Basin Irrigation System (IBIS), including rivers, link canals, and canal commands.

Source: Van Steenberg et al., (2015)

Along with increased water supplies, the construction of large dams, including the Mangla Dam and the Tarbela Dam, have resulted in increased groundwater recharge in Punjab and Sindh Provinces. The changing water balance has been utilized well in Punjab, compared with Sindh. But both Punjab and Sindh are facing problems of salinity and logging due to over-abstraction and under abstraction of water, respectively. In the lower Indus plain, waterlogged conditions are a major concern for farmers, especially during and immediately after the Kharif season, along with the low cropping intensities and crop yields in the Rabi season (van Steenberg et al., 2015).

Despite the fact that overall water availability has improved while inequity over space and time has not relatively improved among farmers. Water use for irrigated

agriculture is around 151 km³ per year, which is 95% more than the total withdrawal of water (Kanwar, 2010). Due to this reason, crop water demand is fulfilled by additional groundwater supplies. Overall differences in crop productivity exist among farmers due to the inequity of water availability between the head, middle and tail reaches of distributaries. Besides, insufficient availability of surface water, farmers at the middle and tail reaches also face the issue of poor quality of groundwater. This results in lower crop yield, degradation of land, and rising inequality in incomes (Latif & Ahmad, 2009; Qureshi et al., 2010). The same scenario has been depicted in studies that the distant farmers face crop productivity loss due to salinity problems (Latif & Ahmad, 2009; Latif & Pomee, 2003; Yercan et al., 2004). Salinity can limit water uptake of crops and can affect soil and water quality (Khodapanah et al., 2009; Mustafa et al., 2017). This will result in the permanent concentration of soil salinity and form environmental degradation (Mays & Todd, 2005). Considering the importance of water use and the prevalence of logging and salinity, it is important to see what literature insights us about the severity of the issue in major irrigated areas of Pakistan.

4.1 Water Quality Measurement Thresholds

Water salinity is usually measured by the levels of total dissolved solids (TDS) or through electrical conductivity (EC), and Sodium Adsorption Ratio (SAR-that indicates the relative concentration of Na⁺ to calcium and magnesium)(Wang, 2013). When water with high SAR is applied to soil, the sodium in the water can dislocate important minerals (calcium and magnesium) in the soil and damages the soil structure. This also reduces the infiltration of water into the soil and decreases crop yield (Nouri et al., 2017). It causes a 53% reduction in wheat crop (Kumar et al., 2017). A substantial amount of literature is available explaining the reduction in different crops due to saline/

poor quality water use (Anjum et al., 2005). A summary of potential yield reduction from saline water for selected irrigated crops is given in Table 4.2. Residual sodium carbonate (RSC) is caused when carbonate and bicarbonate exceed the calcium and magnesium in irrigation water (Naseem et al., 2010). Extensive use of water with high RSC accumulates sodium in the soil and results in plant toxicity and poor plant development associated with excessive soil salinity and sodality. Moreover, Table 4.1 shows permissible limit values of water quality parameters recommended for crop irrigation. The pH and alkalinity affect the suitability of irrigation water for effective crop growth. The normal pH range for irrigation water is 6.5 to 8.4 (Bauder et al., 2011). The alkalinity is produced due to carbonate and bicarbonate ions in the groundwater. This caused precipitation of important minerals such as Ca and Mg in drying conditions.

Table 4.1: Threshold levels of water quality parameters recommended crop for irrigation

Parameters	EC (Ds/m)	SAR(mmol/L) ^{1/2}	RSC(meq/l)	pH
Fit	0-1	0-6	1-1.25	6.5
Marginally Fit	1-1.25	6-10	1.25-2.5	6.5-8
Unfit	>1.25	>10	>2.5	>8

⁷Source: Khan et al. (2016)

The irrigation water quality is generally described by the three parameters, such as EC, SAR and RSC.

⁷ Khan, A. D., Iqbal, N., Ashraf, M., & Sheikh, A. A. (2016). *Groundwater investigations and mapping in the upper Indus plain*. Pakistan Council of Research in Water Resources (PCRWR).

4.2 Water Quantity and Quality Status in Major Irrigated Areas of Pakistan

The Upper Chenab Canal (UCC), is one of the most important canals, having a cultivable canal command area of 0.71 Mha. And more than half of this canal command area is non-perennial. The actual crop water requirement is 20%–40% more than canal water supplies (Shakir & Maqbool, 2011) which requires to use groundwater, calculated as 3.32 billion cubic metre after discounting for losses. Groundwater quality underlying in UCC ranges from fresh with $EC \approx 1500 \mu S.cm^{-1}$ to marginal with $EC 1500\text{--}2700 \mu S.cm^{-1}$. Fresh quality groundwater is underlying in the majority of areas (Jehangir et al., 2002; Shakir et al., 2011).

In the Lower Chenab Canal (LCC), quality of groundwater deteriorated over time and area under different water quality status is found as 23% fit, 55% marginally fit and 21.56% unfit for irrigation (Awais et al., 2020). In the Lagar Distributary, EC ranges from 1270 to $1550 \mu S.cm^{-1}$ from head to tail areas. But the RSC indicator of water quality shows a different perspective in the area. The RSC ranges between 3.75 and $4.18 meL^{-1}$ from head to tail. Poor water quality in the area is associated with the higher RSC caused by a higher concentration of bicarbonate in water irrespective of the location of the farmers. Overall, 21% of tube wells at the head and 79% of tube wells at the middle and tail are found to have marginal to poor quality groundwater (Usman et al., 2016b). Total cropping intensities range from 179% to 192%, whereas the canal was constructed for cropping intensities of 50%. Water at the head of watercourses is found to have $EC < 600 \mu S.cm^{-1}$. While middle and tail end of water courses are found to have salt accumulation due to saline groundwater used as a supplement to canal water with EC ranges from 1600 to $2000 \mu S.cm^{-1}$ (Kazmi et al., 2012).

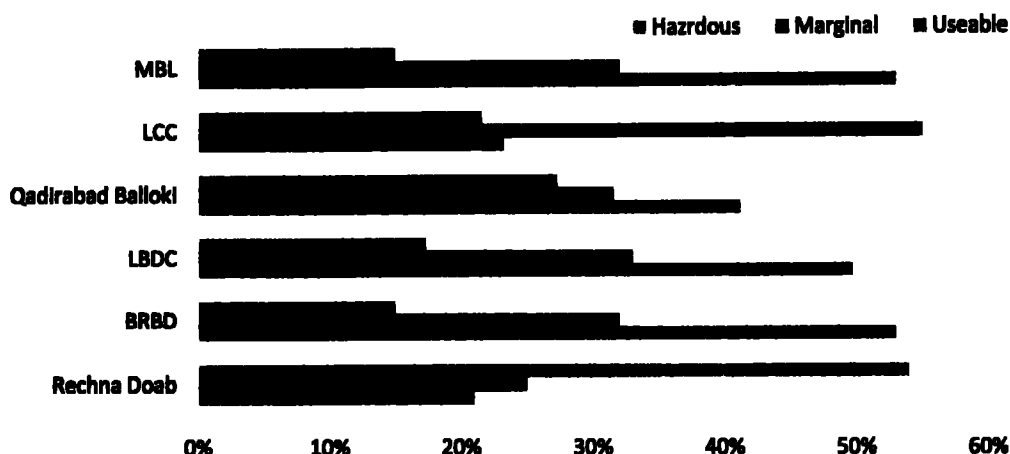


Figure 4.2: Water quality status in canal command areas

Shakoor et al. (2015), collected data for the cultivable command area of the Chenab River at northwest the Gugera Branch Canal on the Southeast, the Qadirabad-Baluki Canal on the Northeast, and the Trimmu-Sidhnai Link Canal on the Southwest. Visible differences in groundwater quality in pre- and post-monsoon seasons were observed. Groundwater quality was measured through EC, SAR, and RSC and found to be significantly affecting crop production. Effects of a 1% increase in EC were so obvious that the crop yield declined by 0.080 and 0.526%, respectively, in marginal and hazardous groundwater areas along the Lower Gugera Branch Canal (about 33.80km wide strip).

Along with other areas of deficient surface water supplies, the Kurianwala, Kilanwala, and Mungi Canals under LCC were found to have an average shortage of water from 36%-72% in Rabi and Kharif seasons compelling farmers to use poor quality groundwater to supplement their water requirement (Waqas et al., 2019).

⁸ Data for figure is extracted from papers Usman et al., (2016), Kazmi et al (2012), Basharat, (2012), Latif (2009), Shakir & Maqbool (2011), Shakoor et al (2015), Iqbal et al (2020).

The Lower Bari Doab Canal (LBDC) is designed for 67% crop intensities while maximum irrigation demand is 8 mm/d and as per normal evapotranspiration of 1 its requirement is 1 ltr/day/second while the current flow is 0.23 lps/ha requires groundwater use for cropping intensities of 160%. Consequently, a fall in WTD of 1.03 ft/year was recorded. It has been observed that the WTD of 3 out of 4 chosen LBDC divisions dropped from 0.04 to 0.34 m/year. Groundwater quality has been found from marginal to hazardous as of 33 to 17%, and wells of marginal quality water have increased over time. Farmers dug the pump of 15-20 m deep in depleted areas of the Khanewal division. The same is the case in the Sahiwal division; farmers are replacing their centrifugal tube wells with electricity-based turbines, which is adding multiple times to their irrigation costs. Due to different hydraulic ingredients, the salinity level is extremely high in Jahanian town and 10 km wide between Pattoki and Chunian starting from Raiwind. Different hydraulic gradients are at the risk of lateral and vertical saline intrusion in the LBDC. Upstream saline water areas are causing groundwater salinity in fresh downstream areas due to groundwater flows. Total groundwater pumping is 1.4 times higher than the groundwater recharge in the area, causing a loss of 0.54 million acre-feet in groundwater storage, which is equivalent to 1.18 ft/year fall in aquifer over 0.8 million GCC hectares of the LBDC (Shakir et al., 2011). Another study has estimated a 30-40 cm/year drop in groundwater level in most of the LBDC command areas (Basharat, 2015).

In Bahawalpur District, Groundwater quality was assessed by comparing values of EC, TDS, SAR, and RSC in samples with standard permissible limits by (Malik et al., 1984). On the EC and TDS values, 34 % and 12% of the samples were found as totally unfit and marginally unfit for irrigation. The highest crop yields are found in the

areas where the groundwater was of fit quality, compared with other union councils (Riaz et al., 2018).

In the Sahiwal canal command area of LBDC, farmers use low-quality groundwater with EC ranges from 0.34- 5.17 ds/m with TDS 215-3309 mg/L. Lower quality water use is adding more to the soil salinity and deteriorating soil quality. The use of marginal and poor-quality water has made non-saline and non-sodic soil to sodic soil ($SAR \approx 18.9$). The majority of the salt was added to rice crops due to excessive use of groundwater. About 3 to 15% of crop reduction was observed due to groundwater as the only water source. The yield of crop water was not affected until the EC of groundwater reaches 5.17 ds/m (Ishaq & Javaid, 2015).

In CCA of the Main branch lower (MBL), groundwater salinity increased from head to lower reaches of all the irrigation channels, i.e., the main, secondary, and tertiary canals. The groundwater is of suitable quality only in about one-half of the command area canal. More than 50% area has EC as 1.5 ds/m, so overall water productivity is declining. 47% of the area has low-quality groundwater that is unfit for irrigation and may cause severe problems to crop yield (Latif & Ahmad, 2009).

Around 40% or more water deficit demand is fulfilled through groundwater use, which caused the capillary rise and hence root zone salinization. As a result, the cropping pattern has observed a reasonable change from low to high delta crop made farmers heavily rely upon marginal quality groundwater (Aslam et al., 2006). This has resulted in a fall in groundwater tables and the use of brackish groundwater and accelerate the process of secondary salinization.

Bakhsh and Awan (2002) concluded that groundwater application having EC between 1.50 to 4.70 dS/m turned the top 300 mm soil depth of a typical non-saline soil into

saline conditions. Hussain et al. (2012) found that salinity was a major obstacle in successful crop production in many semi-arid areas like Pakistan. Hill and Koenig (1999) estimated that the application of poor-quality water reduced the expected yield of alfalfa to 60% of what it could be with good quality water. Sodification of soil occurs within a shorter period of time as of 3 years when sodium and bicarbonate-rich groundwater is used (Aslam et al., 2006). It has been found from soil samples of the Indus River delta that more than 50% of samples are affected by soil salinity (Solangi et al., 2019).

Substantial land parcels in the northern part of the irrigation system in the Upper Jhelum Canal (UJC) and lower parts of the lower Jhelum Canal are affected by logging in spite of 4 years of drought (1999-2000). Moreover, canal command areas with lower irrigation intensities and more canal water supply as Muzaffargarh and the Eastern Sadiqia command areas are also waterlogged. WTD is relatively high in Rachna Doab as 33.4% area is more than the depth of 12 m while Rechan Doab and Bahawalpur (the tail area of Panjnad) have WTD as 0.7% and 4.2% respectively. The difference in canal supplies, crop water demand from north to south is making a fall in groundwater tables, but saline water intrusion in water stress areas is not a point of concern due to very slow groundwater movement, but in areas where saline water is lying over the fresh leaked surface water is making the issue of salinity. The water table in the lower parts of the LBDC is depleting by 16-36 cm/year. The maximum water depth table is found as 23.9 m in Khorr Pacca, Lodhran. Crop water demand is increasing from north to south at the same time, canal water supply, and rainfall are also decreasing. Farmers are intensively using groundwater. Irrespective of canal supply and climatic variability, equitable canal water supply is implemented in Pakistan (Basharat & Tariq, 2014). In the above studies,

it is established that major irrigated areas of Pakistan are under threat of low to high salinity and logging. It is important to understand that how logging and salinity can affect crop growth and can prove detrimental to farmer's wellbeing.

4.3 Water Quality and Crop Growth

Irrigation water quality can affect crop yield and soil's physical conditions, besides fertility need, sustainability and performance of irrigation system and consumptive use of irrigation water. Therefore, knowledge of irrigation water quality is critical to understanding what management changes are necessary for long-term productivity. Water salinity hazard, which is measured through electrical conductivity, is the most influential water quality parameter. Crop productivity is affected due to the inability of plants to compete with ions in the soil solution for water. Higher EC means less availability of water for plants even if soil may appear wet, as plants cannot transpire saline water, Useable water reduces as EC increases, and crop yield is directly related to the amount of water transpired through a plant (Bauder et al., 2011).

Table 4.2: Potential yield reduction from saline water for selected irrigated crops

Crops	% Yield Reduction			
	>0%	>10%	>25%	>50%
	EC (ds/m) at 250C			
Barley	5.3	6.7	8.7	12
Wheat	4	4.9	6.4	8.7
Rice	2.5	6.0	8.8	12.5
Sugar beet	4.7	5.8	7.5	10
Alfalfa	1.3	2.2	3.6	5.9
potato	1.1	1.7	2.5	3.9
Corn(grains)	1.1	1.7	2.5	3.9
Corn(Silage)	1.2	2.1	3.5	5.7
Onion	0.8	1.2	1.8	2.9
Dry Beans	0.7	1	1.5	2.4

Source: Badur et al., 2011

Data is extracted from Bauder et al.(2011) except for rice, which was assessed by Qadir et al.(2014) for Pakistan. Potential reduction in crop yield due to saline use groundwater is given below in Table 4.2.

EC of water primarily the major affecting factor for crop growth, but crop growth can face a further reduction if water with sodium imbalance is applied and condition developed is called sodicity, i.e., excessive accumulation of sodium in the soil. Sodicity reduces water transport through the soil. It keeps water pooled on the surface and prevents roots from taking water. It is assessed through SAR quantification from water. Moreover, only SAR cannot bring proper results if sodicity-related irrigated water is used for irrigation potential. This is because the swelling potential of low salinity EC_w water is greater than high EC_w waters at the same sodium content. Therefore, a more accurate evaluation of the infiltration/ permeability hazard requires using EC_w together with the SAR ((Bauder et al., 2011).

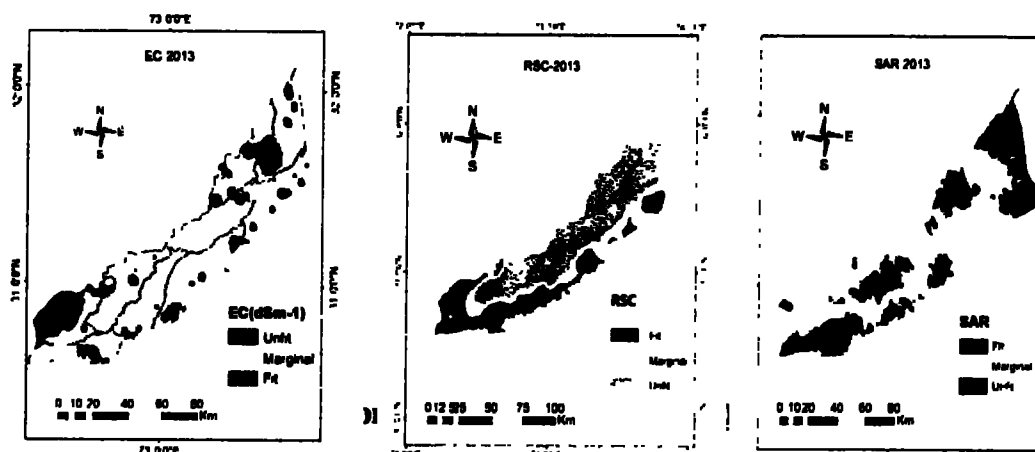


Figure 4.3: EC, RSC, and SAR in LCC in 2013.

Source: (Qadir et al., 2014)

The economic cost of salinity is usually underestimated as it is considered as yield loss as compared with non-salt induced land. Based on grown crops, a loss of 15% to 69%

is observed due to salt if no intervention is made. However, losses are much more if other costs as infrastructure deterioration (including roads, railways, and buildings), losses on property values of farms with degraded land, environmental and social cost of farm businesses are taken into account (Ivits et al., 2013).

A comprehensive study of economic losses and benefits has been conducted by Qadir et al. (2014). Besides other costs, the cost of restoration and reversing of land degradation was added to see the result in terms of favourable environmental and economic benefits. Crop rotation showed the maximum profit followed by digging drain etc. There has been found a 50% to 100% increase in income if proper processes and methods are adopted to reduce salinity from the land.

4.4 Farmers' Perception and Role of Water Quality and Quantity

Farmers' response and role are very important in managing water for irrigation in the context of water flows and salinity. It has been observed in the Lagar distributary that farmers have farms at the head and middle of the watercourse. Groundwater at the head is fit for irrigation as compared with the middle of the watercourse where it is saline. Farmer uses groundwater in the middle of the watercourse, where a flat rate of electricity is applied due to government subsidies and compromised salinity over water costs (Kazmi et al., 2012). However, best practices are required to use surface water in the middle and good quality water at the head of the canal water. This could reduce costs in terms of less energy use due to water table depth.

Farmers are well aware of the losses incurred as a result of low-quality groundwater use. A survey was conducted for farmers understating of water use and its potential impact. It was found that 23% of farmers are fully dependent upon tubewell irrigation. The majority of the farmers reported that water quality is poor as compared to the level

it was 10 years ago. Farmers associated soil quality deterioration with more groundwater use or scarcity of availability of surface water. And 9% of farmers linked salinity with excessive groundwater use. A total of 75% of farmers responded that they are facing a 33% reduction in crop yield due to excessive use of groundwater. The cost of production is also increasing, and they have to bear more costs for managing the land affected by salinity. Due to the loss in marginal profits caused by tube well irrigation, farmers are considering agriculture as non-profitable. Similar concerns are raised by farmers in LCC that groundwater water quality has a significant role in crop yield even with the variation in the combination of ground and surface use (Culas & Baig, 2020). Hence it is observed through literature that farmer's behavior of water use regarding the combination of ground and surface water affects water productivity and farmers' benefits of cropping.

4.5 Agents Based Model Vis-à-Vis Logging and Salinity

It is very important to understand the social and individual behavior of farmers for water use. Behavioral theories suggest different types of behavior, which usually agents possess, as selfish agents, altruistic agents, mixed agents, and cooperative agents (Janssen & Baggio, 2016). The irrigation behaviour of farmers best fits in coupled human and natural systems and can be understood through agent-based models discussed in the previous chapter. Moreover, heterogeneity in farmers' behaviour will help us to understand spatial and temporal patterns. In other words, the reality could be explained up to a better extent. That is how changes in the behaviour and system affect farmers. A conceptual framework of the model is given in figure 4.4.

4.6 Scope of Model

The model is meant to see irrigation water management in Pakistan under different scenarios. The irrigation behavior of farmers is responsible for two menaces of logging and salinity. Farmers who have surface water available more than water demand don't use groundwater irrespective of the fact that conjunctive water use yields more output.

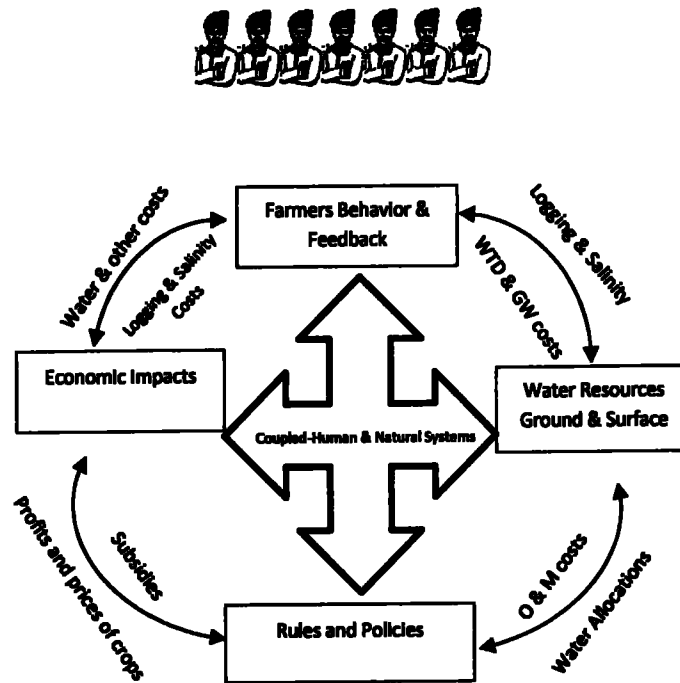


Figure 4.4: Conceptual framework, agents and their interaction in the model.

Source: Author's own developed

Further, due to less or no use of groundwater issues of drainage caused logging in the area. Due to excessive surface water use farmers farther from canals exclusively use groundwater of poor quality with higher energy cost and hence experience loss of benefits associated with irrigation and face the issue of secondary salinization. Pakistan doesn't have a clear irrigation water use framework; this study will fill the gap by assessing farmers' behavior using different water management strategies and will see how farmers will respond to the strategies. Farmer's water use behavior will decide

logging and salinity issues and resultant benefits to the farmers. Overview, design and details are given in chapter 3 and parametrization in appendix A 3.1. The model implementation is made to answer the different objectives of the study. Hypotheses are structured on the basis of objectives.

4.7 Results and Discussion

4.7.1. Hypothesis: Asymmetric access to water and farmers benefits

Asymmetric access to water source produces inequality in farmers' benefits and harms water quality parameters"

In order to assess the dynamics of the irrigation system with asymmetric access to irrigation water, baseline model is run by considering the background information from literature and real-world data. Since logging and salinity and their link to the output of farmers have not been given much attention in irrigated agriculture literature. The analysis of logging, salinity, and irrigation water relationship has always remained undervalued. Data related to salt balances and the relationship between water quality and quality have seldom been given attention by planners and river system authorities (Kijne, 2006). In the majority of irrigated areas there exist inequalities in surface and groundwater usages due to spatial differences among farmers. We have tried to assess how water use inequality along time and space is creating imbalances in the quality-quantity relation of irrigation water. We have made three different scenarios to understand the dynamics in the system. We have specifically made three criteria; Business-as-Usual (BA), Self-Governing-Rules (SGR), and Institutional-Management Perspective (IMP). Model runs twice season-wise for the time period of 25 years. We have considered the cultivation of wheat and cotton sequentially as the major cropping pattern in irrigated agriculture areas of Sindh and Punjab. Details of parameters are

given in Overview, Design, and Details (ODD) of the model in Appendix A 3.1. In BAU we have supposed that the irrigation system is working 'as it is' with no change in conventional irrigation practices of farmers. Farmers are irrigating the crops by turns and also using groundwater to supplement the deficient surface water supply.

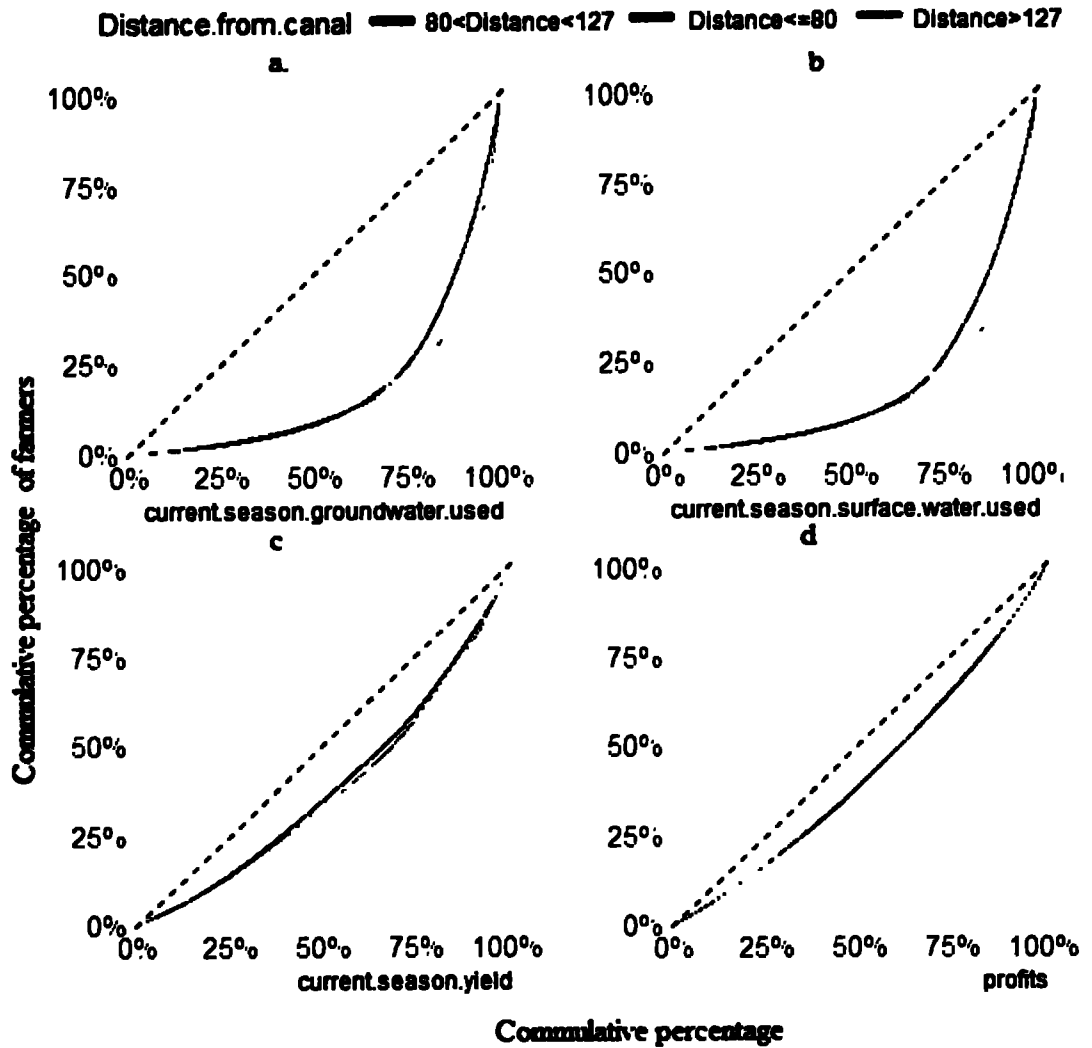


Figure 4.5: Inequality in water use, profits, and yield/acre

Source: Author's own work

In Punjab, Pakistan it has been observed that surface water supply has always been short of 30 to 40% of crop water requirement, and the difference increases for the

farmers located at a farther distance from canals. And the severity of the situation becomes worse under climatic vagaries. We have assessed inequality in water use scenarios as of surface and groundwater use among farmers located at different places in the system depicted in Figure 4.5.

Inequality exists in all level but it persists more among the farmers located at farthest distances and found that for the more distant farmers as of with Distance > 127; 35% of the farmers are using 90% of the ground and surface water. In contrast, the variations in the profits and yield/acre among farmers with different distances from water sources are not much visible. However, inequality among yield and inequality among all farmers for profits and yield is visible. Yield/acre among farmers is found to be less prevalent. This indicates the differences in water productivity and the potential of water-saving through managing the water use behavior of farmers. Similarity can be found with the fact that water endowment and water use in crops may not be strongly linked with the crop yield and hence profits if water is not in critical supply (Fisher et al., 2014). Irrigation is found to be effective if altering the cropping pattern from less to more value-added crops is shifted along with the effective access to markets accompanied by significant institutional support (Kemp-Benedict et al., 2011).

We have further explored results from the model for the type of farmers that how large, small, and medium farmers are using water resources and producing crops in the system. We have found that large farmers with less distance from water source are using more surface water and disparity is more visible among them. Small farmers are found using less surface water at all distances from the water sources. The case of groundwater use is not much different. Large farmers are found utilizing more tube well water at the tails of the water source. More use of groundwater is prevalent from

head to tails of the canals. This is due to the reason that they usually own tube wells and use more groundwater. Majorly, we can presume the fact that a major share of water for irrigation; ground and surface is consumed by large farmers. Incentives of stable water supplies are making medium and specifically large farmers install more tube wells and reap the maximum benefits of government subsidies on electrical tube wells (Qureshi, 2020). Stable groundwater supplies encouraged large farmers with shallow groundwater tables to increase their irrigated area or grow crops with more consumptive use of water/ higher water-intensive crops (Giordano et al., 2021). As it is depicted in figure 4.6 that larger farmers are found using more groundwater along the heads to tails of canals. While surface water use is more near heads of canals by large farmers. But the difference in potential yield/acre and profits are not much visible considering 'the crop/drop' context of water uses for irrigation.

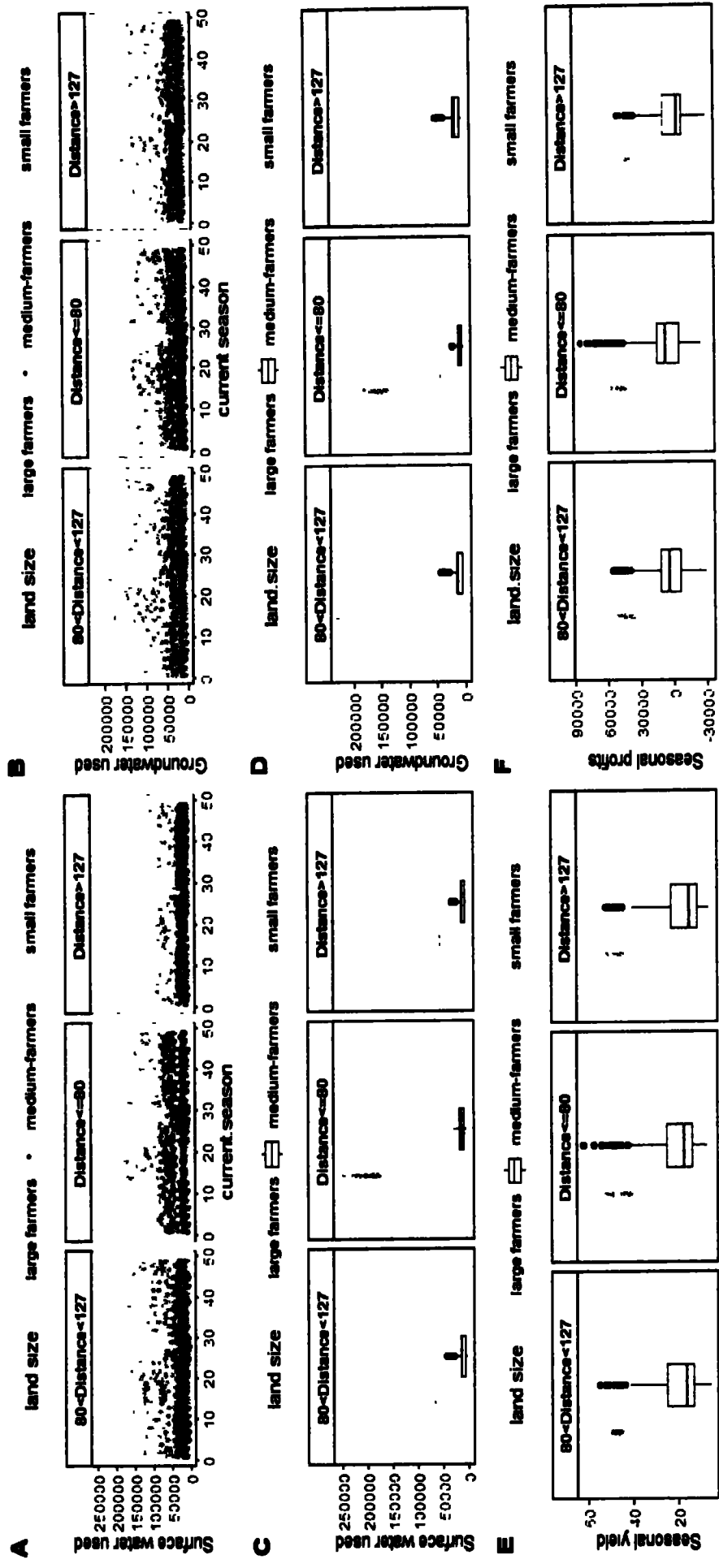


Figure 4.6: Differences in surface and ground water use among small, medium and large farmers.

Source: Author's own work

Generally, there exist differences in water use between farmers irrespective of their land size. Figure 4.7 shows farmer wise surface water used resulted from irrigation turns complemented by groundwater use of farmers and resultant crop profits of farmers. Farmer is spatially located. Farm ID zero to 150 shows nearest and farthest from the water source respectively. Farmer nearest is found using more irrigations turns and hence more surface water while the majority of the tail end farmers are utilizing more of groundwater. Small differences among farmers' profits are found. Differences are skewed more towards the farmers located nearest to the canal heads. The results are similar to the survey of crop yield disparity along the reaches of the irrigation system in the Lower Chenab Canal where the greater availability of abundant surface and good quality groundwater has resulted in disparity in crop yield in the area (Culas & Baig, 2020).

The pattern in the differences in profits among farmers is not much visible in some seasons. Variations in profits are majorly based on the ground, surface, and rainfall water uses. In the season where rainfall is sufficiently high the spatial differences among farmers are not much prevalent. As there will be less need of exchanging turns and combining them to fulfil water demand of crops from surface water. In figure 4.7, part D; shows the less frequent rains and the resultant reduction in the profits of all farmers. Point Y shows that the farmers at tails persistently are earning low profits due to less availability and access to irrigated water. Asymmetric access and inequitable water use bring different output to farmers along with poor water quality and environmental factor which affects long-run stability of output and sustainability of agriculture.

1

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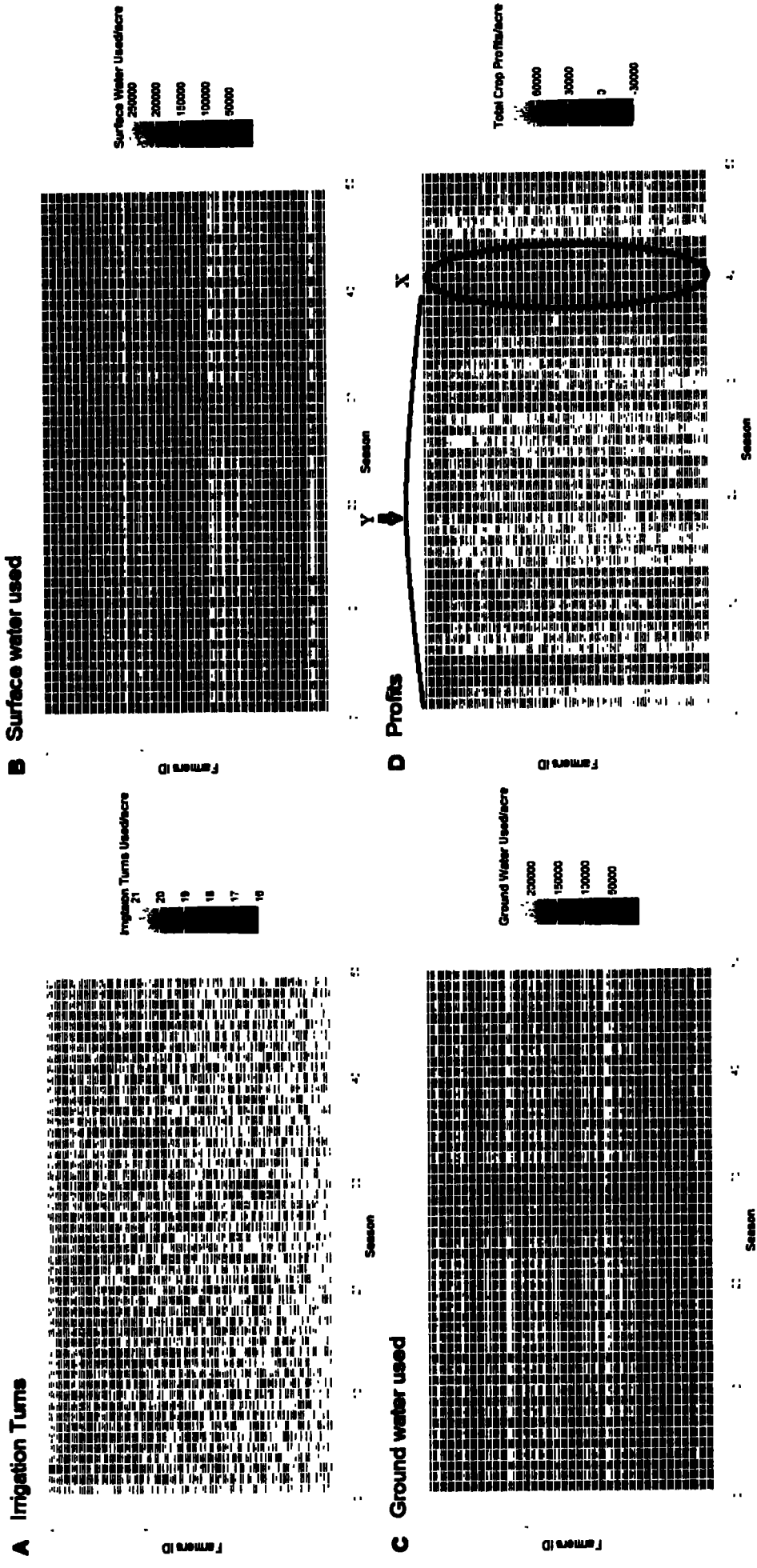


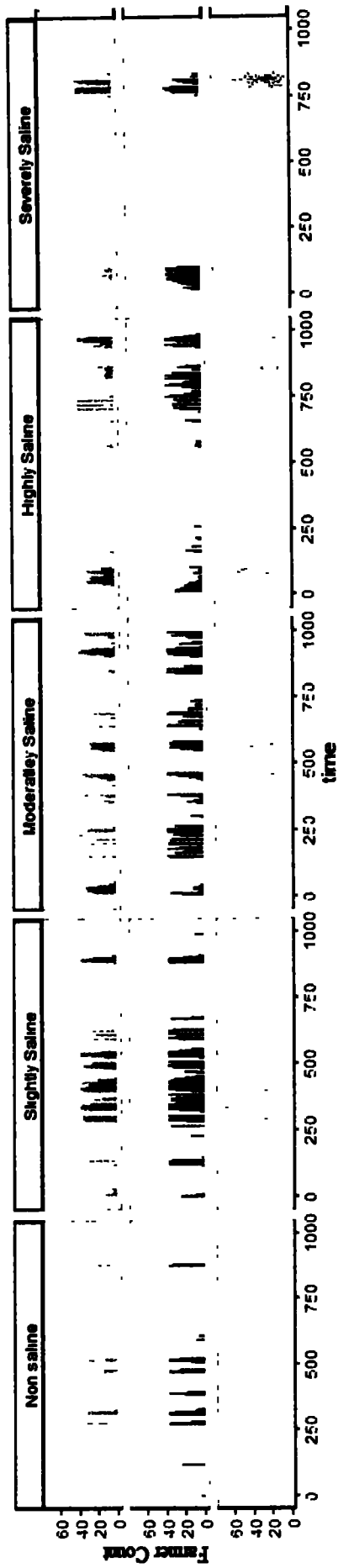
Figure 4.7: Farmer ID wise heat map for water use and profits.
Source: Author's own work

The lack of canal water supply resulted in the heavy use of marginal quality groundwater which has stemmed the problem of secondary salinization and causing loss of cultivable land (Kahlowan & Azam, 2002). We have presented results of logging and salinity resulted from the application of ground and surface water over time. Figure 4.8. Part A shows the salinity profile of farmers over time and the B part shows the logging profile of farmers. The majority of the farmers operate under slightly saline to highly saline conditions. It is depicted from the graph that salinity is increasing over the period of time as farmers complete 25 years consists of 50 seasons of Rabi and Kharif growing wheat and cotton crops. Logging shows a clear pattern; farmers located near canals are having normal water table depth, while the count of farmers increases with disastrous water table depth as farmer grow crops over time. But the condition is worst among farmers located at tails. This is due the fact that farmers are using more ground water to manage water demand at the tails of the water sources. In Figure 4.8 between 800-to-1000-time steps, there are fluctuations in logging; the number of farmers with disastrously depleted water table are reduced and the same case is exhibited for salinity in the upper part of the diagram farmer's salinity profile has improved from severely saline to moderately saline and also resulted in increased profits of farmers as observed in part D of figure 4.7.

The changes in logging and salinity profile can be linked with the rainfall intensity in the time period as it was observed that more than average rainfall in monsoon can bring root-zone salt balance over the period of years. A slight decrease in hydraulic conductivity after monsoon leaching will not be a problem during the irrigation

A. Salinity

Distance from water source  Between 89 & 127  Distance > 127  Less than 89



B. Logging

Distance from water source  Between 89 & 127  Distance > 127  Less than 89

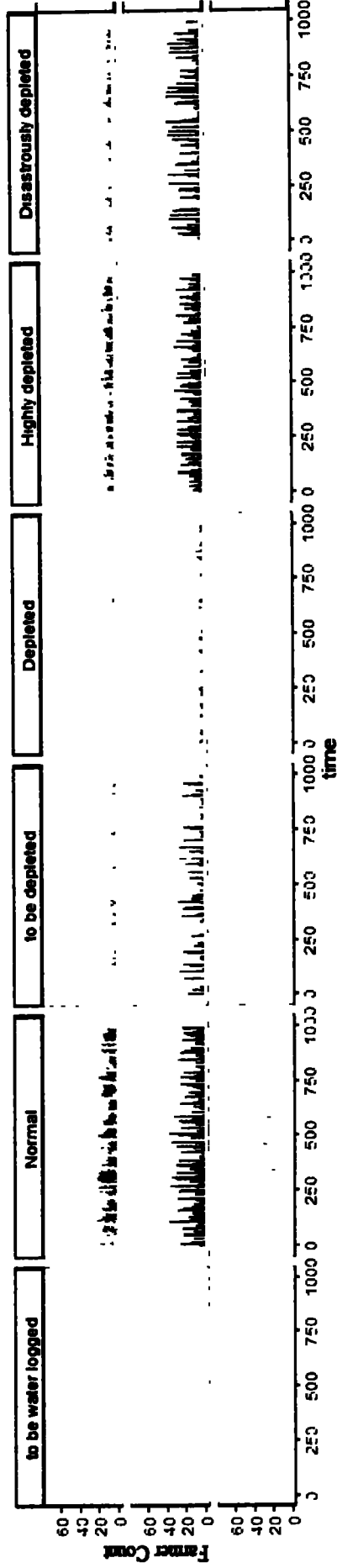


Figure 4.8: Salinity and water table depth situation in 'Business-as-Usual' water use perspective.

Source: Author's own work

season if the negative effects of a high SAR of drainage water are offset by the high salinity of the drainage water (Sharma & Tyagi, 2004). Usually, farmers are well aware of the harmful effects of prolonged irrigation of poor-quality water and try to cultivate the crop which is more water consuming and salt tolerant. The difference is that farmers notice the problem when sodicity and salinity have already affected the crop yield significantly (Johnson, 1991). Some farmers found increasing the number of irrigations as effective way of controlling the salinity in the soil. However, increasing the irrigation without treating the soil from salt deposits can further exacerbate the problem of salinity.

Similar results are presented in plenty of literature e.g., (Hussain et al., 2003; Kijne & Vander Velde, 1992). But the changes in soil salinity and the factor causing the change, and the time period for salinity build-up or reduction have rarely been documented or predicted explicitly in literature. We have tried to reflect some aspects of changes in logging and salinity in response to change in surface, groundwater and rainfall availability. It is concluded from the results of ABM that water quality parameters logging and salinity deteriorated if 'Business as usual' water use is practiced for the time period of 25 years or more. Due to water use practices and inequality in surface water availability; groundwater quality deteriorated from head to tail reaches of the same canal command areas and subsequently lowers the agricultural produce along with the proliferated value of salinity.

The next hypothesis is based on how farmers deal with the potential risk of climatic and economic conditions.

4.7.2. Hypothesis: Potential benefits under uncertain hydro-climatic and economic conditions are affected.

Farmers 'potential benefits deteriorated under different risks arising from uncertain hydro-climatic and economic conditions

Climate changes are manifested through changes in temperatures, precipitation patterns with resultant changes in the form of glaciers melt, and changes in evapotranspiration rates (Gardner et al., 2013; Rodell et al., 2018). This further affects water availability and agricultural produce specifically in the areas where water is already scarce (Khan et al., 2020).

To understand the uncertain hydro-climatic and economic conditions we have taken variations in the following parameters; evaporation, rain moisture rate and groundwater cost. Evaporation is linked with the surface water discharge available and groundwater tables. More evaporation means less surface water available for farmers and vice versa. Secondly, we have taken rain moisture rate which is linked to water table depth, and contribution of rain in surface water moisture rate and water logging of the farmers. Thirdly groundwater cost is considered as a proxy of economic parameters because the change in groundwater cost will create the difference in costs for the farmers having different water table depths.

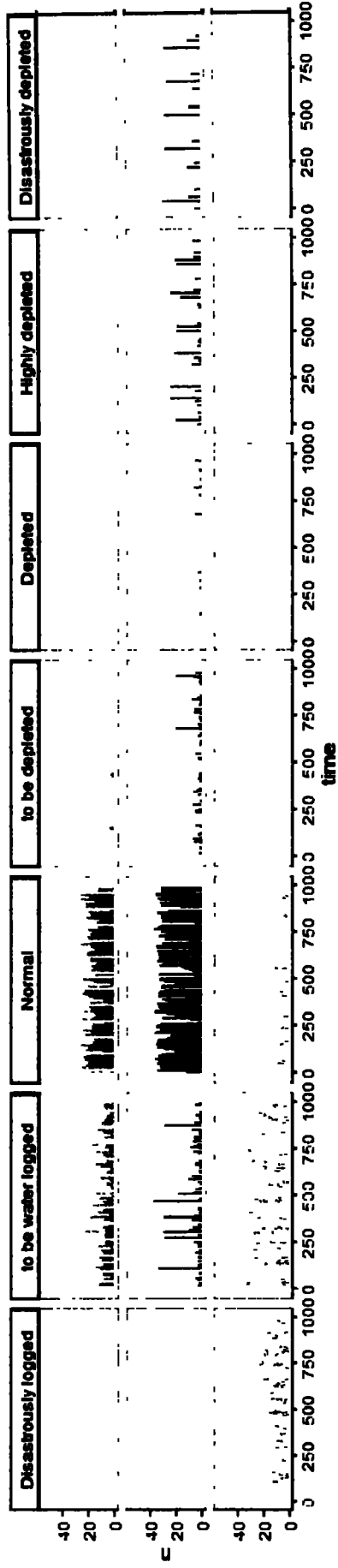
Reducing rain moisture rate to 50% and increasing evaporate rate to 50% than the baseline case to see that how this will affect farmers yield, water use, and water quality parameters as logging and salinity. Figure 4.9 compares Business As usual and rising hydroclimate change. It shows that during the period of 25 years number of farmers in normal WTD areas drastically falls and concentrated in disastrously depleted and highly depleted conditions. Climate change is making evaporation rise along with meagre or no rainfalls causing the rise in groundwater tables and making irrigated

agriculture more expensive coupled with the worsening the water quality Parameters as rising salinity. 85% of the scarcity of surface water is met through groundwater pumping in Pakistan (Bhatti & Akhtar, 2002). Extensive groundwater pumping caused a fall in water table depth to more than 500 cm in more than 50% of the farm area in Punjab which makes small tube wells inefficient (Qureshi, 2020).

Figure 4.10 presents the case of low temperature and high rainfalls. We have found that high rainfalls caused water logged areas to rise for all types of farmers located along the canals, but it become worse for the farmer located near canals. The similar case was observed in irrigated areas of Rahim Yar Khan that heavy rainfalls during 2010-14 made the water tables for farmers to rise with increased incidence of water logging in some areas (Abid et al., 2016).

A. Logging: Business As Usual

Distance from water source Between 89 & 127 Distance > 127 Less than 89



B. Logging: High Evaporation and Low Rain Moisture

Distance from water source Between 89 & 127 Distance > 127 Less than 89

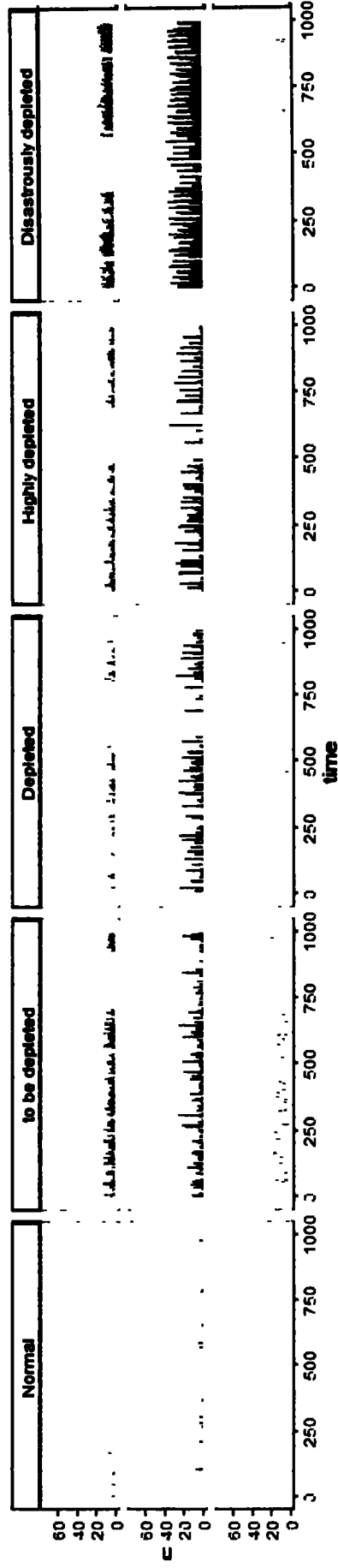
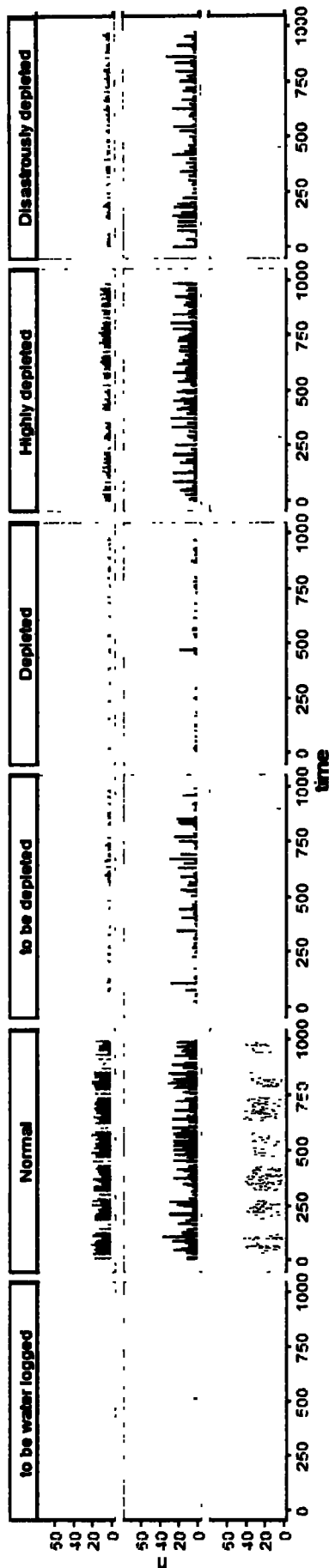


Figure 4.9: Logging in business as usual and high temperature case.

Source: Author's own work

A. Logging Business As Usual

Distance from water source Between 89 & 127 Distance > 127 Less than 89



B. Logging: Low Evaporation High Moisture

Distance from water source Between 89 & 127 Distance > 127 Less than 89

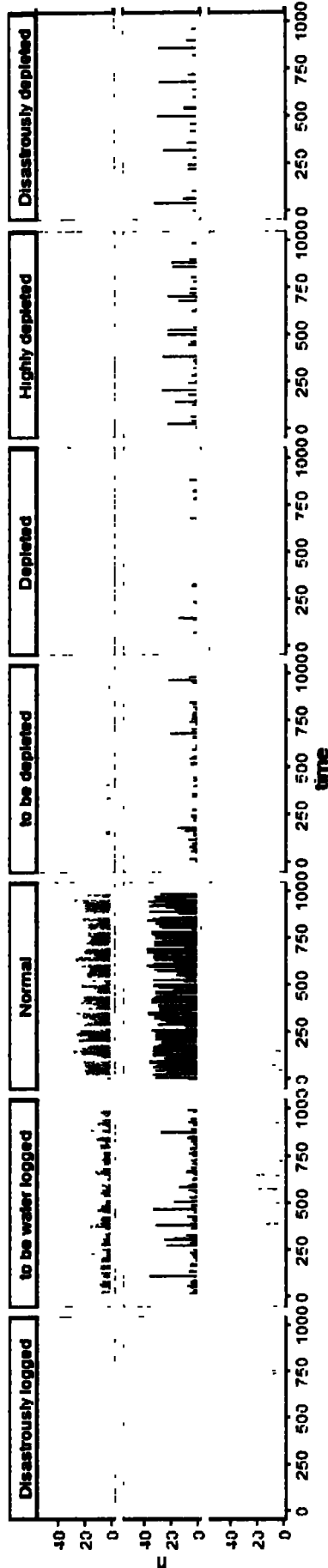


Figure 4.10: Logging in business as usual and low temperature case

Source: Author's own work

In case of higher evaporation and low rains, excessive use of tube well water is practiced it causes salinity and consequently lower agricultural produce. Salinity for all farmers with different distances from water sources rises as a result of over exploitation of groundwater resources. The number of farmers in the non-saline category generally falls and relatively increases in the severely saline category. While farmers from lesser distance from water source rise more in the non-saline category. Results are depicted in Figure 4.11 It can be related to the depleted tables in figure 1 due to which salinity rises. The results are similar to (Qureshi, 2020) that falling water tables are causing salinity in irrigated agriculture of Pakistan. In Punjab majority of the tube wells' water is sodic saline and causing irrigated land into sodic saline.

Studies show that on average 1 ton of salt per acre is added in Pakistan and less productive use of extensive water use is causing more salinity for the farmers at the tails end of the water source (Qureshi & Perry, 2021). Salinity in case of low evaporation and high rains is given in figure 4. Due to rains salinity rises again as more rains cause drainage problems for the farmer near the heads of the canals. The majority of the farmers fall in the category of severely saline land. While crop profits and yield substantially fall in the case of rising temperature as compared with the falling temperatures and rainfalls.

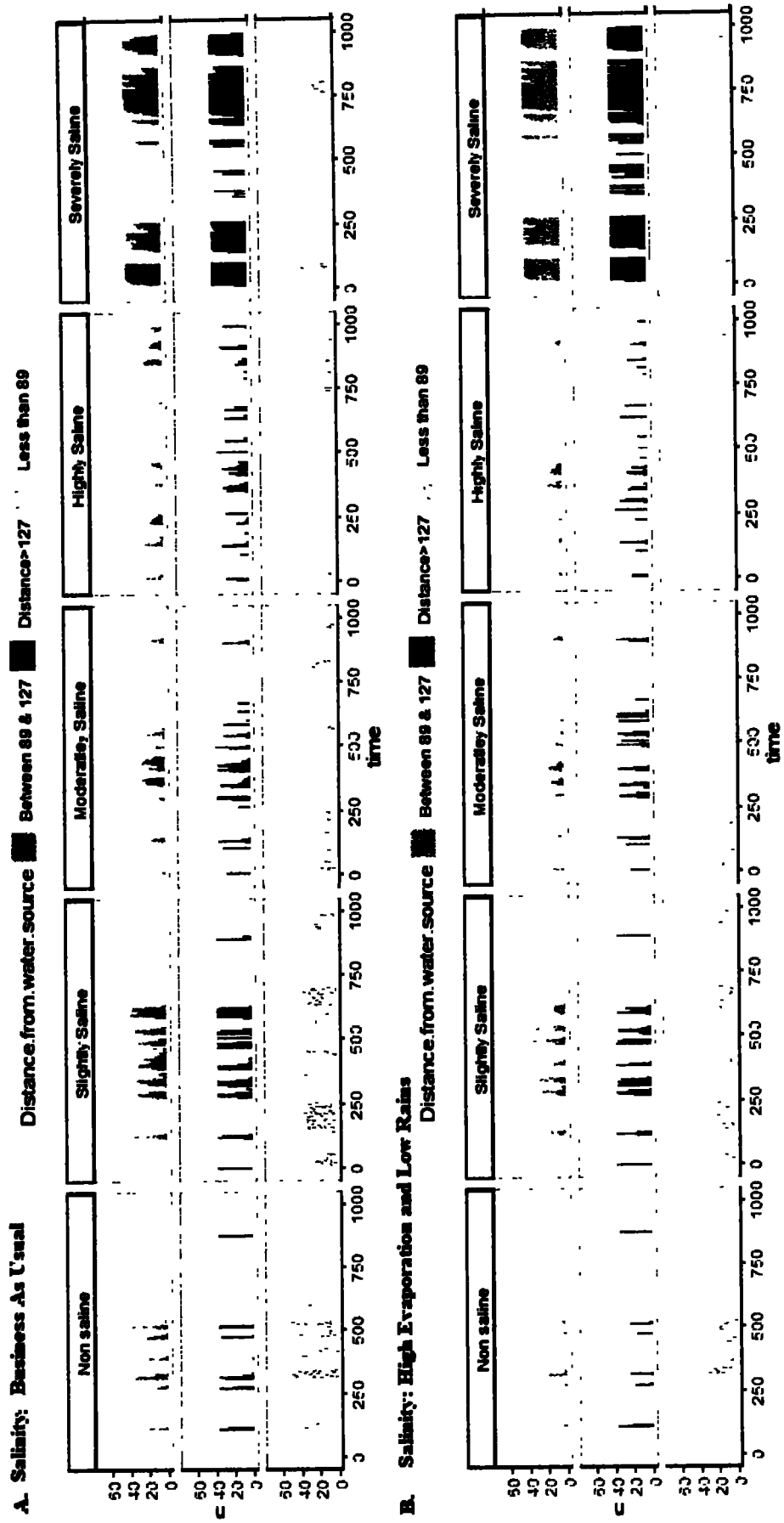
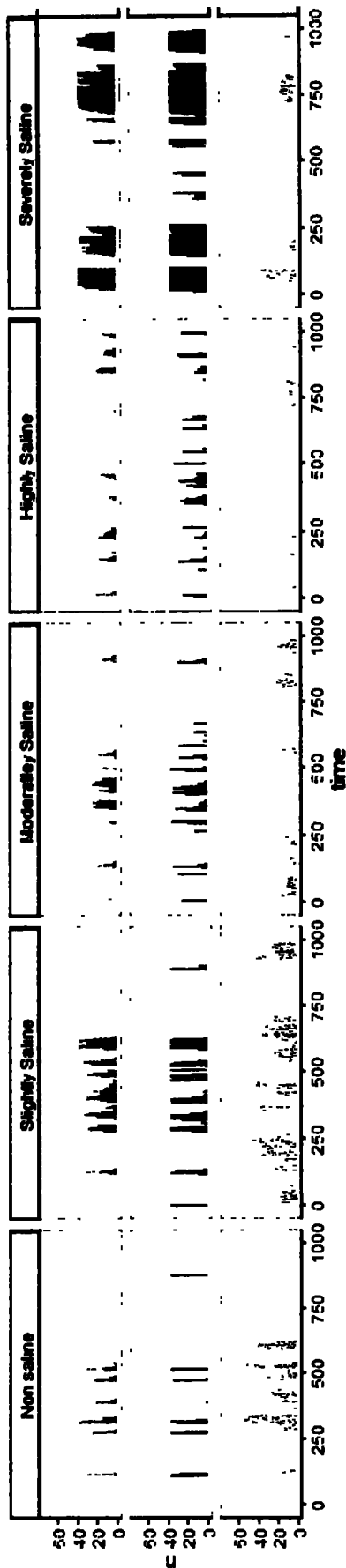


Figure 4.11: Salinity: Business-as-Usual Vs high temperature and low rains.

Source: Author's own work

A. Salinity: Business As Usual

Distance from water source Between 89 & 127 Distance > 127 Less than 89



B. Salinity: Low Evaporation and High Rains

Distance from water source Between 89 & 127 Distance > 127 Less than 89

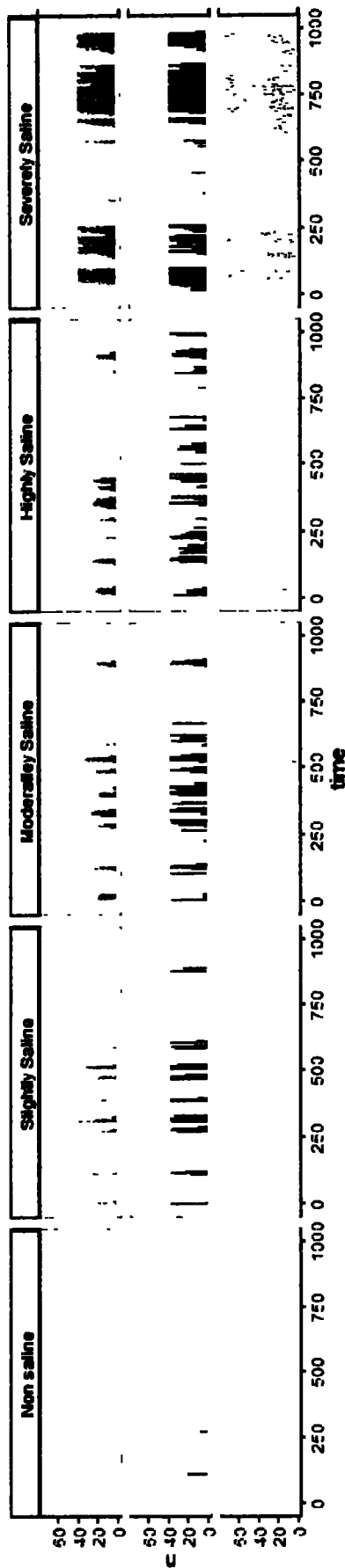


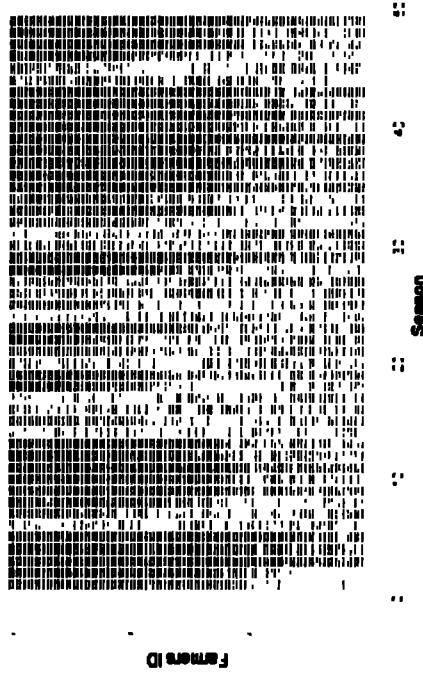
Figure 4.12: Salinity: Business-as-Usual Vs low temperature and high rains.

Source: Author's own work

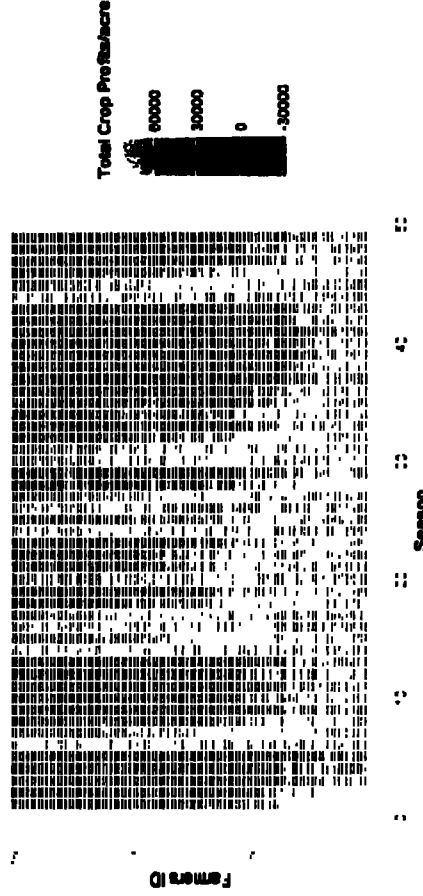
A heat map comparing profits for different scenarios as; Business as Usual, extreme evaporation and low rains, low evaporation and high rains and random rains is given in figure 4.13. The figure shows that in extreme weather conditions maximum profits of highest-earning farmers are 33% less than the Business-as-Usual case. Farmers located nearer to the water source have earned more as compared with the distant farmer. Moreover, for wheat and cotton crops differences in profits are not much visible. The c part of the diagram show low evaporation and high rains and top-earning farmers are earning 10% more profits than the business-as-usual case. This is due to the reason that the farmers are incurring fewer groundwater costs accompanied by less water deficiency due to low evaporation and high rains. In this case, farmers are not bearing losses. In all other cases, farmers are incurring some losses. Moreover, high rainfalls have caused all farmers to earn around maximum profits as depicted in parts A, B, C of the figure. In order to verify the same, we assessed the profits of farmers using random rains instead of crop season rains. D part of figure 5 depicts profits for random rains scenario. Random rains are based on the mean and standard deviation of crop season rains. All farmers near water source earn maximum profits, while other farmers most of them are bearing losses.

Variability of temperature and resultant productivity of crops in irrigated areas is highly sensitive to variability of water supplies and temperature. A temperature rise of 0.5°C-2°C will result in agricultural productivity falling around 8 to 10% by 2040. The impact will be more severe for vulnerable farmers especially small farmers located at the tails of water sources (Chaudhry, 2017).

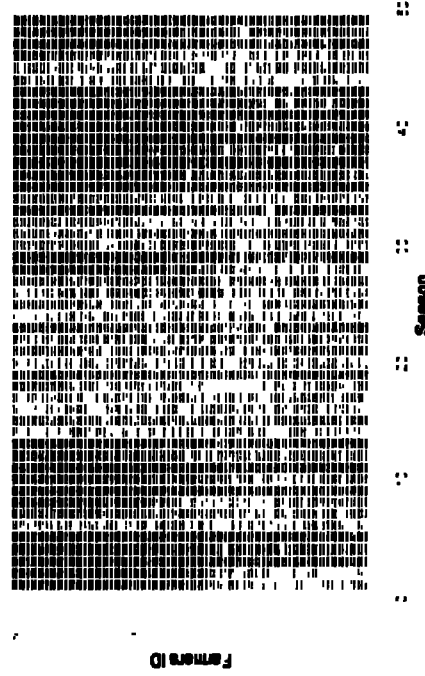
A Business As Usual



B Extreme Evaporation and Low Rains



C Low Evaporation and High Rains



D Random Rains

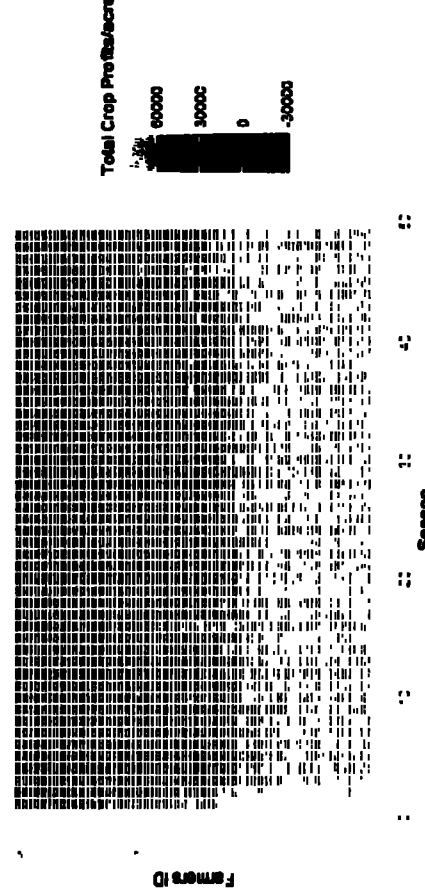


Figure 4.13: Scenario based comparison per acre profits.

Source: Author's own work

4.8 Conclusion

The dynamics of the irrigation system with asymmetric access to irrigation water is assessed. We have tried to evaluate that how water use inequality across time and space is creating imbalances in the quality-quantity relation in irrigated agriculture. Inequality exists at all level but it persists more among the farmers located at farthest distances and found that for the more distant farmers as of with spatial distance more than the average distance, 35% of the farmers are using 90% of the ground and surface water. In contrast, the variations in the profits and yield/acre among farmers with different distances from water sources are not much visible. However, inequality among water use is visible. This indicates the importance of differences in water productivity and the potential of water-saving through managing the water use behavior of farmers. This affirms the fact that water endowment and water use in crops may not be strongly linked with the crop yield and hence profits if water is not in critical supply (Fisher, Harding, & Kemp-Benedict, 2014). Irrigation is found to be effective if altering the cropping pattern from less to more value-added crops is shifted along with the effective access to markets accompanied by significant institutional support (Kemp-Benedict et al., 2011).

Results of the model shows that the large farmers with less distance from water source are using more surface water and inequality in water resource usage is evident among them. Small farmers are found using less surface water at all distances from the water source. The case of groundwater use is not much different. We can clearly verify the most observable fact that a major share of water for irrigation; ground and surface is consumed by large farmers.

Farmer at heads are found using more irrigations turns and hence more surface water while the majority of the tail end farmers are utilizing more of groundwater. Small differences among farmers' profits are found. Differences are skewed more towards the farmers located nearest to the canal heads. The results are similar to the survey of crop yield disparity along the reaches of the irrigation system in the Lower Chenab Canal where the greater availability of abundant surface and good quality groundwater has resulted in disparity in crop yield in the area (Culas & Baig, 2020). Incentives of stable water supplies are making medium and specifically large farmers to install more tube wells and reap the maximum benefits of government subsidies on electrical tube wells (Qureshi, 2020). Stable groundwater supplies encouraged large farmers with shallow groundwater tables to increase their irrigated area or grow crops with more consumptive use of water/ higher water-intensive crops (Giordano et al., 2021).

Our climate change experiment shows that the difference in water use and profits are based on rainfall, ground and surface water use behaviours. In the season where rainfall is sufficiently high the profits based on spatial differences among farmers are not much prevalent due to less need of exchanging turns to fulfil water demand from surface water. We have exhibited logging and salinity resulted from the application of ground and surface water over time. We have found that salinity is increasing over the period of time as farmers complete 25 years' time period for alternative crops. Logging shows a clear pattern; farmers located near canals are having 'normal' water table depth, while the count of farmers increases with 'disastrous' water table depth as farmer grow crops over time. But the condition becomes worst among farmers located at tails. However, between 800 to 1000 time steps, there are fluctuations in logging; the number of farmers with 'disastrously' depleted water table reduced. In the same time fall in salinity is also observed which is depicted in timeline chart of salinity. These

drastic changes in salinity and logging are associated with the heavy rainfall in the mentioned time period. This can be related with the fact that more than average rainfall can bring root-zone salt balance over the period of time.

We have tried to reflect some aspects of changes in logging and salinity in response to change in surface, groundwater and rainfall availability. It is concluded from the results that water quality parameters logging and salinity are deteriorated if same water use practices are adopted for extended period of time. Due to water use practices and inequality in surface water availability and extensive use of groundwater, groundwater quality deteriorated from head to tail reaches of the same canal command areas and subsequently lowers the agricultural produce along with the proliferated value of salinity.

To understand the impact of hydro-climatic and economic conditions we have taken variations in evaporation, rain moisture rate and groundwater costs to reflect the effect of hydro-climatic and economic conditions respectively. Experiment shows that during simulated period numbers of farmers in 'normal' water table depth areas drastically falls and concentrated more in 'disastrously' depleted and 'highly' depleted conditions. This change in climate i.e., rise in evaporation rate along with fewer rains causing the fall in groundwater tables and making irrigated agriculture more expensive. This fall in groundwater tables is resulted from scarcity of surface water which is met through groundwater pumping in Pakistan (Bhatti & Akhtar, 2002). Water tables are found to fluctuate in response of the change in the climatic variables. Extensive groundwater pumping caused a fall in water table depth of 1 metre /year (Qureshi, 2020).

In case of low temperature and high rains we have found that high rainfalls caused water logged areas to rise for all types of farmers located along the canals, but it become worse for the farmer located near canals. The similar case was observed in

irrigated areas of Rahim Yar Khan that heavy rainfalls during 2010-14 made the water tables for farmers to rise with increased incidence of water logging in some areas (Abid et al., 2016).

In case of higher evaporation and low rains, excessive use of tubewell water is a routine practice of farmers. This causes salinity and consequently lower agricultural produce. Salinity for all farmers with different distances from water sources rises as a result of over exploitation of groundwater resources. The number of farmers in the 'non-saline' category generally falls and relatively increases in the 'severely saline' category. While farmers from lesser distance from water source rise more in the 'non-saline' category. The results are similar to (Qureshi, 2020) that falling water table is causing salinity in irrigated agriculture of Pakistan. In Punjab majority of the tubewells' water is sodic saline and converted irrigated land into sodic saline land. Studies show that on average 1 ton of salt per acre is added in Pakistan and less productive use of extensive water is causing more salinity for the farmers at the tails end of the water source (Qureshi & Perry, 2021). Due to rains salinity rises again as more rains cause drainage problems for the farmer near the heads of the canals. The majority of the farmers fall in the category of severely saline land. While crop profits and yield substantially fall in the case of rising temperature as compared with the falling temperatures and rainfalls.

We have exhibited variation in intensity of profits through heat maps. It is observed that extreme weather conditions affect both highest and lowest earning farmers. Extreme weather makes farmer to earn 30% less than baseline experiment. However, spatial distance appears as one of the important factor determining the farmers' profits even in case of climatic vagaries. Favourable weather conditions also bring more profits comparing it with baseline data. This is due to the reason that farmers

are incurring fewer groundwater costs accompanied by less water deficiency due to low evaporation and high rains. In order to verify the same, we assessed the profits of farmers using random rains instead of crop season rains. Major differences in profits are based on spatial distances. Productivity of crops in irrigated agriculture is highly sensitive to variability of water supplies and temperature. It has been estimated that a temperature rise of 0.5°C- 2°C will result in agricultural productivity falling around 8 to 10%. The impact will be more severe for vulnerable farmers especially small farmers located at the tails of water sources (Chaudhry, 2017). Summing up, inadequate surface water is along with extensive groundwater withdrawal is causing salinity. Large farmers use more of surface water and escape the loss associated with saline groundwater and increased groundwater pumping costs. These benefits agglomerated and bring inequity in water use. However, specifically small farmers and generally all farmers are affected by the system of WARA BANDI that leads to over or under irrigation of crops and consequently destroy soil nutrients and reduces crop water productivity (Bhatti et al., 2017).

CHAPTER 5. GROUNDWATER MANAGEMENT

5.1 Groundwater Use Background

Many scientists argue that the explosive growth in groundwater irrigation has had little relationship with the pattern of occurrence of the groundwater resource. In the long run, groundwater development is self-regulating; people cannot pump more water than there is in the aquifers. According to them, long before the hydrogeology of aquifers imposes a check on further development, the economics of pumping water from deep aquifers would do so. It is therefore ironic that global pockets of intensive groundwater use have emerged in regions as North China and South Asia that are not amongst the best endowed for it (Shah, 2007).

5.2 Groundwater: A Common Pool Resource

The Low-excludability and subtractability of groundwater make it a common pool resource (CPR). Every abstraction of groundwater reduces its availability to be used as CPR (Ostrom, 1990). Somewhere ground discharge cause groundwater loss and mines at the same time in some land pockets (Theis, 1940). Moreover, groundwater use also affects groundwater quality for the water seeped into the aquifer (Brentwood & Robar, 2004). However, the non-excludability of CPR in the groundwater management context can be taken as low excludability. Since landowners can't be excluded from consumption groundwater pumped through installed tubewells on their lands. Groundwater development is easily accessible subject to the availability of cheap technology and subsidized energy (Schlager, 2007). These characteristics make groundwater face a common pool resource problem called Tragedy of common, or this can be regarded as a "tragedy of open access" that needs to be considered (Feeny et al. 1990; Grafton 2000). In major groundwater depletion areas there is no policy or

minimal enforced rules for groundwater abstraction from South Asia; China, India, and Pakistan (Shah, 2007).

5.3 Consequences of Overuse of Groundwater

Overuse of groundwater has resulted in the pursuance of the self-interest of farmers aimed at maximizing their crop yield. This problem is aggravated if no regulatory or economic arrangements are imposed (Hardin, 1968). Moreover, farmers misperceive excessive water use with crop yield and sacrifice long-term sustainable water availability with the short-term crop intensity (Stevenson et al, 2019). Irrespective of the fact private and social welfare will be diminished in the long run farmers do not find it beneficial to preserve groundwater if no other farmer is intended to do the same and if there is no monetary compensation is offered for groundwater use reduction. Formal per unit prices are missed in CPR cases, and mostly in developing countries installation and operations are facilitated through subsidies, which resulted as in-discriminated pumping and contributing to excessive groundwater extraction in many locations (Khair et al., 2015; van Steenbergen et al., 2015). Unregulated use of groundwater brings social, environmental, and economic consequences along with aquifer depletion (Harou & Lund, 2008; Skurray et al., 2012). In addition to the social and ecological problems, economic problems of increased irrigation costs have lead farmers to migrate and change their sources of livelihood other than farming (Basharat & Tariq, 2014).

Soil salinization, land subsidence, seawater intrusion, etc. are the main environmental externalities over-drafting of the groundwater in irrigated agriculture areas. Highly depleted water areas are given in Appendix A 5.1. As far as economic externalities are concerned; farmer starts reducing crop production and improved

methods of irrigation when marginal costs of groundwater extraction exceed its marginal benefits.

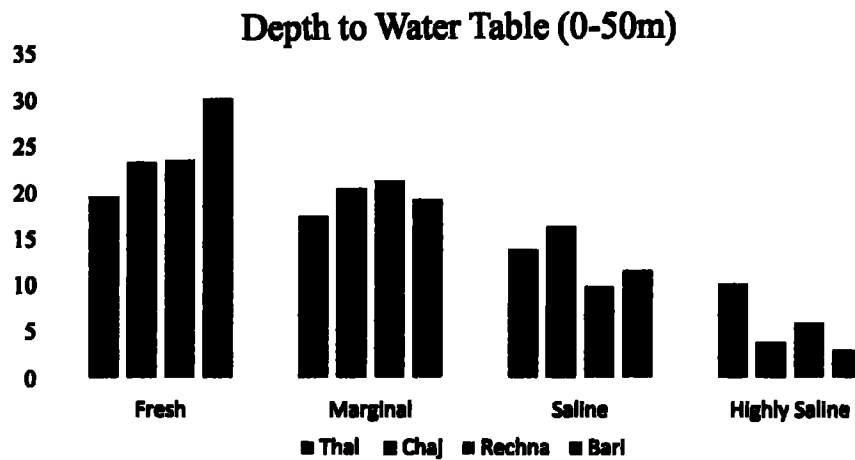


Figure 5.1: Water Quality in shallow groundwater areas across doabs in Pakistan (2016)
Source: Khan et al. (2016)

However, farmers will keep drilling water until the net benefit of its least valued crop is more than the present value of all future pumping costs savings (Harou & Lund, 2008). Moreover, there does exist spatial cost differences in the drilling of 20% to 30% as per water table depths, and hence it makes the differences in costs of water buyers as well and making cropping less profitable for small farmers and tenants (Mustafa et al., 2013). Figure 5.1 shows the difference in water quality across Doab in shallow groundwater. This is a cause of logging and salinity in many areas with the presence and absence of surface water. Farmers keeps their land parcels fallow in order to make land cultivable in future.

5.4 Management Problem

Regulation of groundwater use is the first and foremost response to the overuse of common-pool resources. A suitable institutional framework will become a significant challenge if regulation is hardly accepted as a solution. However, people's behavior may not be tamed by the external institutional framework (Berkes, 1989),

which ignores internal rules, customs, and logic and may prove impotent for common-pool resource management (Blanco & Walker, 2019). The probability of overexploitation remains high due to the misperception of farmers about unlimited availability of the resource, god-given right, and societal needs (St John et al., 2010) and continue to free-riding, which causes significant system collapse (Ostrom, 1990).

5.5 Groundwater Economy

Usually, in Pakistan, groundwater is owned by old and big landlords as they have tubewells on their land and are the fundamental beneficiary of it. Selling merely represents water scarcity price to landless or groundwater buyers. And groundwater buyers are easily denied water when energy shortage or fuel prices are higher than average. As a result, owners tend to have more crop productivity as compared with buyers (Meinzen-Dick, 1996).

5.6 Groundwater withdrawal Status and Issues in Pakistan

The Government promoted private tubewells development in Punjab, Sindh, KP, and Baluchistan. This initiative was specifically taken for agricultural development drainage, food security, etc. Subsidies were provided on power supplies up to 60%. For further development, pump sets and soft loans were provided (Johnson, 1989). Initially, the Government-subsidized tubewells development, and later it was recognized that through private tubewells, the agriculture sector had achieved sustained development in tubewells installation by the 1980s. But Government continued subsidies in electric supply.

The share of groundwater in water supplies at the farm gate has increased to 50%. Groundwater extraction has increased water supply to 75% due to which cultivation area and cropping intensity has increased to 35% from 1960-85. Water productivity of groundwater is more as compared with surface water due to reliable

supply and fewer conveyance losses. The issue of food security and poverty is majorly dealt by groundwater extraction in Pakistan as elsewhere in South Asia (Llamas, 2000). The issue of drainage caused logging in the Indus plain. The problem of waterlogging was observed in the Rechna Doaab and Chaj Doaab in the early 19th century. To identify the issue Water Logging Board (WLB) and Water Drainage Board (WDB) were established in 1915 and 1917, respectively. Many corrective measures were tried, but the issue of logging intensified further due to floods in the 1950s (Rehman et al., 1997). A nationwide survey has been conducted for waterlogging assessment from 1976-79. It was found that the water table was on average at 8 feet depth in almost 50% of the area under study. The issue of salinity was found gripping due to waterlogging in these areas (Choudry, 1977). The Government initiated a vertical drainage program through Salinity Control and Reclamation.

Groundwater use and proliferation have a long history in Pakistan; it started in the 1960s under Salinity Control and Reclamation Projects (SCARPs) with the installation of 20,000 public tubewells, which has now reached 1.4 million. Out of the total installed tubewells, 99% are private tubewells. There has been found a 160% rise in private tube well installation in Pakistan (GOP, 2018). An overview of private tubewell installation is given in Figure 5.1. In Pakistan, groundwater use is becoming more popular due to less development in surface water, which creates inefficiencies of surface water delivery along with an increase in crop intensity, subsidized accessibility, and reliability of compared with the surface water access only (Basharat, 2015). Farmers with groundwater access are able to cultivate 30% more land and their income is substantially higher than the farmers who had access to surface water only (Faruqui, 2004).

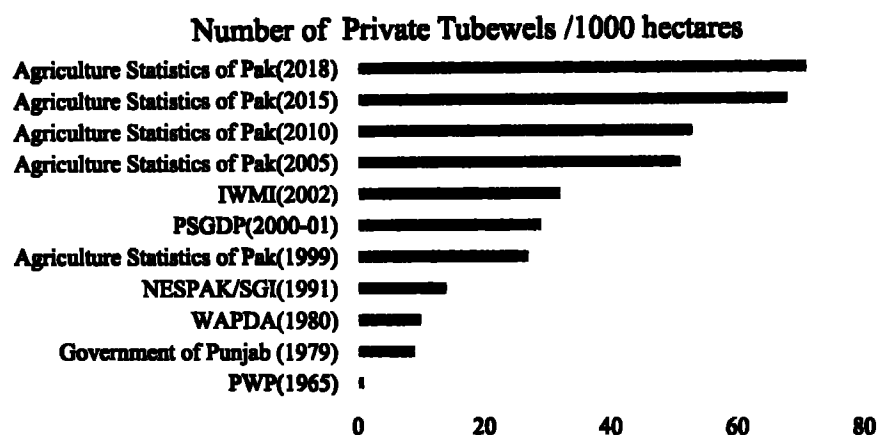


Figure 5.2: Increase in the density of private tube wells in the Punjab province of Pakistan

***Source:** Various reports of government of Pakistan

In Pakistan, specifically in Punjab, groundwater recharge is far less than groundwater extractions. Overexploitation of groundwater in fresh groundwater areas is visible. In Baluchistan development of tubewells has reduced water access for Karez, which deprived many farmers access to vital resources.

5.7 Types of Groundwater Agents in Agriculture

Groundwater users are divided into 3 groups, i.e., tubewell owners, water buyers, and shareholders (Malik et al., 2008). Farmers install tubewell as per installation cost over the land they owned for unrestrained water extraction, shareholder shares installation

⁹ i. Government of Pakistan (2018), Agriculture Statistics of Pakistan (2018). Pakistan Bureau of Statistics.

ii. Government of Pakistan (2015), Agriculture Statistics of Pakistan (2015). Pakistan Bureau of Statistics.

iii. Government of Pakistan (2010), Agriculture Statistics of Pakistan (2010). Pakistan Bureau of Statistics.

iv. Government of Pakistan (2018), Agriculture Statistics of Pakistan (2018). Pakistan Bureau of Statistics.

v. Government of Pakistan (2005), Agricultural Statistics of Pakistan (2005). Ministry of Food, Agriculture & Livestock

vi IWMI. 2002. IWMI world irrigation and water statistics 2002. Colombo, Sri Lanka: International Water Management Institute.

viiPPSGDP. 1999. Database for groundwater management in Punjab - Technical Report No. 30 (Final Report). Lahore, Pakistan: Punjab Private Sector Groundwater Development Project Consultants (A consortium of Arcadis - Euroconsult, NESPAK, NDC & Halcrow).

vii. Government of Pakistan (1999), Agricultural statistics of Pakistan. Islamabad, Pakistan: Ministry of Food, Agriculture and Livestock, Economics Division and Government of Pakistan.

viii. NESPAK/SGI. 1991. Contribution of private tubewells in the development of water potential. Final Report. NESPAK in association with Specialist Group Inc. (Pvt) Ltd.

ix. WAPDA. 1980. Private tubewells and factors affecting current rate of investment economics research section. Lahore, Pakistan: Planning and Development Division and Water and Power Development Authority.

cost and receive water as per their need by paying operational costs, and the third one buys through informal prices at an hourly rate or with the tacit agreement for water as barter systems sharing crops in exchange of groundwater use (Malik et al., 2008). The cost for irrigation for buyers as compared with the former two groups is far higher (Ashfaq et al., 2009). Moreover, differences in the costs are based on the energy source of the tubewell electricity or diesel. Since electricity is subsidized by Government, the cost is far less than diesel based tubewells. These differences create farmers' ability to earn equitable profits (Bashir et al., 2005). Socio-inequalities are created as water monopolies are obtained by the farmers who can afford deep tubewells. Moreover, water buyers tend to produce less valued and less water-intensive crops as compared with tubewell owners this has created fundamental inequalities among them. Crop productivity for groundwater buyers was high in all crops as compared with pump owners as buyers have used a mix of both surface and groundwater. And the share of groundwater in their irrigation was less. Although, pump owners have got more sugarcane crops per hectare as compared with the buyers' crop productivity. Moreover, buyers are getting higher gross value and marginal product from wheat, rice, and sugarcane.

Water buyers are getting slightly more benefits than pump owners. Irrigation costs contribute a larger share in total costs. And out of irrigation costs, groundwater costs are more as surface water charges per hectare, are fixed. Pump owners bear more irrigation costs if costs further divided into buyers and non-buyers. 15% percent of the area has gone uncultivated for poor farmers due to expensive tubewell installation. More than 40% of dug wells are reconstructed or deepened due to falling water tables. Water quality and increasing water table are endangering agriculture growth in general and landless poor farmers' crop yield in specific. Figure 5.3 portrays this scenario.

5.8 Existence of Groundwater Markets in Pakistan

Groundwater extraction has played an enormous role in Pakistan's agriculture development. But it is not sustainably managed. Poor farmers mostly being last in the queue with unreliable surface water supplies are found buying water from tubewell owners. These issues are further exacerbated by conveyance losses. This is due to the reason shallow tubewells are preferred in the country. Buyers usually finds many sellers of groundwater, available prices of leasing water falls as number of sellers increases.

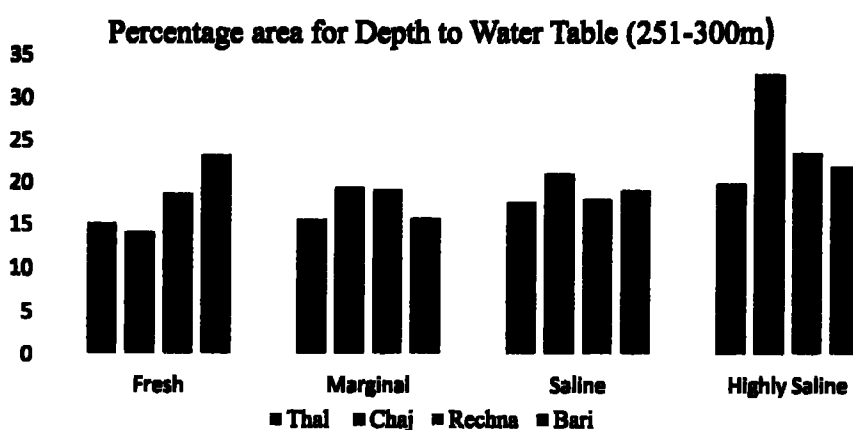


Figure 5.3: Water quality in deep groundwater areas across Doab in Pakistan (2016).

¹⁰Source: (Khan et al., 2016 & Qureshi et al., 2003)

The average prices of tubewell water are given in Table 5.1. This has increased water access and lead to over-drafting of water. Reallocation of surface water is needed between fresh groundwater areas with high and low irrigation costs and saline groundwater areas to reduce water mining in former and salinity control in later areas. Table 5.1 shows that diesel-operated groundwater is more expensive as compared with electric tubewell, this can cause discrimination in earning within and between provinces

¹⁰ Khan, A. D., Iqbal, N., Ashraf, M., & Sheikh, A. A. (2016). *Groundwater investigations and mapping in the upper Indus plain*. Pakistan Council of Research in Water Resources (PCRWR).
Qureshi, A. S., Shah, T., & Akhtar, M. (2003). *The groundwater economy of Pakistan* (Vol. 64). IWMI.

due to elevation and energy sources available for groundwater discharge (Qureshi et al., 2003). Owners usually take advantage of this situation and charge high prices or deny on-demand water provision.

Table 5.1 Selling rates of groundwater in different provinces (US \$/m³)¹¹

Provinces	Electric TWs	Diesel TWs (Diesel Engine)	Diesel TWs (Tractor operated)
Punjab	0.51-0.60	1.27-1.48	1.76-2.73
Sindh	0.78	1.22	X ¹²
KP	0.73-0.77	2.39-4.49	3.77

Source: (Qureshi et al., 2003)

5.9 Paradigm Shift in Groundwater Development

Key to this, in many instances, is a policy paradigm shift from groundwater development to long-term groundwater management (Khair et al., 2019; Mushtaq et al., 2013; Sharma et al., 2010). There are plenty of evidences available in literature for managing groundwater depletion through state control or institutional regulations. Few examples are available or community-level local rules established to manage water resources (Kadekodi, 2004). Currently, the directorate of land reclamation is responsible for groundwater monitoring. Groundwater management is a complex issue that should be dealt including all types of water uses. Considering socio-economic and physical resources government is initiating a special focus on water saving and protection of groundwater quality for sustainable groundwater management (Kori et al., 2009). Groundwater users and the local organization have always been ignored in groundwater management. But from Baluchistan's experience of groundwater management through enforcing rules for common-pool resources suggests that groundwater management must be inclusive of all stakeholders. Inclusion of all

¹¹ Qureshi, A. S., Shah, T., & Akhtar, M. (2003). *The groundwater economy of Pakistan* (Vol. 64). IWMI.

¹² No Data is available

stakeholders require to use ABM to assess groundwater dynamics to find social norms or develop regulatory framework for sustainable groundwater management.

5.10 Agent-Based Groundwater Use Model

Farmer participates differently in water markets as per their choices of irrigation requirement, water quality, and type of tubwell installed. They interact with natural resources and other agents in the system and leave a feedback effect by affecting their neighbors and these types of systems consisting of complex agents and are understood through agent-based modelling. But social norms and collective actions are hardly appreciated to understand emergence in the systems. Studies have been conducted to evaluate farmers violating (Du et al., 2017), and non-violating (Castilla-Rho et al., 2017) behaviour for water management under complete information and imitating the behaviour from neighbouring farmers. This study will stimulate informal markets to understand and extract rules to regulate farmer's behaviour for water withdrawal. Moreover, the regulation regarding water withdrawal rights will also be assessed to see the response of the system. The schematic diagram of the model is given in Figure 5.4.

The groundwater markets are strongly established in all three provinces. Water markets have the potential to move water from low to high value uses, promote investment in increasing the efficiency of water use, and transform water from being a scarce but free resource into an economic good with an opportunity cost (Qureshi et al., 2004; Shah et al., 2000).

Assessment of cooperation in the irrigation system is limited to a theoretical, field, and statistical analysis. Diffusion of governance of irrigation systems and factors responsible for the evolution of cooperation are required to be investigated. Water users have social relationships. Their interaction can lead to having aggregate behavior. The heterogeneity of individuals interacting in different social networks can bring

complexity to the system. Individual learning from social interaction can be made and observed through simulations (Cai & Xiong, 2017).

5.10.1 Scope of the Model

Groundwater is a complex management problem. Farmers interact with each other and with water resources. Large farmers interact with water resources and use unmanaged withdrawal of water causing water depletion for everyone in the system.

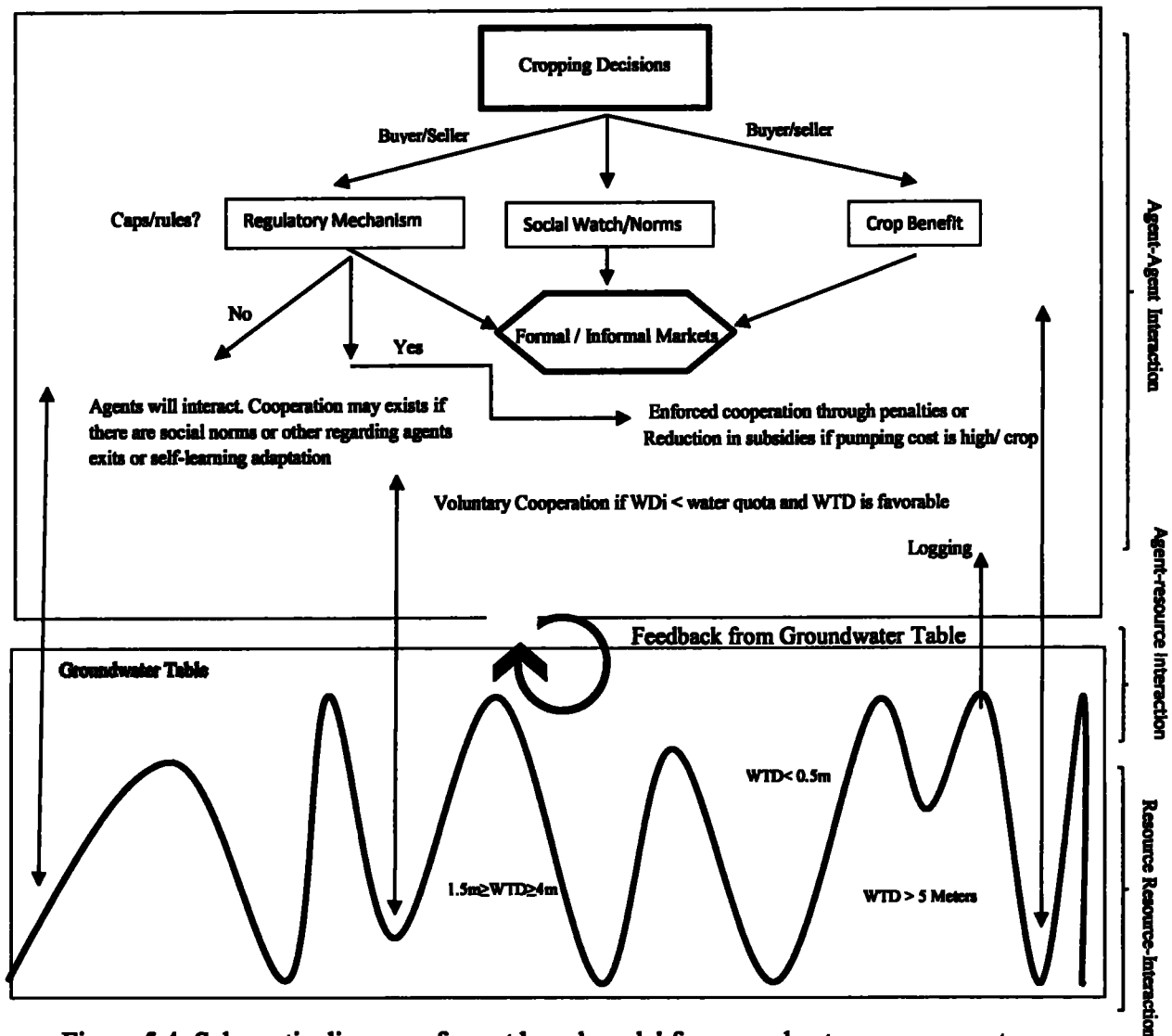


Figure 5.4: Schematic diagram of agent based model for groundwater management

Source: Author's own developed.

Depletion increases groundwater abstraction cost even more. Small farmers, tenants, or sharecroppers, if they buy from large firms, they usually fix a percentage of the crop as barter in exchange for the groundwater they use. If prices are pre-determined among buyers and sellers, then they are denied groundwater use if energy prices observe a fall.

In some areas where groundwater is the only source of irrigation and rainwater is plentiful, small farmers may face logging in some seasons and water shortage in other seasons, or they have to leave their land fallow and wait for the next season.

In Pakistan, no groundwater management framework exists. The unprecedented use of groundwater increases the direct and indirect cost of groundwater withdrawal. Indirect cost includes expensive groundwater and lower water quality and delayed availability in the case of the buyer as an indirect cost of groundwater abstraction. In this chapter, we used an agent-based model to capture these complexities.

5.10.2 State Entities, State Variables, and Scales

Large and small farmers are two types of agents that are buyers and sellers of groundwater. Regulator agent is considered as autonomous in the context of policies for quota or groundwater use rules or fees. Another entity is groundwater depth to table linked with the tubewells and will be updated along with the use of groundwater. Farmers are cooperative and non-cooperative in sharing water and dealing in informal and formal markets. They are cooperative if their water demand is timely fulfilled through tube well water, and energy cost is the same as it was at the time of agreement to share/sell water. But they may not appear cooperative if their demand is not fulfilled and regulators impose a limit on groundwater use or charge a flat fee. 95% of the farmers are small farmers and have land less than 5 ha. And are considered from the area where agriculture mostly is rain-fed or dependent on groundwater used in KP and

in some areas of Punjab with the land having more altitude than canals or some areas where canal water is not available, and precipitation is also limited.

5.10.3 Process Overview and Scheduling

Small farmers decide about cropping their land subject to the availability of groundwater, in Punjab usually three farmers buy water from tubewell owners, and in KP, it is Eight. If irrigation time is delayed or heavy cost is charged or if promised share of the "kind" is not offered to the tubewell owners, then they will not be able to earn potential benefits. Next cropping will be based on previous experience.

5.10.4 Groundwater and Depth to Groundwater

Farmers are set to have different water table depths and distances from surface water. Since water table depth for farmers is supposed between 2-100 feet. This water table depth is distributed among farmers on a spatial basis. Further, 25% of the farmers are supposed to have WTD between 2-30 feet, and the rest of the farmers have water table depths greater than 30 and less than 100 feet. Large farmers use uninterrupted groundwater until or unless quality is stated worsening off or regulation for a limit is imposed. With every tick, ten days of the cycle will be represented, and the model will be updated for wheat and rice/cotton cultivation for a period of 1 year.

5.10.5 Design Concept

Irrigation water demand for crops is calculated as the function of crop water requirement based on crop coefficient and cultivated area of the crop. Based on the behavioural definition of the social norm, the norm is emerged among farmers, as a result of rules, learning processes and adaptability and equation 3.19 to 3.26 can be considered in the context of groundwater for cooperating (C_{it}) and non-cooperating agents (NC_{it})

$$Norms = \sum_i \frac{NC_{it} - C_{it}}{N} \quad (5.1)$$

These norms can emerge in the range of [-1,1] and, in extreme cases, -1 and 1 for fully cooperative and non-cooperative agents. This can help in understanding the prevalence of social norms, regulations, or non-compliance with the rules as a policy to manage water resources. This model is based on the observation that people cooperate if they expect and/or observe others will cooperate too (Ostrom, 1998; Van Lange et al., 2013). We assume that an agent i has the expectation EC that agent i will follow the cooperative norm.

5.10.6 Theoretical and Empirical Background

Initially, artificial groundwater model incorporating social and physical behaviour is developed on the patches of land parcels owned by farmers by assessing changes in water table depth, logging, salinity, etc. Later on, it can be coupled with physical model of groundwater flow. This type of model is developed (Castilla-Rho et al., 2015) in NetLogo named as FlowLogo. It is a modeling environment, which conspicuously facilitates the development of coupled agent-based groundwater models. The FlowLogo modeling environment is capable of modeling different boundary conditions (no flow, fixed head, and constant flux) and a variety of sources and sinks (pumping and injection wells, springs, streams) and, accordingly, it can simulate transient and steady-state 2D groundwater flow in confined and unconfined aquifers (Castilla-Rho et al., 2015).

We assume that only farmers who irrigate have an impact on the dynamics of the coupled human and natural systems. We also assume that farmers solely grow wheat and cotton as these are the predominant crops in the area.

5.10.7 Individual Decision Making

The farmers decide on irrigation based on the previous records of water availability, and impositions of regulations. Buyers reduce their land if face deficiency in water availability or flip to least water-intensive. Large farmers decide about cooperating with the rules or respecting the norms and, together with small farmers, determine system properties. The purpose of farmers is to maximize benefits or avoid losses.

5.10.8 Learning

Individuals will learn from their past behaviour and behaviour of their neighbours. They also consider learning from fittest farmers based on crop yield and cooperation level of farmers.

5.10.9 Sensing

Large farmers will sense water quality if it is excessively drawn from lower depth to the water table and try to act accordingly.

5.10.10 Individual Prediction

Explicit prediction is not modelled, but implicitly prediction regarding farmers' behaviour is used as a tool to bring social norms into practice for the emerging pattern.

5.10.11 Interactions

Farmers interact with each other directly through water markets and indirectly through impacting groundwater quality and quantity.

5.10.12 Collectives

Collectives/ groups or social networks are not formed during simulations.

5.10.13 Heterogeneity

Heterogeneous farmers, depth to water table, crops, different water cost structures are part of the model.

5.10.14 Stochasticity

Initially, stochasticity regarding WTD and change in climatic condition are considered.

5.10.15 Observation

Water requirement is considered if rainwater is not fulfilling the demand while making decisions regarding buying and selling groundwater, water table, irrigations costs, market or non-market exchanges, crop yield, benefits/profit, cooperative agents are the data observations in the model. Results show variability in depth to water table and water costs and profits due to spatial and temporal patterns.

5.10.16 Implementation Details

The model is implemented in NetLogo 6.0. Depth to water table and groundwater transport model is imitated through FlowLogo, a groundwater flow simulation model. The model will be available upon request.

5.10.17 Initialization and Input of the Data

Initially, farmers are created with spatial variation among them, which makes them have a difference in water requirement, DWT, etc. Water table depth will be linked with FlowLogo model, and it changes accordingly. The values of the variables are assigned to the farmers as per the model requirement. An example of selling water is given below

5.10.18 Submodel

There are no sub-models available in the model.

```
to sell-buy-accesswater-r
set potential-buyers other rfarmers in-radius 3 with [(excess-water <= 0)]
ask potential-buyers [set input-cost input-cost + 0.0005 * (excess-water) /
WT set ryield ryield - .005 ]
set income-2 0.5 * (excess-water)
end
```

5.10.19: Model's implementation and Hypothesis

Model is implemented to test the hypothesis for groundwater management and potential cost or pricing of groundwater considering the dynamics of water table depth and water use behaviour under different water use management perspectives.

5.10.20 Validation of the Model

It is important to understand the results obtained from the model are reliable or not. We have estimated all unknown parameters through running the experiments in NetLogo Behavior space. Usually, there are two approaches used for validation of the model, i.e., assessing through structural and outcome validations. Structural refers to compare consistency between model structure and expert opinion from literature, and outcome validation requires model results with empirics from literature (Du et al., 2017; Gonzales & Ajami, 2019). From validation of the model, we have formed certain rules which are verified from historical data and outcomes of irrigation practices in literature. Groundwater table depth, logging, salinity, and farmers' profits are found to have realistic values.

5.11 Results and Discussions

Hypothesis: Assessment of groundwater regulatory framework:

Alternative surface and groundwater use practices over space and time improves groundwater regulation problems

Groundwater is the mainstay of irrigation under continuous depleted surface water resources. Our model presents some macro-scale phenomena of groundwater use that emerged from micro-behaviours of individuals.

Figure 5.5 depicts that increasing groundwater cost is equally feasible under water table depth of 5 meters. For SGR it is more viable to increase groundwater extraction cost to 800 per irrigation per acre. As water table depth increases from 5 to 10 IMP appears to bring better results comparing it with BAU and SGR.

In presence of water table depth of 10, under different water costs, IMP of water management perspective proves more effective as profits, logging and salinity show desirable pattern. At extreme high water table depth all of the water management perspective become impotent. Profits and logging are found 1sd below the mean while salinity is found 1sd above the mean. Only logging parameter is found in required limit which is a result of high water table depth. For WTD of 5 under low cost BAU is performing better while under high cost SGR is performing better than scenarios.

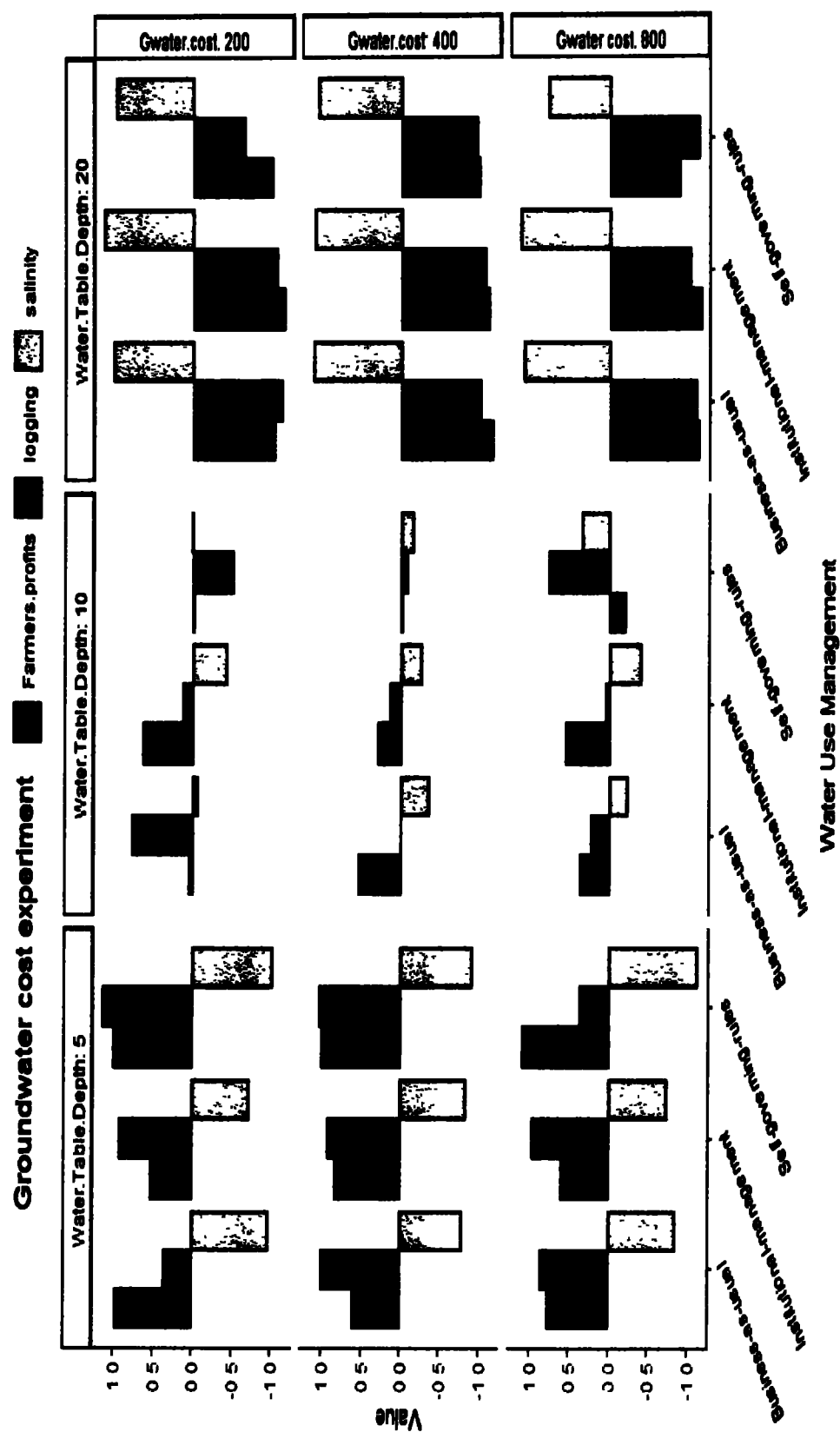


Figure 5.5: Groundwater cost experiment for varying water table depth and abstraction cost.

Source: Author's own work

Under the highest water table depth of 20 profits are found to be 1SD below from mean and salinity as 1SD above from mean. SGR exhibits 3% more profits than BAU and IMP when groundwater abstraction cost is raised to 800. This shows that extreme water table depth situation brings undesirable results for every variation in groundwater cost.

The lower part of figure 5.6 shows that over time salinity reduces to rain influxes. It reduces more in SGR comparing it with BAU and IMP.

Besides groundwater withdrawals, salinity is majorly affected by rainfalls. Maximum salinity is 21, 17, and 20 in BAU, IMP and SGR. However, the average total salinity is found to be highest in BAU followed by IMP and SGR. Comparing salinity over increased groundwater withdrawal cost, it shows that salinity has reduced to a maximum of 18% in SGR at a water table depth of 20 and 13% in IMP. However, comparing salinity from within the management perspective doesn't show any improvement even if water table depth is increasing. But if withdrawal cost is raised it shows improvement at the same level of water table depth. This can reflect the limited true value of depleting groundwater resource as in our model we have not put a limit on groundwater availability rather withdrawal cost is linked with groundwater use.

The upper part of figure 5.6 shows profits. It is observed that managed water use behaviour yield more profits comparing with the BAU scenario. SGR and IMP are exhibiting 6% and 2.7% more average profits than BAU.

Groundwater Cost Variation

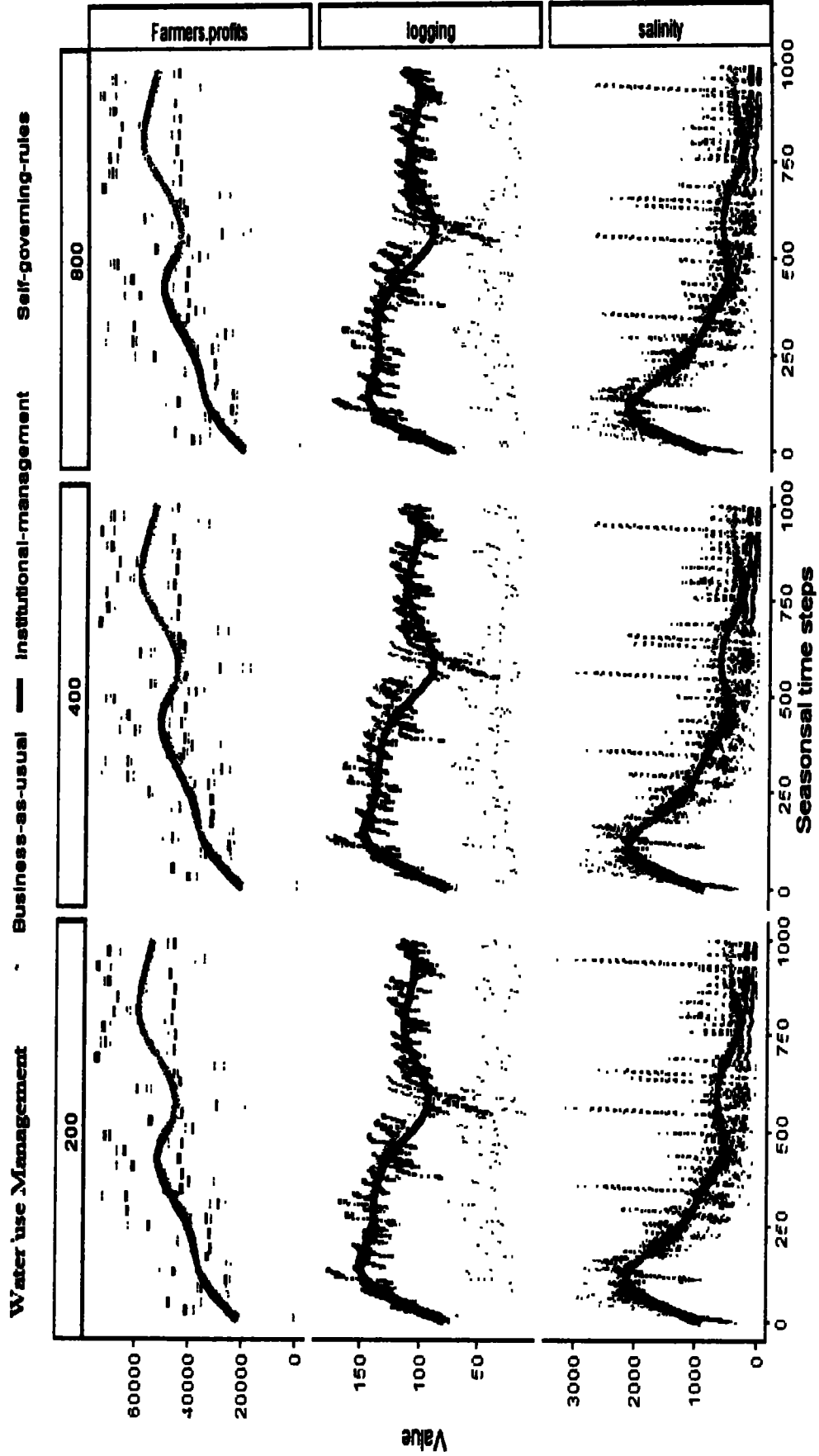


Figure 5.6: Profits, logging, and salinity under groundwater cost variations.
Source: Author's own work

Difference reduces with increased abstraction cost and water table depth scenarios. In BAU increasing water table depth is reducing logging as farmers will be inclined to use less groundwater and utilizing more efficiently their allocated surface water. However, within IMP if groundwater cost is as minimum as 200 then farmers are found irresponsibly using groundwater their logging is even high with high water table depth. Moreover, logging is found to be 8% and 68% less in IMP and SGR if we compare them with BAU. Differences become more visible when the cost rate is high.

Figure 5.7 shows density plots of logging and salinity. Part A shows that tails are thicker under more cost and relatively less water table depth in BAU and IMP. The peak of logging appears early as water table depth rises along with the same high water withdrawal cost. In the case of salinity tails of the density plots are found to be thick and rightly skewed when water table depth is low and it becomes equal for all scenarios under large fall in water table depth.

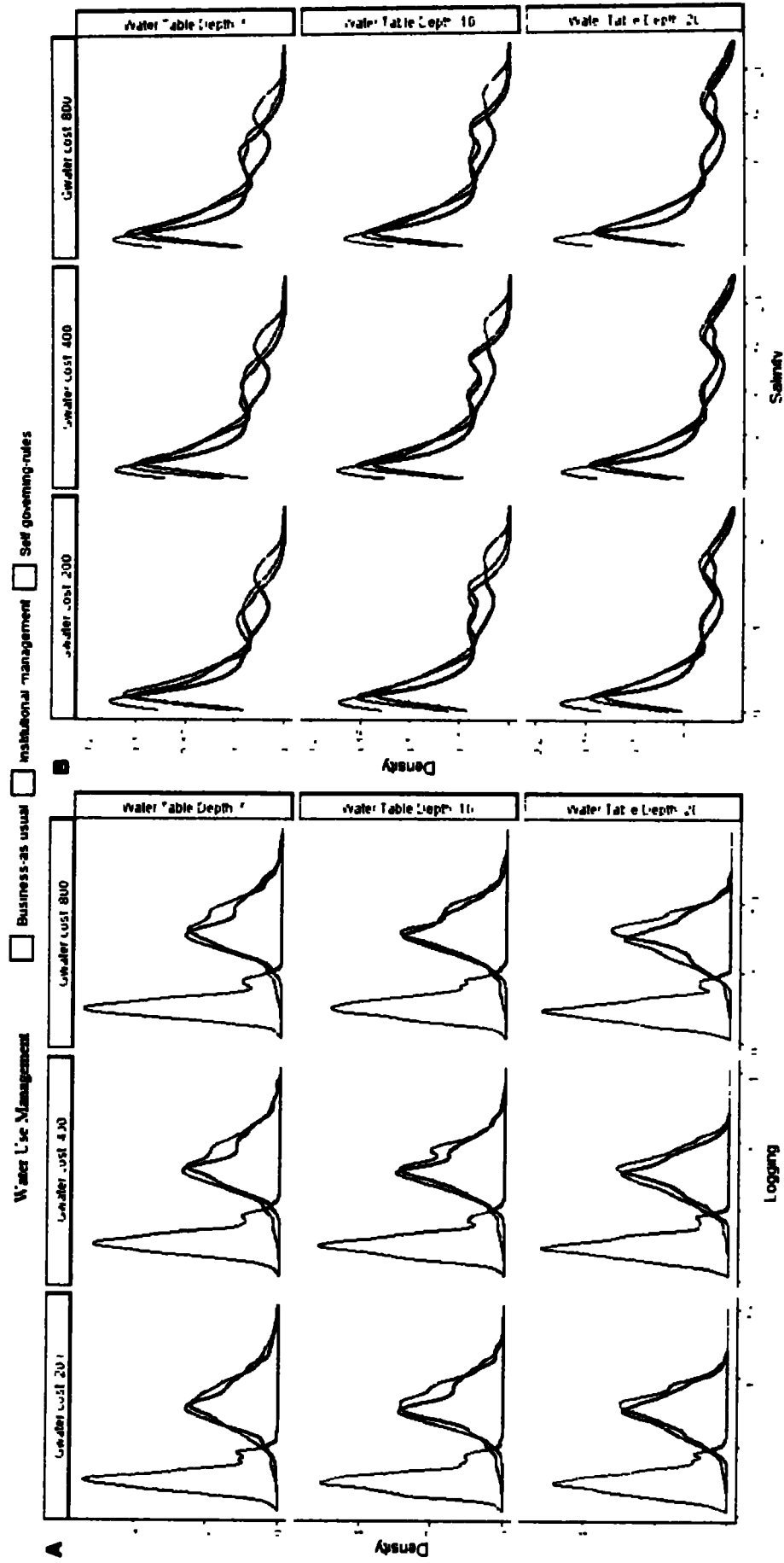


Figure 5.7: Density Plots of logging and salinity in groundwater cost experiment

Source: Author's own work

Figure 5.8 shows the cost limit of groundwater abstraction. It is linked with the changes in WTD. As WTD rises it raises groundwater abstraction costs. This can be observed that groundwater extraction cost can be raised to limit the groundwater use.

It can be observed from the figure that under WTD of 5 with groundwater cost per unit as 200, emerged as 360 rupees for BAU 320 for SGR and 317 fro IMP. However, with the higher WTD of 20 and initial withdrawal cost of 200 groundwater withdrawal cost emerged as 320 depicted in the figure. Moreover, with the initial cost of 800 and WTD of 5, withdrawal cost sharply rose up to 1280. In the extreme cases of 20 WTD and water withdrawal cost of 800 per unit an exponential increment can be observed in case SGR.

The cost initially rises sharply from 800 to 1100 and then increased with declining rate raised maximum up to 1280 per unit. As water table depth rises use of surface water falls in IMP and SGR. In most of the instances, IMP and SGR are utilizing more groundwater and less surface water for the farmers which are located near canals heads.

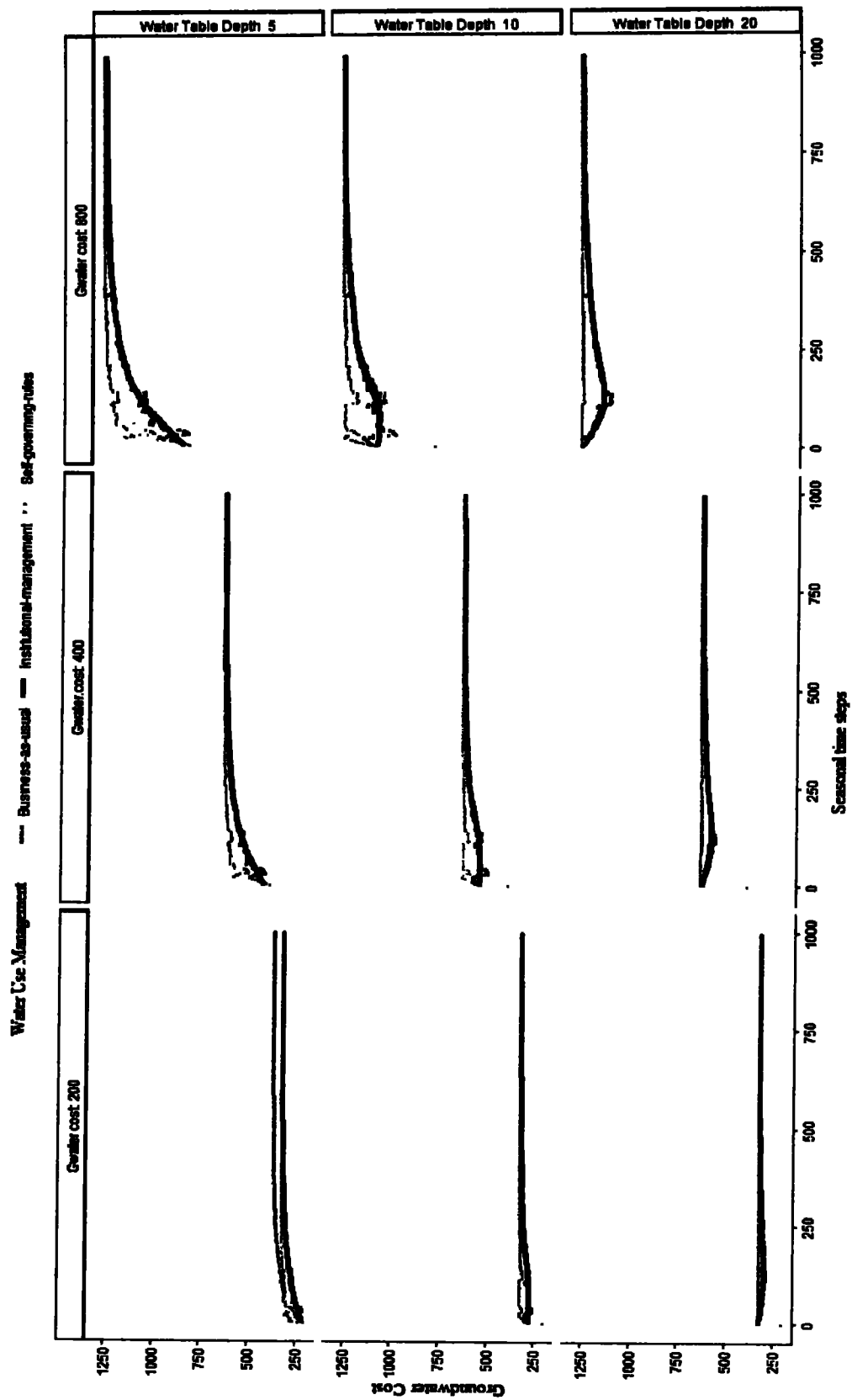


Figure 5.8: Estimated groundwater cost under varying water table depth scenarios.

Table 5.2: Groundwater and Surface water use under different Groundwater cost scenarios

Comparison average surface and groundwater use									
Average groundwater use/ha					Average surface water use/ha				
Business as Usual					Business as Usual				
Cost	WTD	5	10	20	Cost	WTD	5	10	20
200		211.2	211.0	211.0	200		361.3	362.3	362.3
400		211.1	210.8	211.2	400		362.3	362.5	362.2
800		211.2	210.9	211.2	800		362.1	362.4	362.1
Institutional Management Perspective					Institutional Management Perspective				
200		↑17.1	↑1.15	↑1.43	200		↓9.8	↓0.67	↓0.83
400		↓1.32	↑1.16	↑1.11	400		↓0.7	↓0.85	↓0.64
800		↑1.19	↑1.43	↑1.42	800		↓0.7	↓0.82	↓0.82
Self-Governing Rules					Self-Governing Rules				
200		↑33.2	↑33.4	↑33.2	200		↓19.2	↓10.5	↓19.4
400		↑33.1	↑33.2	↑33.4	400		↓19.2	↓19.3	↓19.5
800		↑33.2	↑32.9	↑33.8	800		↓19.4	↓19.11	↓19.7

Source: Author's own work

Data shows that farmers near the canal in BAU and IMP are using on average 70% to 60% more surface water than groundwater and incur less irrigation water cost in the production process. While in SGR surface water use is only 8% to 10% than groundwater. Since more groundwater makes farmers bear more water costs and if they are near canals they can be compensated with the part of the cost of groundwater they pay in addition for compliance with the social norms of using less surface water when they are near the canal. For the farmers using 70% more surface water as observed in the case of BAU, they must be charged equivalent to the groundwater cost for surface water use as of 280 rupees per cubic meter. While farmers with 60% more surface water can be imposed to pay 252 per cubic meter of water used for irrigation.

Table 5.3: Comparing Groundwater costs and Profits under different water table depth scenarios

Comparison average profits and groundwater use cost									
Groundwater use cost					Average profits /ha				
Business as Usual (BAU)					Business as Usual (BAU)				
Cost \ WTD	5	10	20		Cost \ WTD	5	10	20	
200	350.3	305.8	309.9		200	46923	45975	44879	
400	603.3	611.7	619.6		400	46145	46098	44766	
800	1210.1	1222.5	1240.7		800	46175	45859	44646	
Institutional Management Perspective (IMP)					Institutional Management Perspective (IMP)				
200	↓13.789	↑0.263	↑0.345		200	↑0.858	↑3.242	↑2.577	
400	↑0.544	↑0.374	↑0.443		400	↑3.710	↑2.665	↑2.657	
800	↑0.078	↑0.431	↑0.211		800	↑2.253	↑2.838	↑1.685	
Self-Governing Rules (SGR)					Self-Governing Rules (SGR)				
200	↓10.17	↑3.943	↑2.950		200	↑3.409	↑4.364	↑5.753	
400	↑4.095	↑3.879	↑3.151		400	↑4.947	↑3.800	↑5.673	
800	↑4.030	↑3.771	↑2.995		800	↑4.093	↑3.355	↑5.390	

Source: Author's own work

Table 5.3 shows that farmers in IMP and SGR are making 1% to 5% more profits than BAU with WTD 20 to 5 respectively. However, groundwater use cost is 0.5% to 14% more than the BAU case. However, with the lowest WTD and cost groundwater withdrawal cost is more in management scenarios comparing it with the BAU scenario. Figure 5.9 presents ground and surface water use by farmers across time. Farmers are found using more groundwater across time in SGR comparing it with BAU and SGR. And BAU scenario reflects thickened right-skewed tails across time in BAU followed by IMP in surface water use comparing with SGR.

Results show that farmers get benefits from extensive groundwater use but unregulated and unplanned exploitation is endangering sustainable irrigation and caused increased extraction costs due to falling water table (Shakoor et al., 2015).

Depleting the water table results in degrading groundwater quality and intensifying the soil salinity problems (Qureshi, 2020).

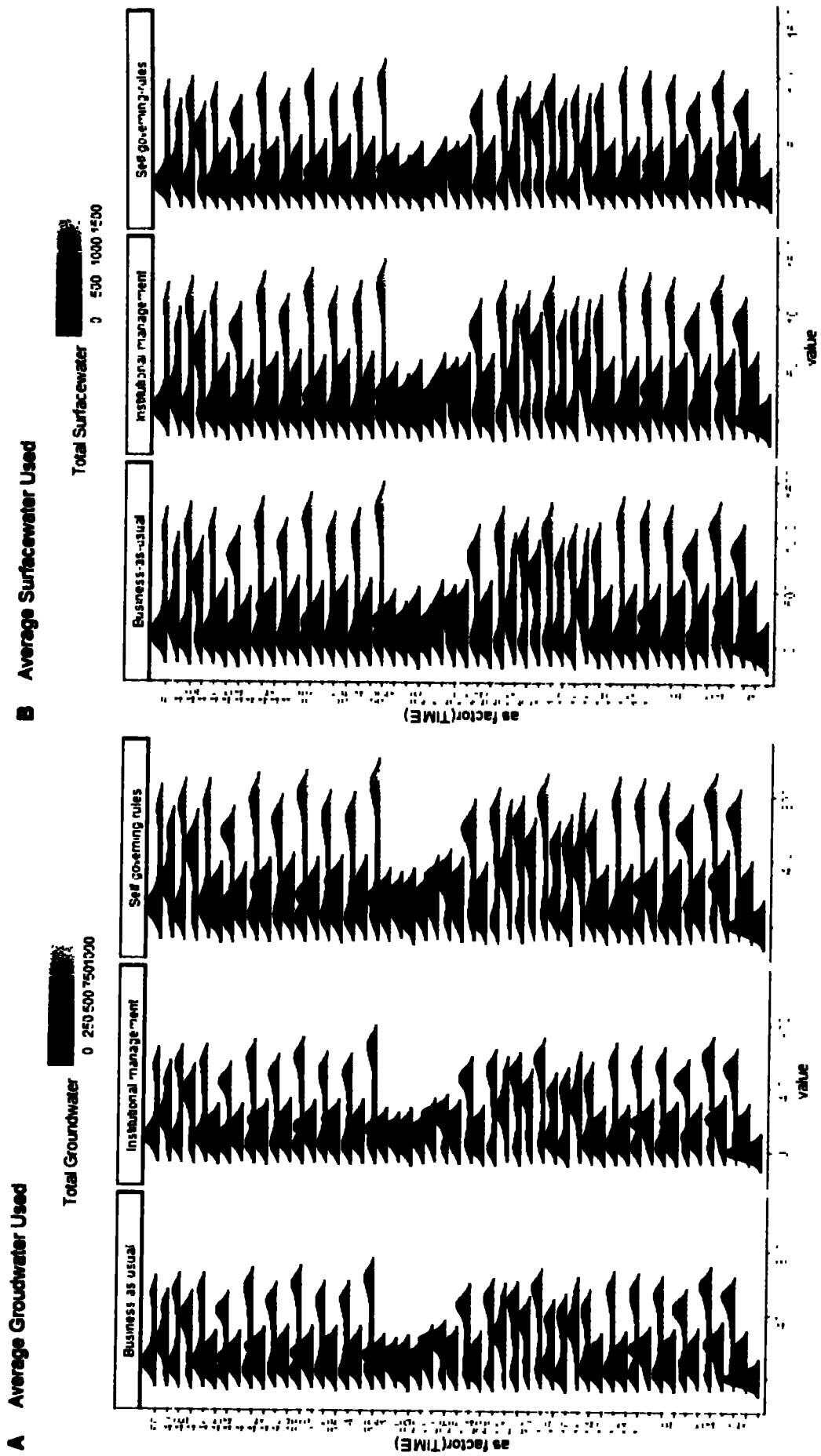


Figure 5.9: Comparison of groundwater and surface water management scenarios under varying groundwater costs.

Source: Author's own work

In the model, seasonal rainfalls and crop water requirement were taken based on estimation by Sadaf & Zaman(2013) Overtime,spatially distributed farmers' caricaturized scenarios were built to include groundwater depth fluctuations for better management of water resources. SGR and IMP try to bring equity in water availability and to prevent agriculture from worsening water quality parameters which bring a rise in overall benefits in the system. However, consistent sustainability may break down in extreme cases of climate change and spatio-physical conditions. We have observed that in extreme depleted water table depth, irrigation water becomes economically inaccessible and has repercussions on agriculture produce and sustainability of irrigation. Climatic, physical, economic conditions along with farmers' water use behaviour are major determining factors for water use management and sustainable farm income for individual farmers and agriculture collectively (Tamburino et al., 2020).

5.12 Conclusion

We have integrated ABM of farmers' decision-making for irrigation with the groundwater cost variations to study the importance of individuals in an agricultural and hydrologic system. Model results show that accounting for individual heterogeneity has impacted at the system and leads to the formation of emergent patterns, while also bring up some groundwater cost or prices related information. Results show that monitoring and regulations make farmers use groundwater rationally. SGR managed to raise groundwater abstraction price 3 times more than the existing rates for the farmers located nears canals heads. For the farmers located at tails IMP appears to manage resource better than other scenarios. But increasing groundwater abstraction cost can appear detrimental for farmers produce and profits at tail ends.

Comparing salinity over increased groundwater withdrawal cost shows that salinity has reduced to a maximum of 18% in SGR at a water table depth of 20 and 13% in IMP. However, comparing salinity from within the management perspective doesn't show any improvement even if water table depth is increasing. But if withdrawal cost is raised it shows improvement at the same level of water table depth. This can reflect the limited true value of depleting groundwater resource as in our model we have not put a limit on groundwater availability rather withdrawal cost is linked with groundwater use. Same is the case of profits. SGR surpasses in bringing more profits comparing with IMP and BAU. Reduced groundwater costs are devising irresponsible behaviour in groundwater use under BAU. Furthermore, salinity is found to be lowest, in less water table depth under all costs scenarios, while increasing water table depth is causing salinity to rise while increasing cost is further exacerbating the problem. Under increasing water table depth none of the water management perspective improves salinity situations. Furthermore, groundwater extraction cost is found to be higher with higher water table depth scenarios. This can be learned that groundwater extraction cost can be raised to limit the groundwater use. But the rise in cost can itself emerged to the relatively lower level if water table depth is higher. It means that rising costs or prices of groundwater when water table depth is lower appears more effective. In other words, regulations of ground water abstraction cost near canals can bring relatively better results. All variations in costs and water table shows emergence in groundwater costs in long-run but at low level of extraction cost less water table depth BAU can effectively raise groundwater costs comparing it with IMP and SGR. This means that near canals heads groundwater cost can be raised even under BAU without more deliberate policy change.

Under IMP and SGR farmers are using relatively less surface water and more of groundwater if they are nearer to the canals. More groundwater makes farmers bear more water costs and if they are near canals, they can be compensated with the part of the cost of groundwater they pay in addition for compliance with the social norms of using less surface water when they are near the canal. Use of surface water can be restricted if farmers are charged progressively equivalent to the groundwater cost for surface water use. Moreover, Farmers are found using more groundwater across time in SGR comparing it with BAU and SGR. BAU scenario reflects thickened right-skewed tails across time in BAU followed by IMP in surface water use comparing with SGR.

Manging farmer's behaviour under socio-economic and climatic conditions can bring life to lost agricultural potential in the country. However, getting benefits of farmers' cooperation in areas where strong norms and societal pressure prevails is a complex and challenging task. This policy of restricting groundwater use can increase the potential benefits of farmers and require a cost of monitoring from the exchequer.

From a policy standpoint, the Government needs to have a better understanding of famer's behaviours of groundwater abstraction under different costs regimes if it is to improve access to the groundwater resource. This requires in-depth knowledge about the farmer's water use behaviour in response to penalties and subsidies for different groundwater use perspectives and resultant benefits of growing crops. In the context of ever-increasing reliance on groundwater use in Pakistan in the last two decades, with its consequences (increased energy demand for water extraction and application, and reduced soil health through increased salinity), this study identifies the formation of rules for the use of groundwater as entry points for policies aimed at addressing the groundwater management problem.

CHAPTER 6. Conjunctive Water Management

6.1 Importance of Conjunctive Water Management

The agricultural sector in Pakistan remained dominant for the provision of employment to 42.3% of the labour force in the country (GoP, 2015-16) This contribution of the agriculture sector is contingent largely on favourable water supplies. Surface water availability in the country has reduced by 46% in the last two decades. There has been found a 10 million acre-feet reduction in the Rabi canal water supply from 2001-2018. Figure 6.1 presents ground and surface water availability at farm gate during the last two decades.

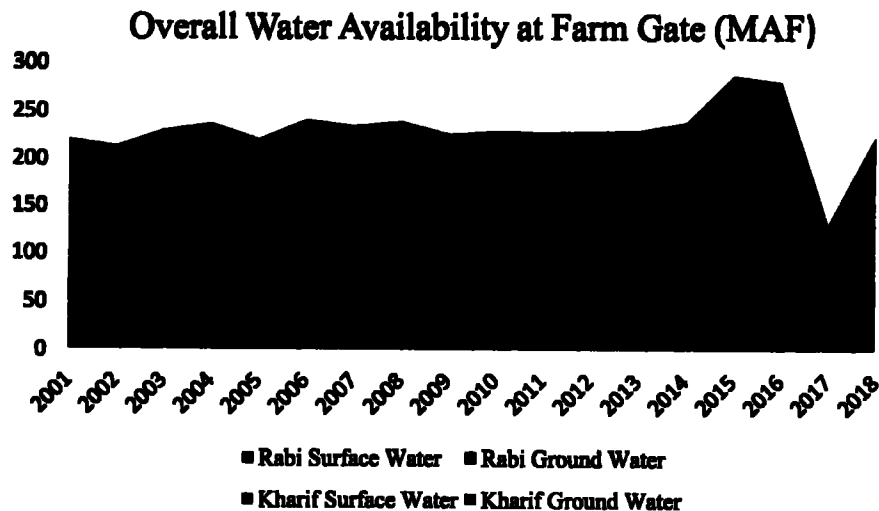


Figure 6.1: Surface and groundwater availability at farm gate (MAF).

¹³Source: Agricultural Statistical Yearbook (2017).

Farmers at the tail end suffer more as they are not only deprived of the canal water but they are also pumping groundwater of low quality more proportionally as compared with the head-end farmers. They are unable to fulfill leaching requirements,

¹³ Government of Pakistan. Agricultural Statistical Yearbook. Pakistan Bureau of Statistics. 2017

lead to increase the soil salinity levels as compared with the upstream farmers. More than 1.4 million hectares of agriculture land are abandoned due to salinity in the country and the majority of this land is found in tail areas (Martin et al., 2006). A limited supply of canal water makes farmers depend more on the groundwater. As surface water is a limited resource, therefore, the Government is trying to complement the surface water with groundwater by installing public tube wells. It resulted in up to 170% increase in cropping intensities in Pakistan (Ahmad et al., 2007). This issue is further exacerbated when crops have different spatial and temporal water requirements. Water requirement of the wheat crop is 20% less in Punjab than that in Sindh. Moreover, within the same province, different crops have different water requirements as well. The average crop water requirement is given in Figure 6.2. Shortages of surface water have intensively affected the growth of water-intensive crops, especially in water shortage areas. This situation compelled farmers to develop alternative plans of switching to low water-intensive crops and dry crops, as well as for the development of shallow and deep tube wells.

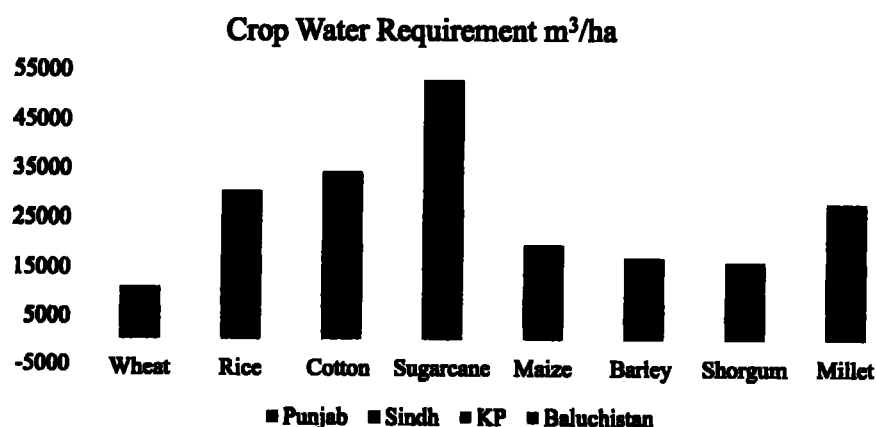


Figure 6.2: Province wise average crop water requirement.

¹Source: (Sadaf & Zaman, 2013)

6.2 Rationalizing Conjunctive Water Management

Food demand and cropping intensity have made excessive groundwater supplement the surface water (Qureshi et al., 2008). In Pakistan, agriculture is becoming heavily dependent on groundwater. Statistics show a 140% increase in private tubwells per 1000 hectares for irrigation over the period of 20 years (Agricultural Statistics Year Book, 2017-18). In contrast to Sindh, groundwater use in Punjab is more prevalent as compared with the surface water. The total irrigated area in Punjab is 14.53 million hectares, out of which 3.62 million hectares are irrigated by canals only, whereas 2.95 million hectares of area is irrigated exclusively by tube wells.

Conjunctive ground and surface water are used in 54% of the irrigated area in Provinces and the remaining area is irrigated through other sources (Ahmad et al., 2007). In some areas, groundwater depth has increased to 16m in Sindh and more than 18m in Punjab. Depth to the water table in some areas of UIB is rising more than 18m; limiting crop yield of the farmers at the tail ends specifically in LBDC. Figure 6.3 exhibits the situation in Pakistan. Some areas are severely affected by heavy groundwater pumping increasing irrigation costs for the farmers heavily dependent on groundwater. Initially, groundwater was in dynamic equilibrium before the inception of the irrigation system.

Water table rise in the area is less than the water table fall. The water table rose on average by 23.5 meters per year and fell on average by 31.4 meters over the period from 1910 to 2010. Figure 6.4 shows the observed fall and rise in canal command areas of the LBDC. The highest fall in water table depth is observed in Mianchunnu canal command areas (Basharat, 2015). Groundwater use in Sindh province is 4% to 8% of the surface water as compared with the canal command areas of Punjab where the ratio of ground and surface water use is almost the same.

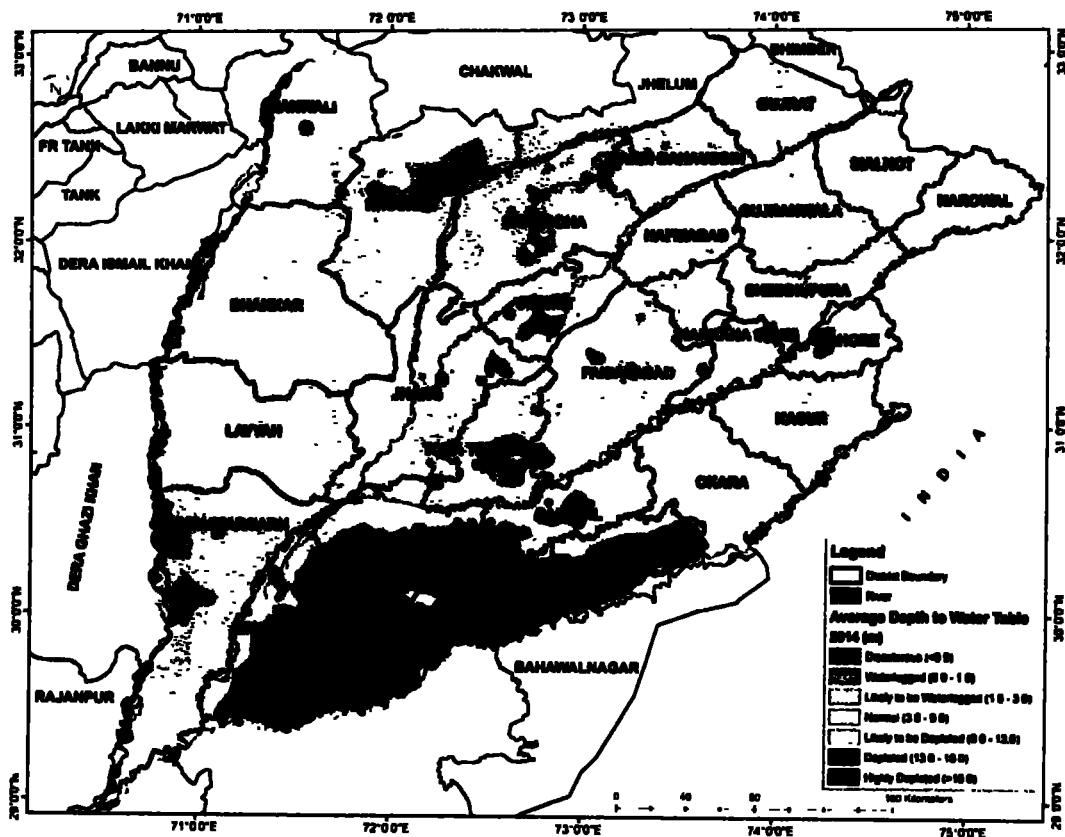


Figure 6.3: Average depth to water table variations in 2014 across Upper Indus Plain Aquifer (Punjab Irrigation Department)

¹⁴Source: Khan et al., (2016)

Groundwater is an underutilized resource in surface irrigated areas of Sindh due to high surface water allocations. The issue of waterlogging is widespread in areas of Sindh due to which water productivity is low as compared with Punjab. Due to sedimentation, the storage capacity of the built reservoirs is decreasing and causing a shortage of surface water over time. And 37% of the water is lost due to insufficient storage capacities in the reservoirs. Moreover, due to flexibility in the nature of groundwater, there has been found an increasing tendency between farmers to extract groundwater, and a more than 3000% increase in tube well installation has been observed since the 1960s (Watto & Mugeru, 2015). However, inefficient irrigation

¹⁴ Khan, A. D., Iqbal, N., Ashraf, M., & Sheikh, A. A. (2016). *Groundwater Investigations and mapping in the upper Indus plain*. Pakistan Council of Research in Water Resources (PCRWR).

practices, poor drainage facilities, and canal conveyance losses caused the problem of salinity and waterlogging (Khan et al., 2008; Qureshi et al., 2010). In recent years, irrigation reliance on groundwater has increased even up to 70% in some areas of the country. Reliable water supplies, higher expected profits, and uncertainties in output are found as main drivers for pursuing reliable irrigation water supplies (Watto & Muger, 2014).

The massive use of groundwater has created the issue of salinity in large tracts of the Indus basin. And many other areas are further under threat of the issue. Farmers are conjunctively using both surface and groundwater. But current strategies are making groundwater unsustainable and exacerbating the issue of secondary salinization (Usman et al., 2016a). Excessive use of groundwater usually happens due to the seasonal or rotational availability of surface water. Fixed rotation irrigation system needed to be corrected as per the water requirement of the crop (Qureshi et al., 2010).

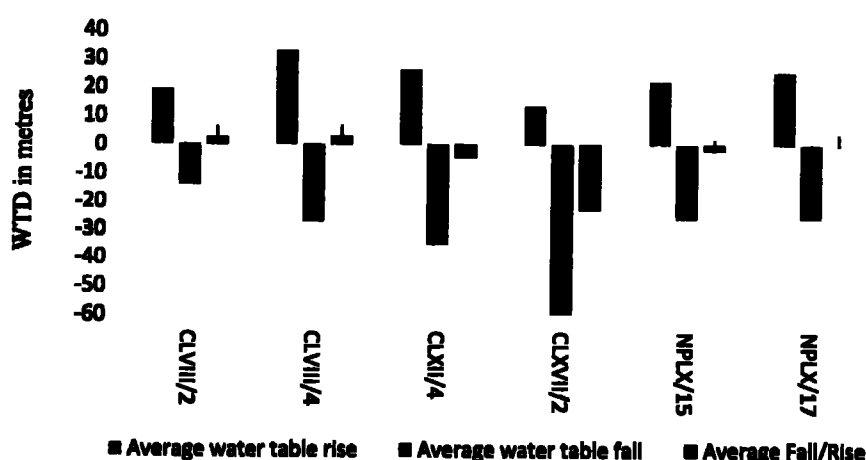


Figure 6.4 Average groundwater level rise/ fall in LBDC command areas from 1910 to 2010

Source: Author's own extraction.

In recent years, irrigation reliance on groundwater has increased to 70%. Greater economic returns from groundwater irrigation impelled farmers to rely on water-

intensive crops. Higher expected profits and uncertainties in output are found as the main drivers for pursuing reliable irrigation supplies (Watto & Mugera, 2014). It has been found that groundwater abstraction in Punjab is far more than its recharge. A mechanism for parallel extraction of groundwater from tail to end can help to reduce the issue of salinity and uneven extraction of the resource (Shafeeque et al., 2016).

6.3 Spatial Management of Conjunctive Water

New regulations can be enacted to avoid this issue to penetrate. Upstream farmers must be encouraged to use groundwater wisely to provide more canal water to tail-enders to avoid losses in agricultural production (Usman et al., 2016a). Moreover, area-specific policies for conjunctive ground and surface water use under the physical characteristics of the resource subject to socio-economic conditions of farmers is an urgent need of the hour (Murray-Rust & Vander Velde, 1994). To increase water productivity to fulfill growing population needs, area-specific conjunctive management of the resource must be given due importance (van Steenberg et al., 2015). To deal with seasonal variations in water availability, conjunctive use of ground and surface water is advocated by water experts. For this purpose, conjunctive water management is considered as one of the most important responses to deal with the issues of equity, efficiency, food security, and sustainable water resource management under climate change adaptation (Sahuquillo, 2009). Technical design of natural resource system requires understanding of interconnectivity of both surface water and water in the aquifer. (Foster & van Steenberg, 2011) argue that spontaneous conjunctive use often exacerbates falling groundwater tables in certain parts of the irrigation system, while excessive surface water irrigation continues to cause water-logging problems in other parts. Therefore, they advocate a more coordinated use of surface water and groundwater within irrigation systems. In principle, conjunctive water management can

be understood as an integrated approach to surface water and groundwater management. Moreover, conjunctive water management differs in different areas depending on the hydro-geological and socio-economic conditions. There are differences and between irrigated areas of Sindh and Punjab and require to formulate a spate policy for the regulation and management of irrigation water resource systems. And conjunctive water management can provide solutions for salinity control, logging, long-term water security, and sustainable agriculture (Foster & van Steenberg, 2011).

6.4 Pricing the Irrigation Water

In Pakistan, groundwater is considered as a supplement resource where surface water is available in abundance to smoothly deal with the uncertain nature of surface water (Tsur & Graham-Tomasi, 1991). To address the scarcity of the resource, it is important that prices of surface water must be justifiable over space and time (Chakravorty & Umetsu, 2003; Knapp & Olson, 1995; Noel & Howitt, 1982), This idea is illustrated through a basic understanding of the demand and supply of irrigation water (Ravago, 2019; Roumasset, 2007) that surface water is supplied from a canal headworks and that farms are located along the canal. Farmers can irrigate crops using diverted canal water or by pumping groundwater on their farms. Canal conveyance losses are increasing with distance from the headworks, although a fraction of the loss percolates to the groundwater aquifer. The marginal cost of groundwater extraction is decreasing in the head level, and precipitation contributes to aquifer recharge. Now, the purpose is to understand groundwater withdrawal and surface water travel costs. Surface water availability decreases along with the distance from the water source hence decrease surface water efficiency. Scarcity value of surface water increases with the increase in distance and determine the critical point where the farmer can start using surface or groundwater. Overtime solution requires changes in the allocation of the common

resources. Either farmers at heads are required to use groundwater more or surface water more to assess the best possible solution. Usually, to determine the price of a resource, marginal cost should be equal to the marginal benefit, but in the case of surface water, even operation and management costs in Pakistan are not realized in their full potential. For surface water; water costs along with the conveyance cost of water must be included while making policies and offering subsidies in surface and groundwater use. Location-wise marginal costs and benefits of the farmers need to be assessed and charged for surface and groundwater. The difference in the price can be determined through the price near the canal head and the farmer's location. A case of two farmers is presented here (Roumasset, 2001; Roumasset & Smith, 2011) having

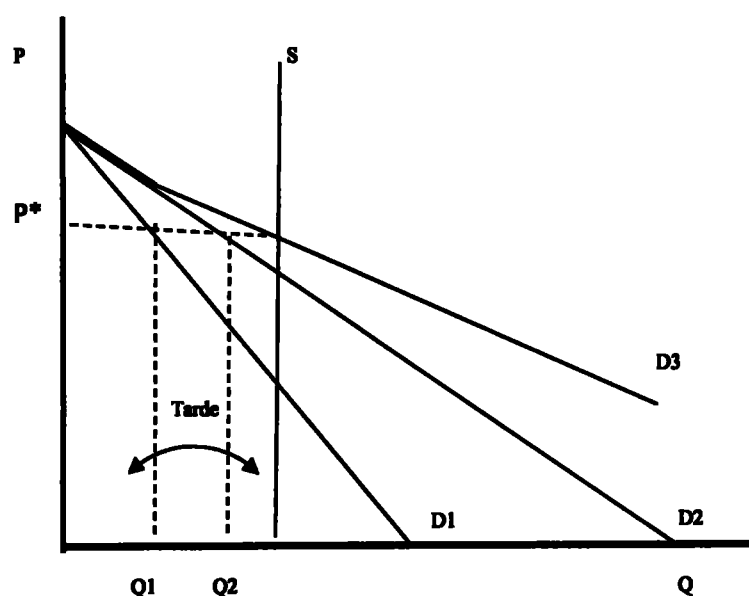


Figure 6.5: Groundwater pricing over time.

¹⁵Source: (Roumasset, 2001)

different demands as D1 and D2 and DD is a combined demand for the farmers in the system and S is the supply of surface water which is considered fixed at a specific point in time. Here P^* is the price for the water Q_1 and Q_2 for respective farmers. A

¹⁵ Roumasset, J., & Smith, R. (2001). Inter-District Water Allocation with Conjunctive Use. *Journal of Contemporary Water Research and Education*, 118(1), 9.

farmer near the head is charged the same price for fewer water quantity as compared distant farmer 2.

Water pricing and trading under a decentralized system can help to achieve these prices. Regulators can implement block prices for different farmers at different prices to practice equity. Prices may be charged for water required more than necessity and water costs of farmers will increase with the increase in water consumption. Prices can be different as per conveyance losses. Farmers can also trade with each other or exchange their turn if they can delay their consumption for better availability of water. Groundwater prices determination must take into account two types of costs; one cost is withdrawal and the other is resource depletion cost. It will increase along with the increase in groundwater use. Further water costs may arise indirectly in the form of reduced benefits of using low-quality groundwater. Farmers may suffer if groundwater use is not rationalized.

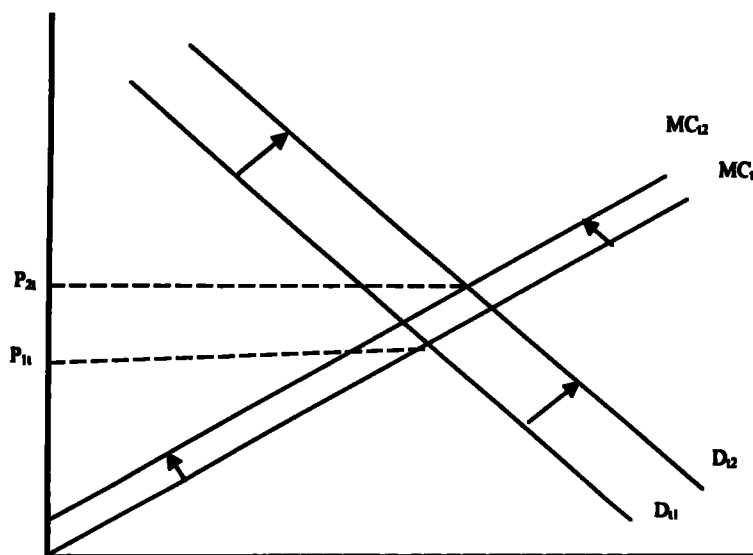


Figure 6.6: Conjunctive use assessment without conveyance losses.

Source: (Roumasset, 2001)

In Figure 6.6, $D1t$ and $D2t$ are the demand for groundwater of a farmer and $MCt1$ and $MCt2$ are the marginal costs of extracting water. The marginal costs must include water

depletion costs.

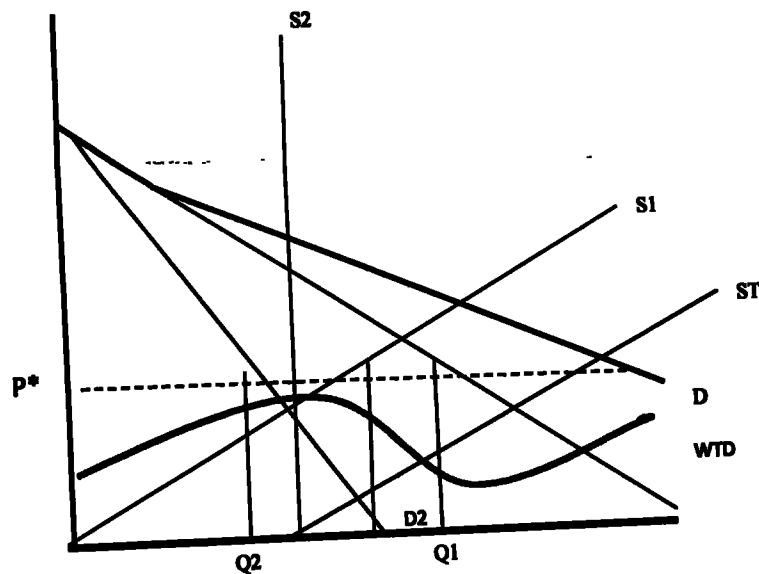


Figure 6.7: Conjunctive use assessment without conveyance losses.

¹⁶Source: (Roumasset, 2001)

These costs can vary, if the farmer is a tubewell owner or buyer or if it is drawing water from public wells. The conjunctive use of ground and surface water in the context of availability of either of the resource can be examined in Figure 6.7. Figure 6.7 represents the spatial demand and supply of ground and surface water. Marginal cost or water supply curves are represented by $S1$ and $S2$ curves, ST is the total supply curve combining ground and surface water. P^* is the equilibrium, efficiency price, or market price. Farmer 2 carrying demand $Q2$ can be filled through surface water supply only and excessive water $S2-Q2$ can be transferred to farmer 1 carrying deficit demand of $Q1-S1$. Moreover, farmer 2 can use cheap groundwater, if there are vagaries in surface water availability but this may cause logging if excessive surface water is not

¹⁶ Roumasset, J., & Smith, R. (2001). Inter-District Water Allocation with Conjunctive Use. *Journal of Contemporary Water Research and Education*, 118(1), 9.

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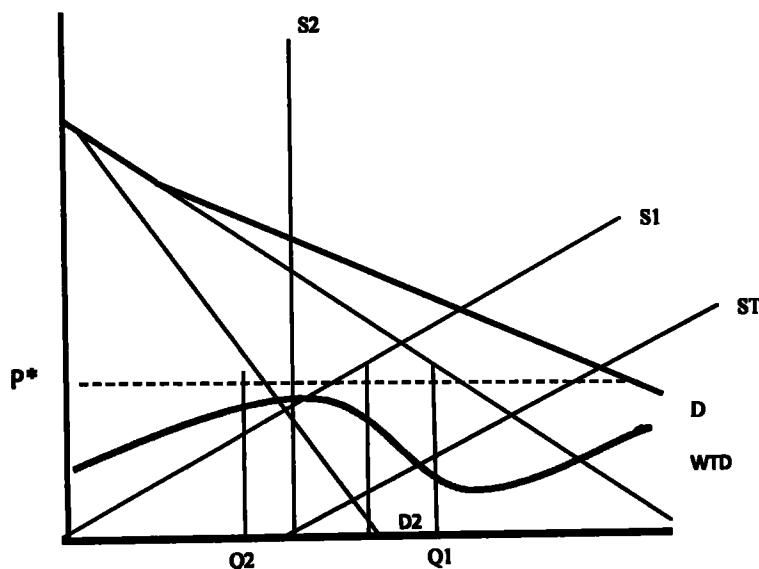


Figure 6.7: Conjunctive use assessment without conveyance Losses.

¹⁶Source: (Roumasset, 2001)

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¹⁶ Roumasset, J., & Smith, R. (2001). Inter-District Water Allocation with Conjunctive Use. *Journal of Contemporary Water Research and Education*, 118(1), 9.

potentially used. For farmer1, surface water is not available, he will only be using groundwater which may cause salinity in long run. Considering the above discussion, it is important to form rational policies for making ground and surface water potentially available to all farmers (Pongkijvorasi, 2007). Moreover, this system becomes more complex when farmers trade surface water and enter into the formal and informal market to buy and sell groundwater. This complexity can be better understood through ABM. A conjunctive water management model is devised to understand the water management perspective and find out emergence and pricing to better manage conjunctive water in Pakistan.

6.5 ABM for Conjunctive Ground and Surface Water

Water resource management includes human and natural agents; farmers, regulators, and hydrological systems. The complexity of interaction between them requires the use of ABM to capture the feedback, adaptability and emergent behaviour in the system. Understanding of socio-natural systems and the complexity between them can deliver policy implications for water management in irrigations systems. To develop ABM, socio-economics, natural and feedback models are to be developed (Giuliani et al., 2016; van Heerden et al., 2008). Every ABM is required to be presented through overview, design, and details (ODD) of the mode; ODD recommended by Grimm et al. (2010a) is given in chapter 3 section 3.5. A flow chart of how the model will work initially considering water turns and water allocation if it met the water need of the crop is as follows.

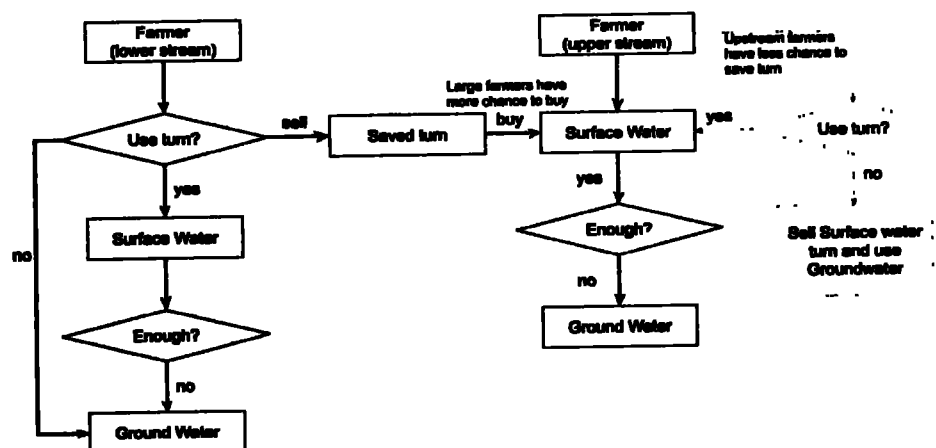


Figure 6.8: Basic surface and groundwater use decision flow.

Source: Author's own developed

6.7 Results and Discussion

Model results are based on implementation of model followed to answer the objectives of the model. To assess the objectives hypotheses are made to see model's parameter through plots and tables if they relate to the real world.

6.7.1 Implementation of Model

Hypothesis: Conjunctive ground and surface water can be better managed through institutional and social enhancement considering spatial surface and groundwater availability of farmers

Conjunctive water use affects ground and surface water availability differently for farmers having spatial differences. Managing water availability on the basis of equity can bring cost and benefits to the system. Maintaining equity can also affect water quality parameters.

6.7.2 Baseline Experiment

Our model is based on three types of water use management Scenarios. We have considered BAU, IMP and SGR aspects of agricultural water management. In BAU;

we have simulated the water use behavior of farmers without changing any parameter. Details of these scenarios are given in ODD of the Model. Results from baseline experiments are given in figure 6.9. The purpose is to see that how IMP and SGR are improving water availability and water quality parameters.

Initially, we have simulated a basic model with the above three types of scenarios without changing parameters; call it Baseline Experiment. The model is simulated 10 times for each type of scenario and it runs 90 times for Baseline experiment in total. Figure 6.9A. depicts water use under crop season rains. It shows that in the BAU scenario, farmer's profits and logging remained 0.8 standard deviations below the mean, while salinity remained 1 standard deviation above the mean value.

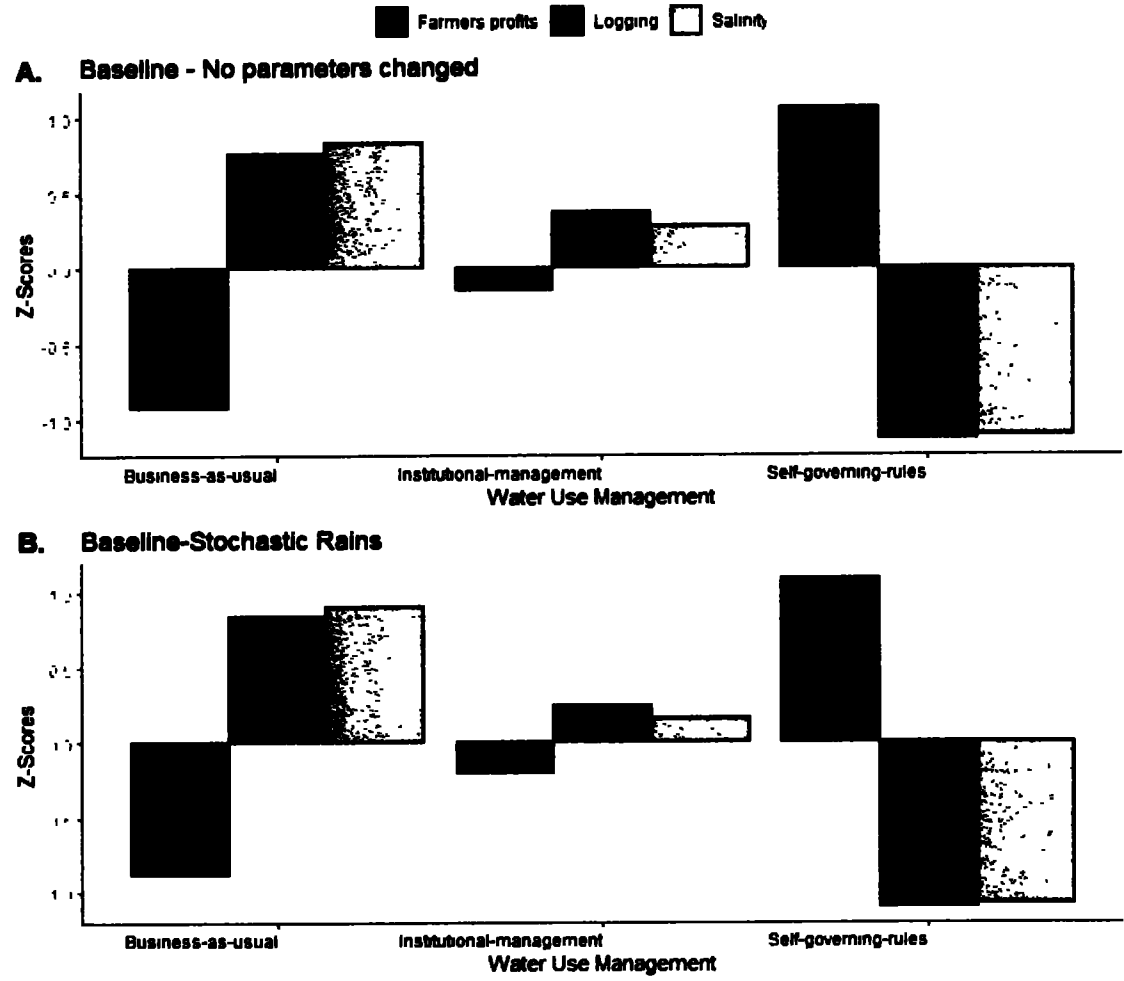


Figure 6.9: Profits, logging and salinity across water management perspectives for baseline experiment.

Source: Author's own work

In BAU salinity was highest; the majority of the farmers are facing an increasing level of salinity along with falling profits majorly below average, while IMP shows some improvement in all variables as compared with the BAU scenario. There is an improvement in profits of 0.6 standard deviations in IMP as compared with the BAU while salinity is improved about 0.7 standard deviations as compared with the BAU scenario. As far as the SGR scenario is concerned, profits are substantially higher as compared with BAU and IMP water use perspectives. Profits are 1.5 standard deviations more than the mean of BAU and IMP.

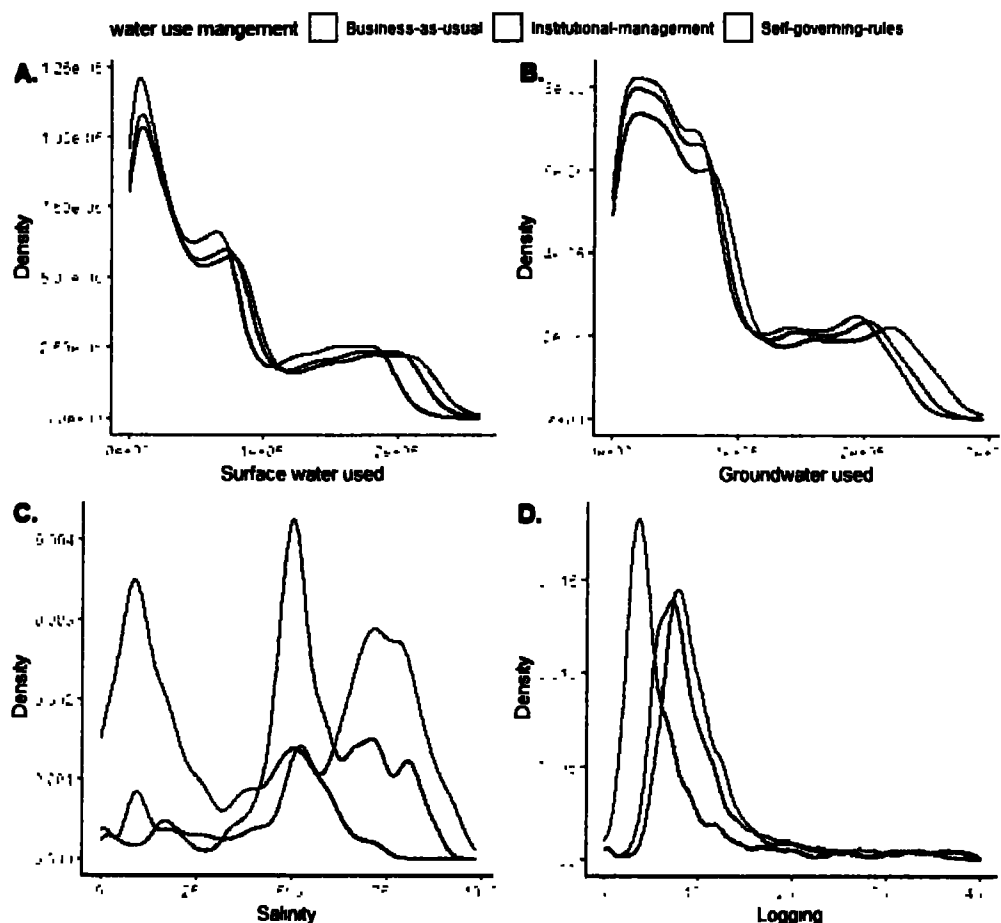


Figure 6.10: Water use, logging, and salinity status in baseline experiment.

Source: Author's own work

Figure 6.10 shows comparison of primary variables in the Baseline scenario, where parameters have changed to see the behavior of primary variables over time. In part A of figure 6.10 shows the volatility in surface water used. It is found that in BAU and IMP, farmers are using 16% and 11% more average surface water than in the SGR scenario of water management perspectives. In intervention scenarios, surface water use is relatively less than the BAU scenario. Moreover, in all three scenarios, maximum water is also used in the BAU scenario and the density plot in part A. shows a more skewed distribution for BAU with 14% and 5% more surface water used than SGR and IMP respectively; tails are found 15% more heavy than in case of BAU comparing with the SGR. While in the case of groundwater, farmers are found using more

groundwater in SGR followed by IMP and BAU scenarios and spread and tails are heavy in the case of SGR. This has resulted in unrestricted surface water use at heads of surface water resource. Most demand is met through surface water use while in the case of SGR farmers are using overall less surface water and more groundwater. Moreover, Furthermore, it is found that in Baseline scenarios BAU is using 4% and 10% more total water for irrigation comparing with other management scenarios. System efficiency may be lost in the case of interventions but desired results for reducing inequality can be met with maintaining water quality parameters.

Besides water use, water quality parameters; logging, and salinity in the baseline experiment are also exhibited in figure 6.11. Salinity is found to expand at a greater rate in BAU comparing with IMP and SGR. A rise in total salinity is found to be 17% and 61% lower in IMP and SGR comparing with the BAU scenario. This is due to the unrestricted use of ground and surface water by spatially located farmers. In BAU, overall farmers are using less groundwater but the farmers at tail ends are using more extensively which is causing a persistent rise in salinity due to falling water table depth.

Water Use Management: Business-as-usual Institutional-management Self-governing-rules

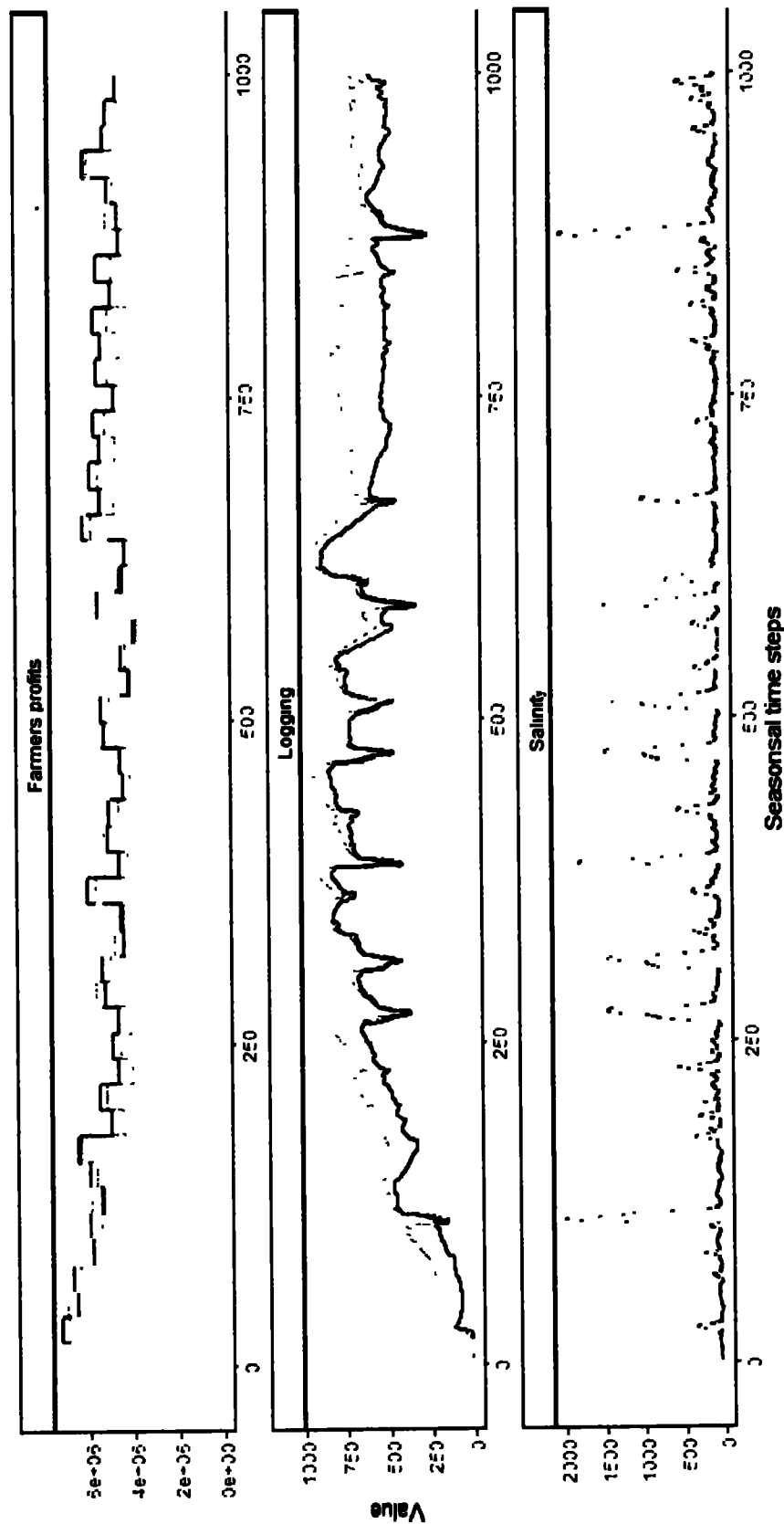


Figure 6.11: Logging, salinity and farmers' profits over time.

Source: Author's own work

We observed tri-model density graph of salinity where the peak of salinity is found to be at the tail in the case of SGR comparing with BAU, while in BAU majority of the farmers are found to have a greater number of salinity concentrations comparing it with other scenarios. Furthermore, logging was also found in greater numbers in BAU comparing it with SGR and IMP. Logging is found to penetrate 5% and 23% lesser in IMP and SGR respectively comparing it with the BAU scenario. While the spread of logging almost remained the same in all scenarios. From the discussion above this can be concluded that total water use in BAU is less than other scenarios but water quality parameters are getting increasingly poor this can be related to the fact that in the system some of the farmers are utilizing more groundwater in the places where surface water use and availability deemed important.

Season-wise profits, logging, and salinity over time are given in figure 6.11. Every time step shows a season and the system follows two seasons sequentially Rabi and Kharif seasons.

Figure 6.11 shows that in the initial time steps BAU management perspective is generating more average profits as compared with IMP and SGR. But over time this privilege is shifted towards SGR followed by IMP and BAU water management perspectives. SGR is generating more profits compared with the other two prescriptive. Salinity is found to be lowest in most instances in SGR followed by IMP and BAU scenarios. However, logging is found to have the same spread of values over time. This is due to the reason that in the majority of the area under discussion water table depth and water availability is already deficient which prevents farmers to face logging. Events of extreme rainfalls may cause farmers to face logging with harmful effects.

6.7.3 Climatic Change and its Impact of Water Use Management Perspectives

We have conducted a climate change experiment to see that how water management perspectives bring different results. We have taken rain moisture rate and evaporation rate to reflect the effect of weather changes on the overall system including farmers' water use behaviour and water quality parameters. Figure 6.12 depicts profits, logging, and salinity across water use management scenarios.

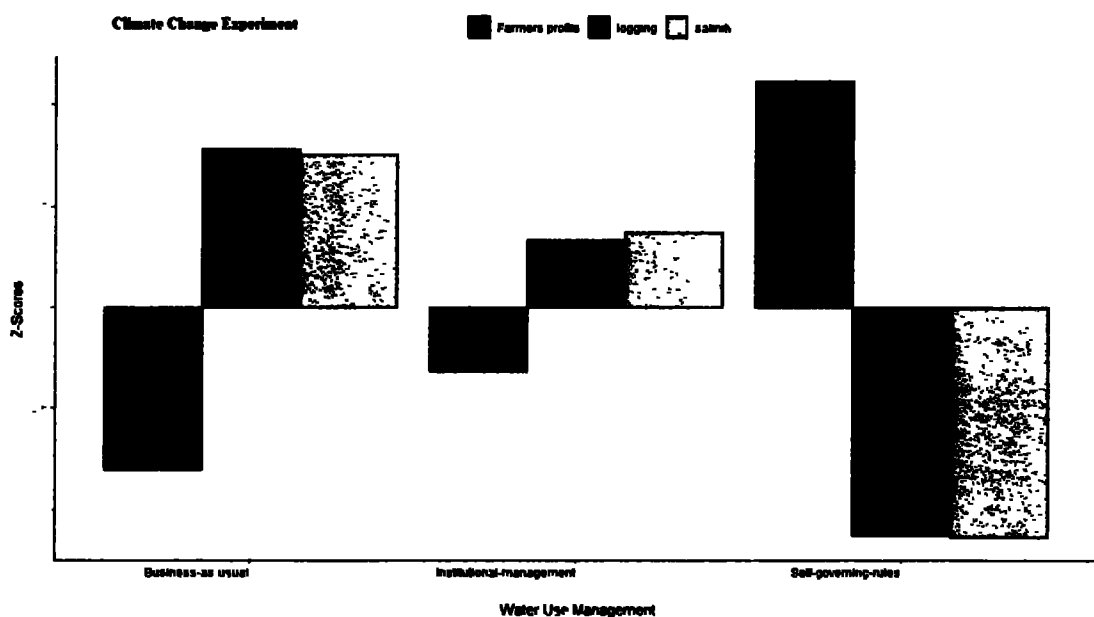


Figure 6.12: Climate change experiment across water management scenarios.

Source: Author's own work

Changes in rain moisture rate and evaporation rates are taken as 0.2, 0.4, and 0.6 these changes have an effect on water demand and availability of surface water groundwater and other system parameters. It can be assessed from the figure above that In SGR results are favorable for the system that profits rates are found to be more than 1SD above the mean and water quality parameters as logging and salinity are found to be more than 1SD below the mean. This is why profits are higher as the rise in logging

and salinity parameters hinder the rise in profits. While IMP also showed some improvement comparing it with the BAU scenario. However, comparing BAU in both climate change and a baseline experiment; both logging and salinity parameters got worst in the climate change experiment. Traditional practices of irrigating crops may become detrimental for system parameters in case of climate change.

Water use, logging, and salinity for climate change experiments are given in figure 6.13. Data shows that pattern of logging is the same as in the case of the baseline experiment. That SGR has the lowest level of salinity followed by IMP and BAU. However, average logging is found to be 48%, 50%, and 62% more than the baseline BAU, IMP and SGR respectively.

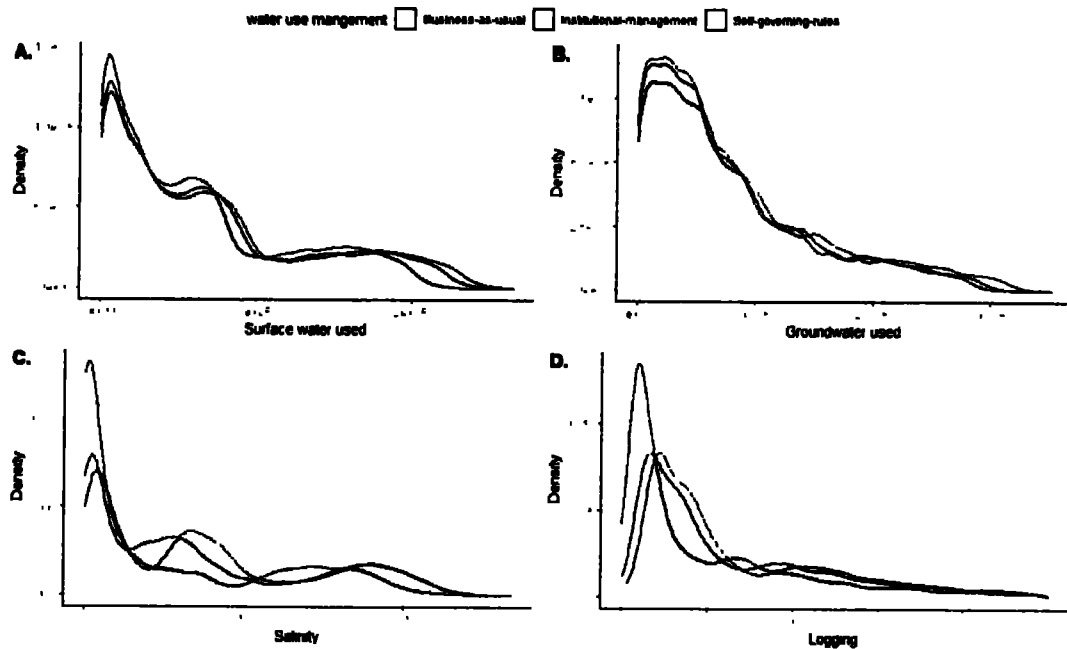


Figure 6.13: Water use, logging, and salinity status in climate change experiment.
Source: Author's own work

SGR appeared better in the climate change experiment for reducing salinity as compared with BAU and IMP. Moreover, SGR and IMP are found to have 6% and 30% less average salinity than BAU. However, comparing the reduction in salinity level across baseline and climatic experience, we have found that in climatic experiment

intervention perspectives as IMP and SGR have reduced salinity to 11% and 32% lesser than in baseline experiments. Which can be linked with the lesser impact of interventions in case of climatic changes. While logging is found to be 3% and 16% more compared with IMP and SGR comparing it with BAU scenario in climate change experiment. Comparing profits, IMP and SGR in case of climate change experiments are doing 2% and 6% better respectively.

We have varied climatic parameters to see how the system emerges for logging salinity values. Figure 6.14 presents logging and salinity. Part A and B show logging and salinity respectively. Distinctive behavior of salinity is found in the case of evaporation rate if it rises to 0.4. The peak of salinity in the case of BAU is found to be at a higher level of salinity followed by IMP and SGR. In the case of evaporation rate 0.6. While with a rain moisture rate of 0.6 along with an evaporation rate of 0.4, peaks of salinity fall comparing with all. Comparing with other variation in rain moisture rate. With evaporate rate 0.2, the peak of all water management perspectives is found to be at a higher level of salinity but SGR peak comes at lesser salinity as compared with other scenarios in case of all rain moisture level. However, distributions are found to be left-skewed in case of rain moisture 0.2.

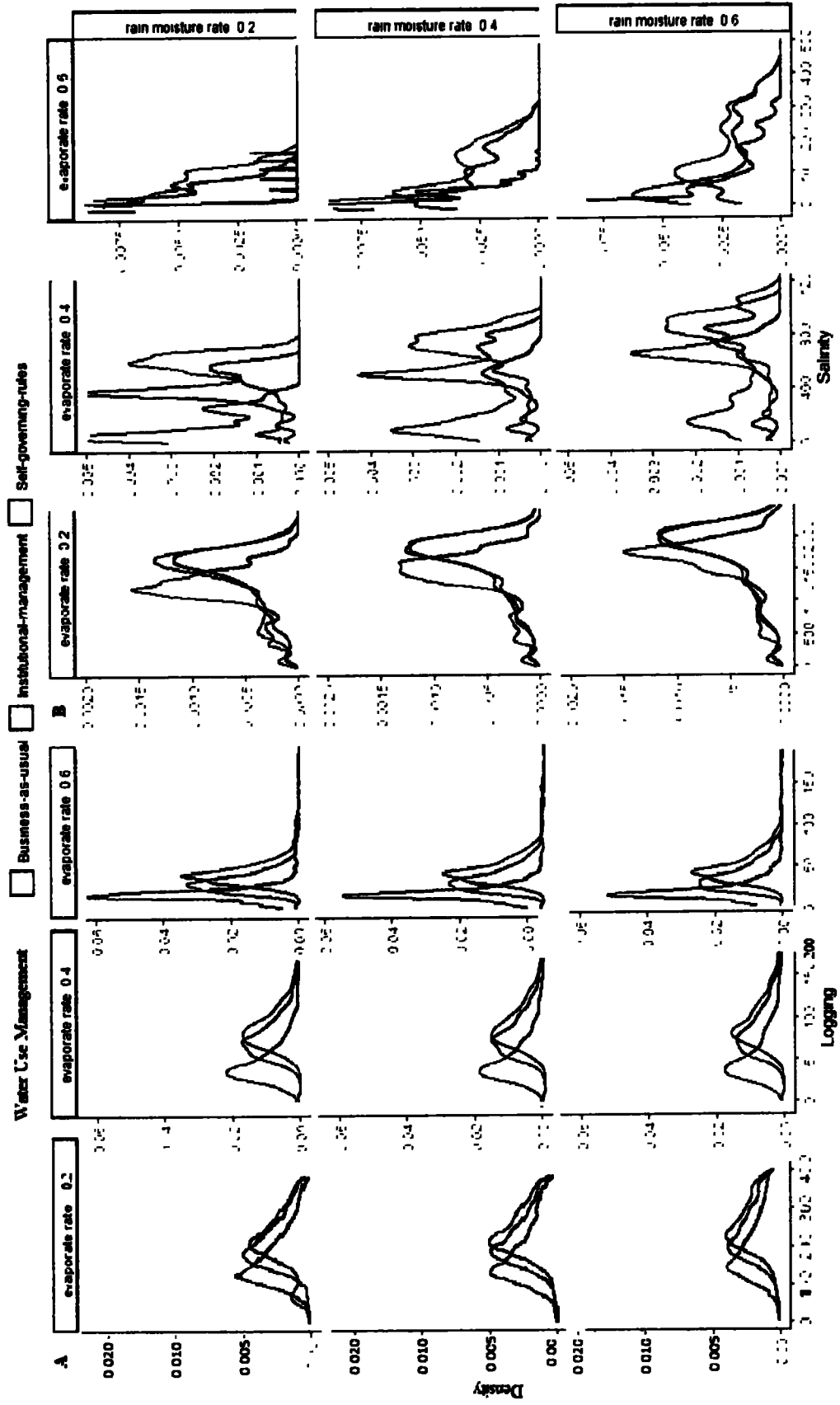


Figure 6.14: Variation in logging and salinity across parameters in climate change experiment.

Source: Author's own work

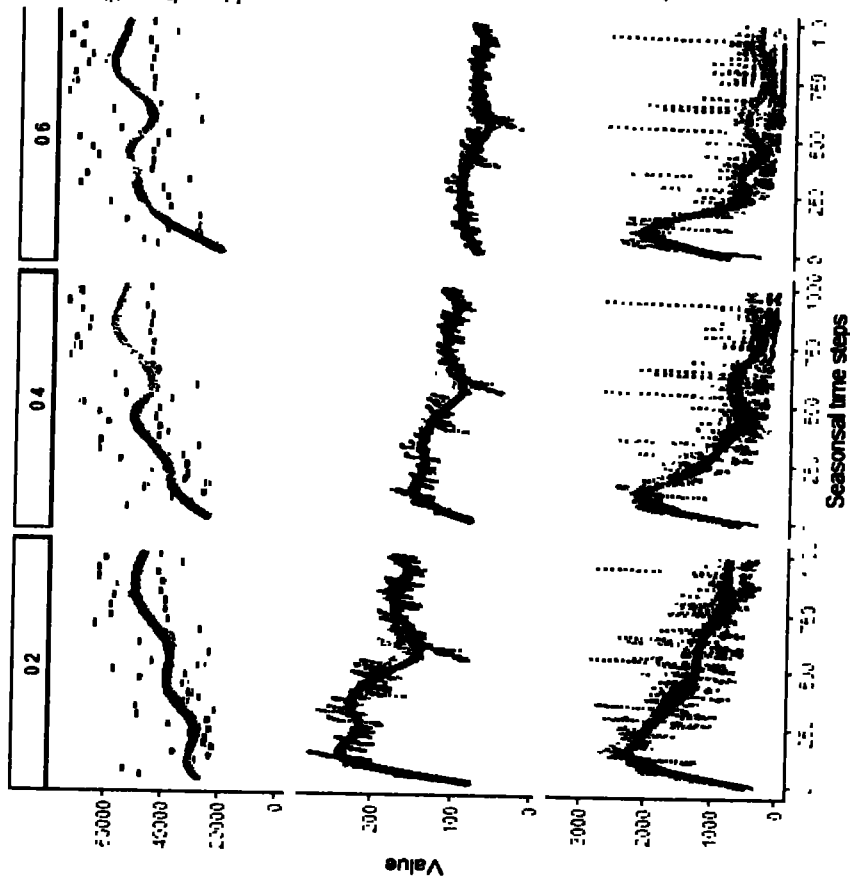
Logging is found to be right-skewed with an evaporation rate of 0.2. Similarly, logging is responding to the higher evaporation rate it falls to the half with every increase in as 0.2% of evaporation rate. However, logging was found to be minimum in the case of SGR followed by IMP and BAU scenarios. Provenance of logging and salinity overtime along with profits is presented in Figure 6.15.

We have assessed that farmers' profits were higher in SGR in extreme high evaporation rate while in the majority of the time period profits in BAU were higher under lower evaporation conditions. This may be due to the fact that farmers were not required to engage in alternative arrangements to fulfill water needs under low evaporation scenarios. While in case of higher rain moisture rate profits are found higher with more fluctuations in them in SGR. However, fluctuation in profits are reduced over time, while rise remind low in the case of SGR as it is found 6% and 30% low for IMP and SGR comparing it with BAU scenario.

Logging is found higher with low evaporation and high rain moisture rate in all water management scenarios while it is lowest in highest evaporation rate comparing it with all other variations in rain moisture and evaporation rate. Furthermore, logging is found 4% and 16% less in IMP and SGR respectively as compared with BAU scenarios.

A. Evaporation Rate

Water Use Management - Business-as-usual - Institutional-management - Self-governance-rules



B. Rain Moisture Rate

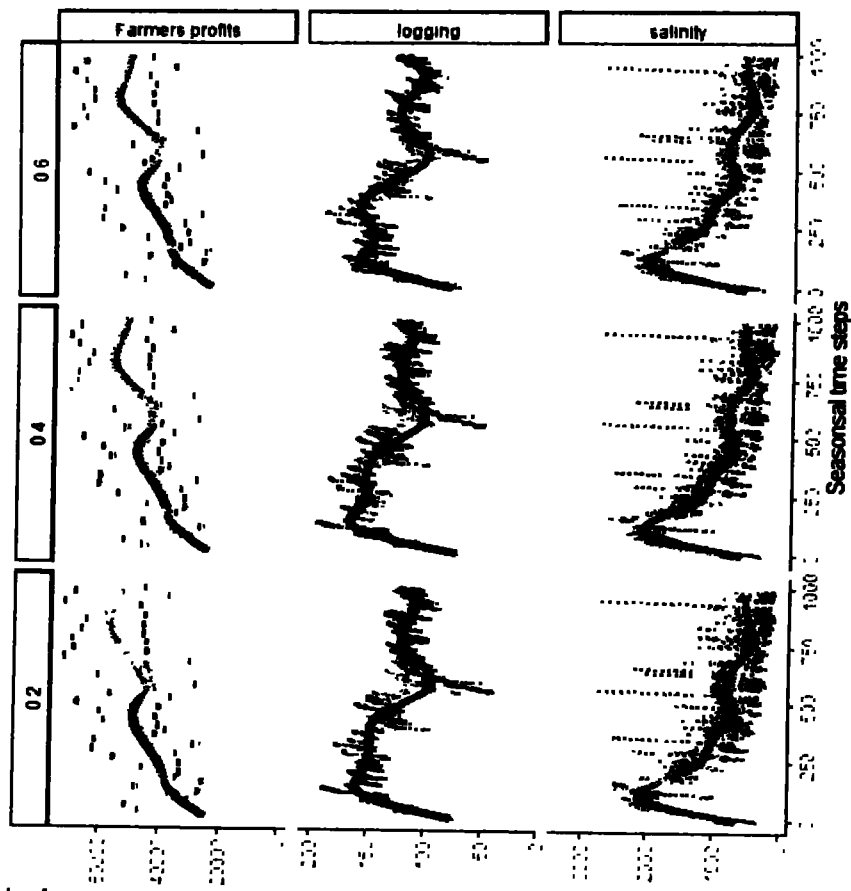


Figure 6.15: Logging, salinity and profits over time

Source: Author's own work



As far as salinity is concerned, it is found to be higher in IMP in lowest evaporation rate and it remained higher and converged at the end of the simulation period in all other scenarios. However, for evaporation rate, BAU scenario is found to have a maximum salinity over time followed by IMP and SGR. Salinity is found to be diverging in all scenarios till the end of the period. Prevalence of salinity is found lowest in SGR comparing with other two scenarios. With the increase in rain moisture rate salinity is found to have increasing values than the averages.

Comparing the water management perspectives, SGR appeared as a better manager of water resource usages and its impact on water quality parameters and resultant profits. However, the intervention scenarios can not completely improve the water quality parameters and profits as generally, farmers face the challenge of maintaining and possibly increasing agricultural production under climatic vagaries. Due to the climatic conditions, human response to the climate, and short-term imposed, temporary and inefficient solutions are making the risk of failing this challenge so high that can backfire in the long run (Kahneman, 2011; Schill et al.).

6.7.4 Spatial-temporal, Physical Changes, and Dynamics in the System for Logging, Salinity and Profits

In order to see how the system will behave differently we have run an experiment by changing the physical properties of the system over time. In physical properties, we have taken water table depth and distance from a water source as the parameters to be changed and see how they are affecting the system. This experiment helps us to test the hypothesis that whether water quality and profit related parameters have improved overtime or not.

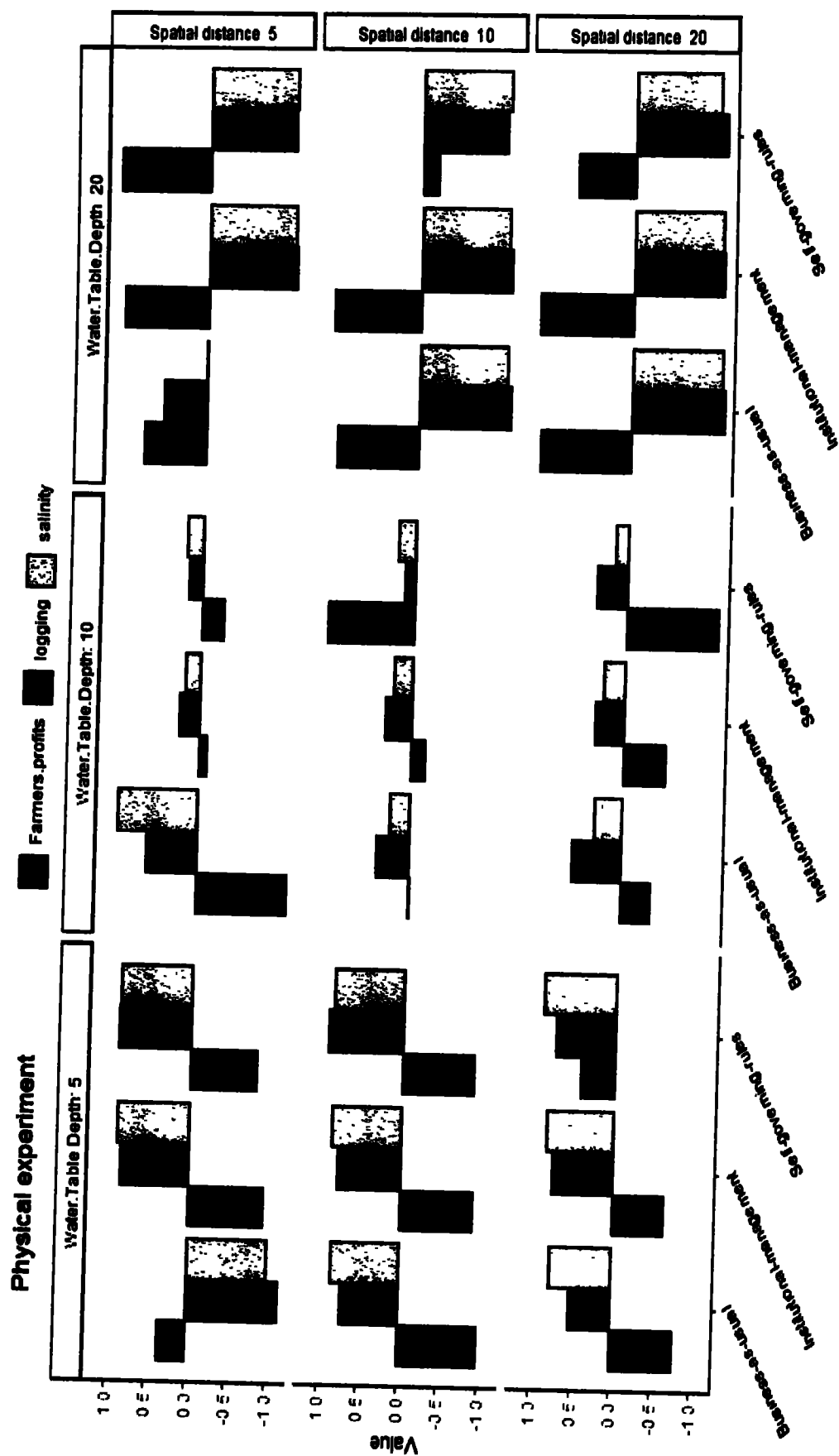


Figure 6.17: Spatio-physical and temporal experiment for water use management.
Source: Author's own work

Hypothesis: “Logging, salinity and profit situation improve due to change in spatial-physical parameters across time”

In order to assess how spatial distances matter, extreme cases for water management are compared below. Figure 6.17 exhibits the above-said experiment.

If we consider low value of the parameters; water table depth and spatial distance from the water source as 5, the BAU scenario is outperforming than the intervention scenarios for managing the output in desirable limits.

If there is no water scarcity and farmers are nearer to canal heads then conventional methods of irrigation give positive profits and a below 1 standard deviation from the mean of water quality parameters. BAU management perspective of water use becomes ineffective while intervention scenarios give better results if we consider a higher water table depth of 20 m along with constant distance from the water source.

To see the dynamics that how model parameters behave if we increase the distance from water source keeping same water table depth of 5 this can be observed that only SGR water management scenario appears relevant and providing desirable results in the system. In case of increasing distance from water source along with water table depth of 10m, SGR provides somehow positive 1 standard deviation profits from mean but water quality parameters stayed around less than 1 SD above the means. Furthermore, for the highest water table depth of 20, IMP was found to be effectively managing profits and water quality parameters for all distances from water sources. However, the SGR perspective was found to be less effective comparing with other water management perspectives in the highest water table depth scenarios.



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We have taken averages to compare logging for different water table depths along with the spatial distance to complement the explanation in the graph above. Average logging is found to be highest with a spatial distance equal to 5 and IMP and SGR are found to have 5% and 23% less logging respectively comparing it with the BAU scenario.

Minimum logging is found to be with the cross tabs of 20 spatial distance and water table depth. Similarly, IMP and SGR are found to manage logging effectively than the BAU comparing the minimum average of logging. Comparing within water management scenarios for temporal calculation shows that the highest reduction in logging is found when spatial distance is raised from 5 to 20 in the case of SGR while logging also showed some unusual pattern with water table depth raised to 20 along with an increase in spatial distance to 10 in SGR. One interesting insight from the data is comparison within and between water management perspectives. It has been observed that for water table depth greater than 5 and spatial distance greater than 5; logging for between water use perspective remain significantly different from BAU and improved in the case of SGR. However, logging for water table depth and spatial distance remained the same with a water use management perspective. For water table depth and spatial distance equal to 5, they remained 13% and 17% less for IMP and SGR. Moreover, for within scenario comparison, SGR is found to bring a maximum reduction of 12% in logging with a water table depth of 5 along with a spatial distance of 20.

In similar to the logging, salinity is found maximum with water table depth 10 and spatial distance 5 in BAU 18% and 128% more than the IMP and SGR with the same water table depth and spatial distance. Details are given in Table 6.1. SGR is found to have more variations in salinity if comparing the range of the values

irrespective of the physical parameters varied. Salinity is found to be decreasing more when water table depth and spatial distance is changed from 5 to 20 as given in table1. Comparing with BAU salinity is reduced from 52% to 66% and 20% to 42% in SGR and IMP respectively. Part B of figure 6.17 shows temporal variations in salinity. Considering all of the variations regarding SD and WTD; BAU, IMP, and SGR start with the same level of salinity, in 500 ticks it colludes and afterward, it rises for BAU, falls for IMP and SGR both. However, the fall in salinity is greater for SGR comparing it with IMP till the end of the simulation period.

It is also evident from figure 6.18 part A that BAU logging remained highest and collides with IMP with less difference in lower water table depth and spatial distance and more difference is relatively high water table depth and spatial distance. Logging and salinity in figure 6.18 can be further explained with the help of density plots given in figure 6.19. From the figure we can see that with the same water table depth as the spatial distance is increasing, the peak of salinity is found the relatively early point in time for all water management scenarios. However, for BAU peak is found at a higher level of salinity followed by IMP and SGR.

Table 6.1: Comparison of average total logging and salinity in water management scenarios

Logging					Salinity				
Business as Usual					Business as Usual				
SD \ WTD	5	10	20		SD \ WTD	5	10	20	
5	193	204	204		5	747	800	774	
10	197	197	196		10	738	726	697	
20	183	183	182		20	604	595	563	
Institutional Management Perspective					Institutional Management Perspective				
5	↓1.1	↓4.9	↓5.1		5	↓43	↓16	↓16	
10	↓5.1	↓5.1	↓5.2		10	↓17	↓17	↓18	
20	↓5.5	↓5.7	↓5.8		20	↓20	↓21	↓21	
Self-Governing Rules					Self-Governing Rules				
5	↓99.4	↓102.4	↓102.5		5	↓52	↓56	↓57	
10	↓23.3	↓29.1	↓23.4		10	↓59	↓59	↓61	
20	↓23.6	↓14.1	↓23.4		20	↓64	↓66	↓67	

Source: Author's own work

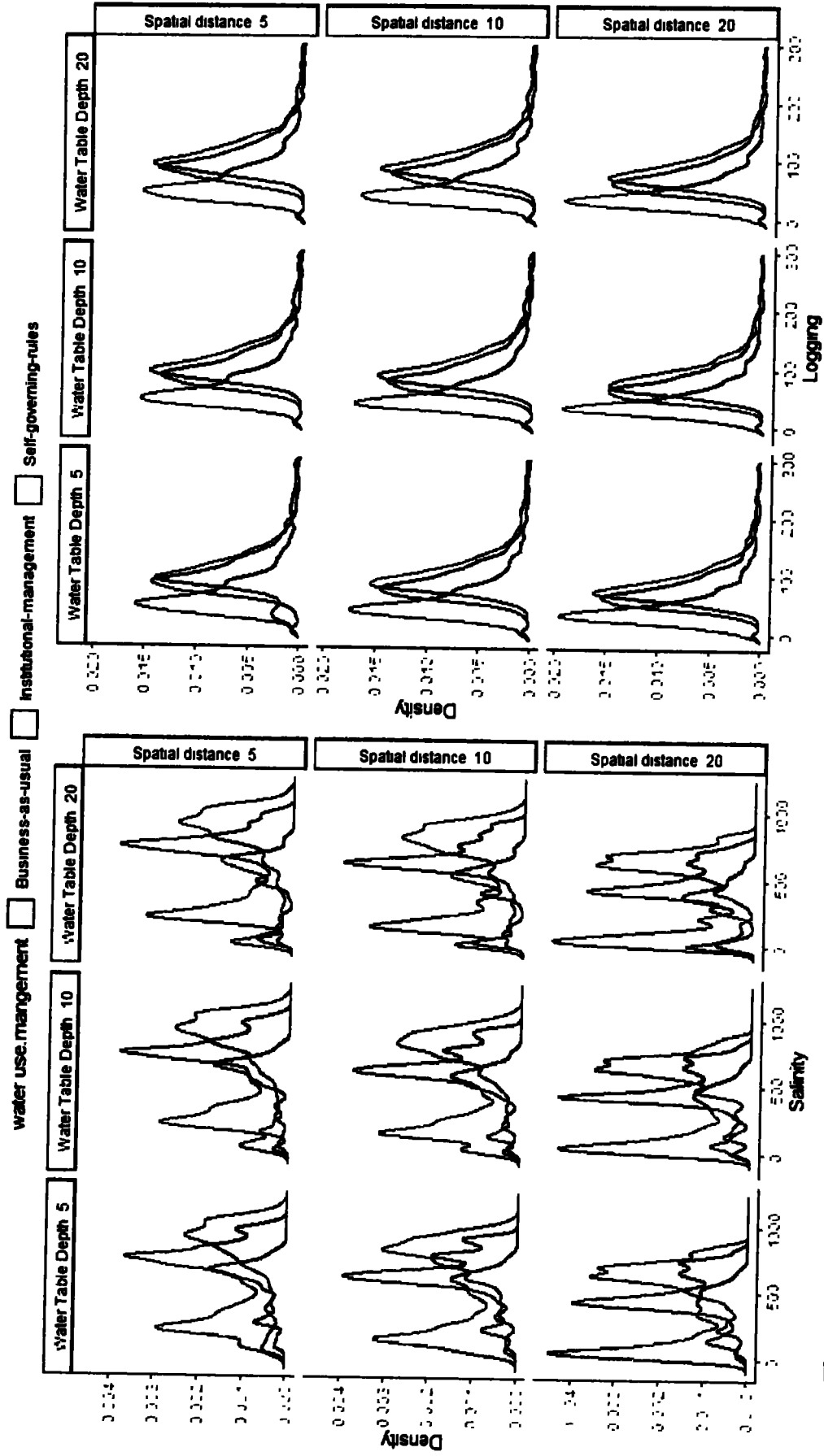


Figure 6.19: Density plots of logging and salinity across water table depth and spatial distance in the physical experiment.

Source: Author's own work

Moreover, comparing across scenarios, IMP has shown relatively high peaks at the lowest spatial distance comparing with other scenarios and SGR showed highest peak when WTD is 20. This means that SGR rules can better manage water resources when spatial distance is increasing. If we compare water table depth 20 and see it against increasing spatial distances, we can see that spread of BAU distribution shrinks. BAU and IMP have a negatively skewed distribution while SGR has a positively skewed distribution. Considering logging for the second part of figure 6.19. For BAU, IMP, and SGR, logging is found to have a positively skewed distribution.

Table 6.2: Comparison of maximum and minimum Average per acre profits in water management scenarios under physical experiment

Maximum Average Profits				Minimum Average Profits			
Business as Usual				Business as Usual			
WTD \ SD	5	10	20	WTD \ SD	5	10	20
5	37286	31296	31825	5	27903	28658	29172
10	32136	32464	32491	10	29437	29465	29984
20	33744	33865	34361	20	30896	31016	31434
Institutional Management Perspective				Institutional Management Perspective			
5	↓3	↑7	↑6	5	↑21	↑8	↑7
10	↑7	↑6	↑8	10	↑8	↑8	↑7
20	↑6	↑5	↑5	20	↑7	↑6	↑6
Self-Governing Rules				Self-Governing Rules			
5	↓1	↑18	↑17	5	↑25	↑22	↑21
10	↑17	↑16	↑16	10	↑21	↑22	↑19
20	↑12	↑11	↑10	20	↑16	↑15	↑14

Source: Author's own work

SGR is found to have the highest peak, the difference is more visible when spatial distances increasing. The concentration of logging is more at the low level of logging for SGR. BAU and IMP share the same distribution. However, logging for IMP is relatively lower than BAU in all possible scenarios under consideration. Profits also

show similar but relatively different trends for BAU, IMP, and SGR. Details are given in Table 6.2 Maximum average profits are falling across the lowest water table depth and spatial distance of 5 in IMP comparing it with BAU. This does fall for SGR with relatively fewer percentage points.

This may be related to the fact that radical changes in behaviors are required in water management perspectives. The highest positive change in profits is observed within IMP for water table depth is 20 along with the spatial distance of 10. SGR provides the highest profits when water table depth increases along with the same spatial distance. The timeline of profits shows that overall SGR performs better compared with other scenarios except in the case of lowest water table depth and spatial distance scenarios. However, minimum average profits are highest under the combination of water table depth and spatial distance of 5 each for both IMP and SGR comparing it with BAU. In both interventions for managing irrigation water scenarios, positive average profits fall as water table depth and spatial distance observe an increase.

Table 6.3 Comparison of climate change and spatio-physical experiments

Parameters		Climate Change Experiment		Spatio-physical Experiment	
Evaporation	Rains	Low Rains	High Rains	Low Rains	High Rains
Low Evaporation		BAU, IMP, SGR	Null	BAU	SGR
High Evaporation		IMP	SGR	SGR, IMP	IMP, SGR, BAU

Source: Author's own work

From the data it is conferred that in low rains and low evaporation, when there is less need of irrigated water as all management perspective become useful. However, in extreme cases as of high rains and low evaporation SGR becomes more effective.

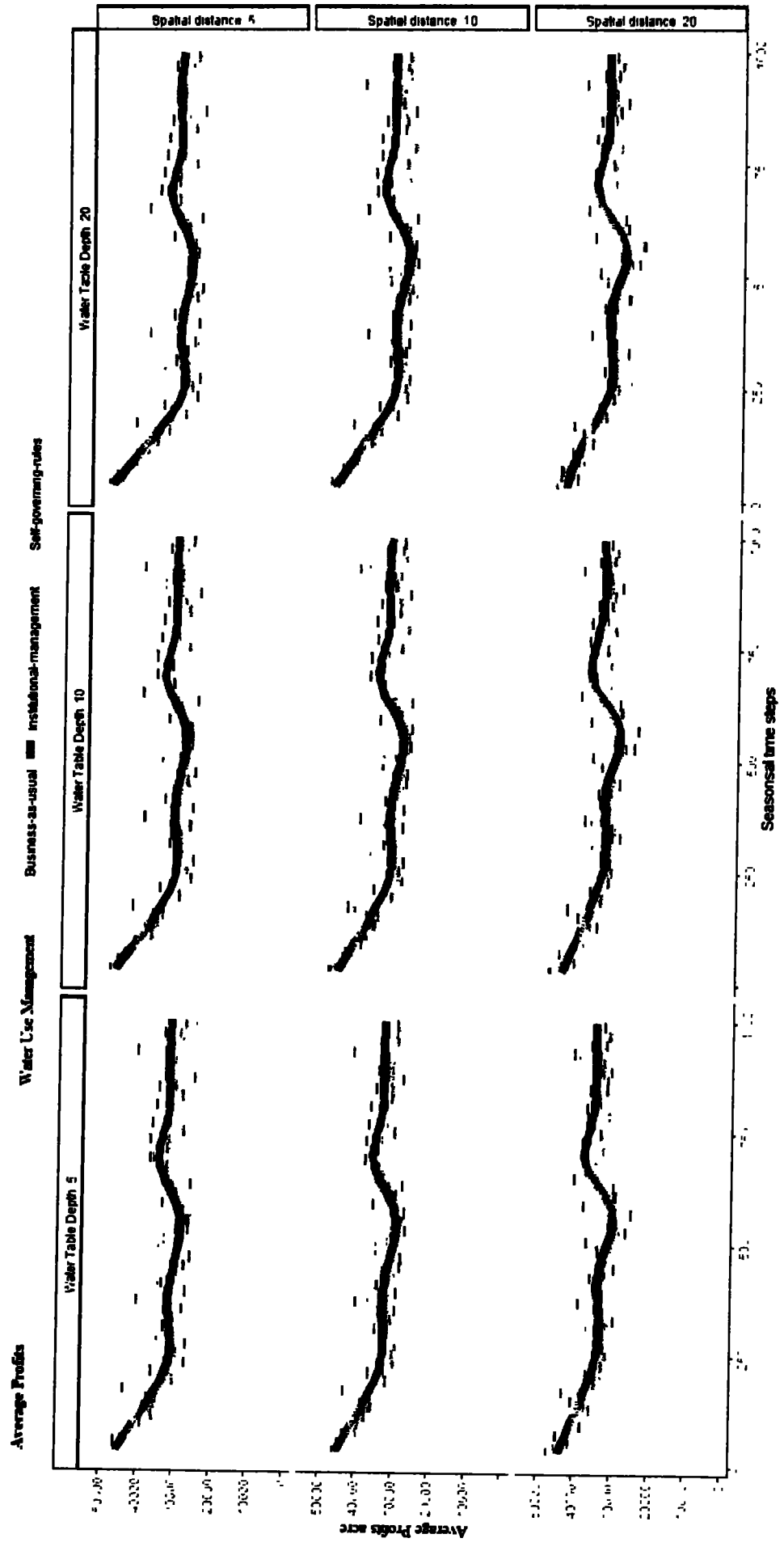


Figure 6.20: Time series plot of profits across changing water table and spatial distance scenarios

Source: Author's own work

Figure 6.19 exhibits that along with changing spatial distances, the difference in per acre profits are decreasing among water management scenarios. IMP and SGR are showing 16% and 26% more growth rate in profits per acre comparing with BAU scenarios when water table depth is 5 and difference is more visible when averaging the profits for the farmers at the farthest distance from the water source. However, when water table depth rises difference in growth rate between BAU and intervention scenarios falls but remained positive. This can be related to the fact that in extreme physical conditions effectiveness of water management scenarios falls. Moreover, figure 6.18 also shows that with the combination of 20 and 5 water table depth and spatial distance respectively, BAU performed better than the IMP perspective. This is due to the rising water table depth and logging-related salinity due to fewer spatial distances.

Profits are also presented for time-based density plots. Our model is run multiple times for the entire period of 1000 time steps. Average/acre profits are plotted. We can see in figure 6.21 that in the majority of the time steps for SGR profits remained above 3000/acre and profits rise as the time span moves from 0 to 1000-time steps. However, in the case of BAU and SGR, the majority of the profits are found to fall around 30,000 rupees/acre.

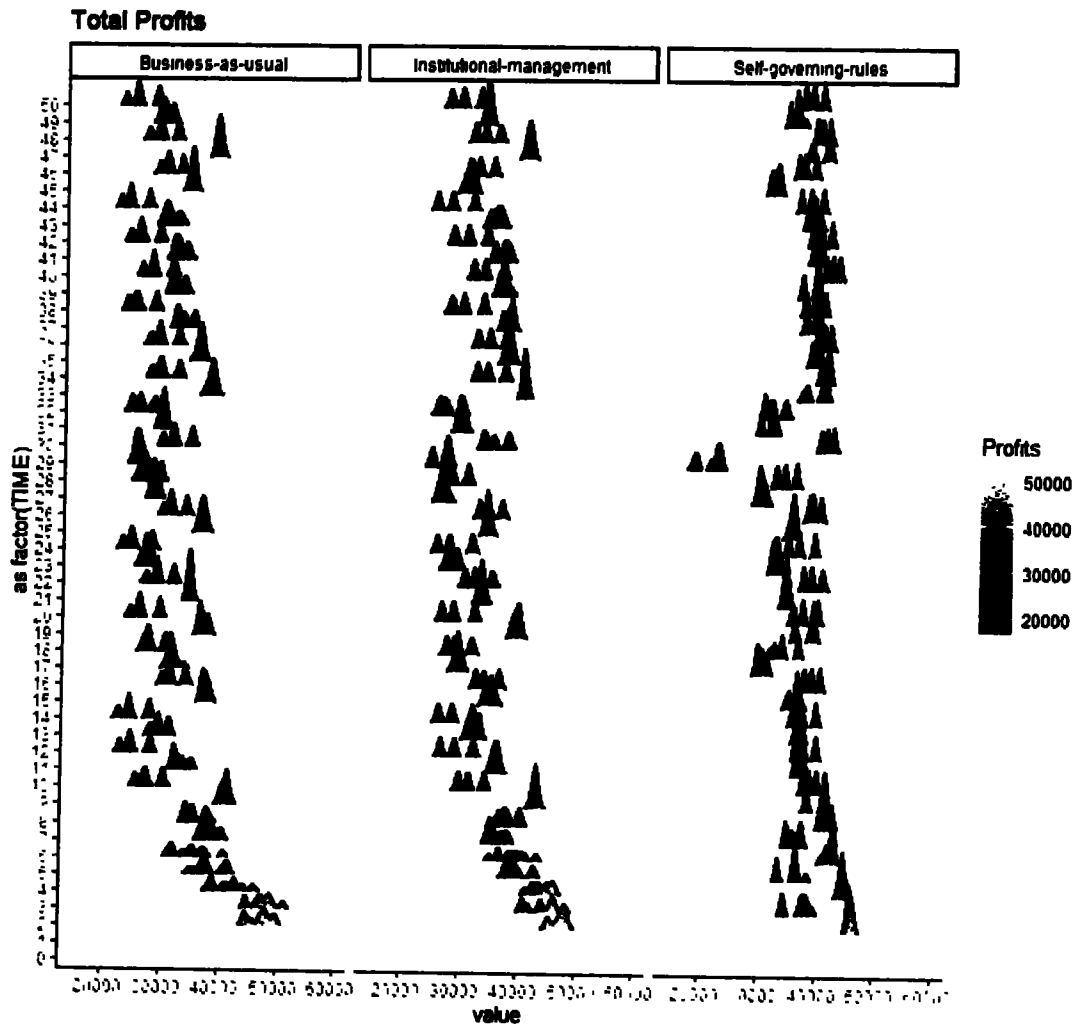


Figure 6.21: Density plots of the timeline of profits under physical experiments.

Source: Author's own work

This can be observed that the BAU perspective of water management shows positive profits of around 50 thousand/acre in major instances at the initial years of cropping in every simulation period. However, in later time period, major instances show highest profits in SGR followed by IMP and BAU. Some exceptions are also there where at the time period of 30 around SGR is earning minimum profits this can be related with the extreme weather conditions as of more or fewer rains and in response farmers behavior regarding

6.8 Conclusion

The water management perspectives are presented in a caricature manner for water use decision-making by farmers in conjunctive irrigated agriculture. BAU allows farmers to look after their individual profits and draw their allocated surface water along with unregulated groundwater abstractions. While in IMP, water use behaviors of farmers are governed and penalized or rewarded accordingly. However, in SGR farmers consider water quality parameters, water use, and water availability and water use behaviour of surrounding farmers.

This chapter shows that how different water management perspectives help to achieve sustainable outcomes for irrigated agriculture. We have assessed this by varying spatio-physical and climatic conditions to see that how the water management perspective can maintain profits, water quality and availability-related issues. From a water management perspective BAU takes the existing condition of the system and is simulated for a period of 25 years. IMP, considers the active role of government in the form of penalties and rewards for water use and saving behaviours. SGR reflects that farmers are abiding by the social norms and bound to be self-accountable if farmers in the neighbourhood are deliberating the social norms of managing the water.

In the baseline experiment, SGR scenario showed more profits per acre as compared with the BAU and SGR rules found 1.5 SD more than the mean of BAU and SGR. However, salinity and logging remained 1SD below the mean, while for IMP they were 0.1 SD above the mean values. However, logging salinity factor remained relatively higher in BAU.

Density plots have been drawn to find out the distributions of logging, salinity, groundwater, and surface water use. Salinity is found negatively skewed for BAU and

positively skewed for IMP and SGR. It is found that in BAU and IMP, farmers are using 16% and 11% more average surface water than in the SGR scenario of water management perspectives. However, farmers are found using more groundwater in SGR followed by IMP and BAU scenarios, and spread on tails is more in the case of SGR. And BAU found to use 4% and 10% more total water used for irrigation comparing with other management scenarios in case of baseline experiment.

In the climate change experiment Z-scores show that under usual weather conditions all management scenarios are performing well in terms of profits and water quality parameters. When there are fewer rains and more evaporation rates IMP becomes more effective. However, in extreme high temperature and fewer rains BAU scenario proved to perform better in managing the agriculture better. Moreover, as evaporation rate increases along with the increase in rains SGR becomes effective in managing irrigated agriculture. Water management perspectives become impotent when there are more rains and lesser evaporation rates. This can be related with the high logging and flood-like conditions in a real-world context.

However, the aggregate effect in climate change experiments shows that logging salinity has become worst in the case of BAU and IMP. But SGR proves to manage resources better than other scenarios for-profits, logging, and salinity. Moreover, intervention perspectives as IMP and SGR have reduced salinity to a lesser extent than in the case of baseline experiments. Similarly, little positive average profits are found in the case of IMP and SGR. This can be linked with the fact that traditional practices of irrigating crops may become detrimental for system parameters in case of climate change.

The highest level of salinity is found to be with the lowest evaporation rate and highest rain moisture rate and it is lowest in the case where evaporation rate is the

highest with the lowest rain moisture rate. Majorly salinity is increasing with increased rain moisture rate.

The timeline of the variables shows some interesting insights, great variations are found in profit with lower evaporation rates comparing it with medium and high evaporation rates. In low evaporation rate BAU is found to produce more profits over time while in medium and high evaporation rates profits are found in SGR. While salinity and logging are found lowest in major instances in SGR comparing it with IMP and SGR. However, salinity is higher in high evaporation rates and logging is higher in all rain moisture rates in BAU. Variation in rain moisture rates exhibits that profitability and water quality parameters have become better off under low evaporation and rain moisture rate around half of the time steps and become worse off for the rest of the time under BAU. However, SGR was found to be better at handling high rain moisture and evaporation rate. Under climatic risk with extreme salinity associated with logging, BAU performs better but SGR performs better otherwise. Human coordination can prove useful if it is based on certain rules for governing their water use behavior even under extreme climate change.

The physical experiment concludes that under no water scarcity conditions or if farmers are located nearer to canal heads, conventional methods of irrigation give positive profits and improved water quality parameters, while intervention scenarios provide better results if farmers are located at a greater distance from the water source. In extreme water table depth scenarios SGR can not effectively manage resources rather IMP proves to be more useful in managing water resources.

The timeline of profits shows that overall SGR performs better compared with other scenarios except in the case of lowest water table depth and spatial distance scenarios. However, minimum average profits are highest under the combination of

water table depth and spatial distance of 5 each for both IMP and SGR comparing it with BAU perspective. In both interventions for managing irrigation water scenarios, positive average profits fall as water table depth and spatial distance observe an increase.

Figure 6.19 exhibits that along with rising spatial distances, the difference in per acre profits are decreasing among water management scenarios. IMP and SGR are showing 16% and 26% more growth rate in profits per acre comparing with BAU scenarios when water table depth of 5 and difference is more visible when farmers are located at more distance from the water source. Moreover, when water table depth rises difference in growth rate between BAU and intervention scenarios falls but remain positive. This can be related to the fact that in extreme physical conditions effectiveness of water management scenarios reduces in comparison with other cases. In the climate change experiment all water management scenarios posit to raise groundwater irrigation cost by 48% to 60% more than the already average per acre groundwater use cost incurred to the farmers in Pakistan to manage water quality parameters. This can also reduce excessive use of groundwater as the need for supplemental irrigation has already led to groundwater over-exploitation in many regions, resulting in a decline of water tables (El-Naqa et al., 2010).

CHAPTER 7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion and Discussion

Eliciting the major objectives of the study this work aims at finding out the conjunctive water management framework to deal with issue of water sustainability for irrigation using ABM. The ABM deals with the complexity of coupled human and natural systems. We have incorporated farmers' behaviour into the natural system managed by regulators. This study has envisioned some important insights regarding water management behaviour and policies.

Introduction and background are given in chapter 1. Chapter 2 builds upon the literature and highlights the gaps which help us to form the objectives of the study. Chapter 3 presents data and methodological framework importantly overview, design and details (ODD) of ABM developed in this study. Rest of the chapters assessed the objectives by implementing different parts of the model through formulation of the hypotheses. Chapter 4 investigated salinity and logging problems in irrigated agriculture. It is very important for farmers to understand the extent and nature of these menaces in water and soil. We have developed different scenarios for small, medium and large farmers based on their land holdings and spatial differences. The variations in the profits and yield/acre among farmers with different distances from water sources are not much visible. However, water use inequality is substantially prevalent. This indicates the differences in water productivity and the potential of water-saving through managing the water use behaviour of farmers. This affirms the fact that water endowment and water use in crops may not be strongly linked with the crop yield and hence profits if water is not in critical supply (Fisher, Harding, & Kemp-Benedict, 2014).

Chapter 5 presents ABM of farmers' decision-making for irrigation with the varying groundwater costs to study the importance of individuals. Model results show that accounting for individual heterogeneity has impacted the system and leads to the formation of emergent patterns. Results show that monitoring and rational regulations make farmers use groundwater rationally. It is observed that the large farmers with less distance from water source are using more surface water and are also complementing it with groundwater where it is reckoned necessary.

A major share of water for irrigation; ground and surface is consumed by large farmers. Differences are skewed more towards the farmers located nearest to the canal heads. The results are similar to the survey of crop yield disparity along the reaches of the irrigation system in the Lower Chenab Canal where the greater availability of abundant surface and good quality groundwater has resulted in disparity in crop yield in the area (Culas & Baig, 2020). The inequality in resource access and use appears worst under severe climatic conditions. This necessitates the implementation of different set of policies for large and small farmers based on their location around water source subject to the change in climate otherwise traditional water use practices can exacerbate water quality-quantity balance in agriculture. Model concludes that groundwater extraction cost emerged to be higher with higher water table depth scenarios over time. This means that alternative cost regimes can be introduced to limit the groundwater use. But the rise in cost can itself emerge to the relatively lower level if water table depth is higher. However, full reflection of the groundwater abstraction cost cannot be achieved if water table depth is reached to the maximum limit. In other words, regulations of ground water abstraction cost near canals can bring relatively better results without deliberate policy change related to cooperation and reciprocity. Under IMP and SGR farmers are using relatively less surface water and more of groundwater

if they are nearer to the canals. This makes them bear more water costs and if they are near canals, they can be compensated with the part of the cost of groundwater they pay in addition for compliance with the social norms of using less surface water. Use of surface water near water source can be restricted if farmers are charged progressively equivalent to the groundwater cost for surface water use. The regulations in case of IMP will require extensive supervision. But in Pakistan, there is no such control or supervision of water drawdown available. Farmers can report water abuse by other farmers or defects in observing the policies implemented by regulators. But social norms hardly allow them to report misuse of groundwater. Subsidies and penalties are found useful up to some extent. Penalties in the form of restricting water withdrawal or subsidies such as getting water withdrawal rights for the time of water shortages can prove useful. Farmer's self-adaptability and learning about the best fit of the model are also important for groundwater use behavior. Farmers learn from their water use and resultant crop yield; in the case of high groundwater-use induced salinity reduced crop yield to make farmers use less water. Our study posits that other than norms, groundwater management must include enforcement, and monitoring which can significantly improve groundwater management performance.

Chapter 6 presents prospects from the analysis of conjunctive ground and surface water management. In Pakistan, surface water is under-priced, and groundwater is subsidized and limitlessly used, making issues of logging and salinity, which has affected more than 20% cultivable area of the country. In this chapter, we have assessed the issue of Warabandi and 'functional' inequality in water provision to farmers at the tail of the watercourses. Groundwater is heavily depleted in some parts of the upper Indus Basin. The spatial difference in the surface water and groundwater abstraction subsidy and limit put a difference in the availability of surface water at the tails of the

watercourse. The effect of fall and rise of water resource usage fee is different from the difference in the initial value of O & M costs and subsidies or groundwater withdrawal charges.

Our results of the model show that moderate weather favour to implement IMP of water management to achieve potential benefits while extreme weather favours traditional irrigation perspective as BAU. SGR becomes more effective in case of high rains and evaporation. This can be linked with the fact that traditional practices of irrigating crops may become detrimental for system parameters in case of climate change. But all water management perspectives become impotent when there are more rains and fewer evaporation rates. This can be related with the high logging and flood-like conditions in a real-world context. Overtime data and plots shows that low evaporation rate BAU is found to have more profits, while in medium and high evaporation rates profits and water quality parameters are well managed by SGR. This means that human coordination can prove useful if it is based on certain rules for governing the water use behavior even under extreme climate change. In the climate change experiment all water management scenarios posit to raise groundwater irrigation cost 48% to 60% more than the existing average per acre groundwater use cost incurred to the farmers in Pakistan to manage water quality parameters. This can also reduce excessive use of groundwater as the need for supplemental irrigation has already led to groundwater over-exploitation in many regions, resulted in a decline of water tables (El-Naqa et al., 2010).

The physical experiment concludes that under no water scarcity conditions for farmers located nearer to canal heads; conventional irrigation practices give positive profits and improved water quality parameters, while intervention scenarios provide better results if farmers are located at a greater distance from the water source.

However, in extreme water table depth scenarios SGR can not effectively manage resources rather IMP proves to be more useful in managing water resources.

In physical experiments, rising spatial distances bring positive profits in intervention perspectives IMP and SGR comparing with BAU while the difference is more visible when farmers are located at more distance from the water source. However, when water table depth rises difference in growth rate between BAU and intervention scenarios falls but remain positive. This can be related to the fact that in extreme physical conditions effectiveness of water management scenarios reduces in comparison with other cases.

The core of the conclusion is that in major experiments SGR is found more effective in bringing up desirable results. That is collective action for water management which can be brought into practice by allowing farmers to formulate their own rules for water management can evolve as institution if complemented by government support in the form IMP. To implement SGR as a tool, an operational model inclusive of all stakeholders' mapped behaviour which corresponds the real world is required. Moreover, it is also likely that IMP is more effective in building general adaptive capacity when weather is moderately changing. This means that IMP can enforce rules to bring desirable results under specific circumstances. Otherwise, the resource will be captured and misdirected by large and powerful farmers. An epitome of management will be that institutions act as passive observers, penalize or reward for better water management and combining it with the decentralizing of the system and leaving it to the farmers to use and develop rules as per their local knowledge. The effectiveness of the model in terms of local and practical knowledge can be mapped better for managing the shocks in the system with the coordinated efforts of institutions, individual farmers, and farmer groups.

Before presenting policy recommendations problems associated with current water use practices are highlighted. Groundwater withdrawal affects canal water diversion and its availability for farmers. Reduction on subsidy on electrical tubewells can substantially reduce groundwater withdrawal. In contrast, an increase in subsidies for the farmer at the heads of water resource under surged fuel prices, the resource can make farmers to divert less or no surface water and make it available for the farmers at tails. Furthermore, the areas where surface and groundwater both are available in plenty a combination of both policies can bring fruitful results. Reducing subsidies in the high elevated areas can reduce groundwater use to a lesser extent as surface water is not available or costly to divert. The regions with critical groundwater table dynamics as water table depth < 1 meter or water table depth > 50 meters will have a greater impact on groundwater management policies. Along with the reallocation of surface water, more time can be fixed for farmers at tails so that they can fulfil water requirements and don't wait to exchange their turns. Cultivable areas on the tails of LBDC as Khanewal, Sahiwal, Jhanian and Vehari are using 70% or more groundwater. Water allowance of 2 days compared with 24 hours can be replaced in these areas to solve the problem of groundwater withdrawal. Groundwater use subsidy should be enacted for the farmers in Okara and Balloki so that water for Khanewal and Sahiwal division can be transmitted. Or social norms and rules can be identified to transmit water with the help of information about the water resource situations in the watercourse.

7.2 Policy Recommendations

- The area with less surface water and falling depth to the water table is recommended to grow less water-intensive crops like pulses and oil crops. As water-intensive crops are highly affected by surface water shortage.
- Informal groundwater markets can be subsidized at the head of canal command areas.
- Conjunctive water management largely depends on the way groundwater is used and managed. Groundwater withdrawal ceiling can be enacted to penalize farmers if they are using more than the ceiling in groundwater areas, which are critically depleted.
- The critical situation of groundwater withdrawal in some areas of UIB and Baluchistan where surface water is not available, communities must be encouraged to manage groundwater extraction. An immediate reduction in subsidies or rationing the electricity can prove useful for slowing down water mining.
- Groundwater markets must be supported by a legal framework by recognizing caps and trade rights of water use as small farmers farther from tubewell or do not have social networks are denied the tubewell water.
- Best irrigation practices should be subsidized and promoted to increase water productivity and reducing the burden on depleted groundwater.
- Surface water distribution in line with the spatial destitution of the farmers should be devised for equitable water management.
- Allocating property rights of surface water to the farmers at the tail and make those at the head to pay for water use.

7.3 Limitations of the Study

- Coupled agent-based/groundwater modelling includes technical complexity, a lack of flexibility in scenario design, and the difficulty of performing coupled sensitivity analysis.
- This study lacks a practical fully mapped behavior of all stakeholders which can make model fully implementable.
- Groundwater flow equations can be calibrated with the ABM model to bring an improved conditions of groundwater flow into the model
- Farmers' crop choices in the study are limited. We have assumed wheat-rice or wheat-cotton crops for cultivation, and data for irrigation water requirement is calculated.
- This study lacks a real time survey of the farmers which can help incorporate true social norms followed by farmers in irrigation practices.
- The Planation and growth module of the crop are not considered. We have directly considered that crop is grown, and crop yield is updated dependent upon the quality and quantity, and type of water used.
- We have not fully reflected farmers' profit-making behaviour as usually, it is available in economics studies as optimization and simulations. Inclusion of complete optimization model.
- This study lacks a real-time survey of farmers reflecting their behaviour of using ground and surface water and their perceptions about water quality and its effect on logging and salinity.
- We have not explicitly considered the improved flow of surface water in case of building up new dams and lining of watercourses.
- We have not included the effect of rising prices of irrigation and other inputs.

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Appendices

Appendix-A

Table A3.1: Parameterization of the Model

Parameter	Description	Values	Units	Notes	
Land	How much land is cultivated by one farmer?	5 -100 Acres	1 Hectare= 2.47 Acres	90% are small farmers and having land less than 5 acres 10% farmers have land > 5 acres.	
DWS	Distance from water source	1-150KM	Kilometre	Distance from water source will determine leakages, water losses	
WTD	Water table depth (cm) 100-5000	<300 (5%) 300-1299 (15) 1300-1800 (65%) >1800 (15%)		Depth to water table will determine ground water availability and ground water travel cost.	
	Below 150 is water logged area and critically dangerous for crop growth. 100-300 is not potentially safe for growth.				
Changes in water logged area or water table depth	1. An increase in GW use by 25% decreased the water logged area by 16%, while an increase in GW use by 50% decreased the water logged area by 25%. (Chandio et al , 2012). 2. IF Groundwater use > 50% of total water water use then WTD will increase by 10-25 % of its WTD. If Groundwater use it is between 25-50% then WTD will increase by 5-10 % of its WTD. 3. Single water unit will cost between 300-500 4. For depleted areas WTD > 1000, every groundwater unit will cost them 600-1500.				
EC	Electrical conductivity			Electrical conductivity determine salinity	
EC of surface water	Electrical conductivity	0.3	DS/m		
EC of groundwater	Every time if groundwater use is more than 50% of total water use will increase EC by 0.5. If it is less then EC will range between 0.1-0.5.				
Salinity in surface water	53% farmers already have salinity with EC > 3. Others have between 0-3. If only surface water is used then salinity will increase by .0005 by every tick..				
Salinity	Salinity will change by the sum of EC of groundwater use and surface water use.				
Reduction in wheat, rice and cotton crop due to salinity threshold	%Reduction in yield	>0%	>10%	>25%	>50%
	WheatEC (DS/m)	4	4.9	6.4	8.7
	RiceEC (DS/m)	2.5	6.0	8.8	12.5
	Cotton	5	7.7	8.37	17
Initialization					
WTD(water table depth)	It is function of farmer's difference from water source. More Distance farmer has more depth to water table.				
Logging	Logging and salinity are the function of WTD and Distance from water source.				

	Logging= X / DWS; It must be the function of WTD ranges between (100-2000) DWS; distance from water source			
Salinity	It is complex phenomena. Drainage problem cause salinity. If only surface water is used then there will be a problem of drainage in areas where DWT is low. Salt may not be leached out. And if only groundwater is used as irrigation source then groundwater related salinity will be created. Initially salinity will be set as a function of DWS $Salinity = DWS / X$; Range=4.69-15.6			
Maximum-Min crop yield.		Wheat	Rice	Cotton
	Max	60maunds/acre	60maunds/acre	40 maunds/acre
	Min	8maunds/acre	11maunds/acre	10 maunds/acre
	Irrigation turns required	Max 5 turns	More than 7 turns with groundwater	Max 5 turns
	Irrigation cost	450/acre	500/acre	90/acre
	Groundwater cost	500/unit	500/ unit	500/ unit
	Surface water cost	95.7/acre	95.7/acre	95.7/acre
	Total production cost	11000/acre	600-12000/acre	5000-20000/acre
	Price of crop	1350/maund	1863/maund	10000/maund
Change in crop growth due the use of irrigation water	Crop growth	Surface Water only	Surface and GW	GW only
	Wheat	80-100%	-9.8	-18.3
	Cotton	80-100%	-4.6	-8.8
	Rice	80-100%	-2.5	-10
Oswh	Standing surface water height	zero		
SWH	New surface water height	4 inches	4-6 cubic feet	
Total Annual Water Discharge	Water discharge every year	12.5 * 6 cubic feet	?	
Water Discharge in canal command areas		300-800 mm/ year in canal command areas		

ava-wdischarge	Water discharge for every turtle	47 * 72 cubic feet	Smallholders receives 50% or less	40 to 60 % land is left stray		
Mywater Losses	Seepage/ leakages	30%		Water losses of every farmer		
Crop-demand		260 cubic metre/ha				
Groundwater Pumping cost		150/hr	500-1000 Rupees/hr	3 hours/1 acre demand of 4-6 cubic feet water. It takes 1 hr/acre from surface water as compared with 3 hours of gw to fill the 4-6 cubic feet of water		
Evaporation						
Change in surface water level	lot of 5 year is a wet year. Logging, salinity and water availability and water requirement will change.					
Seepage rate/ water loss rate		30%		It will be the function of distance from water source as well.		
Abeyana		300 to 500/acre	Depends on the nature of crop			
SW allocation time	Surface water allocation time	1 hr for 1 acre		It's may be the function of land area cultivated by farmer		
Risk coefficient						
Minumum requirement to stay in market						
Irrigation turns	1 st	2 nd	3 rd	4 th	5 th	6
wheat(180-420 mm) (Nov- March)	15-20 days	After 30-35 days	After 30-35 days	After 30-35 days	After 30-35 days	-
Cotton crop(June-Oct)	20 days	After 20-30 days	After 20-30 days	After 20-30 days	After 20-30 days	After 20-30 days
Dry or wet years.(Shock)	Every 1 out of 7 years are wet. Wet year reduces salinity but increase logging. Wet years are not good for wheat but good for cotton crop. There will 1% rise in WTD and 1% fall in salinity. Crop yield will be changed. And this will be considered as shock. Majority of the rains as 80% are received in cotton crop period. But if it is a wet year than crops growth will be affected up to 50%.					
Crop yield for wheat	$\text{yield} = \alpha \times \frac{\text{surafcewater used}}{\text{Toatl water demand}} + \beta \times \frac{\text{Groundwater used}}{\text{Toatl water demand}}$ – crop reduction as function of logging and salinity $\alpha = 60$ and $\beta = 30$					
Crop yield for cotton	$\text{yield} = \alpha \times \frac{\text{surafcewater used}}{\text{Toatl water demand}} + \beta \times \frac{\text{Groundwater used}}{\text{Toatl water demand}}$ – crop reduction as function of logging and salinity $\alpha = 40$ and $\beta = 15$					

Table A3.2. Narrative Description and Purpose of Experiments

Narrative description	Purpose	No.	Name	Rain parameters		Economic Parameters	Physical parameters	Climate parameters	Parameter(s) varied	Specific combination(s)	N-runs (10 repetitions * combos)
				Random-Rain(off)	Seasonal-Rain (on)						
Business-As-Usual(BAU)	Impact of cropping on logging salinity and profitability of farmers is system works as it is	1	Baseline	FALSE	TRUE	FALSE	FALSE	FALSE	0	1	10
Self-Governing Rules(SGR)	Impact of farmers cooperation to not to use surface water in 50% of the turns. They will sell their turns or exchange it with the farmers down streams.	1	Baseline	FALSE	TRUE	FALSE	FALSE	FALSE	0	1	10

Institutional Management perspective(IMP)	Farmers using more surface water nearer to canal will be punished (charged / penalized surface water use equal to the price of groundwater abstraction) and rewarded otherwise equivalent of the price of groundwater they are using.	1	Baseline	FALSE	TRUE	FALSE	FALSE	FALSE	FALSE	0	1	10
BAU, SGR, IMP	Purpose is to see how 3 water management scenarios make difference if water cost is varies	2	Economic -cost	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	Surface and groundwater cost	27	270
BAU, SGR, IMP	Impact of changes in the prices pf crops on the system	3	Economic -prices	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	Wheat and cotton crop prices	27	270
BAU, SGR, IMP	Impact of farmers capacity to stay in system	4	Economic -profits	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	profit threshold for farmer to stay in the system	9	90
BAU, SGR, IMP	Impact of climatic variables on system	5	Climate	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	Evaporation rate and surface-water discharge	27	270
BAU, SGR, IMP	Impact of changes in Physical properties on system and concerned variables	6	Physical	FALSE	TRUE	FALSE	TRUE	TRUE	FALSE	Spatial distance and WTD depth of farmers	27	270

Source: Author's own developed

Table A3.3: Type of variations and Number of Parameters varied under water management perspectives

Management perspectives	Business as usual, Self-Governing-rules, Institutional Management			
Baseline	Null(No parameter is varied)			
Economic	Parameter varied	Type of Variations		
1	Change in prices of cotton crop	2000	4000	6000
2	Change in prices of wheat crop	1000	1350	1600
3	Change in surface water cost	50	100	200
4	Change in ground-water cost	50	100	200
5	Change in profit threshold	3000	5000	10000
Climate	Parameter varied	Types of variation		
1	Rain Moisture Rate	0.2	0.4	0.6
2	Evaporation-rate	0.2	0.4	0.6
Physical	Parameter varied	Types of variation		
1	Spatial-distance	5	10	20
2	Water table depth	5	10	20

Source: Author's own developed

Table A6.1: Canals in Lower Bari Doab Canal

Sr.	Abbreviations	Canals in LBDC
1	CLVIII/2	Guegra Dy
2	CLVIII/4	Qadirabad RS
3	CLXII/4	Budhwala CRH
4	CLXVII/2	Mianchunnu
5	NPLX/15	KachaKhu CRH
6	NPLX/17	NPLX/17

Table A6.2: Classification of depth to water table in Feet

Sr.	Water table Depth (Feet)	Categories
1	0- 5	Waterlogged
2	5 - 10	Likely to be water logged
3	10 - 20	Normal
4	20- 30	Normal
5	30- 43	Likely to be depleted
6	43-59	Depleted
7	>59	Highly Depleted

Source: Khan et al., (2016)

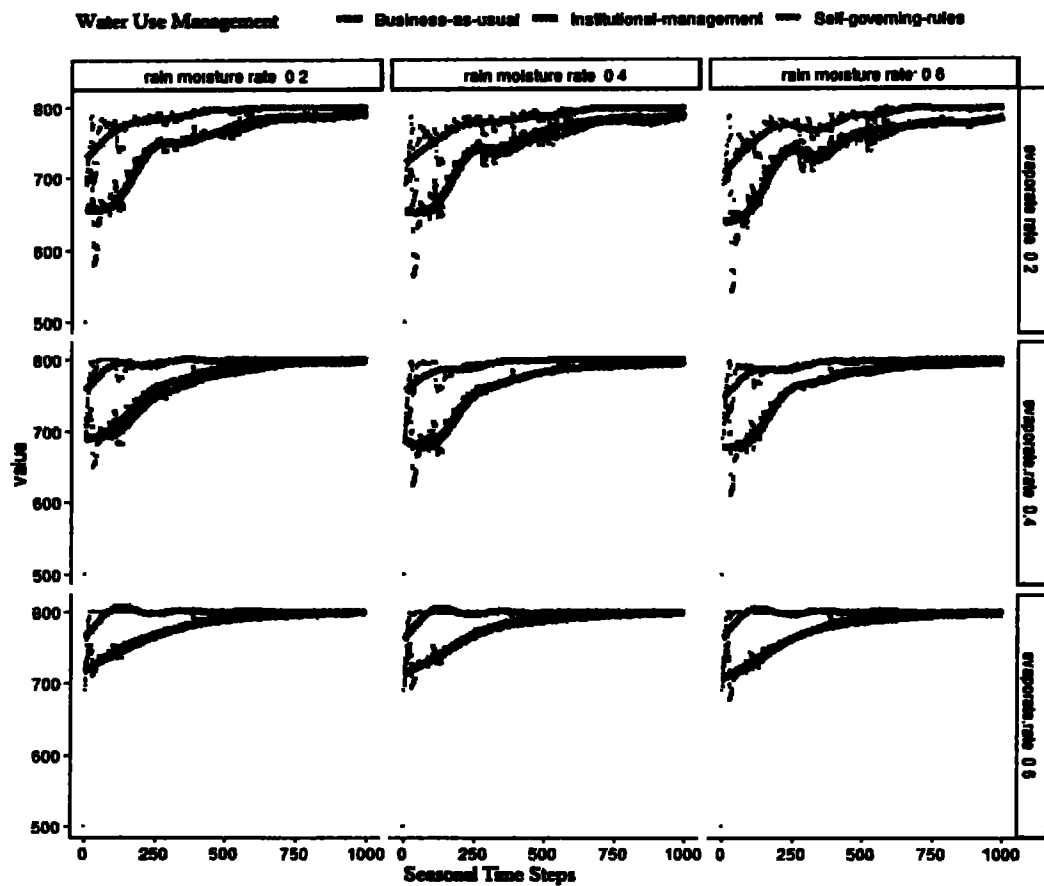
Table A6.3: Classification of Salinity as per Electrical Conductivity

Sr	Electrical conductivity(ds/m)	Saline Categories
1	0-2	Non-Saline
2	2.1-4	Slightly Saline
3	4.1-8	Moderately Saline
4	8.1-16	Highly Saline
5	16.1-32	Severely Saline
6	20.1-45	Extremely Saline

Source:Khan et al., (2016)

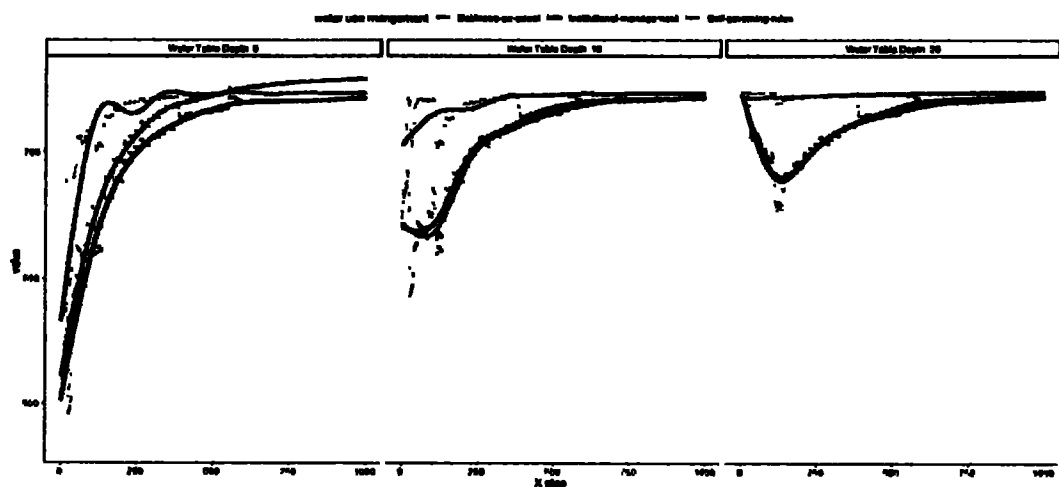
Appendix-B

Figure B 5.1: Groundwater Cost across rain-moisture and evaporate rate



Source: Author's own work

Figure B5.2: Variation in Groundwater Cost across water management perspectives



Source: Author's own work

Figure B6.1: Logging basics for time steps 0-500

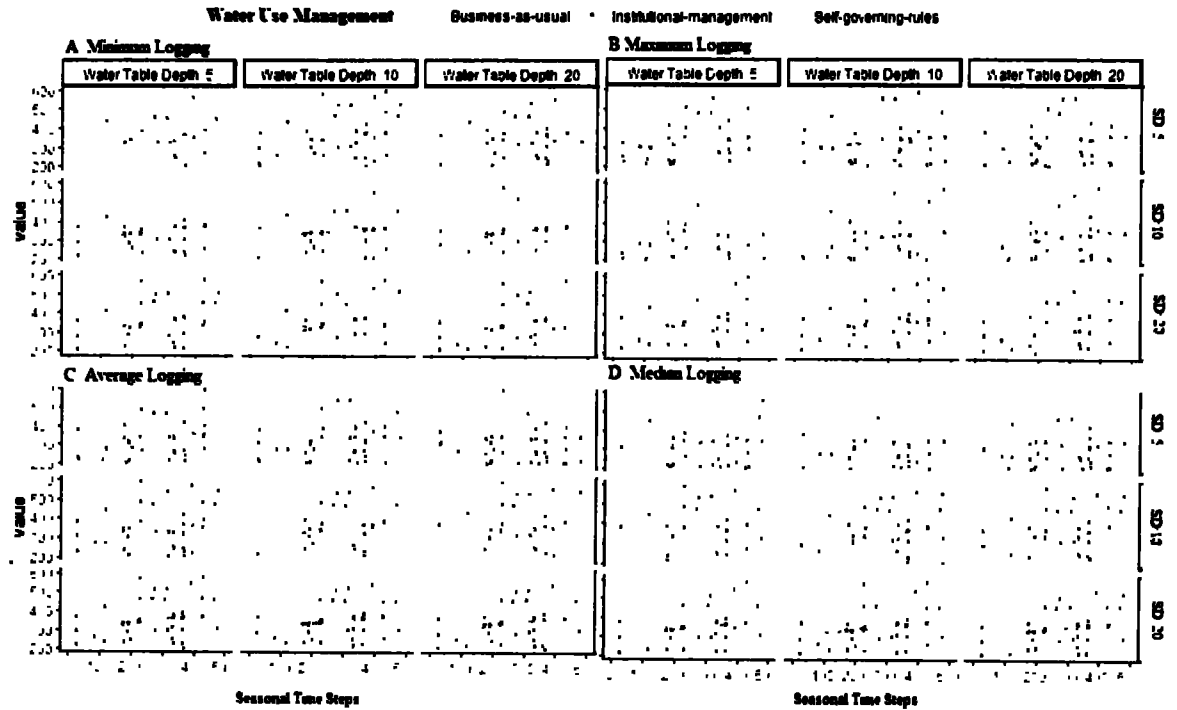


Figure B6.2: Logging basics for time steps 500-1000

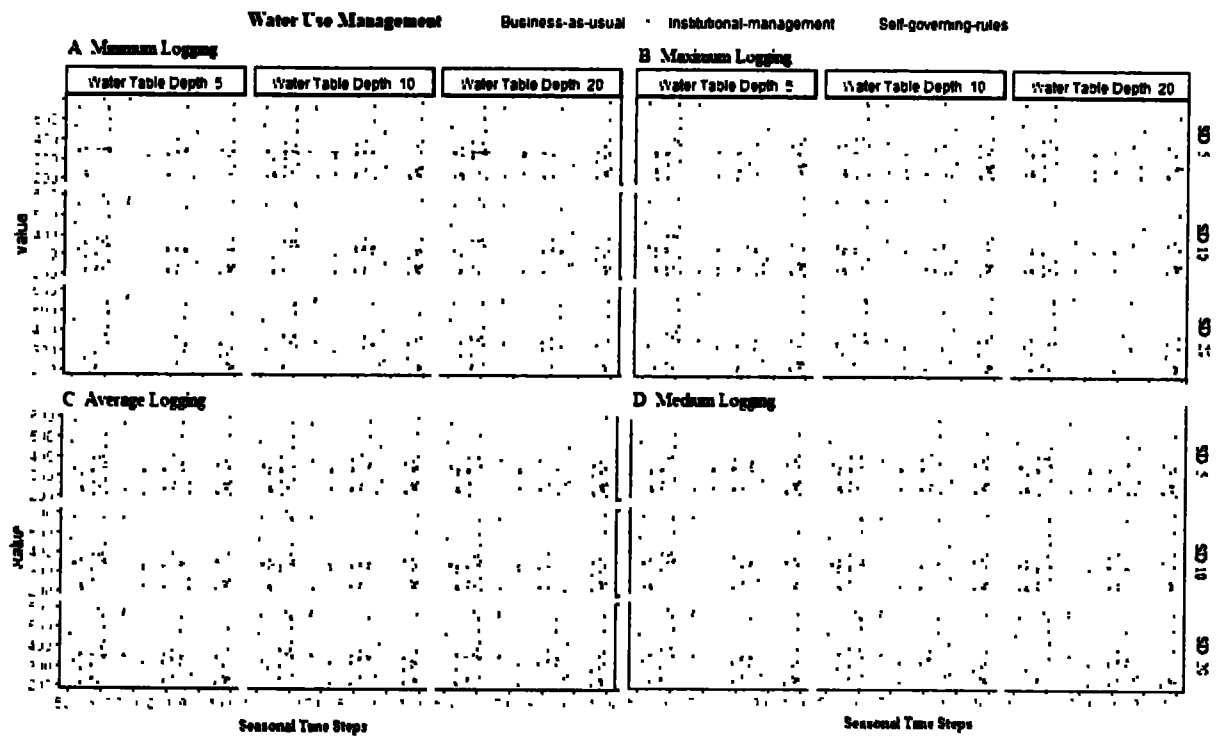


Figure B6.3: Logging value ranges from 200 to 1000 for time steps 500-1000

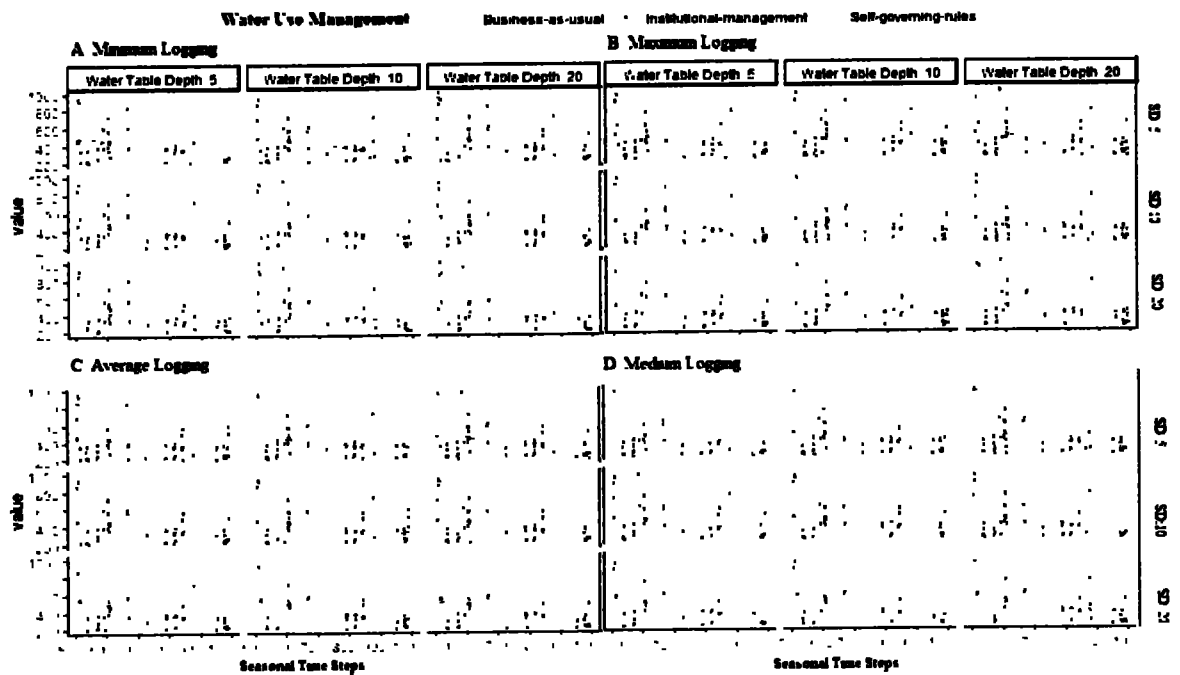


Figure B6.4: Logging value ranges from 200 to 100 for 500-1000 time steps

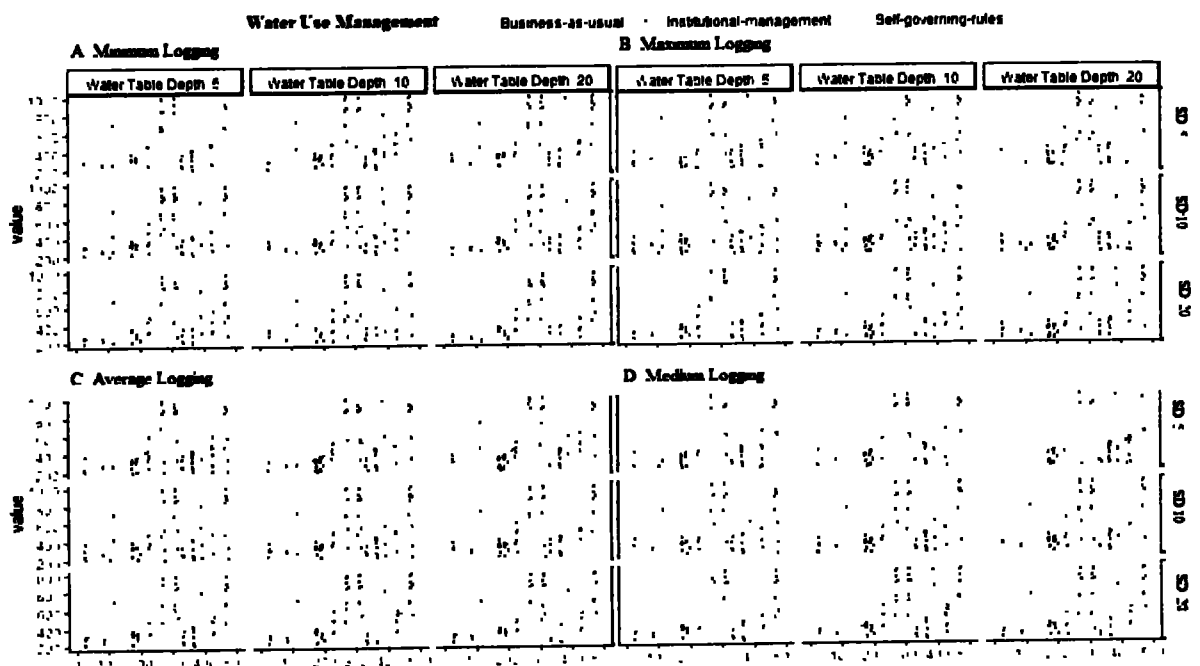
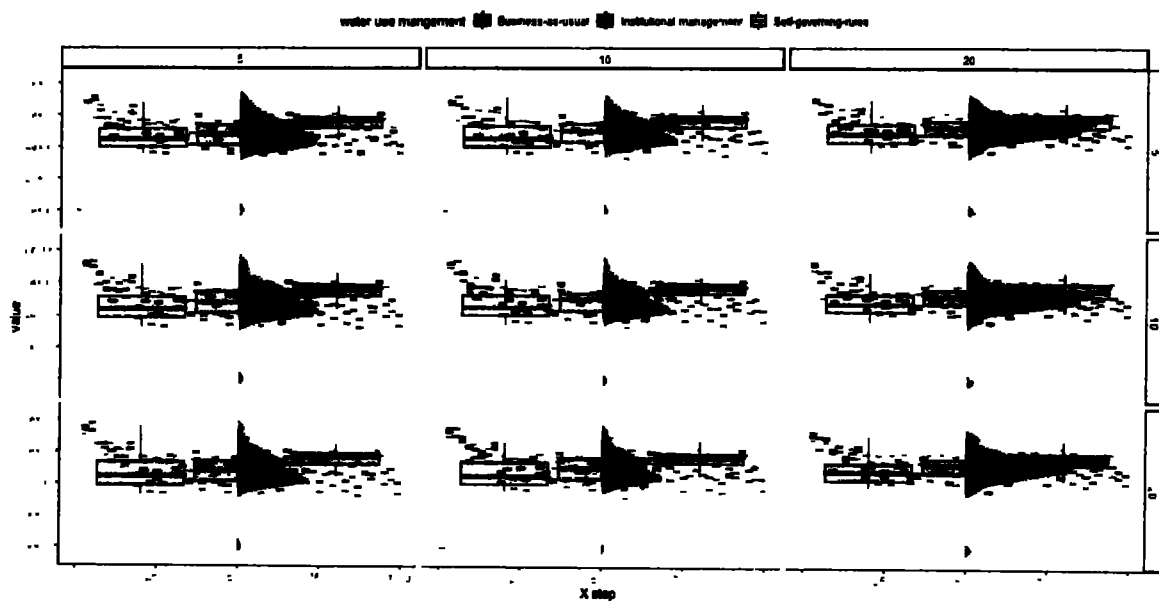


Figure B6.5: Rainbow chart of profits across Physical Scenarios

Profits Across Physical Experiments



Appendix C

Appendix C 3. Water Management Perspectives

Water is allocated as per previous land cultivation area at the time of construction of canals. Now area under cultivation is more and so there is need to allocate more water so that water demand can be fulfilled. In order to understand that how dynamics of the irrigation system works; following arrangements are needed to be considered.

1. Business as usual,
2. Self-governing rules
3. Institutional management Initial Check of the Model

Farmers are located on the canal and they will receive water turns as per schedule every 10 days. It means that over a year a farmer will receive 47 turns approximately out of 53 weeks or total of year. As rest of the days canals usually are not operated for Bhal Safaae(canal maintenance). Farmers usually cultivate two crops wheat and cotton. From November to March wheat is grown and from June to October cotton crop is grown.

In selected area, water is deficient. It doesn't fulfill the demand of farmers. The farmers nearer from water source will have less water deficiency as compared with the distant farmers. Either farmer will combine his turns by exchanging with other farmers or use groundwater as a supplement. Now the farmers who successfully combine their turns will have to use less groundwater and converse is also true. In the area combining turns of surface water help to meet 60-70% of water demand. All variable of farmers as benefits, logging and salinity will change accordingly. As two crops are grown. Yield will change twice in a year period. At every irrigation turn all parameters of the farmer will change and if farmer's demand is not met he

will use groundwater which will change his costs, benefit and other variable scenario as well. Farmer farther from canals will face water losses of seepages. More distant a farmer from water source more he will face water losses his fewer demand will met through surface water rest demand will be fulfilled through groundwater. Initial view of the model is given above.

1. Process Overview Scheduling

Water is received on the basis of rotation to every farm once in every 10 days we call it a turn. Farmers use water they need or if it fulfills their crop demand otherwise they exchange water turns. Or they divert water to other minor crops. The farmers at more distance will be unable to meet demand. And if they are unable to meet water demand by their turns accordingly per acre yield is less. Due to seepage and evapotranspiration water availability will be less at the turn of the farmer at tail. Farmers can trade their water entitlements with other farmers at some agreed prices or exchange turns. A farmer can combine 2 to 3 turns and try to fill the demand and if combining turns can't fill the demand then farmer will use groundwater to supplement irrigation water. A total 12 irrigation turns are required but they receive 47 turns So farmers try combining 2 or 3 turns by exchanging turns with the farmers who want to buy or use turn now than future. In rest of the turns farmers use to irrigate other crops which are not considered in the study.

Initial Model:

4. Farmer will get resource as per allocation with every tick (every 10 days). It means that if there are 10 farmers with 10th tick all farmers would have received water turns and the same will be repeated 47 times.
5. In total farmer maximum required irrigation are 6 for each crop. In a month period they will receive 4 turns.

6. Out of the turns farmer will evaluate if he want to use the turn or not?. He exchange his turn with any farmer who are in need to buy/exchange the turn. And next time buying farmer will return the turn.
7. If farmers are not exchanging turns then they can buy/sell turn as low as Rs200-300 per acre of land.
8. Majorly the farmers having land less than 7 acre will be unable to meet the water demand as they receive less hour of duty. Similarly, even large farmers farther from canal may be unable to meet demand due to the issues of seepage as seepage remains around 30 to 40%
9. Farmer will change its all parameters as logging, salinity, water table depth related parameters. Crop yield will be updated after 4 to 6 months which will be the function of logging and salinity problem.
10. Distant farmer from water source which is assessed through 'who' number of farmer will face more water seepage and evaporation problems.

Model with water trade:

Farmer use allocated water as per his turn. There can be following possible scenarios:

- 35 If farm is at tail and land area is less than <7 acres, one water turn will not be sufficient to meet the water demand. Farmer will trade his turn and then combine his two to three turns to irrigate his land. Wait time may reduce his crop productivity. He will exchange his water turn with upstream farmers. Even this treatment may not fulfill his water demand.
- 36 If farm is at head and farm area is < 7 acres and is at head he may sell his turn to get water exchanged with other neighboring downstream farmers.
- 37 If farm is at head and land area is > 7 acres and water demand is fulfilled. Then farms productivity will be reasonably higher in short run but in long run he will

accumulate logging and salinity which will affect his crop growth in long-run. If demand is not met he may trade water or use groundwater to fulfill the need.

38 If farm is at tail and land area is > 7 ha. He may not be able to meet crop demand.

He will exchange water right with the farmers at head. Or he will use groundwater to meet the crop need.

39 Usually farmers prefer not to use groundwater as it is far more expensive than surface water

Three cases are needed to be assessed

1. Business as usual:

After defining the turns to be exchanged or not. Over time let 'say for the period of 25 years simulations are run to see how system emerge.

2. Self-governing rules

In, self-governing rules; as a seed some of the farmers with land > 7 acres initially cooperate to not to use surface water in 50% of the turns. They will sell their turns or exchange it with the farmers down streams. Initially cooperates will get less benefits but overall system will improve. But doing so they can improve water logging and salinity scenario which have them to have win win situation in long-run. A game-theoretic framework will be used to see if some self governing rules are emerged to have lesser logging and salinity and more crops per drop or water management. In contrast initially, farmers with land < 7 acres will not cooperate and then may adapt if others are cooperating in neighbors.

3. Institutional arrangements

In institutional arrangements, farmers using more surface water nearer to canal will be punished (charged / penalized surface water use equal to the price of groundwater abstraction) and rewarded otherwise equivalent of the price of groundwater they are using. It will be assessed that how long it will take to have sustainable agriculture to

Appendix C6.1. Crop water requirement

Crop water requirement (henceforth referred to as CWR, m³/ha) is calculated by accumulating crop evapotranspiration (evaporation and transpiration) under optimal conditions (henceforth referred to as $ET_{c, opt}$, mm/day) for the complete growing period of a crop. Optimal conditions are referred as the conditions with no shortage of water for evapotranspiration of the crop (Allen, et al, 1998).

CWR is calculated as

$$CWR[c, p] = 10 \times \sum_{t=1}^{l_p} ET_{c, opt}[c, p, t] \quad (1)$$

Here 10 is used to convert the unit of CWR from mm to m³/ha. $ET_{c, opt}$ is the evapotranspiration under optimal conditions for each province (p) and each crop(c) under consideration. And it has been calculated during l_p (full growing period of a crop).

$ET_{c, opt}$ is calculated as

$$ET_{c, opt}[c, p] = k_c \times ET_o[p] \quad (2)$$

This is a derived method from Allen et al., (1998) by Chapagain, et al., (2007) and used by Kampman (2007) and many others. Here ET_o in above equation is reference crop evapotranspiration [henceforth referred to as ET_o (mm/day)] and is calculated by using Penmen Montieth Technique devised by FAO (Allen, et al, 1998). ET_o is the evapotranspiration that shows evaporative demand of a crop, irrespective of crop type. K_c is the crop coefficient that shows the relationship between ET_c and ET_o . K_c keeps on changing during different time period of crop growth.

Appendix C 6.2: Calculating Evapotranspiration

Penman-Montieth method has been used to calculate Reference crop evapotranspiration (ET_0). Wide range of empirical methods are available in literature for the calculation of ET_0 . But Penman-Montieth method is calibrated over other techniques as it has a strong likelihood to predict actual ET_0 under a wide range of agro-climatic conditions even for the short time period data. Moreover, studies conducted in Indus Basin recommended the same method for the calculation of ET_0 (FAO, 1998; Ullah, M. K., et al, 2001).¹⁷Penman-Montieth method uses the following equation to estimate ET_0 .

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (63)$$

Here in above equation

ET_0 reference evapotranspiration (mm/day)

R_n is the net radiation at the crop surface (MJ/m²day)

G soil heat flux density (MJ/m²day)

T mean daily temperature at 2 m height (°C)

u_2 wind speed at 2 m height (m/sec)

e_s saturation vapor pressure (Kpa)

e_a actual vapor pressure (Kpa)

$e_s - e_a$ saturation vapors pressure deficit (Kpa)

Δ slope vapor pressure curve (Kpa/ °C)

γ psychrometric constant (Kpa/ °C)

Data on climatic parameters for the different agro- ecological stations has been obtained from Pakistan meteorological department (PMD, 2011) for the years 1970-

¹⁷ FAO, 1998. Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements, FAO Paper No. 56, Rome.

2008. List of weather stations accompanying the provinces is available in Appendix IIIa. Moreover, list of selected stations with detailed information can be viewed in Appendix IIIb. Meta data has been used as an input in CROPWAT 8.0 (FAO, 2010) to calculate ET_0 of the selected stations for which data are available. Selected stations provide reliable rather than real values of estimates for ET_0 for the entire provinces. Cropwat calculates ET_0 using Penman-Montieth method incorporating monthly data on the following variables as minimum & maximum temperature, sunshine hours, wind speed and humidity. A representative ET_0 has been calculated by averaging the available stations' ET_0 for the provinces.

Precipitation effective (P_{eff} , mm/day) has been calculated by CROPWAT 8.0 from precipitation total (P_{total} , mm/day) for the available stations and then averaged to get provincial level representation for each month in the study period.



bring logging and salinity to the minimum acceptable level suitable for crop growth. Ideal situation for water management will require farmers to use more than 50% of groundwater. But this may not be ideal for individual farmers as it will increase his production cost and reduce crop yield.