© *Pakistan Journal of Economic Studies*
https://journals.iub.edu.pk/index.php/pjes
Vol. 5, No. 1, June 2022, Pages: 135-165

ISSN 2708-1486 (E)
ISSN 2708-1478 (P)

An Agent Based Model for Combining the Climatic, Physical and Behavioral Response to Logging, Salinity, and Farmers Earnings in Irrigated Agriculture of Pakistan

Mamona Sadaf[1], Abdul Jabbar[2] & Asad Zaman[3]

Abstract

Framers use excessive groundwater to meet surface water shortfall in irrigated agriculture of Pakistan. This water use behavior is creating inequalities in Pakistan across time and space in farmer's profit and water quality-quantity balances. The system becomes more fragile under extreme physical and climatic vagaries. We have developed an agent-based model (ABM) to assess how system dynamics related to farmer's profit waterlogging and salinity parameters will change under extreme climatic and physical events if business-as-usual (BAU) water use behavior is practiced. The model indicates that more ground and surface water use doesn't bring more earnings considering the size of farmers. And also, inequality rises more under rising temperatures and low rains. Hence, we have identified that governing the water use behavior can increase water availability and water quality at the tails and heads of the irrigation system by rationalizing area-wise groundwater and surface water use tariffs and subsidies.

Key Words: Agent Based Models; Conjunctive water use, Climate; Water tables, Inequality; Logging; Salinity; Profits
JEL Codes: C63, Q54, Q25, D63

1 Introduction

Irrigation water quality affects crop yield and soil's physical conditions, besides soil fertility, it is detrimental to the sustainability and performance of irrigation systems and consumptive use of irrigation water. Therefore, knowledge of

---

[1] International Institute of Islamic Economics, International Islamic University, Islamabad, Pakistan. Email: mamonasadaf@gmail.com.
[2] International Institute of Islamic Economics, International Islamic University, Islamabad, Pakistan. Email: jabbar@iiu.edu.pk
[3] Director of Social Sciences, Al-Nafi Online Educational Platform & EX-VC, PIDE, asad.zaman@alumni.stanford.edu.

irrigation water quality is critical in the understanding what management changes are necessary for long-term productivity. Salinity is one of the most influential water quality determinants affecting crop yield. The economic cost of salinity is usually underestimated as it is considered as yield loss as compared with non-salt induced costs. Based on grown crops, a loss of 15% to 69% is observed due to salt if no intervention is made (Bauder et al., 2011). However, losses are much more if other costs such as infrastructure deterioration (including roads, railways, and buildings), losses on property values of farms with degraded land, environmental and social costs of farm businesses are taken into account (Ivits et al., 2013). Growers can manage salinity through irrigation methods, drainage, and crop rotation, but these actions are costly, and in many areas salinity accumulation results in land fallowing.

Water salinity hazard, which is measured through electrical conductivity (EC), 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 due to an increase in EC, and crop yield is directly related to the amount of water transpired through a plant (Bauder, Waskom, Sutherland, & Davis, 2011). Wheat is one of the major growing crops sensitive to the smaller changes in salinity as its production declines from 25% to 50% if EC(ds/m) changes from 6.4% to 8.7%. (Qadir et al., 2014). The major determinant of salinity is extensive groundwater pumping it adds 45 metric tons of salt in irrigated areas of Pakistan annually and currently 4.5 Million Hectares (MHs) cultivable areas are affected by different levels of salinity. The cost of reducing the salinity reduces the revenues of farmers by up to 60% in Pakistan (Qureshi & Perry, 2021).

EC of water is primarily the major affecting factor for crop growth, but crop growth can face a further reduction if water with sodium imbalance is applied and the 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 water is greater than high EC waters at the same sodium content. Therefore, a more accurate evaluation of the infiltration/ permeability hazard requires using EC together with the SAR (Bauder et al., 2011). The current study takes EC of water as the most influential parameter of quality as previously indicated (Bauder et al., 2011; Joshi et al., 2009).

A comprehensive study of economic losses and benefits has been conducted by (Qadir et al., 2014). Farmers' responses and roles are very important in managing water for irrigation in the context of water flows and salinity. Farmers acknowledge the fact that soil quality deterioration with more groundwater use or scarcity of availability of surface water is the root cause of salinity. They usually prefer the short-term benefits of electric subsidies and compromised salinity (Kazmi et al., 2012). It is validated in different studies that farmers are considering agriculture non-profitable due to falling marginal benefits caused by the excessive cost of groundwater use and salinity management practices (Culas & Baig, 2020). Studies show that crop rotation and drainage improve the salinity and yield conditions but these costly methods are affecting profitability and accumulating salts and resulting in fallowing the land (Qadir et al., 2014). Different studies documented the need of managing salinity in modern agriculture (MacEwan et al., 2016).

Studies are available for improved water management practices and there exist inefficiencies in access and usage of groundwater since the potential of groundwater development is limited to large framers. Small farmers still buy from large farmers informally from their surplus groundwater (Qureshi, McCornick, Sarwar, & Sharma, 2010). Due to flexibility in the nature of 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).

2 Problem Statement

Studies demonstrated the importance of managing logging and salinity resulting from poor irrigation practices and poor quality irrigation water use. In Pakistan, different studies have assessed salinity control through physical, reclamation, and biological solutions (Qureshi & Perry, 2021). But the methods are costly and have been a success on a limited scale. Salt-tolerant Cropping experiments and seeds germination are currently in practice (Syed et al., 2021) but a larger extent of damages mediated by salinity and reversing the 30% of saline land into cultivable and recovering the cost of US$ 230 million of revenue per year (Aslam, 2016) is a challenging task. If proactive actions are not taken into account, then extreme climatic variability and increasing food demand will make it difficult to improve current soil and water quality balances. Studies have widely demonstrated physical intervention (Syed et al., 2021), economic impact, and costs of salinity management and control (Qadir et al., 2014)) but the behavioural response of irrigation water practices by farmers and the resultant impact on salinity and logging remained largely unexplored in Pakistan. This study will particularly explore farmers' irrigation water use behavior and its impact on salinity-logging and the profits of farmers.

The rest of the paper is organized as follows: Section 2 describes linkage of ABM, logging and salinity for generalizing the idea. Section 3 presents methodology and data used in development of ABM model. Section 4 and 5 scope explain scope and ODD of the model. Section 6 contains hypotheses. Section 7 presents result and discussion. Section 8 concludes the study and section 9 recommends relevant policy suggestions. References are given at the end. Parametrization of the variables is adopted from Sadaf et al. (2022).

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

Literature is available on the prevalence of logging and salinity but crop water use behaviour and its effect on yield and salinity are rarely modelled (Chang & Silva, 2016). To see how farmers' water use decisions are affecting water quality and are in turn behaviour affected by water quality and availability. Furthermore, farmers' profitability can be evaluated considering the individual and collective behaviour of farmers. This is the important relationship for assessment of the cost of salinity & logging and the benefits associated with alternative water management behaviour in presence of logging and salinity. In order to include the human aspect in water resource use and management, agent-based model is developed.

Behavioral theories suggest different types of behavior, which usually agents possess, such 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. Moreover, heterogeneity in farmers' behaviour will help us to understand spatial and temporal patterns. In other words, the reality could be explained to a better extent. That is how changes in the behaviour and system affect farmers.

Studies in agriculture or irrigation are not dealt with 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. As far as pure analytical models are concerned, they do not consider the prospects of managing water and included the human dimension in the model. Since there exist cases where these resources are successfully analyzed (Dietz et al., 2003).

ABM presents potentially the best solution for understanding the complex economic system with an inclusion scale explicitly (Gibson, Ostrom, & Ahn, 2000). The model built 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 analyzing this system (Janssen, 2002).

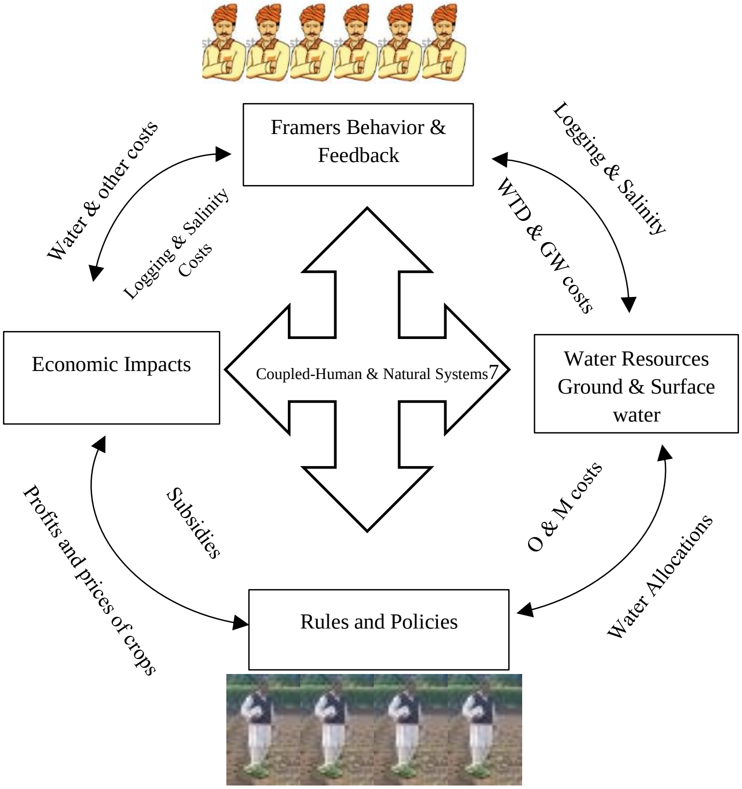
ABM is a computerized simulation of several autonomous interacting agents. The agents can be as heterogeneous as needed e.g., individuals, social groupings, institutions, biological entities, and physical entities. Models in ABM are not built with the assumption to reach some equilibrium state, instead 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 by communication between different stakeholders (Ahn et al., 2003; Ostrom et al., 1994).

4 Data and Methodology

A conceptual framework of the model is given below in Figure 1: It indicates irrigation system is a coupled human and natural system. As farmer’s behaviour is influenced by physical, climatic and economic conditions of the system. Framers behaviour and feedback also affect natural and physical system. Farmers interaction with each other and regulating authorities brings emergence in the system.

Figure: 1

Conceptual Framework, Agents, and their Interaction in the Model



Source: Author’s own developed

The model is developed for two cropping periods over the time for wheat and rice crops.

Framer maximizes utility subject to constraints. The farmers are agents making strategic decisions related to water use and cultivating the crops. Their ultimate purpose is to maximize their profits/benefits from their water use behaviour.

. Two types of farmers i and J small and large farmers are making decisions. At each point in time farmers compare and calculate their water use cost crop-wise

$$WUC_i\_total_{i,t} = \left(\frac{SWC_i \times \alpha SWU_i}{IWRi} + \frac{(1-\alpha) \times GWU_i \times GWC_{i_{actual}}}{IWRi}\right) \times \Delta T \qquad (1)$$

Water use cost of farmers depend on surface water tariff and groundwater use (GWU) cost.

$$GWC_{i_{actual}} = (1 + \gamma WTD) GWC_{intr} \qquad (2)$$

Groundwater cost $(GWC_{i_{actual}})$is higher in high water table depth areas. γ is a ratio of water table depth in t and t-1. Framer's total cost water and non-water use cost is given in equation 3

$$TC_{t,1:20}t = \quad NWInputCost_{t:1} + WUC_{i_{actual}} \qquad (3)$$

Here $NWInputCost_{t:1}$ is the non-water input costs. And WUC_i is the water use costs. Framer tries to maximize total returns over the period of years and his returns are updated seasonally for the growth of crops.

$$Max\ \pi = \sum_{t=i,j:1}^{n} \{(Y_{c=i,j} \times Price_{c=i,j}) - TC_{c=i,j}\} \qquad (4)$$

Famers' yield besides water and non-water parameters also depends on logging and salinity. Which is determined by electrical conductivity (EC; ds/m). If logging and salinity prevail more than the permissible limits, then the crop growth rate will be updated accordingly consequently farmer crop yield and profits will be less than the natural rates. It is required for farmers to maintain a subsistence level of yield and profits for staying in the system. $Cropping =$

$$\begin{Bmatrix} Yes, if\ loggin\ \ and\ saliniy < \text{max\_THV} \\ NO, if\ logging\ and\ salinity > \text{max\_THV} \\ Yes, If\ \pi_t > \min\_THV \quad or\ If\ \pi_{t=1:2} < \min\_THV \\ No, if\ \pi_{t=1:3} < min\ threshold\ value\ \pi \end{Bmatrix} \qquad (5)$$

If logging and salinity are in between the allowable limits; the minimum threshold value ($\min\_THV$) and maximum threshold value (max_THV) then farmers will keep growing the crops otherwise fallow the land. Moreover, farmers also compare the minimum profit threshold required to stay in the system. Farmer calculates costs and profits after completion of crop growth till harvesting. In t1 farmers' expected yield, water requirement, conjunctive use of surface and groundwater is determined. Initially, input costs for farming will be realized in t_1 and it will be based on required seeds, fertilizers, labour, or water costs. At the end of the season farmers' benefits are updated for next season's cropping decisions. The timeline of decisions will be adjusted for the crops to be grown accordingly.

Framers' Utility of cropping $UCrop_{t:20,i,j}$ is measured by the following equation.

$$UCrop_{t:20,i,j} = u(Yield^F_{t:20}) + \ln(Yield^F_{t:20} - \overline{Y}^F + RT) \qquad (6)$$

And $\overline{Y}^F$ is a subsistence level of a crop yield and farmer risk tolerance parameter RT is to be maintained by the farmer. To remain in the system and prevent vulnerability minimum subsistence level yield must be greater than the risk tolerance facto. Non-concavity of the utility function is induced due to the explicit determination of the subsistence level of crop yield. 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 level yield (Tesfatsion, 2006). If the farmer is unable to attain a minimum level of yield, for the period of three consecutive years as $Yield^F_{t:20,i,1:3} < \overline{Y}^F$ then the farmer will exit from the market he may fallow his land. Similarly, if farmers' profits are less than the minimum profits compared with the subsistence level for consecutive three years farmer will fallow his land for a number of periods for reinstating the nutrients in the field.

At the end of each period of irrigation, all states of farmers' land related to logging, salinity, and costs are updated from t to t+1. The role of the Government is taken as exogenous for determining the water and non-water costs and farmers’ ability to use water turns for irrigation. For general understanding, it is important to relate part of the conceptual framework with the equations of the model. From Equation 1 through equation 3 farmers' interaction with the physical system parameter is determined and equations 4-6 can be related to farmer decision making or farmer self-interaction in the conceptual framework. Government intervention in the form of subsidies and taxes is considered as an exogenous factor reflecting the water and non-water costs making farmers form their decisions.

5 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. 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. Since Pakistan doesn’t have a clear irrigation water use framework. This model will help to understand how the system will emerge if the same irrigation and water use behavior remained in practice and also will assess the impact of farmers’ water use behavior on resultant yield and water quality parameters and consequently that how farmers' decisions are affected by yield and water quality parameters. The model is developed in NetLogo 6.2.0.

6 Overview Design and Details (ODD) of the Model

ODD of the model is the established method that how the ABM is presented. Details for our ABM model of water use behaviour are given below.

6.1 Agent Selection and properties

Farmers are the agent in the model which have asymmetric access to surface and groundwater and also own different sizes of land parcels this creates socio-economic and spatial differences in the model. In Pakistan, tale-end farmers receive less or no amount of surface water. Large farmers own tube wells while others buy water for their crops. Surface water is received as per fixed rotation (WARA BANDI. Farmers have different properties based on the difference in surface water availability, groundwater availability, water demand, logging, and salinity levels and if farmers are water buyers and sellers.

6.2 Water Use Behavior of Farmers

The difference in water use behavior exists due to the properties of farmers. If water demand is less than available surface water as the farmer used it is preferable for the farmer to use surface water to fulfill all water demands irrespective of the depth of the water table. Usually, the water table in these areas is high and due non the usage of groundwater drainage is not being done and there are chances of waterlogging and salinity to exist. Logging and salinity are set as a ratio of WTD and it is set to rise to a certain number in response to the use of surface water. In some tale-ends areas where surface water is not available crop demand will be met by groundwater only which will result in higher energy costs and an increase in secondary salinization due to excessive use of low-quality water. The benefits will be affected as per change in WTD and simultaneously waterlogging and salinity will be affected. Under conventional wisdom in most cases, farmers prefer short-term benefits and don’t compare and consider alternative use of surface and groundwater.

6.3 Social behavior

A framer is considered selfish and rational and tries to maximize his profits by using less expansive water along with other inputs. In a business-as-usual scenario, the farmer will not care about his benefits. Cooperation and explicit coordination among farmers are not modeled. But selling and buying behavior of the farmers is traced and modeled.

6.4 Environment

Farmers will operate in spatial and temporal environments since they have unequal access to waters across time and distance from the water source.

6.5 Design Concepts

i. Basic principles

The concept has been taken from the Indus Basin Irrigation System (IBIS) known as WARABANDI. The climatic and physical dynamics of the system affect farmers’ decisions and are also affected by farmers' decisions on water use.

ii. Emergence

Spatial and temporal changes in farmers’ profits and water quality parameters will emerge as a result of farmers’ interaction with each other and the system.

iii. Adaptation

The farmer will assess if available surface water meets his water demand then he will decide to use his turn otherwise he will sell and save his turn to use in the future he will learn how water availability and trading over time have an impact on crop yield.

iv. Objectives

Farmer’s objective is to maximize his benefit. And it will be assessed for different strategies for water use decisions. If the farmer cannot meet the minimum subsistence level of profit due to water quality and availability issues he will decide to leave land uncultivated to reinstate after some random time when farm conditions will improve.

v. Learning

Farmers' crop yield based on water use will help them to decide on cultivating the crop. At every time step, all farm-related variables will be updated and help for cropping and irrigation decisions of the farmers.

vi. Prediction and sensing

The farmer will predict water deficit for exchange of water turns and prospective use or exchange of water turn is determined and also will sense salinization when salt appears and make strategies accordingly.

vii. Interaction

Farmers will trade their entitlements and directly interact with neighbours.

viii. Stochasticity

Some random behaviours for water use and physical properties of the systems are added. Logging and salinity will change as per some set behaviour and some stochastic patterns.

ix. Collectives

There are no collectives introduced at this point in the model.

x. Observation

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

6.6 Initialization

At time t_0, farmers will decide to use ground or surface water as per the availability of water. Large upstream farmers will have more chances to irrigate crops with surface water and deficient demand will be met through groundwater extraction. The small farmers will have a chance to save turns and combine turns to meet the water demand for every 3rd WARABANDI. The simulation will consist of 10 days of rotation for 20-time steps. After every simulation logging and salinity and farmers' benefits are updated. If waterlogging and salinity are beyond a certain threshold, then farmers exit the system. Parameterization of the model for inputs is adapted from Sadaf et al., (2022).

6.7 Experiments

Experiments for assessing the dynamics of the model are set as given in the table to meet the objectives of the study. Climate, physical and economic experiments are conducted by varying number of parameters to see how these variations determine system and emergence of the variables under consideration as logging salinity and farmers profits.

Table: 1

Types of variations and Number of Parameters varied under different experiments

No.	Business as usual			
	Parameter varied	**Type of Variations**		
	Economic Experiments			
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	5000	1000	-
	Climate Experiments			
1	Rain Moisture Rate	0.2	0.4	0.6
2	Evaporation-rate	0.2	0.4	0.6
	Physical Experiments			
1	Spatial-distance	5	10	20
2	Water table depth	5	10	20

Source: Author's Calculations

Agent-based models usually create a large number of data sets as big data. Analysing trends and patterns requires data to be analysed through visualization for concerned variables. The hypothesis is formed, and multiple experiments are for a period of time to see if the hypotheses formed can be related to data generated from the model and then validated for real-world micro and macro behaviour of variables. Validation requires data from literature or survey.

7 Hypotheses

We have formed hypotheses as given below

1. *Asymmetric access to water source produces inequality in farmers' benefits and harm water quality parameters.*
2. *Farmers' potential benefits are affected by different risks arising from uncertain hydro-climatic and economic conditions.*

We have run a number of experiments in NetLogo behavioural space and data visualization is conducted in R4.03. Results are discussed in the following section.

8 Results and Discussion

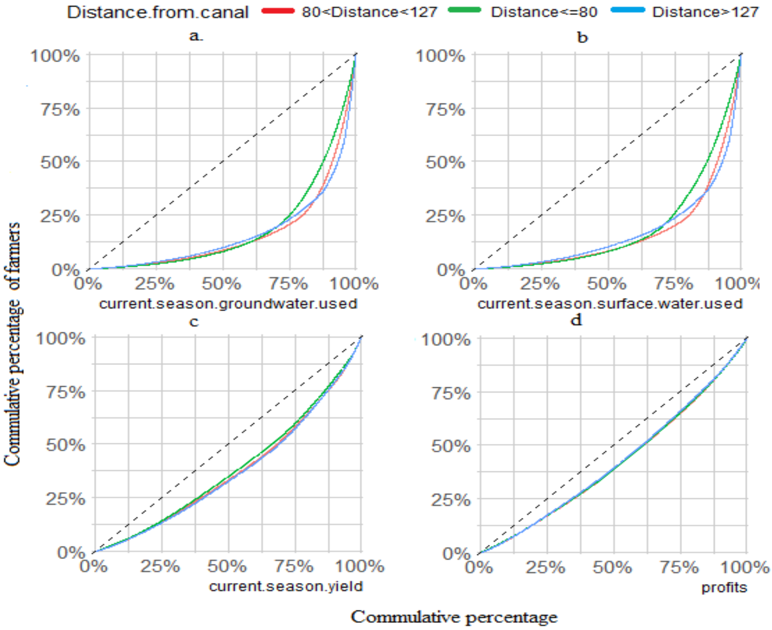
Hypothesis1: Asymmetric access to water quality parameters.

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

In order to assess the dynamics of the irrigation system with asymmetric access to irrigation water, the 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 usage 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 under BAU. Model runs 2 times for every 10 days of 'WARABANDI' covering the wheat and cotton seasons for the period of 25 years. Cultivation of the crops is considered sequentially as per the major cropping pattern in irrigated agriculture areas of Sindh and Punjab. Details of the model are given in Overview, Design, and Details (ODD) of the model, and parameters are given in Appendix A. In BAU we have supposed that the irrigation system is working ‘as it is’ with no change in irrigation conventional wisdom of the farmers. Farmers are irrigating the crops by turns and also using groundwater to supplement the deficient surface water supply. 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 framers located at different places in the system depicted in Figure 2.

Figure: 2

Inequality In Water Use, Profits, and Yield/Acre

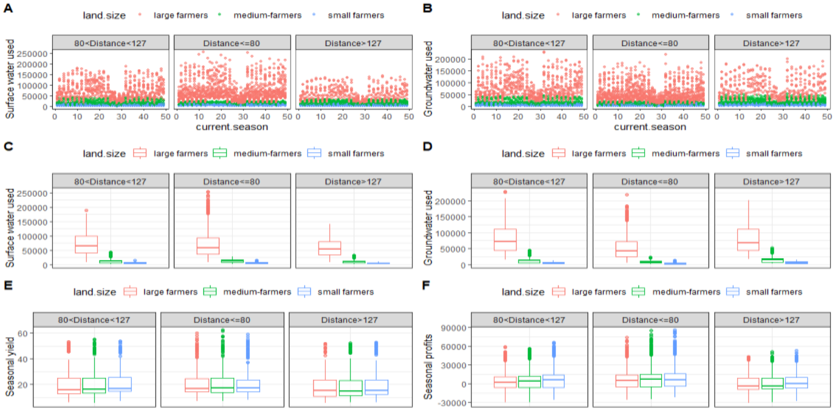


Inequality exists at all levels, but it persists more among the farmers located at farthest distances and found that for the more distant farmers with a distance > 127; 35% of the farmers are using 90% of the ground and surface water. In contrast, the variations in the profits and yield/acre among farmers with different distances from water sources are not much visible. However, inequality in yield and Inequality among all farmers for profits and yield is visible. While 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 in 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 in 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 and how large, small, and medium framers are using water resources and producing crops in the system.

Figure: 3

Differences in Surface and Groundwater Use Among Small Medium and Large Farmers

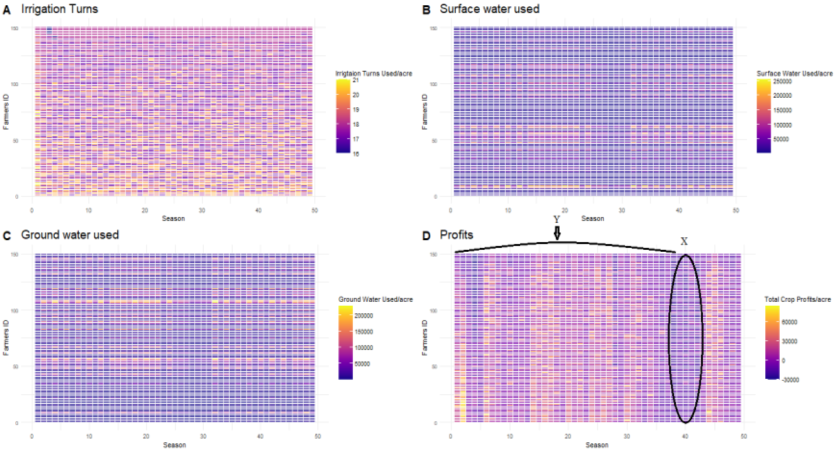


We have found that large farmers with less distance from the water source are using more surface water and the surface water use and the disparity is more visible. Small farmers are found using less surface water at all distances from the water sources. The case of groundwater use is not much different. 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 the 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, Scheierling, Tréguer, Turral, & McCornick, 2021). As is depicted in figure 3 that larger farmers are found using more groundwater along with 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.

Generally, there exist differences in water use between farmers irrespective of their land size. Figure 4 shows farmer-wise surface water used resulted from irrigation turns complemented by groundwater use of farmers use and resulted crop profits of framers. A framer is spatially located. Farm ID zero to 150 shows nearest and farthest from the water source respectively. Farmer nearest is found using more irrigation turns and hence more surface water while most of the tail end farmers are utilizing more groundwater. Small differences among framers' profits are found. Differences are skewed more towards the farmers located nearest to the canal heads.

Figure: 4

Framer ID-wise heat map for water use and profits



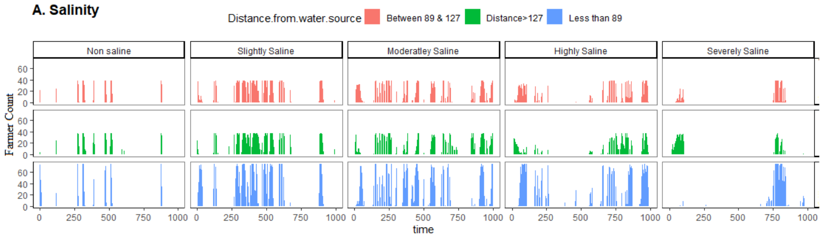
The results are similar to the survey of crop yield disparity along the reaches of the irrigation system in the Lower Chenab Canal where f the greater availability of abundant surface and good quality groundwater has resulted in disparity in crop yield in the area (Culas & Baig, 2020).

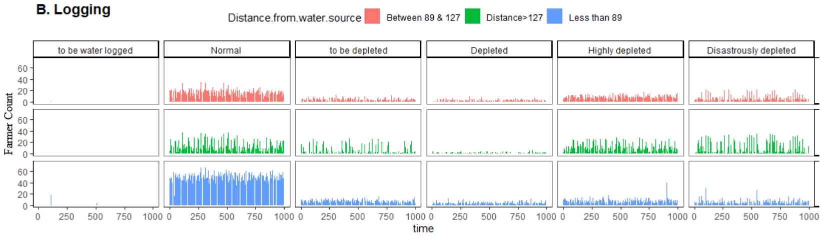
The pattern in the differences in profits among farmers is not much visible in some seasons. Variations in profits are majorly based on the ground, surface, and rainfall water uses. In the season where rainfall is sufficiently high the spatial differences among farmers are not much prevalent. As there will be less need of exchanging turns and combining them to fulfill the water demand of crops from surface water. In figure 4, part D; shows the less frequent rains and the resultant reduction in the profits of all farmers. 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 the long-run stability of output and sustainability of agriculture.

The lack of canal water supply resulted in the heavy use of marginal quality groundwater which has stemmed the problem of secondary salinization and caused the loss of cultivable land (Kahlown & Azam, 2002). We have presented results of logging and salinity resulting from the application of ground and surface water over time. Figure 5. part A shows the salinity profile of framers over time and the B part shows the logging profile of farmers. The majority farmers operate under slightly saline to highly saline conditions. It is depicted from the graph that salinity is increasing over time as farmers complete 25 years consisting 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 farmers grow crops over time. But the condition is worst among farmers located at tails. This is because farmers are using more groundwater to manage water demand at the tail of the water sources. In Figure. 5, part B between 800-to-1000-time steps, there are fluctuations in logging; the number of farmers with disastrously depleted water table is 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.

Figure: 5
Salinity and Water Table Depth Situation in 'Business as Usual' Water Use Perspective.


A. Salinity


B. Logging

The changes in logging and salinity profile can be linked with the rainfall intensity in the period as it was observed that more than average rainfall in monsoon can bring root-zone salt balance over years. A slight decrease in hydraulic conductivity after monsoon leaching will not be a problem during the irrigation season if the negative effects of a high sodium adsorption ratio (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 consumption 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 an 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 & Velde, 1992). But the changes in soil salinity and the factor causing the change, and the period for salinity build-up or reduction has rarely been documented or predicted explicitly in literature. We have tried to reflect some aspects of changes in logging and salinity in response to changes 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 a 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.

Hypothesis 2: Potential benefits under uncertain hydro-climatic and economic conditions are affected.

“Highlighting farmers’ potential benefits under different risks arising from uncertain hydro-climatic and economic conditions”.

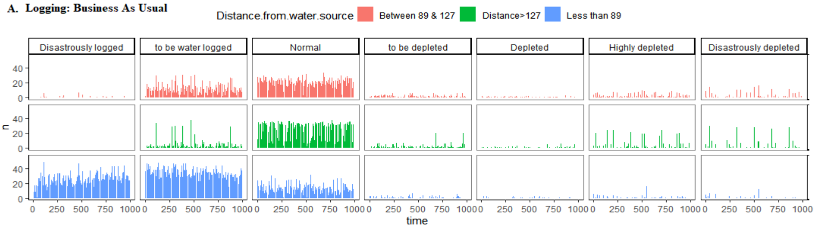
Climate changes are manifested through changes in temperatures, precipitation patterns with resultant changes in the form of glaciers melt, and changes in evapotranspiration rates (Gardner et al., 2013; Rodell et al., 2018). This further affects water availability and agricultural produce specifically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

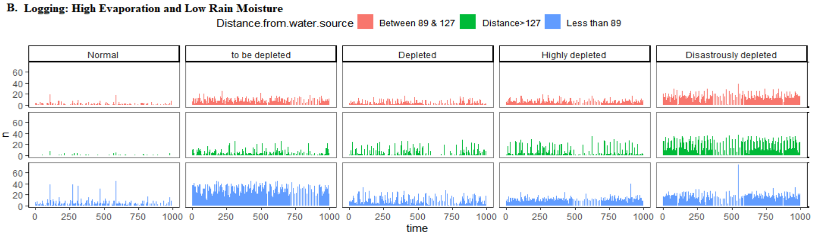
To understand the uncertain hydro-climatic and economic conditions we have taken variations in the following parameters: evaporation, rain moisture rate, and groundwater cost. Evaporation is linked with the surface water discharge available and groundwater tables. More evaporation means less surface 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 to surface water moisture rate, and waterlogging of the farmers. Thirdly groundwater cost is considered as a proxy of economic parameters because the change in groundwater cost will create a 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 how this will affect farmers' yield, water use, and water quality parameters such as logging and salinity.

Figure 6 compares Business As usual and rising hydroclimate change. It shows that for 25 years number of framers in normal water table depth areas drastically falls concentrated in disastrously depleted and highly depleted conditions.

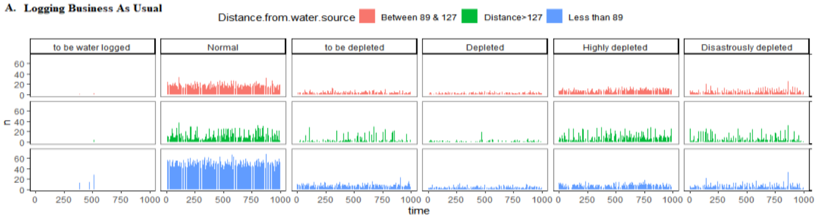
Figure: 6
Logging In Business as the Usual and High-Temperature Case


A. Logging: Business As Usual


B. Logging: High Evaporation and Low Rain Moisture

Climate change is making evaporation rise along with meager or no rainfalls causing the rise in groundwater tables and making irrigated agriculture more expansive 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: 7
Logging in Business as Usual and Low-Temperature Case


A. Logging Business As Usual

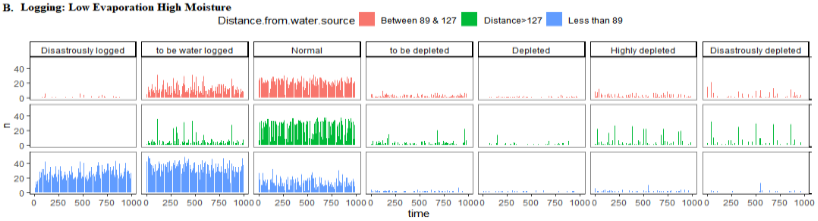

B. Logging: Low Evaporation High Moisture

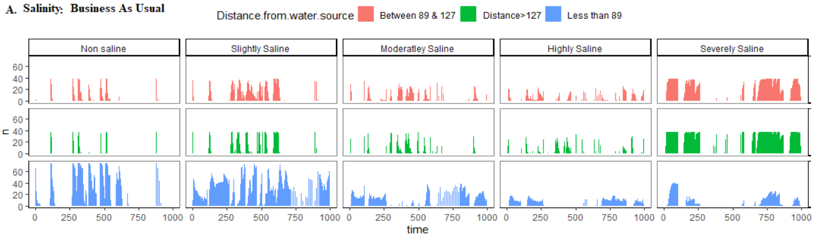
Figure 7. presents the case of low temperature and high rainfalls. We have found that high rainfalls caused waterlogged areas to rise for all types of farmers located along the canals, but

it become worse for the farmer located near canals. A 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 waterlogging in some areas (Abid et al., 2016)

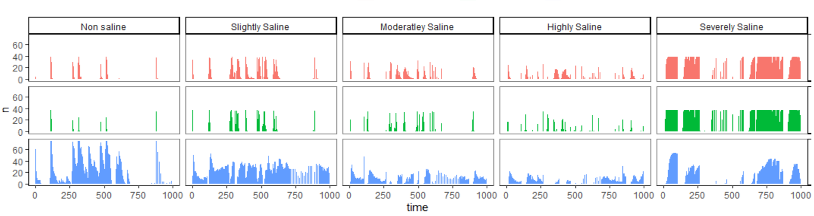
Figure: 8

Salinity; Business as usual Vs High Temperature and Low Rains

A. Salinity: Business As Usual



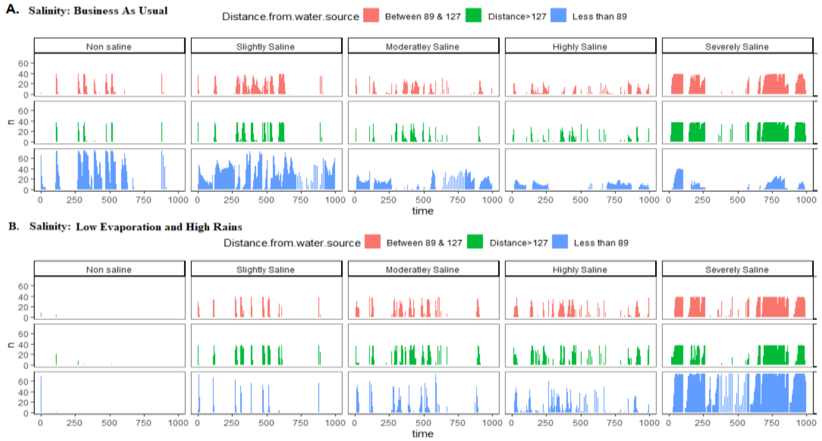
B. Salinity: High Evaporation and Low Rains



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 overexploitation of groundwater resources. The number of farmers in the non-saline category generally falls and relatively increases in the severely saline category. While framers from lesser distance from water source rise more in the non-saline category. Results are depicted in Figure 8 It can be related to the depleted tables in figure 2 due to which salinity rises. The results are similar to those (Qureshi, 2020) that falling water tables are causing salinity in irrigated agriculture in 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 tail end of the water source (Qureshi & Perry, 2021).

Figure: 9

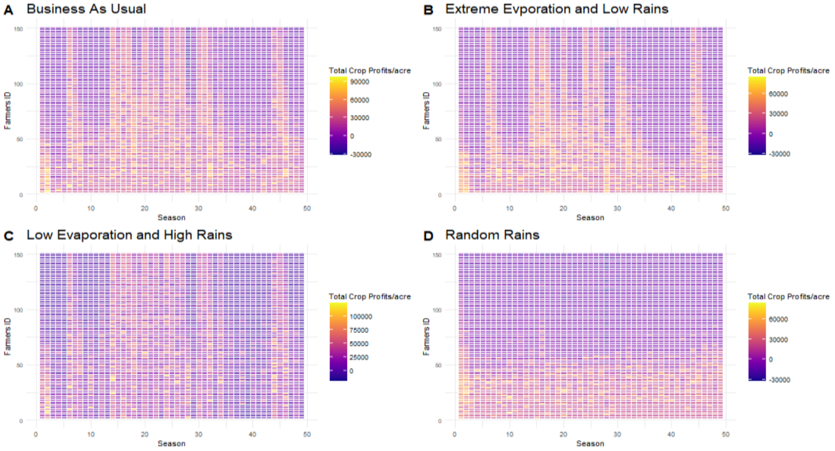
Salinity: Business-as-Usual Vs Low Temperature and High Rains



Salinity in case of low evaporation and high rains is given in figure 9. 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: 10

Scenario-Based Comparison Per Acre Profits



A heat map comparing profits for different scenarios such as; Business as Usual, extreme evaporation and low rains, low evaporation, and high rains, and random rains is given in figure 10. The figure shows that in extreme weather conditions maximum profits of the highest-earning farmers are 33% less than in the Business-as-Usual case. Framers located nearer to the water source have earned more compared with the distant farmer. Moreover, for wheat and cotton crops differences in profits are not much visible. The C part of the diagram shows low evaporation and high rains and top-earning farmers are earning 10% more profits than in 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, and C of the figure. To verify the same, we assessed the profits of farmers using random rains instead of crop season rains. The D part of figure 10 depicts profits for the random rains scenario.

Random rains are based on the mean and standard deviation of crop season rains. All farmers near a water source are maximum profits, while other framers most of them are bearing losses. Variability of temperature and resultant productivity of crops is discussed in irrigated areas that are highly sensitive to the variability of water supplies and temperature. A temperature rises of 0.5ºC- 2ºC 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).

9 Conclusion

The dynamics of the irrigation system with asymmetric access to irrigation water are assessed. We have tried to evaluate how water use inequality across time and space is creating imbalances in the quality-quantity relation in irrigated agriculture. Inequality exists at all levels, but it persists more among the farmers located at farthest distances and found that for the more distant farmers 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 in 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 et al., 2014). Irrigation is found to be effective in altering the cropping pattern from less to more value-added crops are shifted along with the effective access to markets accompanied by significant institutional support (Kemp-Benedict et al., 2011; Sadaf & Zaman, 2013).

Results of the model show that the large farmers with less distance from water sources 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. Majorly, we can conclude the fact that a major share of water for irrigation; ground, and the surface is consumed by large farmers.

Farmers at heads are found using more irrigation turns and hence more surface water while the majority of the tail end farmers are utilizing more groundwater. Small differences among framers' 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 f 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 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, and 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 resulting from the application of ground and surface water over time. We have found that salinity is increasing over 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 farmers grow crops over time. But the condition becomes worst among farmers located at tails. However, between 800 to1000 time steps, there are fluctuations in logging; the number of farmers with ‘disastrously’ depleted water table reduced. At the same time fall in salinity is also observed which is depicted in the timeline chart of salinity. These drastic changes in salinity and logging are associated with the heavy rainfall in the mentioned period. This can be related to the fact that more than average rainfall can bring root-zone salt balance over some time.

We have tried to reflect some aspects of changes in logging and salinity in response to changes in surface, groundwater, and rainfall availability. It is concluded from the results that water quality parameters logging, and salinity deteriorate if the same water use practices are adopted for an extended period. 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 framers 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 causes the fall in groundwater tables and makes irrigated agriculture more expansive. This fall in groundwater tables has resulted from the scarcity of surface water which is met through groundwater pumping in Pakistan (Bhatti & Akhtar, 2002). Water tables are found to fluctuate in response to the change in the climatic variables. Extensive groundwater pumping caused a fall in the water table depth of 1 meter/year (Qureshi, 2020).

In the case of low temperature and high rains, we have found that high rainfalls caused waterlogged areas to rise for all types of farmers located along the canals, but it become worse for the farmer located near canals. A 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 an increased incidence of waterlogging 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 production. Salinity for all farmers with different distances from water sources rises as a result of overexploitation of groundwater resources. The number of farmers in the 'non-saline' category generally falls and relatively increases in the 'severely saline' category. While framers from lesser distance from water source rise more in the 'non-saline' category. The results are similar to those (Qureshi, 2020) that the falling water table is causing salinity in irrigated agriculture in Pakistan. In Punjab majority of the tubewells' water is sodic saline and changing 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 tail 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 the intensity of profits through heat maps. It is observed that extreme weather conditions affect both the highest and lowest-earning farmers. Extreme weather makes the former earn 30% less than the baseline experiment. However, the spatial distance appears as one of the important factors determining the farmers' profits even in the case of climatic vagaries. Favorable 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. 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. The productivity of crops in irrigated agriculture is highly sensitive to the variability of water supplies and temperature. It has been estimated that a temperature rise of 0.5ºC- 2ºC 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 complemented by extensive groundwater which is causing salinity. Large farmers use more surface water and escape the loss associated with saline groundwater and increased groundwater pumping cots. These benefits agglomerated and bring inequality 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 destroys soil and nutrients and reduces crop water productivity (Bhatti et al., 2017).

10 Recommendations

The conclusion recommends that WARABANDI irrigation which creates inequality needs to be reassessed for small farmers to get the equal benefit of their turns. This will require restricting the system can be hindered by political factors (Young et al., 2019). Area-related policies need to be designed and implemented. Rationalizing the conjunctive water use will help to have a quality-quantity balance for farmers located from heads to tails of water distributaries. Importantly, for surface water use volumetric tariffs can be introduced for cost recovery and also trading the water along and across distributaries as increased costs make farmers rationalize water use (Ali Shah, Bell, & Anwar, 2022). Farmers near canals heads should be encouraged to use groundwater this will make surface water available and reliable for tale ends farmers with saline and expansive groundwater. In case of rains, surface water deliveries can be diverted to increase groundwater recharge and also to prevent excess water areas from logging (Qureshi & Perry, 2021). Government can also consider enhancing surface water supplies with artificial groundwater pumping in the system from high water table areas with fresh groundwater rather subsidizing individual farmers in groundwater extraction costs. This will bring equality and increase the productivity of the system.

Acknowledgement

This paper is derived from PhD Thesis entitled as "agriculture Water Management through Human and Natural Systems: An Agent Based Modelling Approach" supervised at International Islamic University and funded by Higher Education Commission(HEC), Islamabad under *Indigenous 5000 PhD* Fellowship program.

References

Abid, M., Schilling, J., Scheffran, J., & Zulfiqar, F. (2016). Climate change vulnerability, adaptation and risk perceptions at farm level in Punjab, Pakistan. *Science of the Total Environment, 547,* 447-460.

Ahn, T.-K., Ostrom, E., & Walker, J. M. (2003). Heterogeneous preferences and collective action. *Public choice, 117*(3), 295-314.

Ali Shah, M. A., Bell, A. R., & Anwar, A. (2022). Enabling volumetric flow measurement in the Indus Basin irrigation scheme: perceptions and conflict reduction. *Water Resources Research, 58*(1), e2020WR029464.

Aslam, M. (2016). Agricultural productivity current scenario, constraints and future prospects in Pakistan. *Sarhad Journal of Agriculture, 32*(4), 289-303.

Bauder, T. A., Waskom, R., Sutherland, P., & Davis, J. (2011). *Irrigation water quality criteria.* Colorado State University. Libraries.

Bhatti, M., & Akhtar, M. (2002). *Increasing irrigated agriculture productivity for poverty reduction in Pakistan.* Paper presented at the Proceedings of the Second South Asia Water Forum, Islamabad, Pakistan.

Bhatti, M. T., Sarwar, M. K., Tahir, A. A., & Yar, M. (2017). Effect of irrigation application on soil and land productivity of wheat under semi-arid environment. *Journal of Agricultural Research (03681157), 55*(1), 1-14.

Chang, A. C., & Brawer Silva, D. (2016). *Salinity and drainage in San Joaquin Valley, California*: Springer.

Chaudhry, Q. U. Z. (2017). *Climate change profile of Pakistan*: Asian Development Bank.

Culas, R. J., & Baig, I. A. (2020). Impacts of irrigation water user allocations on water quality and crop productivity: The

LCC irrigation system in Pakistan. *Irrigation and Drainage, 69*(1), 38-51.

Dietz, T., Ostrom, E., & Stern, P. C. (2003). The struggle to govern the commons. *science, 302*(5652), 1907-1912.

Farmer, J. D., & Foley, D. (2009). The economy needs agent-based modelling. *Nature, 460*(7256), 685-686.

Fisher, M. J., Harding, A., & Kemp-Benedict, E. (2014). The Challenge Program on Water and Food: A new paradigm for research in the CGIAR *Water Scarcity, Livelihoods and Food Security* (pp. 15-28): Routledge.

Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J.,…& Paul, F. (2013). A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *science, 340*(6134), 852-857.

Gibson, C. C., Ostrom, E., & Ahn, T.-K. (2000). The concept of scale and the human dimensions of global change: a survey. *Ecological Economics, 32*(2), 217-239.

Giordano, M., Scheierling, S. M., Tréguer, D. O., Turral, H., & McCornick, P. G. (2021). Moving beyond ‘more crop per drop’: insights from two decades of research on agricultural water productivity. *International Journal of Water Resources Development, 37*(1), 137-161.

Hussain, I., Sakthivadivel, R., Amarasinghe, U., Mudasser, M., & Molden, D. (2003). *Land and water productivity of wheat in the western Indo-Gangetic plains of India and Pakistan: A comparative analysis* (Vol. 65): IWMI.

Ivits, E., Cherlet, M., Tóth, T., Lewińska, K., & Tóth, G. (2013). Characterisation of productivity limitation of salt-affected lands in different climatic regions of Europe using remote sensing derived productivity indicators. *Land Degradation & Development, 24*(5), 438-452.

Janssen, M., & Baggio, J. A. (2016). Using agent-based models to compare behavioral theories on experimental data: Application for irrigation games. *Journal of Environmental Psychology, 46*, 106-115.

Janssen, M. A. (2002). *Complexity and ecosystem management: the theory and practice of multi-agent systems*: Edward Elgar Publishing.

Johnson, R. L. (1991). *Latent Groundwater Demand in Pakistan's Punjab: Theory and Applications*: Cornell University, Jan.

Joshi, D. M., Kumar, A., & Agrawal, N. (2009). Assessment of the irrigation water quality of river Ganga in Haridwar district. *Rasayan J Chem, 2*(2), 285-292.

Kazmi, S. I., Ertsen, M. W., & Asi, M. R. (2012). The impact of conjunctive use of canal and tube well water in Lagar irrigated area, Pakistan. *Physics and chemistry of the earth, parts A/B/C, 47*, 86-98.

Kemp-Benedict, E., Cook, S., Allen, S. L., Vosti, S., Lemoalle, J., Giordano, M.,... & Kaczan, D. (2011). Connections between poverty, water and agriculture: evidence from 10 river basins. *Water International, 36*(1), 125-140.

Khan, A. H., McCornick, P., & Khan, A. R. (2008). Evolution of managing water for agriculture in the Indus River Basin. *CGIAR Challenge Program on Water and Food*, 120.

Khan, M. A. A., Mahmood Ch, K., Ashraf, I., Siddiqui, M. T., & Knox, J. W. (2020). Evaluating socio-economic and environmental factors influencing farm-level water scarcity in Punjab, Pakistan. *Irrigation and Drainage*.

Kijne, J. (2006). Salinisation in irrigated agriculture in Pakistan: mistaken predictions. *Water Policy, 8*(4), 325-338.

Kijne, J. W., & Vander Velde, E. J. (1992). Salinity in Punjab watercourse commands and irrigation system operations. *Advancements in IIMI's Research 1989-91: A Selection of Papers Presented at Internal Program Reviews*, 139.

MacEwan, D., Howitt, R., & Medellín-Azuara, J. (2016). Combining Physical and Behavioral Response to Salinity. *Water Economics and Policy, 2*(01), 1650010.

Ostrom, E., Gardner, R., & Walker, J. (1994). *Rules, games, and common-pool resources*: University of Michigan Press.

Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., . . . Noble, A. D. (2014). *Economics of salt-induced land degradation and restoration.* Paper presented at the Natural resources forum.

Qureshi, A. S. (2020). Groundwater governance in Pakistan: From colossal development to neglected management. *Water, 12*(11), 3017.

Qureshi, A. S., McCornick, P. G., Sarwar, A., & Sharma, B. R. (2010). Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. *Water Resources Management, 24*(8), 1551-1569.

Qureshi, A. S., & Perry, C. (2021). Managing Water and Salt for Sustainable Agriculture in the Indus Basin of Pakistan. *Sustainability, 13*(9), 5303.

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J., Beaudoing, H. K., Landerer, F. W., & Lo, M.-H. (2018). Emerging trends in global freshwater availability. *Nature, 557*(7707), 651-659.

Sadaf, M., & Zaman, A. (2013). Potential of water management through Pakistani Provincial Trade of Agriculture Commodities. *Int. Water Technol. J, 3*(3), 131-137.

Sadaf,M., Jabbar, A., Zaman, A.(2022) Agriculture Water Management through Human and Natural Systems: An Agent Based Modelling Approach, Unpublished PhD Thesis, International Islamic University, Islamabad, Pakistan.

Sadaf, M., Jabbar, A., Zaman, A. & Beekma, J. (2019) *Assessing Conjunctive Water Management Through Coupling Human And Natural System In Pakistan: An Agent Based Modelling Approach*. [Paper Presentation]. 3rd World Irrigation Forum (WIF3), Bali, Indonesia.

Sharma, D., & Tyagi, N. (2004). On-farm management of saline drainage water in arid and semi-arid regions. *Irrigation and Drainage, 53*(1), 87-103.

Syed, A., Sarwar, G., Shah, S. H., & Muhammad, S. (2021). Soil salinity research in 21st century in Pakistan: its impact on availability of plant nutrients, growth and yield of crops. *Communications in Soil Science and Plant Analysis, 52*(3), 183-200.

Tesfatsion, L. (2006). Agent-based computational economics: A constructive approach to economic theory. *Handbook of computational economics, 2,* 831-880.

Young, W. J., Anwar, A., Bhatti, T., Borgomeo, E., Davies, S., Garthwaite III, W. R., ... & Saeed, B. (2019). *Pakistan: getting more from water*. World Bank.