: Agent based Model for Development of Groundwater Framework vis-à-vis Surface Water Management for improved Returns of Water Resources in Irrigated Agriculture of Pakistan

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Abstract

Modeling socio-ecological interactions are one of the essential requirements for water resource management in water-stressed areas. Mismanagement of water resource combined with extensive withdrawal by farmers in Indus Basin is putting pressure on freshwater resources. In some areas sever depletion of groundwater is evident. Waterlogging remains a bigger problems in the areas with higher surface water endowments, causing salinization; a greatest threat to long-term groundwater sustainability. 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. We have developed an ABM model simulating the system by varying different agro-climatic parameters for water withdrawal behaviours of framers 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 depth fluctuations for better management of water resources. Self-governing Rules (SGR) and Institutional Management Perspective(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 price 3 times more than the existing rates for the farmers located near water source. For the farmers located at tails IMP appears to manage resource better than other scenarios. Better and sustainable water withdrawal management requires to have area-wise policies and institutional support for promotion of norms.

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1. **Key Points**

- Self-governing rules improve water withdrawal behavior at heads of water sources
- Institutional support improves water use behavior at the tails of water sources
- Area-wise policies work well for better returns of water resources in Pakistan

1. **Abstract**

Modeling socio-ecological interactions are one of the essential requirements for water resource management in water-stressed areas. Mismanagement of water resource combined with extensive withdrawal by farmers in Indus Basin is putting pressure on freshwater resources. In some areas sever depletion of groundwater is evident. Waterlogging remains a bigger problems in the areas with higher surface water endowments, causing salinization which is greatest threat to long-term groundwater sustainability. 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. We have developed an ABM model simulating the system by varying different agro-climatic parameters for water withdrawal behaviours of framers 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 depth fluctuations for better management of water resources. Self-governing Rules (SGR) and Institutional Management Perspective(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 price 3 times more than the existing rates for the farmers located near water source. For the farmers located at tails IMP appears to manage resource better than other scenarios. Better and sustainable water withdrawal management requires to have area-wise policies and institutional support for promotion of norms.

1. **Introduction**

Irrigation system in arid countries specifically in developing economies are the center of socio-economic development and not only provides livelihood to million farmers but also source of growth in industrial sector and urban centers [*Small and Svendsen*, 1992]. Worldwide irrigation system observed large scale investments for rural development and food security but failed to bring efficient outcomes along with the poor management and maintenance have made it economically non-viable [*Ostrom et al.*, 1993]. Unreliable water supplies under current and future climatic vagaries are creating water scarce conditions for arid agriculture. Human response to the problem further exacerbate the problem [*MacAllister et al.*, 2022; *Schill et al.*, 2019]. For instance groundwater extraction as a solution to deficit surface water supply is creating water table and water quality related problems [*El-Naqa et al.*, 2010; *Wada et al.*, 2012]. Developing economies lack resources to implement appropriate solutions in large scale irrigation system. Implemented policies are already challenging social ecological systems and is a burden on economic resources of the country [*Bussmann et al.*, 2016].

Most water crisis of the world is believed to be stemmed from misgovernance and underutilization of water resources [*Pahl-Wostl et al.*, 2008; *Winpenny and Camdessus*, 2003]. Similarly, inefficient use and low conservation of water are considered as a root cause 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 needs of food, water, and energy. Pakistan is projected to be water-stressed in 2025 as per capita water would be as low as 850 m^3 while it was 1200 m^3 in the year 2005 [*PEPA*, 2005]. These water shortages and stress situations are also responsible for interprovincial conflicts on water distribution [*IUCN*, 2010]. Degradation costs of the Indus Delta caused by poor management are estimated to be around US$2 billion per year [*Young et al.*, 2019]. This demonstrates that Pakistan gets a poor economic return from its significant water resource. Moreover, mismanagement of water resources is responsible for a great amount of water losses. As per an estimate, 30% of diverted water is lost through system losses (Qureshi, 2011; 2020). It is a unanimous view of all stakeholders that poor water management is responsible for persistent inequalities in water distribution at upper, middle and end tail of water channels [*Altaf et al.*, 2009]. Due to dwindling and uneven surface water supplies over time and space; reliance on groundwater use in Pakistan is increasing [*Watto and Mugera*, 2015]. It has been estimated that the share of groundwater in irrigation supplies has been 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 framers. Small farmers still buy from large farmers informally from their surplus groundwater [*Qureshi et al.*, 2010]. Due to flexibility in the nature of groundwater, there has been an increasing tendency between farmers to extract groundwater. However, inefficient irrigation practices, poor drainage facilities, and canal conveyance losses cause the problem of salinity and waterlogging [*A H Khan et al.*, 2008; *Qureshi et al.*, 2010].

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 agents 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. To include agents in water management process agent based modelling (ABM, henceforth) is one of the useful tool to simulate social and ecological behaviour of the system. We have developed an ABM for groundwater management framework for the area like Upper Indus Basin (UIB) considering it a part of social ecological system by delineating alternative surface and groundwater practices over space and time.

1. **Groundwater Economy and withdrawal Status in Pakistan**

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]. The Government prompted 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% this makes extensive use of groundwater. Due to the reason the share of groundwater in water supplies at the farm gate has increased to 75% due to which cultivation area and cropping intensity has increased to 35% since 1960. Out of the total installed tubwells, 99% are private tubewells [*Llamas*, 2000]. There has been found a 160% rise in private tube well installation in Pakistan [*GOP*, 2018].

In Pakistan, groundwater use is becoming more popular due to less development of surface water. Inefficiencies in surface water delivery resulted from an increase in crop intensity, subsidized accessibility, and reliability of groundwater. Farmers with groundwater excess are able to cultivate 30% more land as compared with the farmers who have surface water access only [*Basharat*, 2015].Number of private tubewells per 1000 hectares rose up to 100% between 1965 and 2018 (Agricultural Statistics of Pakistan, 2018). The income of farmers is substantially higher than the farmers who had access to surface water only [*Faruqui*, 2004]. In Pakistan, specifically in Punjab, groundwater recharge is far less than groundwater extractions. Overexploitation of groundwater is local to fresh groundwater areas is visible. In Baluchistan development of tubewells has reduced water access for Karez, which deprived many framers of access to vital resources.

Types of Groundwater Agents in Pakistani 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 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 as electricity or diesel. Since electricity is subsidized by Government and the cost is far less than diesel based tubwells. 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 tubwells. 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 form 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 charger per hectare, are fixed. Pump owners bear irrigation costs as if costs further dig 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.

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 tubwells are preferred in the country. Buyers usually have many sellers' available prices of leasing water falls accordingly.

The average prices of tubewell water are given in Table 1 This has increased water access and lead the 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 1 shows that diesel-operated groundwater is more expensive as compared with electric tubewell, this can cause discrimination in earning within and between provinces 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.

Groundwater Development and Management

Water resource experts argue that in the long run, groundwater development is self-regulating; people cannot pump more water than there is in the aquifers. 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]. Experts are of the view to manage groundwater as a common pool resource as the Low-excludability and subtractability of groundwater make it a common pool resource (CPR). Every abstraction of groundwater reduces its availability as of common-pool resource [*Ostrom*, 1990]. Moreover, 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 reconsidered (Feeny et al. 1990; Grafton 2000). Major groundwater depleted areas do not have a policy or minimal enforced rules for groundwater abstraction in South Asia; China, India, and Pakistan [*Shah*, 2007].

Problem 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 is resulted in indiscriminate pumping and contributing to excessive groundwater extraction in many locations [*Syed Mohammad Khair et al.*, 2015; *van Steenbergen et al.*, 2015]. Unregulated use of groundwater brings social, environmental, and economic consequences along with aquifer depletion [*Harou and 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 and Tariq*, 2014]. Soil salinization, land subsidence, seawater intrusion, etc. are the main environmental externalities over-drafting of the groundwater in irrigated agriculture areas. Water quality in 40-45% area ranges from marginal to highly saline in shallow groundwater areas across Chaj, Thal and Rachna Doab in Pakistan and in deep groundwater areas the percentage of area increases up to 70% under marginal to highly saline water quality category(PCRWR,2018, [*A Khan et al.*, 2016; *Qureshi et al.*, 2003].

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. 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 and 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]. The farmer keeps their land parcels fallow in rotation to cultivate crops in sever cases of logging and salinity.

Need of Agent Based Model in Groundwater Management

Regulating groundwater use is the first and foremost solution 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, farmers' behaviour 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 and 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]. Key to this, in many instances, is a policy paradigm shift from groundwater development to long-term groundwater management [*Syed Muhammad 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]. Groundwater management is a complex issue that should be dealt including all types of water uses considering socio-economic and physical resources [*Kori et al.*, 2009].

Groundwater users and the local organization have always been ignored in groundwater management. But from agent level experience of groundwater management through enforcing rules or development of local rules or social norms [*Sampson and Perry*, 2019]suggests that groundwater management must be inclusive for all stakeholders. Inclusion of all stakeholders required to use ABM to assess groundwater dynamics to find social norms or regulatory framework for sustainable groundwater management.

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 [*J C 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 1.

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 and Xiong*, 2017].

1. **Methods**

   (a)

Conceptual Framework 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 cause water depletion for everyone in the system.

Depletion increases groundwater abstraction cost even high. 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 with the drawl. Indirect cost includes expansive 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. From conceptual frame implicit buying and selling of groundwater and its impact on costs and farmers behaviour and decisions will be assessed.

The model is developed for two cropping periods over the time for wheat and cotton 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

$$\mathrm{WU}C_{i}\_total_{i,t} = \left(\frac{\mathrm{SWC}_i \times \alpha \mathrm{SWU}_i}{\mathrm{IWRi}} + \frac{(1-\alpha) \times \mathrm{GWU}_i \times \mathrm{GWC}_{i_{\mathrm{actual}}}}{\mathrm{IWRi}}\right) \times T \qquad 1$$

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

$$\mathrm{GWC}_{i_{\mathrm{actual}}} = (1{+}\gamma WTD)\mathrm{GW}C_{\mathrm{intr}} \qquad 2$$

Groundwater cost ($\mathrm{GWC}_{i_{\mathrm{actual}}}$)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

$$\mathrm{TC}_{t,\ 1:20}t = \quad \mathrm{NWInputCost}_{t:1}{+}\mathrm{WU}C_{i_{\mathrm{actual}}} \qquad 3$$

Here $\mathrm{NWInputCost}_{t:1}$ is the non-water input costs. And $\mathrm{WU}C_i$ 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

$$Max\ \ \pi \ = \ \textstyle\sum_{t=i,j:1}^{n} \{(Y_{\ c=i,j} \ \times \mathrm{Price}_{c=i,j}) - \mathrm{TC}_{c=i,j}\} \qquad 4$$

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.

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

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 $\text{UCrop}_{t:20,\ i,j}$ is measured by the following equation

$\text{UCrop}_{t:20,\ i,j} = u(\text{Yield}^F_{t:20}) + \ln\ (\text{Yield}^F_{t:20} - \overline{Y}^F + RT)$ 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 $\text{Yield}^F_{t:20,i,1:3} < \ \overline{Y}^F$ 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.

1. **Overview Design and Details of ABM**

   (a)

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.

Process Overview and Scheduling

Small farmers decide about cropping their land subject to the availability of groundwater, or if they come up with some explicit or implicit farmers around them 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.

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 framers 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 cotton cultivation for a period of 1 year.

Conjunctive Ground and Surface Water Use ABM model

Akhbari and Grigg [2013], proposed the ABM model to see cooperation between conflicting interests. ABM is calibrated through real time data on water demand and water supplies along with other necessary variables to capture the dynamics of the system, the 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 famers 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

Since $\mathrm{TAW}^{F}_{t=1:20} = Surface\ water + Groundwater$ (7)

And Available Surface Water$^{F}_{t=1:20} = Q_{in-sw} - Q_{min-sw}$ (8)

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.,

$$\mathrm{ASW}^{F}_{t=1:7} = \frac{[\ Q_{in-sw,1:7} - Q_{min-sw1:20}]}{\mathrm{DWS}} \quad (9)$$

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

If $\mathrm{ASW}^{F}_{t=1:20} \geq D_{\max t=1:20} = Farmer\ water\ use\ is\ the\ surface\ water$

Here $D_{\max t=1:20}$ is farmer maximum demand for irrigation water. The share of groundwater will be negligible. And if

$$\mathrm{ASW}^{F}_{t=1:7} \leq D_{\max t=1:20}$$

Farmer water use will be the conjunctive surface and groundwater. There will be a cap on groundwater use as $Q^{\mathrm{optFi}}_{gw,\ t=1:20}$. 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 $\mathrm{ASW}^{F}_{t=1:20} \geq D_{\max t=1:20}$ and will agree to withdraw the optimized amount of groundwater $Q^{\mathrm{optFi}}_{gw,\ t=1:7}$

Case 2: Agents will not cooperate if $\mathrm{ASW}^{F}_{t=1:20} \leq D_{\max t=1:20}$ and will not accept the optimized level of groundwater allocation $Q^{\mathrm{optFi}}_{gw,\ t=1:7}$

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

$$\mathrm{U}^{\mathrm{Fi}}_{t=1:20}(C \rightarrow C) = a\ \times V^{n-F}_{t=1:20}(C) + F_m \tag{10}$$

And $U^{\mathrm{Fi}}_{t=1:20}(C \rightarrow NC) = b\ \times V^{n-F}_{t=1:20}\,(\mathrm{NC})$ (11)

$$\mathrm{U}^{\mathrm{Fi}}_{t=1:20}(NC \rightarrow C) = c \times V^{n-F}_{t=120}\ (C) + F_{\mathrm{m}} \tag{12}$$

$$\mathrm{U}^{\mathrm{Fi}}_{t=1:20}(NC \rightarrow NC) = d\ \times V^{n-F}_{t=1:20}\,(\mathrm{NC}) \tag{13}$$

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. $U^{\mathrm{Fi}}_{t=1:20}(C \rightarrow C)$ shows behaviour cooperative farmer who is willing to keep the same behaviour. And $U^{\mathrm{Fi}}_{t=1:20}(C \rightarrow NC)$ shows a farmer's behaviour who is willing to change his behaviour from cooperative to non-cooperative behaviour. $V^{n-F}_{t=1:20}(C)$ is the proportion of neighbour of farmers having cooperative behaviour and $V^{n-F}_{t=1:20}(NC)$ 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

$$F_m = (1-a) \times \{\alpha i_{\mathrm{train}}\} + \left\{ (1-\alpha) \times \frac{\left[(ASW^{F}_{t=1:7} + Q^{\mathrm{optFi}}_{gw,\ t=1:20}) - D_{\max t=1:20}\right]^2}{Q^{\mathrm{optFi}}_{gw,\ t=1:20}} \right\} \tag{14}$$

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

$$\mathrm{NWD}^{F}_{i=1:20} = [D_{\max t=1:20} - (ASW^{F}_{t=1:20} + Q^{\mathrm{optFi}}_{gw,\ t=1:20}) \times (1 - U^{\mathrm{Fi}}_{t=1:20})] \tag{15}$$

$$\mathrm{NWD}^{F}_{i=1:20} = D_{\max t=1:20} = (ASW^{F}_{t=1:20} + Q^{\mathrm{optFi}}_{gw,\ t=1:20}) \tag{16}$$

Quantity of water demand γ will be calculated based on $\frac{D_{\max t=1:7}}{Q^{\mathrm{optFi}}_{gw,\ t=1:20}}$ 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 $\mathrm{D}_{\max t=1:20}$, if after intervening $D_{\max t=1:20}$ of farmer lies between $\gamma \times Q^{\mathrm{optFi}}_{gw,\ t=1:20}$ and $Q^{\mathrm{optFi}}_{gw,\ t=1:20}$ then the farmer will be charged with a little tax/fine. Modification factor for non-cooperative agents can be calculated as

$$F_m = (1-b) \times \{\beta i_{\mathrm{train}}\} + \left\{ (1-\beta) \times \frac{[D_{\max t=1:7} - (ASW^{F}_{t=1:20} + \gamma \times Q^{\mathrm{optFi}}_{gw,\ t=1:20})]}{\gamma \times Q^{\mathrm{optFi}}_{gw,\ t=1:20}} \right\}^2 \tag{17}$$

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

Water management perspectives: A design concept

Three cases are needed to be assessed

1. **Business as usual(BAU)**

In BAU we have supposed that the irrigation system is working 'as it is' with no change in the conventional wisdom of the farmers. Farmers are irrigating the crops by turns and also using groundwater to supplement the deficient surface water supply. 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.

1. **Self-governing rules (SGR)**

In, self-governing rules; as a seed some of the farmers with land > 5 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 slef 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.

1. **Institutional arrangements (IMP)**

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 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.

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 19 to 26 can be considered in the context of groundwater for cooperating *(C_{it})* and non-cooperating agents *(NC_{it})*

$$Norms = \sum_i \frac{\mathrm{NC}_{i,t} - C_{\mathrm{it}}}{N} \tag{18}$$

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 to understand 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.

Individual Decision Making

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 these are the predominant crops in the area. The farmers' decision of irrigation based on the previous records of water availability, and impositions of regulations. Buyers reduce their land if face deficiency in water availability Large farmers decide about cooperating with the rules or respecting the norms and, together with small farmers, determine emergence.

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.

Sensing

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

Individual Prediction

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

Interactions

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

Collectives

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

Heterogeneity

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

Stochasticity

Initially, stochasticity regarding depth to water table, change in climatic condition is considered.

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.

Implementation Details

The model is implemented in NetLogo 6.0., simulated in NetLogo Behaviroal Space 6.0 and anlayzed in R4.03. The model will be available upon request.

Initialization and Input of the Data

Initially, farmers are created with spatial variation among them, which makes them to have a difference in water requirement, water availability and depth to water table. Water table depth is linked with the extractions costs and water quality and it will change as per decisions of framers. The values of the variables are assigned to the farmers as per the model requirement. Parametrization of the model is given in supplementary table 1.

Submodel

There are no sub-models available in the model.

1. **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.

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 6.0.0. List of experiment conducted is given in supplementary table 2. After experiments validation is performed. 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 and 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.

Results and Discussions

Following hypothesis is made and assessed for validation through visualizing the data set derived from experiments.

Hypothesis: Assessment of groundwater regulatory framework: "Understanding policy options for groundwater regulatory framework by delineating alternative surface and groundwater practices over space and time"

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 2 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. Under the highest water table depth of 20 profits is 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 2 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 3 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. 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 4 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 shows the cost limit if of groundwater abstraction. It is linked with the changes in water table depth. As water table depth rises it raises groundwater abstraction costs. This can be learned 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 for IMP. However, with the higher WTD of

20 and initial withdrawal cost of 200 groundwater withdrawal cost emerged as 320 for this is also depicted in the diagram. Moreover, with the initial cost of 800 and WTD of 5, withdrawal cost sharply rose up to 1280 and exponential increment can be observed and with the more increasing rate in case SGR. In the extreme cases of 20 WTD and water withdrawal cost of 800 per unit. The cost initially rises sharply from 800 to 1100 and then increased with declining rate reached 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.

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, they use for irrigation crops with surface water.

Table 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 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]. In the model, seasonal rainfalls and crop water requirement were taken based on calculations [*Sadaf and 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].

Discussion and 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 an impact on 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 rational regulations make farmers to use groundwater rationally. SGR managed to increase groundwater abstraction price 3 times more than the existing rates for the farmers located near canals heads. For the farmers located at tails IMP appears to manage resource better than other scenarios. But increasing groundwater abstraction cost 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. 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.

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]. In the model, seasonal rainfalls and crop water requirement were taken based on calculations [*Sadaf and Zaman*, 2013]. Overtime spatially distributed farmers' caricaturized scenarios were built to include groundwater depth fluctuations for better management of water resources. SGR and IMP bring equity in water availability and to prevent agriculture from worsening water quality parameters which can bring relatively more benefits in the system. However, consistency in the benefits 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 is detrimental to 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]. Manging farmer's behaviour under socio-economic and climatic conditions can bring life to lost agricultural potential in the country. However, getting benefits of framers' 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.

1. **Policy Implication**

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. The behavioural governance have a a 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]. Area-wise policy should be devised to get better, equitable and sustainable returns.

This study lacks generalization due to calibration of the model with real time physical properties of ground flow and water table depth of area under selection as developed by [*J Castilla-Rho et al.*, 2015] can give a better indication of groundwater abstraction and related costs and resultant behaviour of farmers

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Conflict of interest

The authors declare no conflict of interest.

Data Availability Statement

Data and software used in development of the model are publically available.

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Table and figure captions

Table 1: Selling Rates of Groundwater in Different Provinces (US $\$/m^3$)

Table 2: Groundwater and Surface water use under different Groundwater cost scenarios

Table 3: Comparing Groundwater costs and Profits under different water table depth scenarios

Figure 1: Schematic Diagram of Agent Based Model for Groundwater Management

Figure 2: Groundwater cost experiment for varying water table depth and abstraction cost.

Figure 3: Profits, logging, and Salinity under groundwater cost variations

Figure 4: Density Plots of logging and salinity in groundwater cost experiment.

Figure 5: Estimated Groundwater cost under varying water table depth scenarios.

Figure 6: Comparison of groundwater and surface water across water management scenarios under varying groundwater costs.

Table 1: Selling Rates of Groundwater in Different Provinces (US $/m^3$)[1]

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[2]
KP	0.73-0.77	2.39-4.49	3.77

Source: [*Qureshi et al.*, 2003]

Table 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	C
200	211.2	211.0	211.0	2
400	211.1	210.8	211.2	4
800	211.2	210.9	211.2	8
Institutional Management Perspective	Institutional Management Perspective			
200	↑17.1	↑1.15	↑1.43	2
400	↓1.32	↑1.16	↑1.11	4
800	↑1.19	↑1.43	↑1.42	8
Self-Governing Rules	Self-Governing Rules			
200	↑33.2	↑33.4	↑33.2	2
400	↑33.1	↑33.2	↑33.4	4
800	↑33.2	↑32.9	↑33.8	8

Table 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
200	350.3	305.8
400	603.3	611.7
800	1210.1	1222.
Institutional Management Perspective (IMP)	Institutional Management Perspective (IMP)	
200	↓13.789	↑0.26

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

[2] No Data is available

Comparison average profits and groundwater use cost		
400	↑0.544	↑0.37
800	↑0.078	↑0.43
Self-Governing Rules (SGR)	Self-Governing Rules (SGR)	
200	↓10.17	↑3.94
400	↑4.095	↑3.87
800	↑4.030	↑3.77

Figure 1: Schematic Diagram of Agent Based Model for Groundwater Management

Source: Author’s own developed.

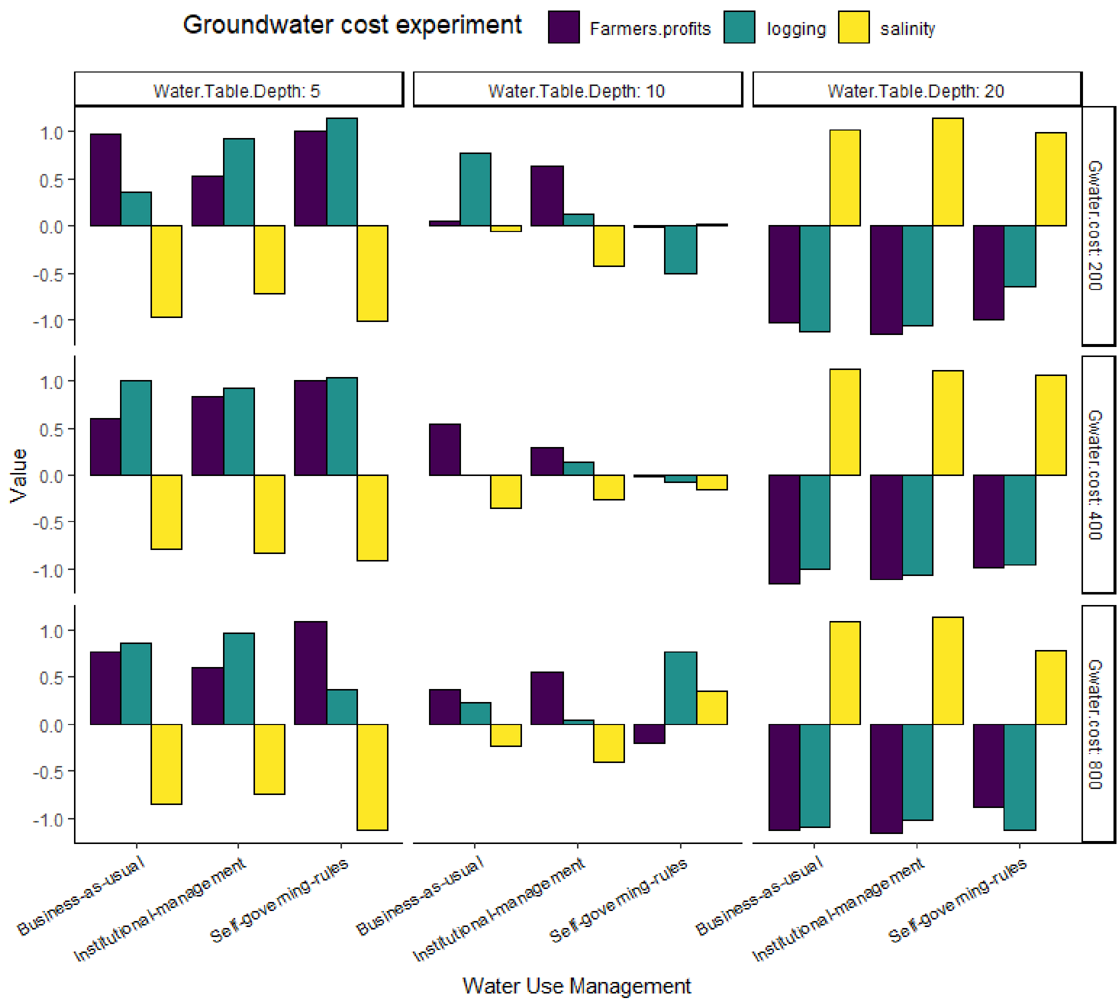

Figure 2: Groundwater cost experiment for varying water table depth and abstraction cost.

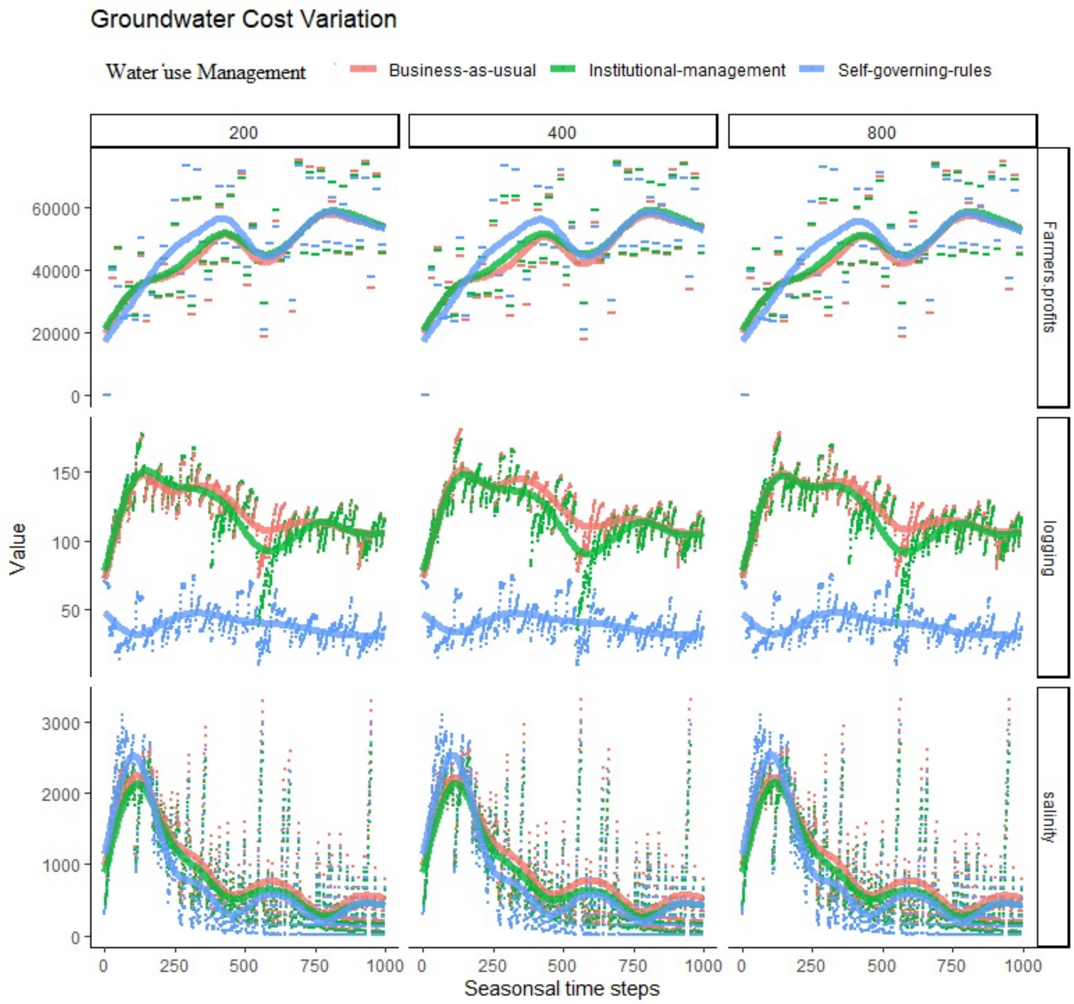

Figure 3: Profits, logging, and Salinity under groundwater cost variations

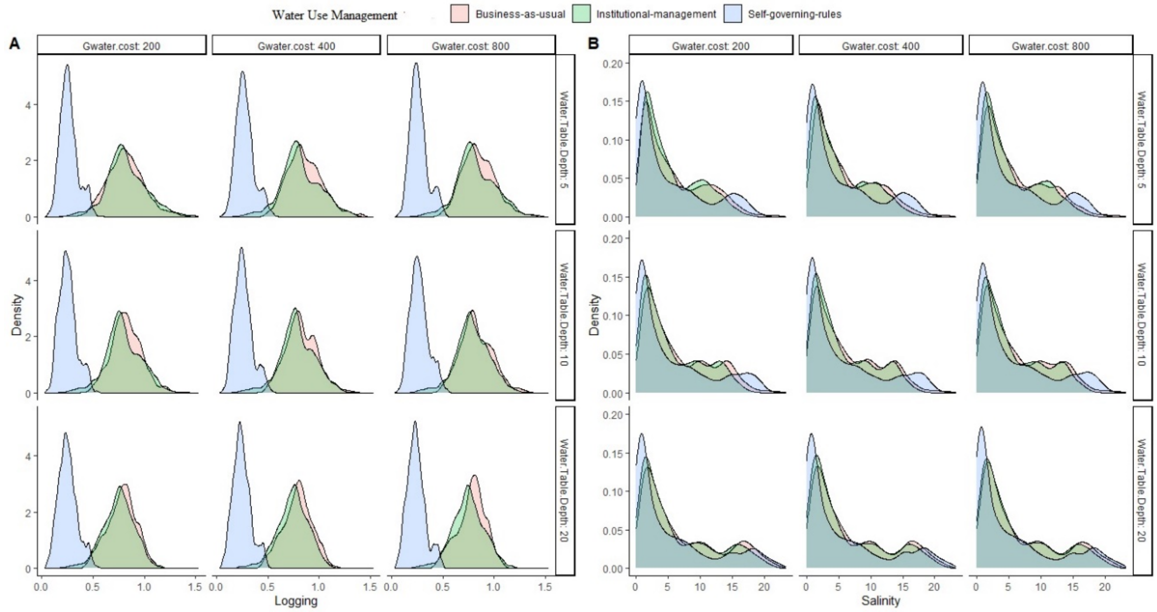

Figure 4: Density Plots of logging and salinity in groundwater cost experiment.

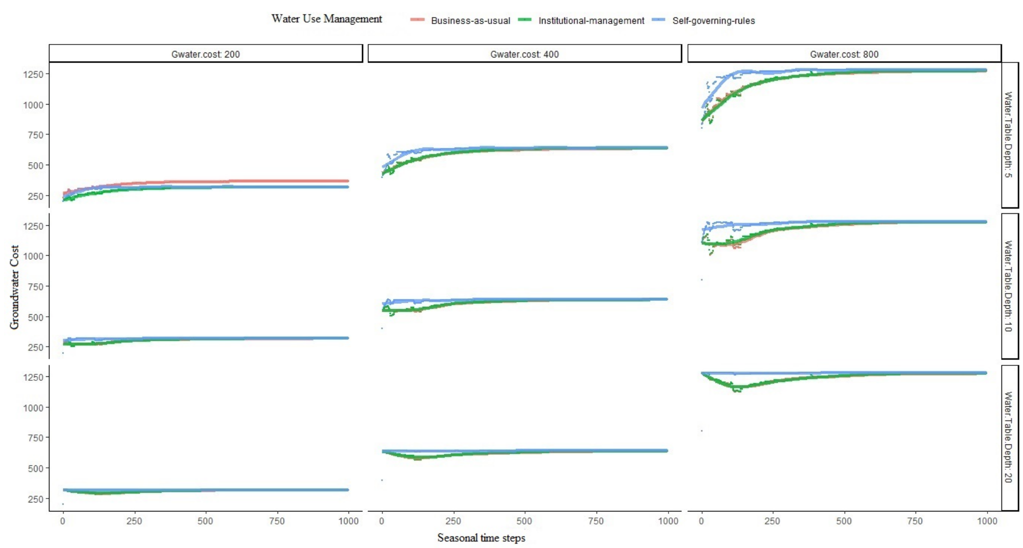

Figure 5: Estimated Groundwater cost under varying water table depth scenarios.

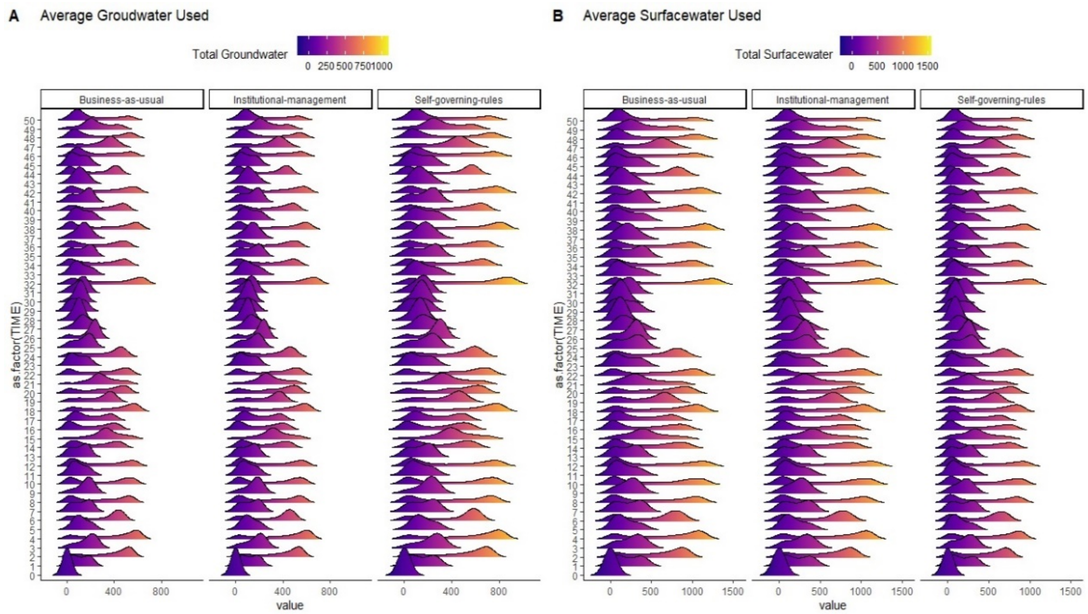

Figure 6: Comparison of groundwater and surface water across water management scenarios under varying groundwater costs.