A VCG Mechanism for Demand Management of Irrigation Systems ⋆

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Abstract:
Global climate change has induced changes in snow covers and precipitation patterns leading to unreliable availability of surface water for agricultural usage. Moreover, the increasing population has put additional strains on precious freshwater resources such as groundwater, leading to unsustainable practices of agriculture. Many studies suggest that demand based surface water management instead of supply based management may greatly mitigate the problem of supply-side fluctuations. Moreover, the rigidity of supply-based distribution rosters and fixed tariffs may be overcome using flexible pricing schemes. In this work, we propose a demand-driven allocation scheme for irrigation canal water enabled by the use of precision sensor technologies. The allocation is coupled with an auction based pricing mechanism. In the proposed approach, the demand can be met using surface water from an irrigation canal network, which is regulated by a principal agent such as a regulatory authority. In the face of shortage, the farmers resort to expensive pumping of non-renewable groundwater to meet their demand. A cropping season is divided into equal slots of fixed duration. At the beginning of each time slot, the principal-agent solicits the valuations of the farmers and sorts the bids received from the players in decreasing order and starts fulfilling the demands from the top. The principal agent uses Vickrey Clarke Groves (VCG) mechanism to compute the payments. The VCG mechanism for payments ensures user truthfulness. Our simulation results demonstrate that under certain realistic assumptions, this mechanism can increase profitability by reducing costs, help decrease groundwater pumping and conserve the surface water.

Keywords: Optimal control and operation of water resources systems.

1. INTRODUCTION

Water is not only important for life on earth but agriculture is also largely dependent on it. Almost 70% of the Earth's freshwater is used by agriculture (Baroni et al. (2007)). Unfortunately, water scarcity and fluctuation is increasing in many parts of the world due to climate change, population and economic growth (Distefano and Kelly (2017)). In this situation, we need to consider demand-side management schemes along with supply-side measurements to increase water efficiency in the agriculture sector. In this spirit, some countries have now institutionalized water markets. Australia has setup the biggest water market in the world which is being used extensively to transfer water amongst users in the Murray-Darling Basin (Quiggin et al. (2010)). Similarly, water markets are also operational in Colorado and California, USA.

The Indus basin irrigation system (IBIS) is the largest constant flow irrigation system in the world (Yu et al. (2013)). Despite this, the agriculture sector in Pakistan operates in water deficit conditions (Meehl et al. (2007)). Even today, surface water is distributed through a mechanism introduced during colonial rule. Under this mechanism, farmers get water in fixed turns during a rotation cycle. This system of availability of water during fixed time slots is known as round-robin (locally known as warabandi). This open-loop distribution mechanism has been shown to limit surface water productivity as compared to if the farmers themselves have influence over the timing of water distribution (Easter et al. (1998)).

In most cases, water markets reallocate water from low to high value users to improve individual and social economic utility (Brooks and Harris (2008)). Past studies suggest that water markets are also more effective in communicat-

ing water productivity and sustainability issues to the end users. For water markets to work properly, clearly defined private water rights are important. Water markets usually reward those who participate in trade but do not consider the spillover effects of the trade on individuals outside the market itself, so specific procedure for the compensation of these individuals need to be introduced (Ostrom (1993)). In the context of developing economies such as Pakistan, this implies that water markets may lead towards further inequity and advantage of influential players. Therefore, instead of trading water between individuals, we consider a system by which water is allocated by a central planner (we call this the principal agent) based on individual demand with the cost being determined by an auction based pricing mechanism.

In this paper, we propose a water market governed by a principal agent where all farmers are connected via the irrigation system. For each farmer, we assume that a soil moisture sensor is installed on the farm. In our system, each farmer provides information about her water demand and price she is willing to pay for that demand. After getting bids from farmers the principal agent sorts the bids received from the players in decreasing order and starts fulfilling the demands from the top. The principal agent computes each farmer's cost using Vickrey-Clarke-Groves (VCG) mechanism. We adopt this mechanism in the form originally presented in Vickrey (1961), Clarke (1971) and Groves et al. (1973). It has been shown that VCG-based pricing ensures truthful reporting by the agents as there is no incentive to misreport the true value of the good being traded. VCG-based pricing mechanisms are already being used to compute payments in similar settings such as in smart grids (Samadi et al. (2012)) and computer and communication networks (Nisan et al. (2007)). There are other methods that have been studied in arid and semi arid areas to get better irrigation performance. In this regard, automation based approaches are also very relevant (see for example Hassani et al. (2019)). After presenting the distribution and pricing mechanism, we investigate its impact on ground water pumping, surface water efficiency and economic benefits through simulations. Our results show that under the assumptions of the model, the VCG-based mechanism enables the farmers to get more economic benefits, decrease ground water pumping, and avoid wastage of surface water in the form of run-off.

The remainder of the paper is organized as follows. Section 2 explains the basic irrigation model, farm soil moisture dynamics and proposed water distribution systems. Section 3 presents the simulations for comparison between the proposed VCG-based water distribution mechanism with the round-robin mechanism. We conclude in Section 4.

2. SYSTEM DESCRIPTION & DYNAMICS

The irrigation system supplies water to the farms via a large network of canals. In the open-loop distribution system, the water supplied to each farm is conventionally pre-determined in proportion to the land area of that farm. The amount of water supplied in the proposed demand-based system, is set according to the soil moisture requirements of the farm. In this section we first describe the irrigation system, followed by an explanation of the

ODE (ordinary differential equation) system depicting the dynamics of the soil moisture.

2.1 Irrigation System Model

Real-world irrigation networks typically consist of a hierarchy of canals. In the Indus Basin Irrigation System (IBIS), main (primary) canals draw water directly from reservoirs/rivers to feed multiple minor (secondary) canals which in turn feed water to distributary (tertiary) canals and finally the water courses. The farmers draw water for their farms directly from the water courses (or "khalas" in local jargon). Since our model focuses on water distribution at the tertiary level, we lump the farms at a common water course into a single representative farm. An illustrative diagram is given in Figure 1. We assume a total of N farms, connected through a common tertiary canal. The soil moisture level for farm k at time t is given by $\theta_k(t)$ where $k \in \{1, 2, 3.......N\}$. The soil moisture level is typically described as a percentage ratio of the volume of absorbed water to the total volume of the soil sample under consideration. We assume that each farm is equipped with a soil moisture sensor.
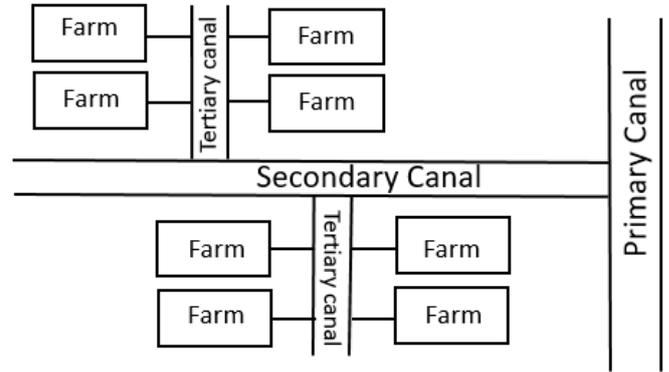
Fig. 1. Irrigation system hierarchy in typical large-scale canal networks, such as those found in the Indus river basin.

2.2 Farm Soil Moisture Dynamics

Here we describe the dynamics of the farm soil moisture level. Depending upon the crop in question, the soil moisture level must be kept within a pre-specified range. A moisture level above this range may result in water-logging. A moisture level below this range exerts potentially detrimental stress for the crop. We represent these threshold levels as $\theta_k^{max} \in (0, 1)$ and $\theta_k^{min} \in (0, 1)$ respectively, with $\theta_k^{max} > \theta_k^{min}$. The objective of farmer k is to keep the instantaneous moisture level $\theta_k(t)$ within the interval $(\theta_k^{max}, \theta_k^{min})$. For the moisture dynamics, we adopt the model presented in Ooi et al. (2008) and given as follows

$$\dot{\theta}_k(t) = I_k(t) - E_k(t) - D_k(t)$$

where $I_k(t) \in \mathbb{R}^+$ is the water flow applied through irrigation, $E_k(t) \in \mathbb{R}^+$ is the rate of water loss to crop evapotranspiration and $D_k(t) \in \mathbb{R}^+$ is the rate of water loss to deep percolation (physical interpretations of these and related terms can be found in Allen et al. (1998)). Assuming a constant evapotranspiration rate e_k and a

deep percolation rate proportional to the moisture level i.e., $D(t) = c_k \theta_k(t)$, we get the following equation

$$\dot{\theta}_k(t) = \sum_{i=1}^{N_w} I_k^i \delta(t - t^i) - E_k - c_k \theta_k(t). \quad (1)$$

where the irrigation flow $I(t) \geq 0$ is modelled as an impulse train applied at times t_i, $i \in \{1, \ldots, N_w\}$. N_w is the total number of weeks in the season, with I_k^i representing the water applied to farm k at time t_i and includes both the allocated surface water and the groundwater. It is important to note that in the model, all volumes are normalized w.r.t the total soil volume of the land area under consideration implying that $\theta_k(t) \in [0,1] \ \forall \ t$.

Figure 2 shows a representative trajectory of the soil moisture level for a single farm. The instantaneous water demand of farm k is the difference between the moisture level $\theta_k(t)$ and the maximum limit θ_k^{max}. We represent this by $d_k(t) \in [0, \theta_k^{max} - \theta_k^{min}]$. Note that water is applied either when surface water is made available or when the moisture level reaches the minimum threshold θ_k^{min} in which case the farmer fulfills the demand through groundwater pumping. There is no constraint on groundwater withdrawal. We assume that surface water is distributed to the farmers every seven days. Next, we discuss the distribution mechanism practiced conventionally in the IBIS followed by our proposed mechanism.
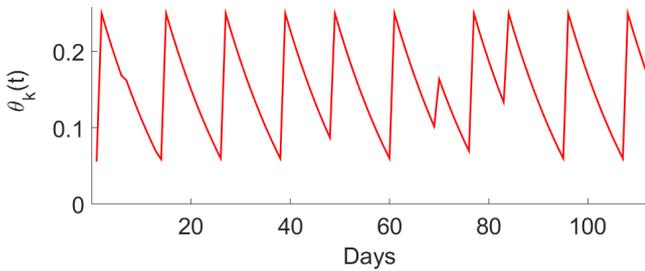
Fig. 2. Instantaneous water state $\theta_k(t)$ of a typical farm.

2.3 The Warabandi Distribution System

Warabandi is a water allocation system introduced in the IBIS under colonial rule and is still widely prevalent today. Under the system, a fixed amount of water is supplied to each farmer in proportion to the size of the farm. The entire season is divided into slots of fixed duration (typically one week). During each time slot, one farm is scheduled to receive water based on a predetermined order. However, this mechanism does not take into account the actual on-farm demand of water. Water in excess of the demand is wasted in the form of runoff. If the water schedule for a farmer as determined by the irrigation authority does not align with the on-farm water requirements, the farmer either has to invest in groundwater or face a poor yield. In what follows, we propose an active mechanism-design based approach to address exactly this issue.

2.4 Proposed Water Distribution Mechanism

Next, we describe the setup for our proposed approach. Let S^i denote the average quantity of water that will be available in time slot $i \in [t^i, t^{i+1})$. In our model, we have alternatively used t instead of t^i. We have assumed that S^i is random throughout the season and players don't have exact knowledge of S^i at the time they are bidding for slot t^i. For player k, the demand function $d_k^i(t)$ is the amount of water that it should receive in this time slot. If this demand is not fulfilled by the surface water, player k will pump water from ground at a higher rate to fulfill its demand requirement only if soil moisture level $\theta_k(t)$ is less or equal to minimum soil moisture level threshold θ_k^{min} i.e $\theta_k(t) \leq \theta_k^{min}$. The valuation of player k for a unit of surface water for time slot t^i is $v_k^i(t)$, which is

$$v_k^i(t) = f(C_g, \theta_k(t), \alpha_k, n_k(t)). \quad (2)$$

Where C_g is per unit price of water pumped, $\theta_k(t)$ is current water moisture level or instantaneous water state of the farm, $n_k(t)$ is the uncertainty in surface water supply predicted by farmer k and α_k is the discount factor. The discount factor α_k can be adjusted to model players behavior towards uncertainty in water supply.

At the start of each time slot t^i, the principal asks all the players for their valuations. The bid of player k is $b_k^i = (\hat{v}_k^i(t), d_k^i(t))$, where $d_k^i(t)$ is the units of water that she wants and $\hat{v}_k^i(t)$ is how much she claims to value a unit of surface water. The actual valuation of player k for a unit of surface water is $v_k^i(t)$. Players will truthfully report how much water they need. However, when it comes to valuation, a strategic player may have incentive to misreport his valuation. After receiving the bids, the principal agent has to make two decisions. Firstly, she needs to decide how to divide water among the players. Secondly, she needs to decide how much players need to pay for the water. In mechanism deign, payments have to be selected to ensure that truthful reporting of player actual valuations is a dominating strategy and player cannot receive higher payoffs by misreporting their valuations. To decide regarding allocation of water, the principal agent simply computes how much each player is willing to pay for water by computing

$$p_k^i = \hat{v}_k^i(t).d_k^i(t). \quad (3)$$

Then, principle agent sorts the bids received from the players in decreasing order and starts fulfilling the demands from the top. Suppose at time t^i, the player are indexed such that $p_{k_1}^i > p_{k_2}^i > \cdots > p_{k_n}^i$. Then, depending on the available supply of surface water, the principal agent starts by providing water to player k_1. If $S^i > d_{k_1}^i(t))$, then principle agent provides water to the player k_2 and this continues until all the surface water is distributed among the players.

The decision of the principal agent is a vector $D(t) \in R^n$. Based on the water allocation rule defined above, player k receives $D_k^i(t)$ units of water in time slot t^i. The allocation of water is such that $S_{min}^i \leq D_k^i(t) \leq d_k^i(t)$. Here S_{min}^i corresponds to the minimum amount of water flow required in the canal to ensure surface water supply to a player. Thus, the utility of player k in time slot t^i is

$$u_k(t) = v_k^i(t)D_k^i(k) - C_g\tilde{d}_k^i(t) - C_k^i(\hat{v}_k^i(t), \hat{v}_{-k}^i(t)) \quad (4)$$

where $\tilde{d}^i_k(t)$ is the unfulfilled demand at the deadline i.e surface water received by farmer k is less then its demand $D^i_k(t) < d^i_k(t)$ then farmer k will have to pump $\tilde{d}^i_k(t)$ units of water from ground at a unit cost of C_g. $C^i_k(\hat{v}^i_k(t), \hat{v}^i_{-k}(t))$ is the payment that players will have to make when their demands are fulfilled through surface water.

To compute the payments, we will rely on VCG (Vickrey Clarke Groves) mechanism. For computing payments based on VCG mechanism, the principal will have to compute $W^i(t)$ and $W^i_{-k}(k)$ for each player, where $W^i(t)$ is the social decision vector by principal agent i.e how much water each farmer will get during time slot t^i and $W^i_{-k}(t)$ is the hypothetical social decision vector if player k did not participate in the bidding process. Then, the payment for player k would be computed as follows:

$$
\begin{aligned}
C^i_k(\hat{v}^i_k(t), \hat{v}^i_{-k}(t)) = & \sum_{j \neq k} u_j(W^i_{-k}(t), \hat{v}^i_j(t)) \\
& - \sum_{j \neq k} u_j(W^i(t), \hat{v}^i_j(k)).
\end{aligned}
\tag{5}
$$

Payment in (5) is equal to the difference in social utilities of other farmers in the presence and absence of farmer k. This method of calculating payments incorporate social impact of participation in bidding of a farmer. In the bidding the players who did not receive water in time slot t^i will not have to pay, i.e., $C^i_k(\hat{v}^i_k(t), \hat{v}^i_{-k}(t)) = 0$ if $W^i_k(t) = 0$. Let $k_1, k_2, \cdots, k_n$ be an indexing of players such that $p^i_{k_1} > p^i_{k_2} > \cdots > p^i_{k_n}$, where $p^i_{k_i}$ is defined in (3). This indexing sorts the players in the decreasing order of priority for receiving a share. Suppose that the supply of water was such that the first m players received water, i.e., $W^i_{k_l}(t) > 0$ for $1 \leq l \leq m$. The decision and water allocation rule ensures that the demand of the first $m - 1$ players was fully satisfied, while the player k_m received a share of water which can be less than her demand. i.e.,

$$
W^i_{k_l}(t) = \begin{cases} d^i_{k_l}(t) & 1 \leq l \leq m - 1 \\ \hat{d} & l = m \end{cases}
\tag{6}
$$

where $\hat{d}$ is the quantity of water supplied to player k_m such that $S^i_{\min} \leq \hat{d} \leq d_{k_m}(k)$. To compute the payment for player k_l, we need to compute $W^i_{-k_l}(t)$. Among the players receiving water at time k, the bid of k_l will only impact the player k_m whose demand was not fully met. The players $k_1, \cdots, k_{l-1}, k_{l+1}, \cdots, k_{m-1}$ will still receive water equal to their effective demand whether k_l participates in the bidding or not. Therefore,

$$
u_j(W^i_{-k_l}(t), \hat{v}^i_{k_j}(t)) - u_j(W^i(t), \hat{v}^i_{k_j}(t)) = 0
\tag{7}
$$

for all $j \in \{1, \ldots, i-1, i+1, \ldots, m-1\}$. If player k_l did not participate in the bidding, the quantity of water received by player k_m will definitely increase because $W^i_{k_l}(t)$ additional units of water are now available. Let $D^i_{k_m, -k_l}(t)$ be the quantity of water received by player k_m if player k_l did not participate in the bidding process at time t^i. Then,

$$
D^i_{k_m, -k_l}(t) = \begin{cases} d^i_{k_m}(t) & D^i_{k_l}(t) \geq d^i_{k_m}(t) \\ & \quad - D^i_{k_m}(t) \\ D^i_{k_m}(t) + D^i_{k_l}(t) & \text{otherwise} \end{cases}
\tag{8}
$$

Thus, if $D^i_{k_l}(t)$ is sufficient then the effective demand of player k_m will be completely satisfied. Furthermore, if

$D^i_{k_l}(t) > (d^i_{k_m}(t) - D^i_{k_m}(t)) + S^i_{\min}$, than players who did not originally received water may receive water as well. Suppose that the quantity $D^i_{k_l}(t)$ was sufficient to not only satisfy the requirement of player k_m but p additional players as well. In the hypothetical case in which player k_l did not participate in the bidding process, the utilities of players $k_m, k_{m+1}, \cdots k_{m+p}$ are increased. Therefore, the payment for player k_l will be

$$
\begin{aligned}
C^i_{k_l}(\hat{v}^i_k(t), \hat{v}^i_{-k}(t)) = & \sum_{j=k_m}^{k_m+p} u_j(D^i_{-k_l}(t), \hat{v}^i_j(t)) \\
& - u_j(D^i(t), \hat{v}^i_j(t)).
\end{aligned}
\tag{9}
$$

3. SIMULATION AND DISCUSSION

In this section, we present simulations to compare the performance of the VCG-based distribution mechanism with warabandi. We evaluate performance based on the amount of surface water wasted, extra ground water pumped and the cost incurred to the individual farmers. We first simulate a single season under a selected set of nominal parameter values for the system. Next, we carry out repetitive numerical simulations by randomly varying the parameters over a range that mimics real-world behavior.

3.1 Performance over a Single Season

In our simulations, all volumes are normalized i.e.. all volumes are in the range $[0, 1]$. We assume a total of four farmers i.e., $N_k = 4$, engaged in farming activities over a season of sixteen weeks i.e., $N_w = 16$. Under the nominal parameters assumed for this particular simulation, we assume constant upper and lower threshold levels for the moisture level so that $\theta^{max}_k = 0.25$ and $\theta^{min}_k = 0.05$. The surface water supply for each week is varied using uniform distribution over an interval $[0.2, 0.4]$ as shown in Figure 4. Furthermore, we assume deep percolation rate of $c_k = [0.05, 0.08, 0.12, 0.15]$ and evapotranspiration rate $e_k = 0.01$. Each week, the farmers compute their water demand and announce their bid using a discount factor of $\alpha_k = 1$. The farmers compensate for any deficit in supply by pumping groundwater, the unit cost of which is assumed to be $C_g = 100$. Groundwater may also be pumped during the week if the moisture level $\theta_k(t)$ touches the lower threshold θ^{min}_k. Figure 3 shows the fluctuation in soil moisture level of the farms over the entire duration of the season while initial conditions were $\theta_k(0) = [0.07, 0.15, 0.12, 0.1]$. In case of round-robin water entailment for each farmer is 25% of total capacity. In round-robin water distribution mechanism each week one farmer get surface water either on the first, second, third or forth priority. This schedule is rotational and repeat after four weeks. The results of the simulation are shown in Figures 5 and 6. Figure 5 shows the weekly difference in groundwater pumped by all farmers combined, over the season. A positive difference indicates more pumping in the round-robin case. We see that the difference is positive for all weeks. The difference is almost zero in weeks 8 and 12. Water pumped is approximately equal during these weeks in round-robin and proposed mechanism, but we can't compare performance of both mechanisms on weekly pumped water as weekly demand could be different for a farmer when water distribution mechanism is different.

Further in Figure 5 we show the difference in surface water wasted in the form of run-off. In the round-robin system, any water in excess of demand is not drawn by a farmer and results in wastage. Note that there is no wastage in the VCG-based mechanism since only the required amount of water is released to the farmer.

Finally, Figure 6 shows the difference in cost incurred by farmers while getting water through the round-robin distribution as compared to the VCG-based mechanism. In order to calculate payments for surface water in proposed mechanism, we assume that valuation in equation (2) is directly proportion to farmer's demand. When water is distributed using round-robin mechanism the farmers pump more groundwater and since water pumping cost is higher as compared to the surface water. In case of round-robin we have assumed zero surface water price per season. The results of the simulation suggest that at least for the nominal parameters, the VCG-based distribution mechanism performs much better than the round-robin distribution mechanism.

3.2 Performance Comparison while changing Parameters

We evaluate difference in pumped water, wasted surface water and difference in cost incurred to compare both mechanisms while varying surface water supply, soil type and crop type over the physically realizable rang. Surface water supply range is $[0.2, 0.8]$. Soil moisture decay rate range c_k is $[0.05, 0.15]$ and this range of c_k cover almost all type of soils. The minimum required level of moisture in the soil for a plant is 5% and maximum allowable moisture level varies for different crops from 25% to 50%. Therefore, maximum soil moisture level threshold θ_k^{max} range is $[0.25, 0.5]$ and minimum soil moisture level threshold $\theta_k^{max} = 0.05$ for all farmers.

Fig. 7 shows the various scenarios to depitct the difference in total water pumped between round-robin and VCG-based mechanisms. As difference in pumped water is positive so farmers pump more water in round-robin as compare to VCG-based mechanism. Difference in pumped water is always positive because in round-robin case farmers can get water greater than their demand at the same time there are farmers in the system who are not getting water or getting water less then their demand. Therefor other farmers have to pump water to fulfill their demand. In the case of VCG-based mechanism, all available water is used to fulfill demands of farmers and no one gets water more than her demand. So farmers will pump less water as compared to round-robin mechanism.

Scenario (D), (E) and (F) shows the water wasted by farmers when water is allocated using round-robin mechanism. The water wasted is observed when soil moisture decay rate for all farmers are different, farmers are sowing different crops and surface water supply is fluctuating. Fig. 8 shows the difference in cost incurred when water is distributed through round-robin as compared to VCG-based mechanism. As difference in cost is positive so farmer's incurred cost is greater when water is distributed using round-robin as compare to propped mechanism. The difference in cost incurred is observed when soil moisture
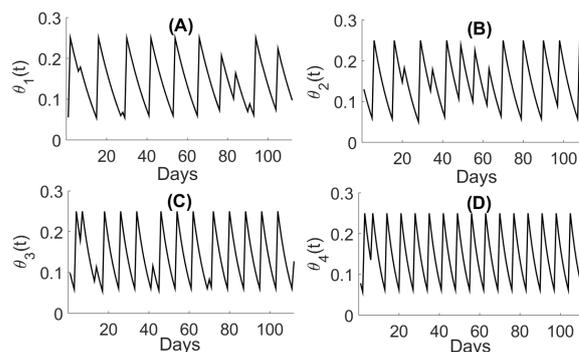
Fig. 3. Soil moisture level of all four farmers. **(A)**,**(B)**,**(C)** and **(D)** show the water demand of all four farmers respectively.
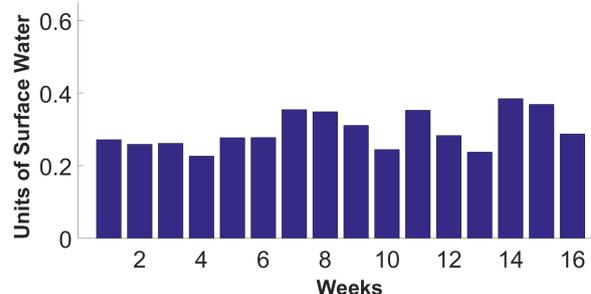
Fig. 4. Surface water supply per week during season.
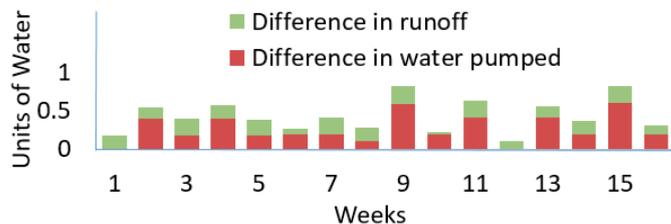
Fig. 5. Difference in water pumped and total water wasted per week between total round-robin distributions and aggregated VCG-based allocations.
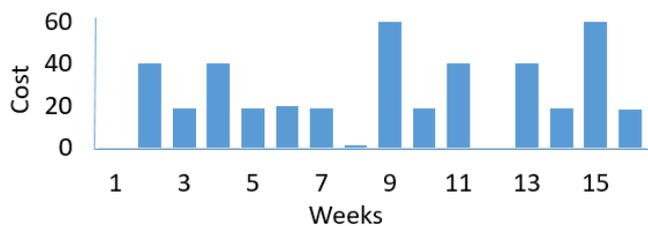
Fig. 6. Difference in total cost incurred by all farmers between round-robin allocations and VCG-based allocations.

decay rate is varying, farmers are sowing different crops and surface water supply is fluctuating.

4. CONCLUSION

In this paper, we have proposed a demand based surface water distribution mechanism. This VCG-based proposed mechanism aims to distribute surface water in a socially optimal manner while decreasing ground water pumping and resulting cost incurred by farmers. Through simula-
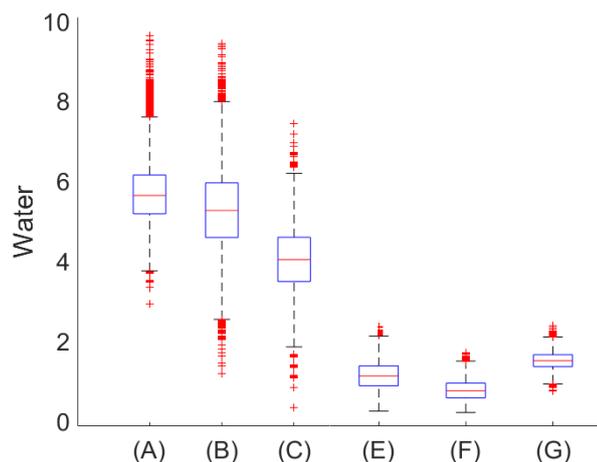
Fig. 7. Total difference in water pumped by farmers when water is distributed through round-robin mechanism as compared to VCG-based mechanism. Scenario (A): varying soil moisture decay rates. Scenario (B): heterogeneous crops. Scenario (C): variations in surface water supply. Total water wasted by farmers when water is distributed through round-robin mechanism. Scenario (D): varying soil moisture decay rates. Scenario (E): heterogeneous crops. Scenario (F): variations in surface water supply.
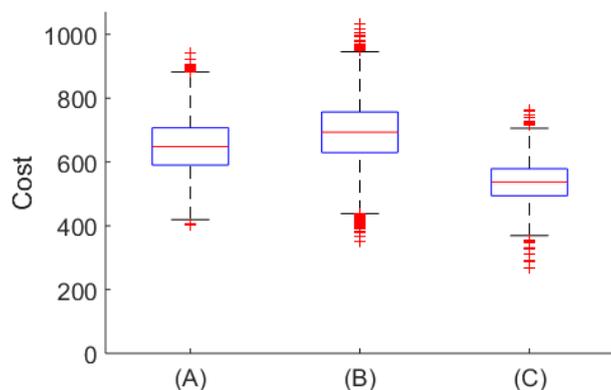
Fig. 8. Total difference in cost incurred by farmers when water is distributed through round-robin mechanism as compared to VCG-based mechanism. Scenario (A): varying soil moisture decay rates. Scenario (B): heterogeneous crops. Scenario (C): variations in surface water supply.

tions, we have shown that the total ground water pumping decreases significantly when compared in traditional round-robin distribution, promising a more sustainable future for non-renewable groundwater resources. There is no surface water wastage in the proposed mechanism as farmers are only getting water as per their demand. We also see that under the proposed mechanism, the crop production costs incurred by farmers are low. This is attributed mainly to the low usage of ground water under the proposed scheme, and that ground water pumping is significantly expensive than obtaining water from canals in typical irrigation systems.

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