Irrigation water policies for sustainable groundwater management in India: a case study of irrigated northwestern plains of India

ABSTRACT

Increasing global water shortage emphasizes the need for demand-side water management policies, especially in the agriculture sector, being the largest consumer of freshwater. Such policies are relevant in India, where groundwater depletion may have severe implications at various socioeconomic levels. In this paper, using mathematical programming, we assess the feasibility of two alternative irrigation water pricing policies; (1) uniform water pricing policy (ii) differentiated water pricing policy wherein farmers growing less water requiring crops (<4488m^3/ha) get an incentive for saving water, while those growing water-intensive crops pay for it. Using a case study of Indian Punjab, the breadbasket and one of the fastest groundwater-depleting states, alternative cropping patterns are also suggested. The findings revealed that the current rate of groundwater withdrawal could not sustain the agricultural intensification in the state. Although optimization of resource allocation has the potential of saving water by 8%, it alone is unlikely to break the rice-wheat mono-cropping pattern in the state. The analysis of two different volumetric irrigation water pricing showed that differentiated water pricing would be more effective in halting groundwater depletion in the state. However, adequate investment in irrigation water supply infrastructure, mainly for installing water meters, is required for implementation of the policy.

Keywords: Sustainable intensification; Water allotment right; volumetric water pricing

INTRODUCTION

The Green Revolution (GR) technologies have led to greater rice and wheat production, the two staple food crops of India, and turned on economic growth in the country[1]. The northwestern state of Punjab, situated in the Indo-Gangetic Plains, reaped these technologies' earliest and maximum benefits[2&3]. The policy support, including providing incentives by subsidizing water and energy and minimum support prices and procurement, has played a crucial role in technology adoption and increasing cereal production in this region[4]. However, the policies intended to support GR technologies also have created a harmful effect on the health of agriculture, natural resources, biodiversity, and human beings and posed challenges to achieving the Sustainable Development Goals[5-7].

Water and electricity policies are interconnected and are often considered the main driver of growth in the area under rice, which led to overexploitation of groundwater and loss of crop diversity in the state. The electricity for agriculture, which was subsidized partly up to 1996-97 (charged on a per-unit basis up to 1970s and a flat rate based on power load basis up to 1996/97), is now free in the state. The situation is almost similar in the case of irrigation water pricing, and policies do not encourage water conservation and its efficient use. The irrigation water pricing in India is non-volumetric and mainly applies to canal-sourced systems, depending on the area and type of crops grown. The prices in this particular region are among the lowest for water-guzzling crops encouraging farmers to allocate more area under these crops[7-8]. During this period, the area under rice and wheat has increased from 47% of the total cropped area in the 1970s to more than 80% in 2019. Though not a traditional crop of Punjab, paddy practically wiped out oilseeds and pulses, besides markedly replacing maize and cotton.

The Government of Punjab enacted a law called 'The Punjab Preservation of Subsoil Water Act, 2009' to reverse these trends by mandatorily delaying paddy transplanting beyond June

10, when the most severe phase of evapotranspiration is over. However, evidence of its impact on checking the groundwater depletion rate is limited[9]. The annual groundwater extraction in the state is 64.42 higher than the recharge, and the rate of depletion is also the highest among the states[10]. The groundwater depletion has other associated costs, including the increased costs of securing water availability. The GR supportive policies also have brought inefficient use of energy and promoted indiscriminate use of pesticides and chemical fertilizers, leading to degradation of land, water and soil resources. Management of paddy straw has emerged as another challenge raising serious human and soil health issues. Studies suggest that Punjab agriculture is overcapitalized and has reached a stage where input use has been saturated. The cost of production has increased, putting an additional financial burden on farmers, thus making agriculture unsustainable[11-13].

Various researchers, expert committees, and agricultural policy analysts have highlighted the need for diversifying agriculture towards high-value commodities and strong possibilities of doing so through corrections in energy and water pricing policies[14-17]. The National Water Policy 2012 recommends water pricing on a volumetric basis, irrespective of the sector. Accordingly, in its draft National Water Framework Bill, the Central Water Commission has proposed a water law on volumetric water pricing to meet considerations of equity and efficiency. Analyzing and understanding the effectiveness of water pricing policies on cropping patterns and saving of water becomes a decisive contribution to policy analysis, particularly when water scarcity becomes the leading sustainability issue. This study, therefore, has two major objectives (1) to assess the feasibility of an incentive-oriented volumetric irrigation water saving policy and its effect on changes in cropping pattern, water use and farmers' income, and (2) to suggest crop and enterprise plans for sustainable use of resources in the state. The following section describes the data and methodology, while the results are presented and discussed in the subsequent chapter. The key conclusions and some policies implication are presented in the last section.

DATA AND METHODOLOGY

The Data

The study is mainly based on plot-level data collected under the "Comprehensive Scheme for Studying the Cost of Cultivation of Principal Crops” of the Directorate of Economics and Statistics (DES), Ministry of Agriculture & Farmers Welfare, Govt. of India. It is the most reliable database on the cost of cultivation and an essential basis for determining the Minimum Support Prices of the important crop in the country. Under this scheme, each sample household is surveyed consecutively for three years. In the present study, the data pertains to Triennium Ending 2013-14 (the latest year for which such data is available). Under this scheme, the plot-wise data are collected from the 300 representative households of 30 sub-districts (administratively called tehsils). From three agro-climatic zones of the state, farmers are selected using a three-stage stratified sampling technique: (1) *tehsil* as stage one (2) a village or cluster of villages as stage two, and (3) operational holdings within the cluster as stage three. From each cluster, a sample of 10 operational holdings, two each from the five size classes, *viz*. marginal (< 1 ha), small (1-2 ha), semi-medium (2-4 ha), medium (4-6 ha), and large (> 6 ha), are selected randomly thus representing all the climatic conditions, farmers’ categories and crops of the state. Besides, the data from secondary sources and published studies were also used to work out resource use coefficients and availability levels.

Analytical tools

Computation of costs and returns

The cost of cultivation was estimated based on the cost principle adopted by the Commission for Agricultural Costs and Prices (CACP). All the paid-out expenses by the farmer in cash and kind (including rent paid) and the imputed value of family labour formed the part of total costs. Technically, it is termed as 'A_2 + Family Labour' cost (for more details, see the reference, MOSPI Undated[18]). Some of the components of Cost A_2 were directly retrieved from the unit level dataset of the cost of cultivation scheme, while few others were imputed. For example, depreciation of implements and farm buildings and interest on working capital was computed by using the standard method of CACP[18]. Similarly, the cost of family labour was imputed by multiplying the working hours of family labour by the prevailing wage rate in the state. Once the total cost is calculated, the net returns are calculated by subtracting costs from the gross return (value of main product + by-product).

Mathematical specifications of the model

Linear Programming is one of the widely used mathematical programming techniques to assist the decision-making in allocating areas under different crops and deciding various enterprise combinations. It is an easy and flexible method for assessing different ways to use limited resources under variable objectives and constraints. Moreover, the model allows simulating the effect of various policy options. In the present study, alternative crops and livestock enterprises plans (scenarios and plans are used interchangeably in the rest of the paper) were developed using a quasi-dynamic *linear programming* (LP) model. The objective was to maximize the returns (defined in Equation 1) under the constraints of cultivable land, human labour, irrigation water, farm power, fertilizers and working capital (Equations 2 to 7). The second component in the objective function (Equation 1) allowed to simulate the different pricing scenarios, including incentive payments to the farmers wishing to opt water-saving cropping pattern. The fodder availability constraint was captured endogenously in the model (Equation 8). The cropping pattern must generate a sufficient quantity of feed, fodder and concentrate on maintaining the livestock in the state. It is worth mentioning that the returns from fodder crop activities were considered zero being an intermediate activity. The mathematical specification of the model is presented through a set of the following eight Equations. The notations used in the equations are given in Table 1.

$$Maximizing\ Z = \sum_{c=1}^{n} (Y_c\, P_c\ - C_c)\, A_c\ + (WAR - IW_c) WPR \quad (1)$$

Subjected to:

$$\sum_{c=1}^{n} A_c \leq\ NSA \qquad (2)$$

$$\sum_{m=1}^{12} \sum_{c=1}^{n} HL_{mc} A_c \leq\ THL_m \quad (3)$$

$$\sum_{c=1}^{n} IW_c A_c \leq\ TIW \qquad (4)$$

$$\sum_{c=1}^{n} FP_c A_c \leq\ TFP \qquad (5)$$

$$\sum_{c=1}^{n} FERT_{fc} A_c \leq\ TFERT_f \qquad (6)$$

$$\sum_{c=1}^{n} WC_c A_c \leq\ TWC_c \qquad (7)$$

$$\sum_{c=1}^{n} FR_c\, A_c \leq\ 0 \qquad (8)$$

$$A_c\ \geq\ 0 \qquad\qquad \forall_c = 1{,}2 \ldots . n$$

Almost the entire cropped area in the state is under irrigation. Usually, crops in the state are grown in three seasons: (i) monsoon, also called Kharif (July to October), (ii) winter, also called rabi (November to March), and (iii) summer (March to June). The major crops grown during the Kharif season are rice, cotton and maize, while other crops like cluster bean, pigeon pea, green gram, groundnut, black gram and fodder crops are also cultivated in a smaller area. In rabi season, wheat, potato and mustard are the major crops, whereas chickpea, field pea, lentil and barley are some of the traditional crops losing their area in the state. Green gram and fodder crops like sorghum and pearl millet are also grown in the short window of 50-70 days during summer, also called *zaid* season. The crop-wise planting and harvesting months are given in Supplementary Table S1. The livestock sector is mostly represented by milch animals (crossbred cow and buffalo) for farm household consumption, and it contributed one-third to agricultural GDP. In this model, 20 crops and two livestock activities were included.

Table 1: Description of notations used in the mathematical model

Notation	Description
Y_c	Yield (per ha/per animal) of crop/livestock species 'c'
c	Crop/livestock species
P_c	Price of crop/livestock output (Rs./unit of crop/livestock produce)
C	Cost of cultivation (Rs./ha) or maintenance crop (Rs./animal);
A_c	Decision variable, i.e., area under crop/number of animal
WAR	Water Allotment Right (m^3/ha)
IW_c	Volumetric irrigation water use (m^3/unit)
WPR	Water pricing rate (Rs./m^3)
NSA	Net sown area excluding area under perennial crops
HL_{mc}	Monthly human labour use coefficient (per ha or animal)
TIW	Irrigation water availability, both from groundwater and surface sources
FP_c	Farm power use (HP hours/unit)
TFP	Available farm power in the state
$FERT_{fc}$	Per ha use of fth fertilizer (N, P & K)
$TFERT_f$	Availability of fth fertilizer
FR_c	Fodder use per animal unit (on a dry matter basis). In the case of crops, the FR_c was used with a minus sign as crops generate fodder rather than consuming it. FR_c for crops was computed by applying grain to the straw ratio (on a dry-matter basis) to crop yield.

Crop and enterprise planning using linear programming primarily captures the supply side behavior, more precisely the area response based on net returns and resource constraints, ignoring the demand aspects. As a result, such models tend to overestimate or under-estimate the area allocations for some crops. Consequently, a single crop may cover an infeasible larger area (over-estimation) or null or negligible size (under-estimation). Therefore, two nonresource constraints were also imposed to avoid undesirable over-estimation or under-estimation bias.

While the per-unit requirement coefficients of labour, capital, farm power, and fertilizer were estimated using data from the cost of cultivation, the per ha requirement of irrigation water for various coefficients was calculated using the approach suggested in earlier studies[17]. The resource availability was mainly based on three different data sources. In the case of land, the net sown area (excluding area under perennial crops) was considered the total available land resource, whereas the number of cultivators and agricultural labourers was used to estimate the total labour availability in the state. Since the existing use of farm power, working capital, and fertilizers usage in Punjab is already on the higher side[11], the use of these resources under the existing cropping pattern formed the Right Hand Side (RHS) of the constraint equations (Equation 5 to 7). The minimum and maximum area that should be retained under different crops were determined based on experts' advice.

Policy scenarios

Current water pricing policy in India

The irrigation water pricing in India is non-volumetric and mainly applies to canal-sourced systems, depending on the area and type of crops grown. The approach adopted by the states even for flow and lift irrigation are not uniform. The focus of the water pricing is given to recovering the cost of creation and operation and maintenance of the irrigation projects rather than ensuring the sustainable use of water resources. Though consideration is also given to demand-side factors, differences in water rates are not very encouraging to diversify the cropping pattern towards low water requiring crops. For example, there is no difference in water rates for paddy compared to oilseeds and pulses in the states of Gujarat, Himachal

Pradesh, Punjab and Tripura (Table 2). In some of the states (Assam, Maharashtra and Rajasthan), the rates are rather higher for oilseeds/pulses than those for paddy.

Table 2: States-wise water rates for paddy and oilseeds/pulses under flow irrigation in India

States	Paddy	Oilseeds/pulses
Andhra Pradesh	370.50 - 494.00	148.20 - 247.00/©
Assam	281.24 - 751.00	562.50
Bihar	108.40 - 247.00	74.10 - 98.80
Chhattisgarh	200.07 - 494.00	123.50 - 247.00
Gujarat	160.00	160.00
Haryana	123.50-148.20	111.15 - 123.50/ 86.45 -98.80©
Himachal Pradesh	49.92	49.92
Jammu & Kashmir	298.87	150.67/ 121.03©
Jharkhand	108.68 - 217.36	74.1 - 98.8
Karnataka	247.10	148.25/ 86.5©
Kerala	37.00 - 99.00	@
Madhya Pradesh	85.00 – 155.00	50.00 – 75.00
Maharashtra	119.00 – 476.00	476.00 - 1438.00
Manipur	305.00 – 602.00	184.00
Orissa	@	60.00 – 170.00
Punjab	123.50	123.50
Rajasthan	49.40 -197.60	64.22 - 113.62/ 49.40 - 79.04©
Sikkim	60.00 - 100.00	@
Tamil Nadu	5.56 - 49.42	2.77 - 8.35
Tripura	312.50	312.50
Uttarakhand	40.00-287.00	@
Uttar Pradesh	40.00-287.00	@
West Bengal	37.06-123.50	@

Note: ©Separate rates for oilseeds and pulses; @ Not available; Source: Based on data collected from Central Water Commission[19]

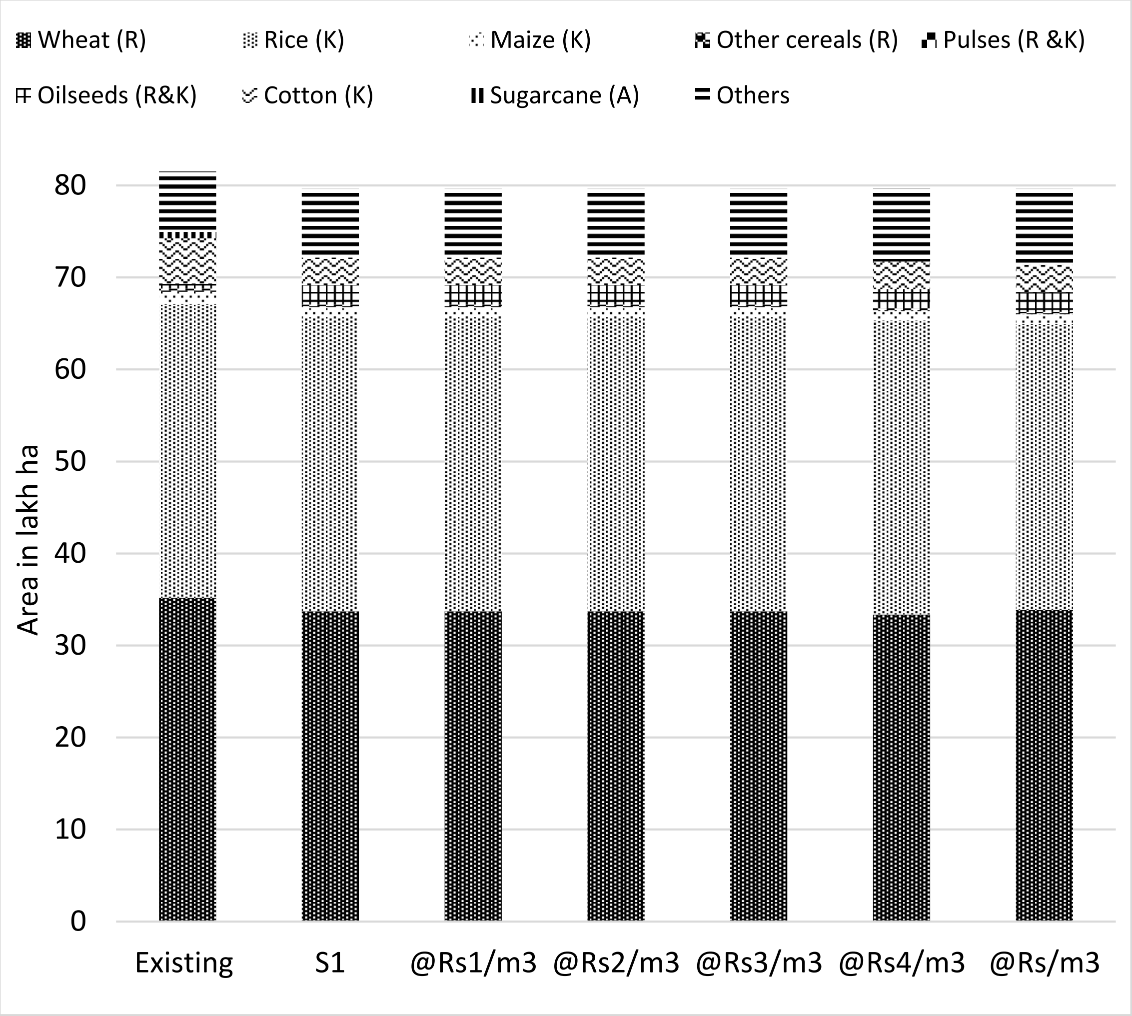
Three different scenarios were built by simulating the effect of resource reallocation and changes in policies on diversifying cropping patterns, minimizing resource use, and maximizing the net economic margins. In the first Scenario (Scenario S1), the effect of optimizing the existing resource use allocation was observed. The effect of two different water pricing policies was analyzed in the subsequent two scenarios. In the first case (Scenario S2), we simulated the impact of a uniform volumetric water pricing policy for all the crops. In contrast, in the second case (Scenario S3), differential water pricing was considered depending on the volume of water use. In the latter case (Scenario S3), farmers who save irrigation water are paid for, while those who overuse groundwater beyond a specific benchmark (generally call it farmer's water allotment right (WAR) pay for it. It is expected that the payment for saving water and pricing for its overuse will change cropping patterns to more diversified towards less water requiring crops and will induce farmers the adoption of water-saving irrigation technologies. In both the Scenarios, a range of water prices varying between 1/m^3 to Rs.5.00/ m^3 at Rs.1/m^3 interval was analyzed. The rates that are in practice in different countries[20] or proposed in various studies[21-22] formed the basis for this study. The irrigation water use for rice, the most popular staple food of the country, grown under best management practice (4488 m^3/ha), was assumed as WAR, above which farmers pay for its use. The difference between irrigation water use by the crop grown in the field and WAR revealed the volume of water saved.

RESULTS & DISCUSSION

The linear programming in this study was solved using MS Excel (Solver add-in). The datasheet is prepared in Excel to develop optimum crop plans based on the compiled data and methodologies described above. Many iterations were run for refining crop plans during various stages of the model development and are presented in Tables 2, 3 & 4. The results are presented to show, *first*, the changes in cropping and livestock enterprises pattern, *second*, the corresponding variations in resource use level, and *third*, the changes in the income of farmers and financial implications in terms of government spending on payment for ecosystem services.

Effect on cropping and livestock enterprise patterns

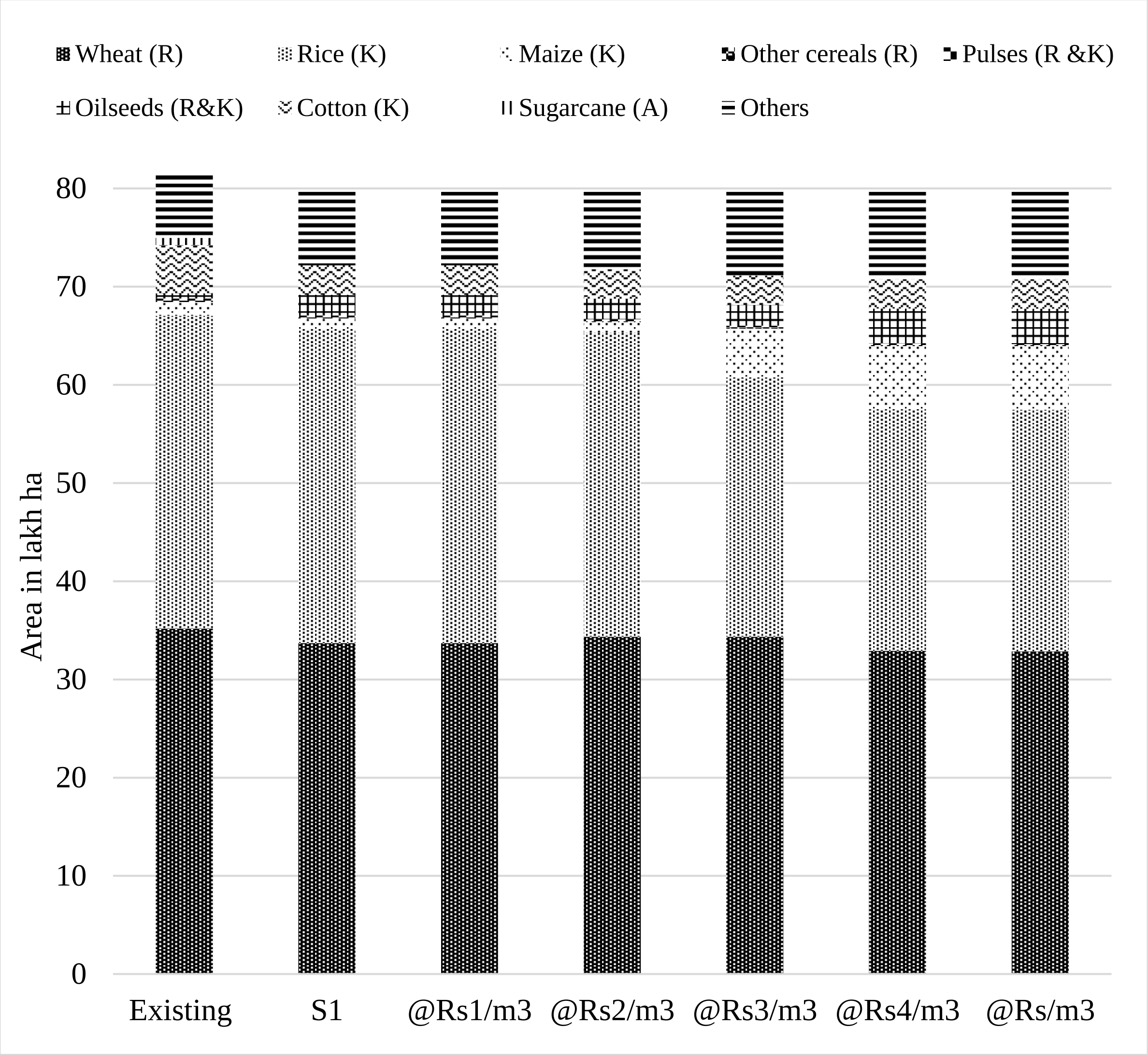
In the first Scenario (S1), the possibility of resource reallocation was explored by their optimization with the existing set of policies. The results suggest that the depleting groundwater resources cannot sustain the further increase in the gross cropped area in the state as the total cropped area declined by 2.29% (81.5 lakh ha to 79.6 lakh ha) (Figure 1). The optimum plan (S1) suggested decreasing area under long-duration, water- and labor-intensive crops. The maximum decrease was in cotton from 4.9 lakh ha under the existing cropping pattern to 3.0 lakh ha (minimum area set) in the optimum plan. The crop matures in almost seven months, while the returns per ha are much lower than the paddy. Wheat is another crop under which acreage reduces by 1.5 lakh ha from the existing area of 35.5 lakh ha. Sugarcane was completely wiped out from the cropping pattern. Interestingly, the area under low water requiring oilseeds under S1 increases by 1.6 lakh ha. However, it is equally worrying that the area under rice remained unchanged, indicating that with the existing set of policies, there is unlikely to reduce the area under rice and check the groundwater depletion in the state. The findings further imply that farmers generally ignore the duration of the crop while making their crop planning decisions and hence have scope for optimizing the resource allocation.



Note: S1 indicates optimization with existing policies; @Rs1/m^3 to @Rs5/m^3 are the water prices varying between Rs. 1/m^3 to Rs.5.00/ m^3 at Rs. 1/m^3 interval; K=Khrif season crop; R=Rabi season crop; A= Annual crop

Figure 1: Changes in cropping pattern on optimal of resources under uniform water pricing policy in Punjab

The analysis of two different volumetric irrigation water pricing showed that uniform pricing would be ineffective in halting groundwater depletion in the state. This is evident when comparing the results presented in the next five bars of Figure 1. The finding showed that the cropping patterns would almost remain unchanged when implemented uniform water pricing policy. A slight shift in the area in favor of other crops, mainly vegetables and fodder, will start when the water prices are fixed as high as Rs.5/m^3. On the other hand, a significant change in cropping patterns will happen when differential water prices are applied. The area under rice will reduce by almost 23%, while the area with low water requiring crops like maize and oilseeds will increase more than three times compared to the existing one (Figure 2). However, these changes will only occur when the incentives for saving water are sufficient to compensate farmers for substituting rice (Rs.2/m^3). The apparent reason for the low elasticity of shifting is the vast difference in the net economic margins of rice vis-à-vis competing crops.



Note: Those who use water over and above 4488 m^3/ha pay for an additional cubic meter of water used while those use below the threshold get the benefit for saving water at the rate varying between 1/m^3 to Rs.5.00/ m^3 at INR1/m^3 interval (S3@1 to SS@5); K=Khrif season crop; R=Rabi season crop; A= Annual crop.

Figure 2: Changes in cropping pattern on optimal of resources under differentiated water pricing policy in Punjab

For more insights, the ratios of relative economic margins before and after the introduction of the payment system were computed and are presented in Supplementary Tables S2 & S3. It was observed that the economic margins in rice (Basmati) are highest among the Kharif season crops. These are 18.41, 4.65, 2.30, 2.29 and 1.64 times higher than crops that can compete, viz., pigeon pea, black gram, maize, cotton, and groundnut. Similarly, the economic margins in the case of rice (non-Basmati) are also higher by 15.27 times, 3.86 times, and 1.9 times compared to the red gram, black gram, and maize and cotton, respectively. Though the proposed payment/pricing system at Rs.2/m^3 will improve the relative profitability ratio for groundnut (0.61 to 0.71), maize (0.44 to 0.49), cotton (0.44 to 4.45), and black gram (0.21 to 0.34) when compared to rice (Basmati), these are still far lower compared to rice. When the water pricing is fixed at a significantly higher rate, the economic margins start turning in favor of low water-requiring crops. For example, when the water pricing is fixed at Rs.5/m^3, the economic margins turn in favor of groundnut compared to rice.

The livestock population is another factor that will guide the future cropping patterns in the state. The dual-purpose crops, mainly maize, have a high probability of competing with rice due to their ability to supply better quality and quantity of fodder for livestock. The area under maize can be increased by 2.5 times if the farmers are incentivized at the rate of Rs.3 per cubic meter of water saved or by charging rice-growing farmers for extracting water beyond WAR (4488m^3/ha in this case). The area under maize can be further increased by 3.6 times if the incentives are increased to Rs.5/m^3 (Figure 2). On the other hand, the corresponding decrease in area under rice will be 2.76% and 22.68%, respectively. Under this Scenario, the farmers will tend to rear 36% more livestock, mainly buffaloes, than at the current level.

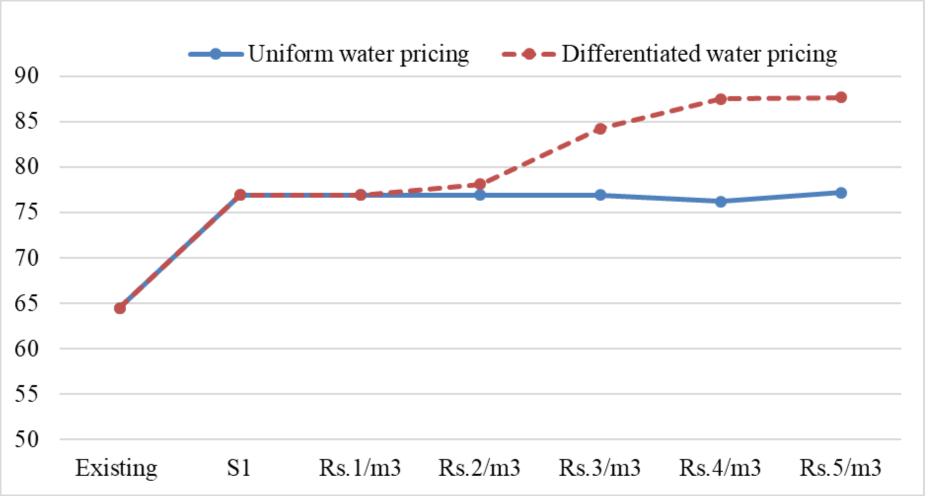
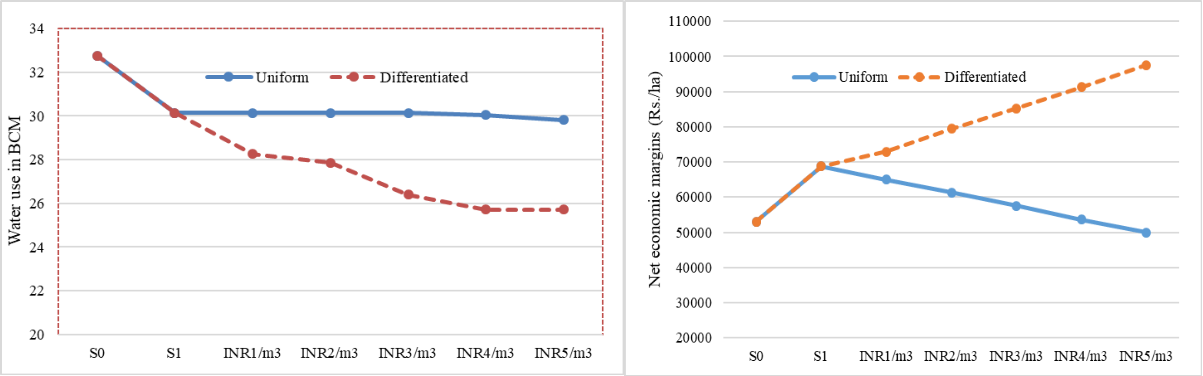


Figure 3: Changes in livestock on optimal of resources under different water pricing policies in Punjab

Effect on resource use and income

The results showed that the optimization of cropping patterns saves irrigation water use by 8% (2.62 BCM), farm power by 2.74% (389 million HP hours), fertilizer use by 5.14% (0.1 million tons), and increases net economic margins by 27% as compared to the current practice. Among the two proposed water pricing policies, the differentiated volumetric water pricing (S3) was found to be more responsive in saving water and other resources. On the one hand, the uniform water prices do not make any significant impact over S1 scenarios in terms of saving resources even though the prices are fixed at a very high rate of Rs.4/m^3, one the other hand, a very low water pricing of Rs.1/m^3 under the differentiated water pricing found to be effective in saving water by around 2 BCM (Figure 4a). When the prices are fixed at a relatively higher rate (Rs.4/m^3), the extent of water-saving increases to around 4 BCM. The differentiated water pricing policy is more pragmatic from the farmers' acceptability point of view as the farmers are incentivized to save water (Figure 4b). Besides saving water, these will also help reduce labour requirements and mitigate greenhouse gas emissions[23-24]



(a) Water use in BCM (b) Net economic margins (Rs/ha)

Figure 4: Resource use and farmers' income under differentiated water pricing in Punjab

Conclusions

Using a case study of Punjab, India's most agriculturally intensive yet fastest natural resource degrading state, this paper analyzed the potential of optimizing cropping patterns and the effectiveness of two different volumetric water pricing policies in saving resources and enhancing farmers' income. The finding suggested that the depleting groundwater resources cannot sustain the further increase in the gross cropped area in the state. While the optimization can save little water and enhance farmers’ income, there is unlikely to reduce the area under rice and check the groundwater depletion in the state unless the externalities of agricultural production, mainly the natural resource depletion, are not internalized into the cost of production. The simulation of two possible alternatives for internalizing the externalities through two different volumetric water pricing policies produced a clear differential effect on water saving and the overall agricultural income of the state and strongly suggested compensating farmers to mitigate any adverse economic impacts.

Direct and visible incentives are required for diversifying the cropping pattern in the state. As long as the water is accessible, the tendency for its indiscriminate use of this resource will remain until incentive oriented pricing mechanism is in practice. The volumetric water pricing will also encourage the efficient use of surface water. However, a perspective planning is required for the implementation of the policy. A policy of volumetric irrigation water pricing system can be implemented in a phased manner and the wells and tube-well-irrigated areas and for surface irrigation. The water allotment rights (4488 m^3/ha) used in the study are based on the current situation of groundwater and technological development and provided a rough idea. However, WAR can be fixed after having the stakeholders' consultation and should make a good balance between efficiency and equity objectives and needs much discussion with the stakeholders.

The change in irrigation water policy is necessary but not sufficient to promote diversification, halt groundwater depletion and bring sustainability to agricultural production systems in the state. Therefore, a paradigm shift in technology, agronomic practices, and how farmers are being supported is needed. Concerted efforts are needed for large-scale adoption of technologies like Direct Seeded Rice (DSR), an alternative to conventional puddled transplanted rice, and short-duration rice varieties. Besides saving water, these will also help reduce labour requirements and mitigate greenhouse gas emissions. The long-run goal of the government should be phasing out the environment distorting subsidies on the one hand and mainstreaming the payment for ecosystem services in the agricultural policies on the others. Above this, the volumetric water pricing policy cannot be implemented in isolation but requires multifaceted policy actions on associated factors with the Government playing a key role.

Conflict of Interest Statement: The authors of the paper have no conflict of interest to declare

Conflicts of interest: The authors declare that there is no conflict of interest.

Ethical approval: Not applicable as this article does not contain any studies with human or animal subjects.

Consent to participate: The authors agree to be part of the publication.

Consent for publication: The authors give their consent to publish the contents of the work.

REFERENCES

1. Mukherji, A., Sustainable groundwater management in India needs a water-energy-food nexus approach. *Appl. Econ. Perspect. Policy,* 2020, **44**(1), 394-410. https://doi.org/10.1002/aepp.13123
2. Singh, Y. and Sidhu, H. S., Management of cereal crop residues for sustainable rice-wheat production system in the Indo-Gangetic Plains of India. *Proc. Indian Natl. Sci. Acad.*, 2014, **80**(1), 95-114. https://doi.org/10.16943/ptinsa/2014/v80i1/55089
3. Pingali, P., Mittra, B. and Rahman, A., The bumpy road from food to nutrition security – slow evolution of India's food policy. *Glob. Food Sec.*, 2016, **15**, 77–84. https://doi.org/10.1016/j.gfs.2017.05.002.
4. Cabral, L., Pandey, P. and Xu, X., Epic narratives of the Green Revolution in Brazil, China, and India. *Agric. Human Values*, 2021, **39,** 249–267. https://doi.org/10.1007/s10460-021-10241-x
5. John, D. A. and Babu, G. R., Lessons from the aftermaths of green revolution on food system and health. *Front. Sustain. Food Syst.*, 2021, **5**, 644559. https://doi.org/10.3389/fsufs.2021.644559
6. Roul, C., Chand, P., Pal, S. and Naik, K., Assessment of agrobiodiversity in the intensive agriculture: a case study of the Indo-Gangetic Plains of India. *Biodivers. Conserv.*, 2022, **31**, 397-412. https://doi.org/10.1007/s10531-021-02336-y
7. Rasul, G., Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environ. Dev.,* 2016, **18**, 14-25. https://doi.org/10.1016/j.envdev.2015.12.001
8. Chaudhuri, S. and Roy, M., Irrigation water pricing in India as a means to conserve water resources: challenges and potential future opportunities. *Environ. Conserv.*, 2019, **46**, 99-102. https://doi.org/10.1017/S037689291800036X

9. Tripathi, A., Mishra, A. K. and Verma, G., Impact of Preservation of Subsoil Water Act on groundwater depletion: the case of Punjab, India. *Environ. Manage.* 2016, **58**, 48–59. https://doi.org/10.1007/s00267-016-0693-3
10. CGWB., *National Compilation on dynamic groundwater resources of India, 2020*. Central Ground Water Board Department of Water Resources, Government of India, Faridabad, India, 2021.
11. Gulati, A., Roy, R. and Hussain, S., Getting Punjab agriculture back on high growth path: sources, drivers and policy lessons. Indian Council for Research on International Economic Relations, New Delhi, India, 2017.
12. Sarkar, A. and Das, A., Groundwater irrigation electricity –crop diversification nexus in Punjab: trends, turning points and policy initiatives. *Econ Polit Wkly*, 2014, **49**(52), 64-73.
13. Roul, C., Chand, P. and Pal, S., *Developing Agricultural Sustainability Index for the Indo-Gangetic Plains of India*, Policy Brief 46, ICAR-National Institute of Agricultural Economics and Policy Research, New Delhi, 2020.
14. Johl, S. S., *Report of the expert committee on diversification of agriculture in Punjab*, Government of Punjab, Chandigarh, India, 2002.
15. Alagh, Y. K., *Report of the Expert Committee on the World Trade Organization for Punjab*, Government of Punjab, Chandigarh, India, 2005.
16. Government of Punjab, *Agriculture and rural development of Punjab: transforming from the crisis of growth*. Punjab State Farmers' Commission, Chandigarh, Punjab, India, 2006.
17. Chand, P., Rao, S., Jain, R. and Pal, S., Identifying sustainable rice cultivation zones in India: the implications of the crop water footprint. *Agric. Econ. Res. Rev.*, **33**(2), 2021, 147-160. https://doi.org/10.22004/ag.econ.310321

18. MOSPI, *Manual on cost of cultivation surveys*. Report No. CSO-M-AG-02, Ministry of Statistics and Programme Implementation, Government of India, New Delhi. https://mospi.gov.in/documents/213904/301563//manual_cost_cultivation_surveys_23july08_01598445943288.pdf/710fb322-6020-ed30-210c-d5b7b18234e6
19. CWC, *Pricing of water in public system in India*. Central Water Commission, Government of India, New Delhi, 2017.
20. Parween, F., Kumari, P. and Singh A., Irrigation water pricing policies and water resources management. *Water Policy*, 2021, **23**(1), 130–141. https://doi.org/10.2166/wp.2020.147
21. Iglesias, E. and Blanco, M, New directions in water resources management: the role of water pricing policies. Water Resour. Res., 2008, **44**(6), W06417. https://doi.org/10.1029/2006WR005708
22. Haque, M. M., Ahmed, A. and Rahman, A., Impacts of water price and restrictions in water demand: a case study for Australia. In: *Water Conservation: Practices, Challenges and Future Implications,* M. A. Imteaz (Ed.), Swinburne University of Technology, Melbourne, Australia, 2013, 127-145.
23. Singh, J. M., Singh, J., Kumar, H., Singh, S., Sachdeva, J., Kaur, B., Chopra, S. and Chand, P., Management of paddy straw in Punjab: an economic analysis of different techniques. *Indian Journal of Agricultural Economics*, 2019, **74**(3), 301-310.
24. Downing, A. S., Kumar, M., Andersson, A., Causevic, A, Gustafsson, Ö., Joshi, N. U., Kiran, C., Krishnamurthy, B., Scholtens, B. and Crona B. Unlocking the unsustainable rice-wheat system of Indian Punjab: assessing alternatives to crop-residue burning from a systems perspective. *Ecol. Econ.*, 2022, **195**, 107364. https://doi.org/10.1016/j.ecolecon.2022.107364