Irrigation water policies for sustainable groundwater management in irrigated northwestern plains of India

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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 socio-economic levels. In this study, using mathematical modelling, we assess the feasibility of two alternative irrigation water pricing policies – (i) uniform water pricing policy and (ii) differentiated water pricing policy, wherein farmers growing less water-requiring crops (<4488 m^3/ha) get an incentive for saving water, while those growing water-intensive crops pay for it. Using a case study of Punjab, the breadbasket and one of the fastest groundwater-depleting states in India, alternative cropping patterns are also suggested. The findings reveal that the current rate of groundwater withdrawal could not sustain agricultural intensification in the state. Although optimization of resource allocation has the potential to save water by 8%, this alone is unlikely to break the rice–wheat mono-cropping pattern in Punjab. The analysis of two different volumetric irrigation water pricing policies shows 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 to implement the policy.

Keywords: Agriculture, groundwater management, irrigation, sustainable intensification, water pricing policies.

THE green revolution (GR) technologies have led to greater rice and wheat production, the two staple food crops of India, and helped in economic growth in the country[1]. The northwestern state of Punjab, situated in the Indo-Gangetic Plains, reaped the earliest and maximum benefits of these technologies[2,3]. The policy support, including providing incentives by subsidizing water and energy and minimum support prices (MSP) 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 have an adverse effect on the health of agriculture, natural resources, biodiversity and human beings, and pose challenges to achieving the sustainable development goals[5–7].

Water and electricity policies are interconnected and are often considered the main drivers of growth in the area under rice, which led to overexploitation of groundwater and loss of crop diversity in Punjab. Electricity for agriculture, which was subsidized partly up to 1996–97 (charged on a per-unit basis up to the 1970s and a flat rate based on a 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 region are among the lowest for water-guzzling crops, encouraging farmers to allocate more area under such crops[7,8]. 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 ‘The Punjab Preservation of Subsoil Water Act, 2009’ to reverse these trends by mandatorily delaying paddy transplanting beyond 10 June, 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 the highest among all the states in India[10]. Groundwater depletion has other associated costs, including the increased costs of securing water availability. The GR supportive policies have also brought inefficient use of energy and promoted indiscriminate use of pesticides and chemical fertilizers, leading to the 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

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financial burden on farmers and thus making agriculture unsustainable[11–13].

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, Government of India (GoI) has proposed a law on volumetric water pricing to meet the considerations of equity and efficiency. Analysing and understanding the effectiveness of water pricing policies on cropping patterns and saving water are necessary for policy analysis, particularly when water scarcity is the leading sustainability issue. This study, therefore, has two major objectives: (i) 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 (ii) to suggest crop and enterprise plans for sustainable use of resources in Punjab.

Data and methodology

Data

This 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, Ministry of Agriculture and Farmers' Welfare, GoI. It is the most reliable database on the cost of cultivation and an essential basis for determining the MSP of important crops in the country. Under this Scheme, each sample household is surveyed consecutively for three years. In the present study, the data pertain to triennium ending 2013–14 (the latest year for which such data are available). The plot-wise data were collected from the 300 representative households of 30 sub-districts in Punjab (administratively called tehsils). From three agro-climatic zones of the state, farmers were selected using a three-stage stratified sampling technique: (i) tehsil as stage one, (ii) a village or cluster of villages as stage two and (iii) operational holdings within a cluster as stage three. From each cluster, a sample of ten 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), were selected randomly, thus representing all the climatic conditions, farmer categories and crops of Punjab. Besides, data from secondary sources and published studies were also used to determine the 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), GoI. All the paid-out expenses by the farmers in cash and kind (including rent paid) and the imputed value of family labour formed a part of the total costs. Technically, this is known as 'A_2 + family labour cost' (for more details, see ref. 18). Some of the components of cost A_2 were directly retrieved from the unit-level dataset of the cost of cultivation scheme, while a few others were imputed. For example, the depreciation of implements and farm buildings and interest on working capital were computed 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 was calculated, the net returns were calculated by subtracting the costs from the gross return (value of the main product + by-product).

Mathematical specifications of the model: Linear programming (LP) is a widely used mathematical technique to aid 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 simulation of the effect of various policy options. In the present study, alternative crops and livestock enterprise plans (scenarios and plans are used interchangeably) were developed using a quasi-dynamic LP model. The objective was to maximize the returns (defined in eq. (1)) under the constraints of cultivable land, human labour, irrigation water, farm power, fertilizers and working capital (eqs (2)–(7)). The second component in the objective function (eq. (1)) allows to simulate the different pricing scenarios, including incentive payments to the farmers wanting to opt for water-saving cropping patterns. The fodder availability constraint was captured endogenously in the model (eq. (8)). The cropping pattern must generate a sufficient quantity of feed and fodder to 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 in eqs (1)–(8). Table 1 describes the notations used in these equations.

$$\text{Maximizing } Z = \sum_{c=1}^{n}(Y_c P_c - C_c)A_c + (\text{WAR} - \text{IW}_c)\text{WPR}, \tag{1}$$

subjected to:

$$\sum_{c=1}^{n} A_c \le \text{NSA}, \tag{2}$$

$$\sum_{m=1}^{12}\sum_{c=1}^{n} \text{HL}_{mc} A_c \le \text{THL}_m, \tag{3}$$

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 animals.
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).
THL_m	Total human labour availability in the mth month.
TIW	Irrigation water availability, both from groundwater and surface sources.
FP_c	Farm power use (HP hours/unit).
TFP	Available farm power in Punjab.
$FERT_{fc}$	Per ha use of fth fertilizer (N, P and K).
$TFERT_f$	Availability of fth fertilizer.
FR_c	Fodder use per animal unit (on dry matter basis). In the case of crops, FR_c is used with a negative sign as crops generate fodder rather than consuming it. FR_c for crops is computed by applying grain-to-straw ratio (on dry matter basis) to crop yield.

$$\sum_{c=1}^{n} IW_c A_c \le TIW, \tag{4}$$

$$\sum_{c=1}^{n} FP_c A_c \le TFP, \tag{5}$$

$$\sum_{c=1}^{n} FERT_{fc} A_c \le TFERT_f, \tag{6}$$

$$\sum_{c=1}^{n} WC_c A_c \le TWC_c, \tag{7}$$

$$\sum_{c=1}^{n} FR_c A_c \le 0, \tag{8}$$

$$A_c \ge 0,\ \forall_c = 1, 2, \ldots, n.$$

Almost the entire cropped area in Punjab 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 the *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 short window of 50–70 days during summer, also called *zaid* season. The crop-wise planting and harvesting months are given in Supplementary Table 1. The livestock sector is mostly represented by milch animals (crossbred cow and buffalo) for farm household consumption, and contributing one-third to the agricultural GDP. In this model, 20 crops and two livestock activities were included.

Crop and enterprise planning using LP primarily captures the supply-side behaviour, 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 underestimate the area allocations for some crops. Consequently, a single crop may cover an infeasible larger area (overestimation) or null/negligible size (underestimation). Therefore, two non-resource constraints were also imposed to avoid undesirable overestimation or underestimation 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 in Punjab is already on the higher side[11], the use of these resources under the existing cropping pattern form the right-hand side of the constraint equations, viz. (eqs (5) to (7)). The minimum and maximum areas 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 is not uniform. Water pricing focuses on recovering the cost of development 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 encouraging to diversify the cropping pattern towards low water-requiring crops. For example, there is no difference in the water rate for paddy compared to oilseeds and pulses in Gujarat, Himachal Pradesh, Punjab and Tripura (Table 2). In some states (Assam, Maharashtra and Rajasthan), the rates are higher for oilseeds/pulses than for paddy.

Three different scenarios were developed 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 analysed in the subsequent two scenarios. In scenario S2, we simulated the impact of a uniform volumetric water pricing policy for all the crops. In contrast, in scenario S3, differential water pricing was considered depending on the volume of water use. In this scenario, farmers who save irrigation water are paid for, while those who overuse groundwater beyond a specific limit (generally called 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 become more diversified towards less water-requiring crops and will induce farmers to adoption-of-water-saving irrigation technologies. In scenarios 2 and 3, a range of water prices varying between Rs 1/m^3 and Rs 5.00/m^3 at Rs 1/m^3 intervals was analysed. The rates used in different countries[19] or proposed in various studies[20,21] formed the basis for this study. The irrigation water use for rice, the most popular staple food of India, grown under best management practice (4488 m^3/ha), was assumed as WAR, above which the farmers paid for its use. The difference between irrigation water use by the crops grown in the field and WAR gave the volume of water saved.

Table 2. States-wise water rates for paddy and oilseeds/pulses under flow irrigation in India (Rs/ha)

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
Odisha	**	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 the Central Water Commission, Government of India[24].

Results and discussion

LP model in this study was solved using MS Excel Solver – a tool used to find optima; solution for decision-making problems. The datasheet was 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 model development (Figures 1–4). The results show the changes in cropping and livestock enterprises patterns, the corresponding variations in resource use level, and the changes in farmers' income and financial implications in terms of Government spending on payment for ecosystem services.

Effect on cropping and livestock enterprise patterns

In scenario S1, the possibility of resource reallocation was explored by optimizing the existing policies. The results

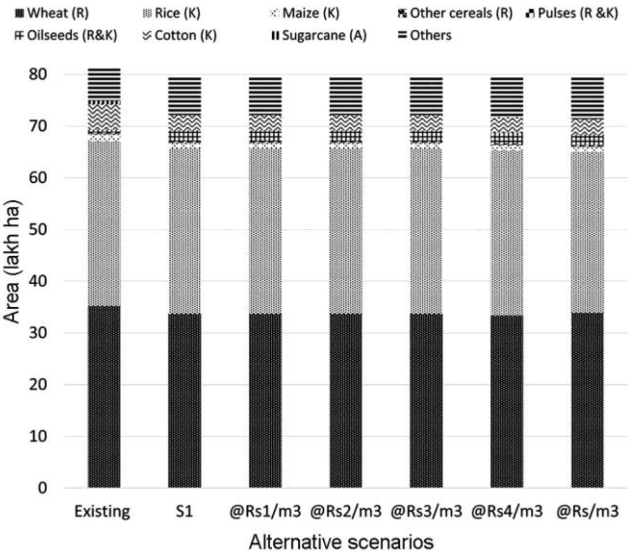

Figure 1. Changes in cropping pattern on optimization of resources under uniform water pricing policy in Punjab, India. Note: S1 indicates optimization with existing policies; @ Rs 1/m^3 to @ Rs 5/m^3 are the water prices varying between Rs 1/m^3 and Rs 5/m^3 at Rs 1/m^3 interval. *K*, *Kharif* season crop; *R*, *Rabi* season crop; *A*, Annual crop.

suggest that the depleting groundwater resources cannot sustain a further increase in the gross cropped area in Punjab as the total cropped area declined by 2.29% from 81.5 to 79.6 lakh ha (Figure 1). The optimum plan (S1) suggested decreasing area under long-duration, water- and labour-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 that in paddy. Wheat was another crop under which acreage was reduced 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 increased by 1.6 lakh ha. However, it is equally worrying that the area under rice has remained unchanged, indicating that with the existing set of policies, it is not possible to reduce the area under rice and check groundwater depletion in the state. These findings further imply that farmers generally ignore the duration of the crop while making their crop planning decisions and hence there is scope for optimizing the resource allocation.

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

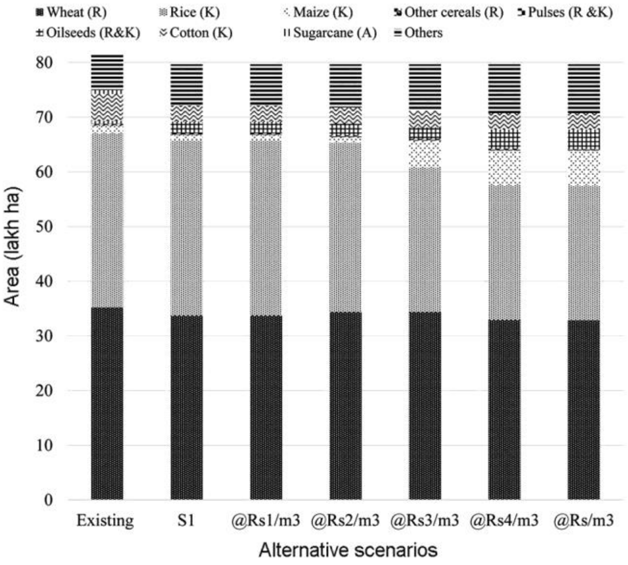

Figure 2. Changes in cropping pattern on optimization of resources under differentiated water pricing policy in Punjab. Note: Those who use water over and above 4488 m^3/ha pay for an additional cubic metre used, while those who use below the threshold get the benefit for saving water at the rate varying between Rs 1/m^3 and Rs 5/m^3 at Rs 1/m^3 interval.

For further insights, the ratios of relative economic margins before and after the introduction of the payment system were computed (Supplementary Tables 2 and 3). It was observed that the economic margins in rice (basmati) were the highest among the *kharif* season crops. They were 18.41, 4.65, 2.30, 2.29 and 1.64 times higher than those of pigeon pea, black gram, maize, cotton and groundnut respectively. Similarly, the economic margins in the case of rice (non-basmati) were also higher by 15.27, 3.86 and 1.9 times compared to red gram, black gram, maize and cotton respectively. Though the proposed payment/pricing system at Rs 2/m^3 will improve the relative profitability ratio for groundnut (0.61–0.71), maize (0.44–0.49), cotton (0.44–4.45) and black gram (0.21–0.34) when compared to rice (basmati), they are still far lower compared to the latter. When the water pricing is fixed at a significantly higher rate, the economic margins favour low water-requiring crops. For example, when the water pricing is fixed at Rs 5/m^3, the economic margins favour groundnut compared to rice.

The livestock population is another factor that will guide future cropping patterns in Punjab. 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 the livestock. The area under maize can be increased by 2.5 times if the farmers are incentivized at the rate of Rs 3/m^3 of water saved or by charging rice-growing farmers for extracting water beyond WAR (4488 m^3/ha in this case). The area under maize can be 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 the 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).

Effect on resource use and income

The results show 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 tonnes) and increases net economic margin by 27% compared to the current practice. Among the two proposed water pricing policies, scenario S3 was found to be more responsive to saving water and other resources. On the one hand, the uniform water prices did not significantly

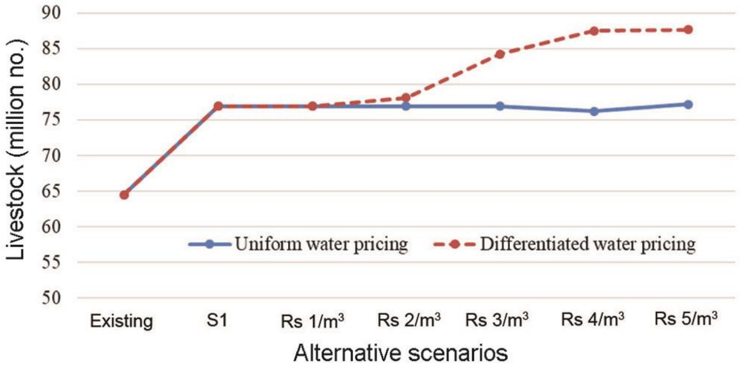

Figure 3. Changes in livestock on optimization of resources under different water pricing policies in Punjab.

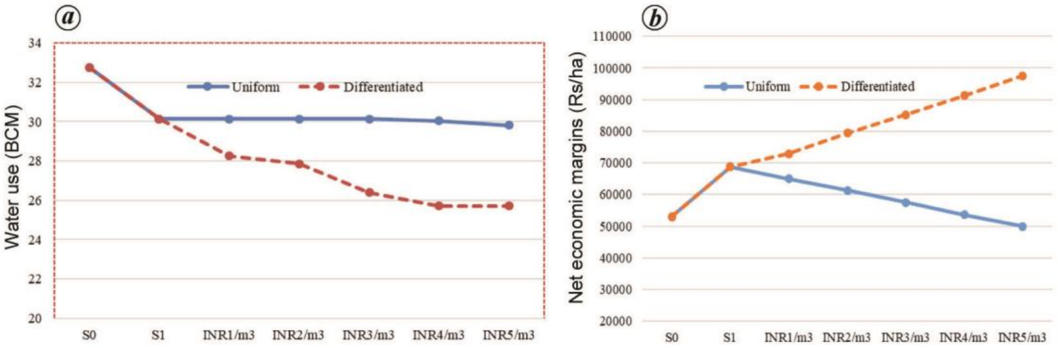

Figure 4. Resource use and farmer's income under differentiated water pricing in Punjab. ***a***, Water use (BCM). ***b***, Net economic margin (Rs/ha).

impact scenario S1 in terms of saving resources, even though the prices were fixed at a high rate of Rs 4/m^3. On the other hand, a low water pricing of Rs 1/m^3 under the differentiated water pricing policy effectively saved water by around 2 BCM (Figure 4 *a*). When the prices were fixed at a relatively high rate (Rs 4/m^3), the extent of water saving increased to around 4 BCM. Thus, the differentiated water pricing policy is more pragmatic from the farmers' acceptability point of view, as they are incentivized to save water (Figure 4 *b*). Besides saving water, it will also help reduce labour requirements and mitigate greenhouse gas (GHG) emissions[22,23].

Conclusion

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

Direct and visible incentives are required to diversify the state's cropping pattern. As long as the water is accessible, the tendency for its indiscriminate use will remain until an incentive-oriented pricing mechanism is in practice. The volumetric water pricing will also encourage the efficient use of surface water. However, 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 starting with wells and tube-well-irrigated areas where measurements are easy to do. The water allotment rights (4488 m^3/ha) used in this study are decided based on the current situation of groundwater and technological development and only provide a rough idea. However, WAR can be fixed after having consultations with the stakeholders, and could provide a good balance between efficiency and equity objectives.

The change in irrigation water policy is necessary but insufficient to promote diversification, prevent groundwater depletion and bring sustainability to agricultural production systems in Punjab. Therefore, a paradigm shift is needed in technology, agronomic practices and how the farmers are being supported. Concerted efforts are needed for the large-scale adoption of technologies like direct-seeded rice, an alternative to conventional puddled transplanted rice, and short-duration rice varieties. Besides saving water, they will also help reduce labour requirements and mitigate GHG emissions. The long-time goals of the Government should be phasing out the power subsidies for pumping groundwater on the one hand and mainstreaming the payment for ecosystem services in the agricultural policies on the other. Also, 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: The authors declare that there is no conflict of interest.

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