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Optimal Crop Plans for Sustainable Water Use in Punjab

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Abstract

A linear programming model has been formulated to suggest the optimal cropping pattern for maximizing net returns and ensuring significant savings of groundwater with the aim of sustaining groundwater use in the Punjab agriculture. The primary data obtained from the project, "Comprehensive scheme to study the cost of cultivation of principal crops in Punjab" for the year 2002-03 pertain to 170 farmers selected through three-stage stratified random sampling technique. As the period of transplantation of paddy has a significant bearing on the amount of groundwater used and its sustainability, the paddy crop has been further classified into Paddy 1 (transplanted before 10th June); Paddy 2 (transplanted during 11th June to 20th June) and Paddy 3 (transplanted after 20th June). At the existing level of water availability, the optimal crop plan has not revealed any significant changes in the production pattern. Restricting the availability of groundwater has resulted into a major shift in the cropping pattern. Such changes could ensure groundwater savings of almost 25 per cent, without any adverse impact on the net returns from crop production. Introduction of new crops in the production plan, such as Bt cotton, has further enhanced the returns from crop production by about 4 per cent along with groundwater savings of 26.55 per cent. The study has suggested that alternate wetting and drying, adoption of system of rice intensification (SRI), use of tensiometers and direct plantation of paddy are some of the other techniques which can save water.

Introduction

Water is an important natural resource and its increasing scarcity has resulted into the emergence of various issues for its efficient use, management and sustainability. Only 2.7 per cent of the global water is available as fresh water, out of which only 30 per cent can be used for meeting the demand for humans and livestock. The demand for water (of appropriate quality) is expected to rise manifold owing to ever increasing population, rising demand for food, urbanization and industrialization and may even exceed its supply (ENVIS Centre, Punjab, 2005). Such a phenomenon will prevail in almost every part of the world, more pronounced in those economies where agriculture occupies a dominant position and accounts for a major chunk of water use (Third World Water Forum, 2003).

In Punjab, almost 97 per cent of the cultivated area is under assured irrigation with nearly 80 per cent of the water resources being used for agricultural production. Surface water and groundwater resources are used for irrigation to a large extent. The Punjab state is traversed by four major rivers, namely Sutlej, Beas, Ravi and Ghaggar, with the total stretch of canals, distributaries, etc. being approximately 14,500 km. On an average, canal water available from the Sutlej river is 6.45 MAF (million acre-feet) or 0.796 M ha-m (million hectare-metre) with Sirhind Canal, which is the main canal from the river Sutlej originating at Ropar Headworks and providing on an average about 0.67 M ha-m surface water per annum; Bist-Doab canal and Bhakra Main Line Canal System provides approximately 0.04 M ha-m and 0.086 M ha-m water every year, respectively. The total supply of Ravi-Beas waters in the state is of 0.78 Mha-m. As a result, the overall surface water supplies in the state amount to 1.57 M ha-m.

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There has been a rapid increase in the area under paddy crop, a water- intensive crop, replacing relatively less water-intensive crops like oilseeds and pulses in the production pattern. The area under paddy crop increased from 227 thousand ha in 1960-61 to 2015 thousand ha in 1990-91 and further to 2642 thousand ha in 2005-06. Similarly, area under wheat crop increased from 1400 thousand ha in 1960-61 to 3468 thousand ha in 2005-06 (*Statistical Abstract of Punjab*, various issues). Thus, area under rice-wheat cultivation has increased 3.6-times during the past four decades due to government support through stable prices, massive procurement programme and other institutional and infrastructural backup, even though rice has not been a staple crop of the state. The dominance of paddy-wheat crop rotation has converted the Punjab state from a water-surplus to a water-scarce state. At present, gross water requirements[1] for the state are estimated at 6.15 M ha-m, against the current availability of only 3.66 M ha-m, comprising 1.52 M ha-m of surface water and 2.14 M ha-m of groundwater resources (DoI, Punjab, 2005; WRD, Punjab, 2005). It indicates a deficit of about 2.49 M ha-m of water — a case of severe water imbalance in the state.

Empirical studies have revealed a fast depleting groundwater-table in many parts of the state due to excess of draft over the recharge. The entire Central Punjab falls in the 'over-exploited' category'of groundwater resources (Singh, 1991; Singh and Sankhayan, 1991; Singh, 1992; Singh, 1995; Parihar *et al.*, 1993; and Sondhi, 2004). The proportion of area irrigated through groundwater resources in Punjab increased from 41.04 per cent in 1960-61 to 71.77 per cent in 2006-07, while such proportion increased from 70.96 per cent to 88.71 per cent in the Central Zone, respectively (*Statistical Abstract of Punjab*, various issues) of the state. Such a situation threatens the sustainability of water resources and hence, the agricultural productivity in Punjab, calling for an efficient and sustainable management of water resources (Draft Water Policy, 2004). It involves developing new crop plans, which may ensure sustainable water-use without adversely affecting the net returns from farming. Keeping these things in mind, the present study was undertaken with the objective of finding the optimal crop plans against a sustained water supply situation. The optimal production plan developed at reduced water availability showed the trade-off between the water-saving and returns to fixed farm resources. Apart from optimal crop plans, the study has outlined other effective techniques which can result into saving of significant amount of water.

Material and Methods

The solution to the linear programming model was obtained using the Simplex method with a commercially available computer program. The study was conducted for the Punjab state. A list of all 72 *tehsils* (sub-regions) in the state for the year 2002-03 was prepared. From these *tehsils*, only those were chosen where paddy-wheat was the major crop rotation, electric bore-well intensity to pump out groundwater was high, and problem of falling groundwater-level was severe. These *tehsils* were arranged in the ascending order of the water-table depth as it best reflected the extent of depletion of groundwater resources. Hence, forty-six *tehsils* (with groundwater-table depth ranging between 6.65 m and 23.89m) constituted the population frame of the study. These were classified into three zones on the basis of groundwater-table depth by using the cumulative cube root method. Zones I, II and III comprised tehsils with water-table depth ranging from 6.65 m to 9.74 m; from 10.04 m to 12.46 m and from 12.50 m to 23.89 m, respectively. These 46 tehsils were matched with the tehsils covered in the scheme entitled "Cost of Cultivation of Principal Crops in Punjab", for which data were being collected by the Department of Economics & Sociology, Punjab Agricultural University, Ludhiana. Out of the population frame of 46 tehsils, 17 tehsils became the study sample and further one village was selected from each tehsil. The data for the latest available year, i.e. 2002-03 was used. The sample comprised a total of 17 villages with 170 farming households, which were further classified into 68 small, 68 medium and 34 large farming households. The zone-wise distribution of the 170 farmers was 50, 60 and 60 for Zones I, II and III, respectively.

Programming Model

The data were compiled and budgetary analysis was performed to work out the economics of different enterprises. The existing production pattern was computed and estimated by the tabular methods and percentages. The results have been discussed on the basis of linear programming analysis carried out by considering the constraints on availability of land (during both *kharif* and *rabi*); labour (month-wise labour availability); capital (*kharif* and *rabi* seasons, separately) and irrigation water (month-wise water-use on the farm). Further, the objective of maximizing net returns with different water availability regimes on the farm was considered to obtain sustainable water using crop plans. The linear programming model in farm management research is a very powerful technique, which can efficiently handle a large number of linear constraints and variables (activities) simultaneously (Sankhayan and Cheema, 1991; Panda *et al.*, 1983). The model used was as given below:

$$\text{Maximize } Z = \sum_{j=1}^{n} Cj \quad Xj$$

$$\text{Subject to } \sum_{i=1}^{m} a_{ij}\, x_j \leq b_i$$

i = 1, 2, ……..., m

j = 1, 2, ………, n

$X_j \geq 0$

where,

Z = Total returns to fixed farm resources,

C_j = Return to fixed farm resources per unit of an activity,

X_j = Level of the j^{th} activity,

b_i = Availability of the i^{th} resource,

a_{ij} = Input of the i^{th} resource per unit of the j^{th} activity,

n = Number of real activities,

m = Number of resource constraints, and

$Xj \geq 0$ indicate non-negativity constraint for the activities.

Resource Restrictions

(i) Land Area Availability and Utilization: Land is one of the limiting resources on all farm situations. It was defined as operational area, which was equal to owned-land plus leased-in land minus leased-out land. The average size of operational holding was 3.68 ha during the *kharif* and 3.64 ha during the *rabi* seasons.

(ii) Human Labour Restriction: The human labour resource restrictions were examined by assessing the available family labour and permanent labour on the farms. This labour was converted into adult man hours. An adult labour was assumed to work eight hours a day and twenty-five days a month. To calculate the availability of female adult labour hours, one-third of her percentage of work on farm was taken for crop production activities and the rest was left for livestock tending and other routine farm activities. One female labour unit was assumed to be equivalent to 0.75 male labour unit (Kaur, 2001; Thusoo, 2005). Human labour availability does act as a constraint, especially in the months when labour requirements are high during harvesting and paddy transplanting seasons.

(iii) Working Capital: To calculate capital use on the farm, the costs of seed, manures, fertilizers, pesticides, insecticides, hiring of machinery, casual labour payment, irrigation charges, etc. were added up and thus the cash requirements for *kharif* and *rabi* crops were worked out separately. For estimating capital availability on the farm, it was assumed that the expenditure incurred on variable inputs in the previous season was available for the next crop season by the same amount. The borrowing was introduced at the interest rate of 9 per cent per annum. Hence, cash availability was enhanced by introducing cash-borrowing activity in both the seasons, which carried the negative sign in the objective function as cost of borrowing funds.

(iv) Irrigation Water-use: The electric motors having different horse powers were brought out/changed on the same denominator by allocating the weight (i.e., discharge rate in litres/second) to different horse power electric motors. Based on water-table depth below 12 m average discharge of pump sets with prime mover of 3 HP, 5 HP, 7.5 HP was considered as 5 litres/sec, 10 litres/sec and 13 litres/sec, respectively (Anonymous, 2006; Taneja and Sondhi,1988), whereas for some villages in the Patiala and Sangrur districts with water-table depth ranging between 12 m and 21 m, estimates were arrived at by using average discharge rate of 5 HP as 7 litres per second, 7.5 HP (electric motor) as 9 litres per second and 7.5 HP (submersible pump) as 17 litres per second, based on the rationale that the rate of discharge reduces with increase in the water-table depth. Irrigation water-use for each crop was computed by estimating the monthly irrigation hours and multiplying it with the volume of water drawn out per hour by the electric motor. The volume of water drawn out by a motor differed with the horse power of the motor.

(v) Groundwater Availability: To calculate groundwater availability for different farm-size categories, electricity was assumed to be available for 8 hours a day from 10th June till 20th September and 4 hours a day for rest of the days in a year. Thus, per month electricity supply was calculated in hours. These hours were further converted into volume of groundwater drawn in each month by considering the total number of electric motors available on the farms in a particular zone. The computational procedure involved two steps. First, the number of electric motors available in each zone was calculated. Then, per hour volume of groundwater drawn with available motors was estimated. Second, per hour volume was multiplied with hours of electricity supply. Hence, the total volume of groundwater so obtained was divided by the total number of farms to have volume of groundwater available (per farm) in a particular month.

(vi) Canal Water Availability: The availability of canal water was calculated by taking into account the volume of canal water available to irrigate number of hectares per month. Then, the number of hectares so obtained was multiplied by the hours of electric motor required to irrigate one hectare. Thus, the canal irrigated area (in hectares) was converted into electric motor hour equivalents and then into volume of water using the water discharge rate per hour of electric motor use. Hence, total availability of irrigation water was the sum total of both groundwater and canal water available. The present study aimed at equalizing the water draft and water recharge to achieve water sustainability in the region. So the irrigation water availability of all the monthly irrigation constraints of the present LP model was worked out (on the basis of number of electric motors/submersible pumps present in the sample) but was not used, rather availability was considered not more than the present water use in the existing cropping pattern.

(vii) Input-Output Coefficients for Newly Introduced Crop Activities: In order to determine the optimum production plans for different regions in Punjab, it was essential to incorporate such enterprises, which were technically feasible to grow and acceptable to the cultivators. The input-output coefficients for the new crop activities were developed by using the "cost of cultivation data" of the farmers sowing these crops in the state. The data were rationalized in consultation with the farmers, agricultural extension specialists and agronomists of the respective regions in light of the peculiar agro-climatic conditions of the study area.

(viii) Crop Maxima and Minima: There were some crop enterprises used in the matrix which gave quite high returns per hectare. Acreage under these crops was restricted depending upon the risk-bearing ability of the farmers, these enterprises being very risky in terms of productivity and price. Area restrictions were imposed on vegetables at the existing level of area under each of these crops. The area under *kharif* and *rabi* fodders was considered as fixed farm activity and was restricted to the existing area under these crops.

Subdivision of Paddy Crop into Paddy 1, Paddy 2 and Paddy 3

The area under paddy, a major *kharif* crop, was sub-divided into three independent crops, viz. Paddy 1, Paddy 2 and Paddy 3. This division was done on the basis of dates of transplanting because the water requirements of paddy varied considerably with the date of transplanting of paddy and it significantly influenced the extent of water saving possible through alternative crop plans.

Paddy 1: Paddy 1 refers to the paddy transplanted before 10th June. In discussion, it has also been termed as early-transplanted paddy as the period of such transplantation was falling earlier than that recommended by the Punjab Agricultural University (PAU), Ludhiana, Punjab. One of the main reasons for the fall in water table in Punjab has been the early transplantation of rice (before mid-June), which means severe withdrawal of groundwater, as the monsoon is still far away, temperatures are very high and evapo-transpiration rate (ETR) is maximum. On the initiative of the Punjab State Farmers Commission, "The Punjab Preservation of Sub Soil Water Act" (not to sow paddy nursery before May 10 and not to transplant paddy before June 10) was promulgated as an Ordinance in 2008 and encouraged by the response, it has been changed into an Act in March 2009 (Singh, 2009).

Paddy 2: Paddy 2 included the paddy crop, transplanted from 11th June to 20th June. In case a farmer started transplanting on 9th of June and completed it by 12th June, then he was counted in that category, in which maximum area was transplanted. Paddy 2 has also been termed as timely-transplanted paddy in the following discussion as the period corresponds to that as recommended by PAU for transplantation.

Paddy 3: Paddy 3 represented the crop transplanted after 21st June. Paddy 3 has been called as late-transplanted paddy also in further analysis.

The model was run at the current level (100 % water availability) and 64 per cent of current water availability. The water cut of 36 per cent of total water availability was imposed only for the *kharif* season as water demand in *rabi* season does not bring any fall in water-table depth. The optimal crop Plan-II was based on the rationale that reduction in water-use by 36 per cent, would ensure sustainability of groundwater resources, as the draft exceeded the recharge in the study area by 36 per cent (calculated from the block-wise figures provided by the Water Resources Directorate, Punjab). The formula used was:

$$\text{Percentage overdraft} = \frac{\text{Recharge} - \text{Draft}}{\text{Draft}} \times 100$$

For developing Optimal Plan-III, new crops were introduced in addition to the resource restrictions imposed in the Optimal Plan-II, to examine the shift in cropping pattern and its impact on the extent of water saving.

Results and Discussion

Land Area Availability and Utilization

The land was fully utilized on all the farms, as shown by the area utilization for the cultivation of different crops in Table 1.

In the present analysis, the area under paddy was sub-divided into three independent crops, viz., Paddy 1, Paddy 2 and Paddy 3 on the basis of date of paddy transplantation. It was done to get a clear picture of the month-wise irrigation water requirements of paddy sown before 10 June, between 10 and 20 June and after 20 June. The largest proportion of the total cultivated area was occupied by Paddy 1, accounting for 33.97 per cent in *kharif* season. The existing production pattern clearly revealed that paddy in *kharif* season and wheat in *rabi* season were the most commonly grown crops, covering 76.91 per cent and 81.32 per cent of the cultivated area, respectively. Pulses and oilseeds were being cultivated on very small areas. While none of the farmers was found raising orchards, the area under vegetable crops was also small.

Table 1. Area occupied by and irrigation requirement of different crops under existing cropping pattern in Punjab

Crops	Area (ha)	As a per cent of total cultivated area	Irrigation water requirement (m^3/ha)
	***Kharif* crops**		
Paddy 1	1.25	33.97	13710
Paddy 2	1.13	30.71	12587
Paddy 3	0.45	12.23	10822
Basmati	0.21	5.71	9653
Desi cotton	0.004	0.11	1281
Arhar	0.003	0.08	3462
Moong	0.013	0.35	2098
Mash	0.014	0.38	1958
Maize	0.02	0.54	1458
Kharif fodder	0.40	10.87	2324
Sugarcane	0.188	5.11	11914
Sub-total	3.68		
	***Rabi* crops**		
Wheat	2.96	81.32	3661
Gram	0.01	0.27	1899
Sarson	0.028	0.77	2362
Garlic	0.001	0.027	4500
Shimla mirch	0.006	0.16	5639
Peas	0.007	0.19	1527
Potato	0.083	2.28	3390
Carrot	0.002	0.05	2175
Barley	0.013	0.36	1519
Massar	0.003	0.08	2298
Rabi fodder	0.33	9.06	6384
Sub-total	3.64		

Human Labour Availability and Use

The labour use was of 2973 human hours, whereas availability was of 5106 human hours, indicating human labour utilization to the extent of 58.22 per cent of the available labour.

Capital Use

The capital used during the *kharif* season amounted to Rs 43386, whereas it was Rs 39658 during the *rabi* season. The *kharif* capital-use was more than capital used in the *rabi* season. It was due to the fact that variable costs incurred on paddy, the most predominant crop of *kharif* season, was more than that for the crops sown in the *rabi* season.

Availability of Irrigation Water and its Use

The irrigation water availability was considered equal to the current water-use. The estimated irrigation water-use (both surface and groundwater) is given in Table 1. Average per hectare irrigation water-use for all the crops collectively in the existing plan was 54986 m^3. Per hectare irrigation water-use was of 13710 m^3 for Paddy 1, 12587 m^3 for Paddy 2 and 10822 m^3 for Paddy 3. Water-use of Paddy 1 was the highest among *kharif* crops and that of basmati rice was almost equal to that of Paddy 3. The water-use was much lower by *kharif* pulses and oilseeds than by vegetable crops. Annual irrigation water-use of sugarcane was 11914 m^3/ha (for both the seasons collectively).

Variable Costs

The variable costs included the costs incurred on different inputs such as seed, insecticide, manures and fertilizers, micro-nutrients, farm yard manure, irrigation charges, hired machine charges, tractor charges, human labour charges and marketing cost. The highest amount of variable costs (per hectare) were being incurred on the cultivation of early-transplanted paddy, followed by normal-transplanted and late- transplanted paddy (Table 2). However, the variable costs were lower in basmati rice than paddy. The variable costs incurred per hectare on sugarcane crop were calculated annually. In the *rabi* season, variable costs were higher for wheat crop as compared to its other competing crops such as gram, sarson, etc. The costs were much higher in the case of vegetable crops (between Rs 7825/ha and Rs 32622/ha) due to very high use of human labour in vegetable cultivation.

Comparative Profitability

A perusal of Table 2 reveals that returns to fixed farm resources were relatively high from Paddy 1 (Rs 24200/ha), basmati (Rs 24500/ha) and wheat (Rs 21300/ha). Though the returns from vegetables were also high, ranging from Rs 12800/ha to Rs 29878/ha,

Table 2. Net return and variable costs of different crops in the study area of Punjab

(Rs/ha)

Sl No.	Crops	Variable costs	Gross returns	Returns over fixed farm resources
		***Kharif* crops**		
1	Paddy 1	11979	36179	24200
2	Paddy 2	11178	34778	23600
3	Paddy 3	10974	33374	22400
4	Basmati	9162	33662	24500
5	*Desi* cotton	9950	32100	22150
6	Arhar	5988	13300	7312
7	Moong	4314	12389	8075
8	Mash	2945	9611	6666
9	Maize	7958	16058	8100
10	*Kharif* fodder	6223	16497	10274
11	Sugarcane	22826	57132	34306
		***Rabi* crops**		
12	Wheat	10436	31736	21300
13	Gram	4906	18990	14085
14	Sarson	6253	17379	11125
15	Garlic	32622	62500	29878
16	Shimla mirch	32087	61850	29763
17	Peas	15254	28170	12916
18	Potato	28394	41194	12800
19	Carrot	7825	25375	17550
20	Barley	8393	20696	12303
21	Massar	3005	10450	7445
22	*Rabi* fodder	12342	31122	18780

but these crops showed high volatililty with respect to prices and productivity. Sugarcane yielded an annual return of Rs 34306/ha. Pulses and oilseeds on an average yielded relatively low net returns of around Rs 8500/ha and Rs 12200/ha because of their low productivity. The overall profitability of other cereal crops, i.e. maize and barley, was very less at Rs 8100/ha and Rs 12303/ha per hectare, respectively. In nutshell, paddy, especially early-transplanted paddy, gave higher returns as compared to other *kharif* crops, while wheat was the most profitable *rabi* crop. Basmati was competing well with Paddy 2 and Paddy 3 on all the farms and may provide a better alternative for early-transplanted rice for sustainability of water resources due to its lower irrigation water requirements.

Fodder is grown on all farm situations to meet the fodder requirements and is therefore considered as a fixed activity. Its profitability does not mean much as it is not grown for the market purposes. All the *rabi* vegetables competed well with the wheat crop on the profitability aspect, but large shift in the area from wheat to vegetables may cause a huge fall in their profitability due to their high price elasticity of demand. Hence, there was a need to develop such crop plans, which may ensure significant savings in groundwater without endangering the returns from farming. Thus, optimal crop plans were developed at varying levels of water availability to depict the trade-off between income and water-saving.

Optimal Crop-mix

The area under Paddy 1 and Paddy 2 was 44.56 per cent and 26.09 per cent, respectively of cultivated area at 100 per cent water availability level, which totally disappeared at 64 per cent water availability level (Table 3). Though the area under Paddy 1 and Paddy 2 totally disappeared at reduced water availability level but at the same time a major chunk of area shifted to Paddy 3, i.e. late-sown paddy. It was mainly due to lower irrigation requirements of late-sown paddy than of early- and timely-transplanted paddy. Maize did not appear at all in the optimal Plan-I, whereas this crop covered a significant area of 5.43 per cent at 64 per cent water availability level.

The reduced *kharif* water availability of irrigation water brought maximum area under *desi* cotton in optimal Plan-II, but the area under *desi* cotton was restricted to the maximum of 0.80 ha, based on the risk-bearing ability of the farmers and market conditions for the crop.

The second optimal plan was developed by limiting the water availability to 64 per cent of the existing water-use during *kharif* season, as groundwater was the major constraint during this season. Less water requirements of crops during the *rabi* (winter) season, as compared to its sustainability, warranted no need for limiting its availability for developing the second optimal plan. It was due to this fact that there was no change in the area under wheat in *rabi* season at 100 per cent and 64 per cent water availability levels, respectively. It implies that the farmers, with no restriction on water-use, are producing almost optimally during the *rabi* season. The cultivated area under garlic, peas, carrot and fodder crops remained unchanged even at reduced water availability level and occupied the maximum area imposed under each crop which was kept at the existing level of production pattern.

There were only marginal water savings and marginal increase in returns under optimal Plan-I as compared with the existing plan. However, the reduction in water availability by 36 per cent under Plan-II resulted in significant shifts in *kharif* area in favour of Paddy 3 and maize. These shifts led to more than 26 per cent reduction in water-use, while the increase in returns was around 0.42 per cent (Table 3).

In the third alternative plan, when Bt cotton was also introduced, the savings in water-use were 26.55 per cent. However, the returns increased by 3.91 per cent. Increase in returns was due to higher profitability of Bt cotton. Paddy 1 and Paddy 2 disappeared, while 59.78 per cent area shifted to Paddy 3 and 21.74 per cent to Bt cotton. Introduction of Bt cotton in the production plan reduced the total area under paddy from 76.91 per cent in the existing production plan to 59.78 per cent in the optimal Plan-III. Changes in the *rabi* crop pattern were almost absent. The only thing required for this type of crop pattern to succeed would be strengthening of the market infrastructure for maize, gram, *desi* cotton and Bt cotton for assured lifting of the produce, as is the case in paddy and no fall in the prices due to increased production. The savings in groundwater amounted to 26.55 per cent under second and third optimal plans. Therefore, it is a trade-off between water savings and crop profitability and the farmers have to choose either of the two; if they are interested in the long-term sustainability of water

Table 3. Optimal crop plans for sustainable water use in Punjab: 2002-03

(area in ha)

Crops	Existing production pattern	Optimal Plan-I	Optimal Plan-II	Optimal Plan-III
		***Kharif* crops**		
Paddy 1 (before 10 June)	1.25 (33.97)	1.64 (44.56)	0	0
Paddy 2 (from 10 to 20 June)	1.13 (30.71)	0.96 (26.09)	0	0
Paddy 3 (after 21 June)	0.45 (12.23)	0	2.11 (57.34)	2.20 (59.78)
Paddy (overall)	2.83 (76.91)	2.60 (70.65)	2.11 (57.34)	2.20 (59.78)
Basmati	0.21 (5.71)	0.44 (11.95)	0.08 (2.17)	0.03 (0.81)
Desi cotton *	0.004 (0.11)	0.23 (6.25)	0.80 (2.17)	0
Arhar	0.003 (0.08)	0	0	0
Moong	0.013 (0.35)	0	0	0
Mash	0.014 (0.38)	0	0	0
Maize	0.02 (0.54)	0	0.20 (5.43)	0.16 (4.35)
Kharif fodder *	0.40 (10.87)	0.40 (10.87)	0.40 (10.87)	0.40 (10.87)
Sugarcane	0.188 (5.11)	0	0.09 (2.44)	0.09 (2.44)
Bt cotton *	-	-	-	0.80 (21.74)
Sub-total	3.68	3.68	3.68	3.68
		***Rabi* crops**		
Wheat	2.96(81.32)	2.96 (81.32)	2.96 (81.32)	2.96 (81.32)
Gram	0.01 (0.27)	0.29 (7.97)	0.25 (6.87)	0.25 (6.87)
Sarson	0.028 (0.77)	0	0	0
Garlic *	0.001(0.027)	0.001 (0.027)	0.001 (0.03)	0.001 (0.03)
Capsicum *	0.006 (0.16)	0	0	0
Peas *	0.007 (0.19)	0	0.007 (0.19)	0.007 (0.19)
Potato	0.083 (2.28)	0	0	0
Carrot *	0.002 (0.05)	0	0.002 (0.05)	0.002 (0.05)
Barley	0.013 (0.36)	0	0	0
Massar	0.003 (0.08)	0.05 (1.37)	0	0
Rabi fodder *	0.33 (9.06)	0.33 (9.06)	0.33 (9.06)	0.33 (9.06)
Sub-total	3.64	3.64	3.64	3.64
RFFR (Rs)	154666	161709	155316	160715
Increase in returns (%)	-	4.55	0.42	3.91
Water use (m^3)	54986	53775	40388	40388
Water saving (%)	-	2.20	26.55	26.55

Notes: Sugarcane being a perennial crop, its area has been counted in *rabi* season as well
*indicates maximum area restriction on these crops
Plan – I: Optimal plan (water availability 100 per cent)
Plan – II: *Kharif* water availability decreased by 36 per cent
Plan – III: Introducing Bt cotton and *kharif* water availability decreased by 36 per cent
Figures within the parentheses indicate percentage to cropped area

resources, they may have to accept a slight reduction in farm incomes as compared to the existing plan.

Other Management Strategies to Save Groundwater

Apart from adoption of timely transplantation of paddy (instead of early-transplantation) and introduction of new crops such as Bt cotton in the production pattern, sustainability of irrigation water resources can be further enhanced by adopting more efficient irrigation methods and cultivation practices. The rice crop is usually irrigated by continuous flooding of the fields and the water is never allowed to drain down. There is ample evidence that applying irrigation to rice two days after

Table 4. Water-use efficiency under different irrigation methods for rice crop in Punjab

Method	No. of irrigations	Water requirement (cm)	Average depth of irrigation* (cm)	Yield (t/ha of paddy)	Water saving w.r.t. flooding (cm)	Cost saving w.r.t. flooding (Rs/ha)	IWUE (kg/ha-cm)
Continuousflooding	24	190	7.9	5.51	-	-	29
1-Day after drainage	18	145	8.1	5.44	45	1492	38
2-Days after drainage	16	125	7.8	5.53	65	2155	44
4-Days after drainage	14	113	8.1	5.11	77	2553	45

Notes: 1- day drainage means that irrigation should be applied one day after the water is completely drained.
*Average depth of irrigation has been calculated by dividing total water requirement with the number of irrigations.

the previous water drains down can significantly reduce the irrigation requirements of the crop without having any adverse effect on the crop yields. Such a practice will reduce the demand for water in the state by 1.71 M ha-m, will save 1922 MkWh of electricity and will reduce the cost of cultivation of rice by Rs 2155/ ha (Table 4). Further, use of 'tensiometer', a device that helps in assessing the exact time and amount of irrigation water on the basis of available water in the soil, can reduce irrigation water requirements of rice from 148 cm to 102 cm without any loss in productivity and saving of 1360 M kWh of electricity (Hira *et al.*, 2006). There is an additional saving of water by 20 per cent as compared to the 2-day drainage method.

Adoption of appropriate irrigation schedule in wheat crop can also bring a saving of 0.52 M ha-m of water (Singh and Sandhu, 2006). Reduction in the size of plots can also reduce the water requirements significantly (Singh *et al.*, 2006).

Conclusions

A linear programming model has been formulated to suggest the optimal cropping pattern for maximizing the net return and ensuring significant saving of groundwater at different levels of groundwater availability for sustainable use of groundwater resources in Punjab. It has been found that the area under paddy has reduced from 70.65 per cent of cultivated area at 100 per cent water availability level to 57.34 per cent at 64 per cent water availability level. The area has shifted towards less water-consuming crops like maize, *desi* cotton and Bt cotton. The study has revealed that a shift in transplanting dates of paddy from early June to third or fourth week of June could save water without having any adverse impact on the profitability, if new crops were introduced in the cropping pattern along side the restrictions on water-use. Introduction of Bt cotton could improve water savings along with enhancing the farm incomes. Its area can be increased in those districts, where it was grown before the introduction of paddy. For instance, the area under Bt cotton can be expanded in the erstwhile cotton-growing districts of Bathinda, Ferozepur, Sangrur, Ludhiana and Faridkot.

To ensure sustainable use of groundwater resources in Punjab, a single strategy will not work and a multi-pronged strategy encompassing improvement in productivity of alternative crops, increase in their prices and strengthening of market infrastructure, will be required. Alongside, electricity supply to the farm sector shall have to be priced to reduce inefficient use of groundwater resources. Above all, the farmers shall have to be educated to timely transplant the paddy on the basis of PAU recommendations. Shifting transplantation of paddy to the period later than 10 June will save huge amount of precious water resource without having any negative impact on the farm incomes. Appropriate legislation to prevent farmers from transplanting paddy before 10 June, has been enacted but its proper implementation for sustainability of water resources is still an issue (Singh, 2009; Hira and Singh, 2007).

Introduction of pulses and oilseeds in the cropping pattern does not seem feasible under the present regime of prices and productivity. Government support to encourage research and development for enhancing productivity of pulses and oilseeds will go a long way to ensure sustainability of water resources in Punjab. Alternate wetting and drying (Tabbal *et al.*, 2002), adoption of system of rice intensification (SRI) (Thakur *et al.*, 2009; Zhao *et al.*, 2010), use of tensiometres (Hira *et al.*, 2006; 2007) and direct plantation of paddy (Cabangon *et al.*, 2002; Johnkutty *et al.*, 2002; Singh *et al.*, 2005) are some of the other techniques which can save water.

Note

The gross water requirements were estimated by multiplying area under each crop with water requirements of the crop per unit of area. The total water requirements of Punjab were estimated by Water Resources Directorate, Punjab, Chandigarh at 6.15 M ha-m based on the cropping pattern of the year 2000-01.

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Annexure I

Cost of irrigation for different crops in Punjab

(Rs/ha)

Crop	Cost of irrigation
***Kharif* crops**	
Paddy 1 (before 10 June)	2569
Paddy 2 (between 10 and 20 June)	1611
Paddy 3 (after 20 June)	1500
Basmati	593
Desi cotton	1400
Arhar	1400
Moong	467
Mash	-
Maize	188
Kharif fodder	458
Sugarcane	832
Bt cotton	995
***Rabi* crops**	
Wheat	679
Gram	-
Sarson	213
Garlic	-
Capsicum	-
Peas	-
Potato	132
Carrot	-
Barley	143
Massar	-
Rabi fodder	400

As electricity and canal water supply to agriculture sector was free of cost during the reference year 2002-03, hence the cost of irrigation include only the expenditure on diesel oil.

***** Due to no use of diesel engine in some crops, the cost of irrigation was zero.

Annexure II

Quantity of irrigation water saved in Punjab

Particulars	Quantity of water (M ha-m)
Existing cropping pattern	6.28
Optimal cropping pattern	4.61
Water saving per annum	1.67
Water saving in next five years	8.35