Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Agricultural Water Management 82 (2006) 279–296

Agricultural
water management

www.elsevier.com/locate/agwat

Management of declining groundwater in the Trans Indo-Gangetic Plain (India): Some options

S.K. Ambast *, N.K. Tyagi, S.K. Raul

Irrigation and Drainage Engineering, Central Soil Salinity Research Institute, Zarifa Farm,
Kachwa Road, Karnal 132 001, Haryana, India

Accepted 4 June 2005
Available online 8 September 2005

Abstract

The average productivity of rice–wheat sequence is quite impressive in the Trans Indo-Gangetic Plain (India) but these gains are over-shadowed due to declining groundwater, particularly in the areas, where groundwater quality is either good or marginal. The groundwater decline can be reversed through artificial groundwater recharge and by adopting suitable land and water management practices. Groundwater recharge is found technically feasible through vertical shafts conducting water from the ground surface directly to aquifers, after it has been passed through a sand-gravel filter. The recharge rate through this system is almost equal to a shallow cavity/filter well yield (about 11 l/s) and its cost is estimated at about INR 10/100 m^3 (1 US$ = 45 INR). Further study in the Kaithal and Karnal districts of Haryana for stabilizing watertable within 6–7 m, which permits continuous use of shallow tubewell technology, indicated that the rice area could be supported at 60% of cultivable command area (CCA) and wheat between 65 and 80% of CCA with the existing management practices. The cultivation of wheat crop is sustainable in larger area, mainly due to its medium water requirement, salt resistance characteristics and consistent market demand resulting in assured returns. There is a possibility of supporting rice at a higher level, if part of the area (up to 10%) is left fallow and used for rainwater conservation and recharge. The fallow area may be subsequently put under early *rabi* (winter) crops like mustard, gram and other pulses. The effect of varying irrigation and fallowing would increase 23% equivalent wheat yield by changing land and water management practices. The analysis further indicated that the adoption of proposed irrigation management

---

* Corresponding author. Tel.: +91 184 2291399; fax: +91 184 2290480.
E-mail address: skambast@cssri.ernet.in (S.K. Ambast).

doi:10.1016/j.agwat.2005.06.005

practices might stabilize watertable at desired level of 6–7 m in 10–15 years in high (3–4 m), 5 years in medium (5–10 m) and 40 years in deep (>10 m) watertable areas.

Keywords: Groundwater management; Rice–wheat cropping; Artificial recharge; Rainwater conservation; Irrigation management; Salinity; Trans Indo-Gangetic Plain

1. Introduction

Rice–wheat cropping sequence is the major food production system in the Indo-Gangetic Plain (IGP) of India (Fig. 1). In the trans Indo-Gangetic part of the plain (States of Punjab and Haryana), which earlier supported upland crops like maize, cotton and sorghum during *kharif* (summer) season and wheat during *rabi* (winter) season, introduction of rice crop was largely a consequence of waterlogging in canal irrigated areas and development of intensive network of shallow tubewells. The cultivation of wheat is practiced in about 80% of the area, which even includes marginal quality groundwater areas, mainly due to its low water requirement, salt resistance characteristics and consistent demand resulting in an assured return (Tyagi et al., 2004). Therefore, rice–wheat cropping sequence in the region has evolved due to specific regional climatic and geo-hydrological conditions. The average productivity of 7–8 t/ha for rice–wheat cropping sequence in the trans IGP is quite impressive against the average of 4.0 t/ha in the IGP. In fact, the region contributes about 52% in national food production (Abrol, 1999). However, these significant gains are over-shadowed by the emerging land and water management problems on regional scale.

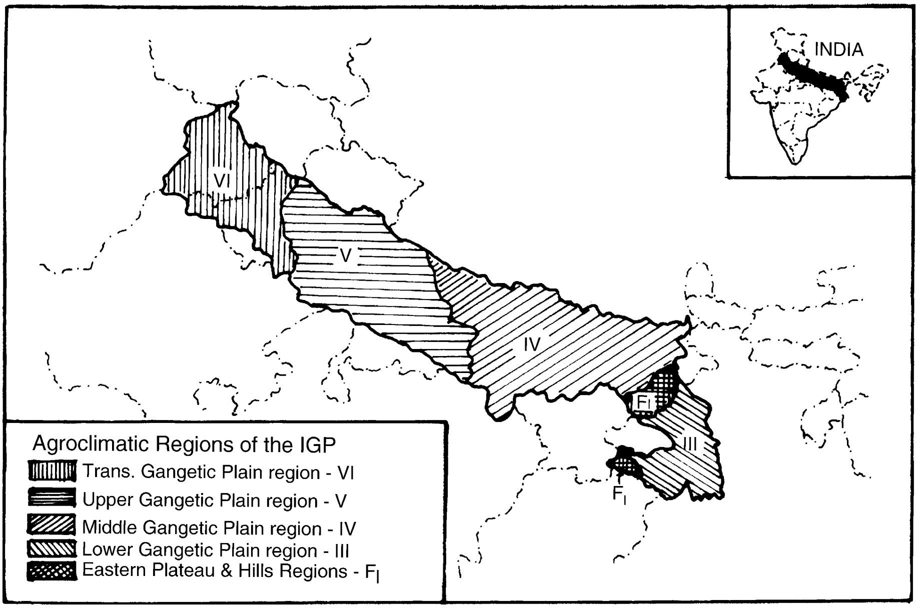


Fig. 1. Indo-Gangetic Plain showing agro-climatic regions.

Although, the average productivity in trans IGP is one of the highest in the country, there are considerable yield differences in rice–wheat productivity within this part (Ambast et al., 2004). In this region, the protective irrigation is in vogue through a rotational system of canal irrigation cycles of fixed duration, frequency and priority level, commonly known as 'warabandi' (Malhotra, 1982). Despite this effective and well-adopted method of water distribution, its supply is unreliable and inadequate to meet the crop water demand and the amounts of water received by the farmers do not correspond with the allocation principle of warabandi (Jacobs et al., 1997). The canal water allowance is very low (1 m^3/s for 5000 ha that comes to 0.2 l/s/ha) and it supplies about 150–200 mm of water during rice–wheat cropping season. About 70% of the region has fresh (<2 dS/m) or marginal (2–6 dS/m) quality groundwater at shallow depth (<40 m), which supplements the crop water requirement (Hira et al., 2004; Tanwar, 1995). Since the water requirement of rice–wheat crop sequence is about 1800 mm and the annual rainfall is ranging between 250 and 900 mm, watertable is falling rapidly in most of the area. Therefore, the major sustainability issues in this region relate to adverse salt and water balance and declining groundwater. However, in this paper emphasis is laid on managing the problem of declining watertable.

2. Extent and magnitude of the problem

With the advent of the "Green Revolution" in 1960s and due to specific regional geo-hydrological conditions in the trans IGP, a significant area is occupied under rice–wheat cropping sequence. In this region, wheat occupies nearly 80–85% of cultivated area during *rabi* (winter) and rice occupies about 50–60% area during *kharif* (summer) season (Anonymous, 2003a, 2003b). The average productivity of rice–wheat sequence in trans IGP, which exceeds 8.0 t/ha in Punjab and 6.5 t/ha in Haryana are comparable with the best in the world. The growth in rice and wheat cropping area, production and productivity in the States of Punjab and Haryana are depicted in Fig. 2. In Punjab, rice crop continues to show an overall steady increase in area, production and productivity, though it appears that productivity is reaching the plateau. In case of wheat, though there is very little increase in cultivated area (by 4%) over the past decade, the increase in production is still high (by 28%) due to increase in productivity (by nearly 23%). In Haryana, though the increase in rice cultivated area (by 65%) and its production (by 40%) has been registered over the past decade, but the productivity has decreased significantly (by 15%). One of the reasons for this may be the adoption of low yielding scented basmati variety, which fetches better returns than other varieties. In case of wheat, in spite of no change in cultivated area, production has increased significantly (by 50%) due to increase in productivity (by 20%). Thus in the trans IGP, the area under rice is increasing but its productivity is stagnating, whereas area under wheat has attained its maximum limit but its productivity is still increasing.

For detailed analysis, district-wise cropping system (Yadav and Subba Rao, 2001), water quality, tubewell density and watertable position maps for Trans IGP are combined in geographical information system environment (Fig. 3). The isohyets-cropping system and groundwater quality maps (Fig. 3a and b) show that rice–wheat sequence is mostly

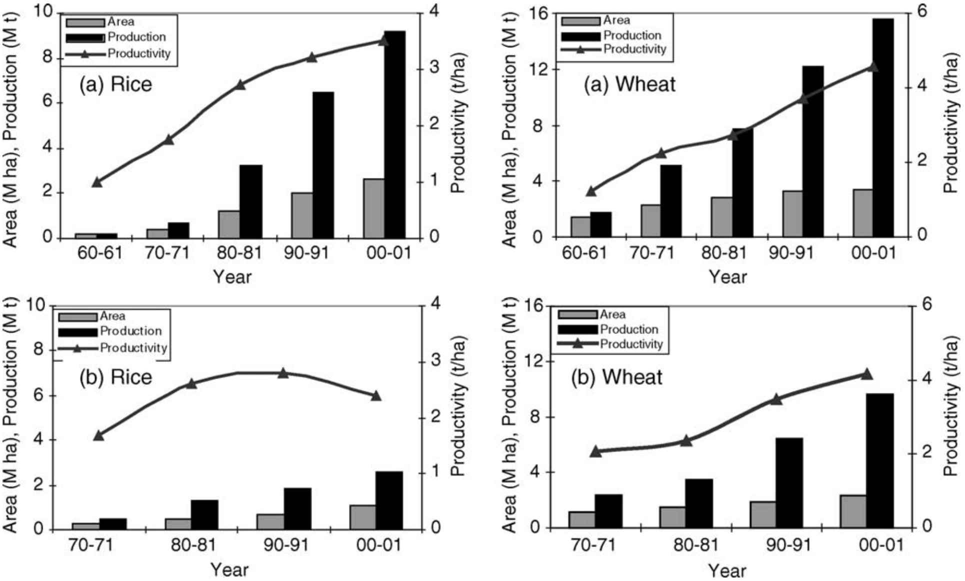


Fig. 2. Area, production and productivity in (a) Punjab and (b) Haryana.

prevailing in the region where rainfall is more than 500 mm and groundwater is either fresh or of marginal quality. The tubewell density map (Fig. 3c) indicates that in most of the rice–wheat growing area tubewell density is more than 15 km^{-2}. In the poor quality groundwater areas, where tubewell density is low with rainfall less than 400 mm, major crop system is cotton–wheat, pearl millet–wheat or pearl millet–mustard in place of rice–wheat. The overall impact of these factors on groundwater decline is shown in Fig. 3d. It may be observed that groundwater is declining in both, fresh and marginal quality groundwater areas where rice–wheat is the major cropping system. A rise in watertable is registered in areas where groundwater is of poor quality and where non rice–wheat cropping is practiced. The problem of declining groundwater is observed serious in the parts of Jalandhar, Ludhiana, Moga, Bathinda, Sangrur and Patiala districts in Punjab and Kurukshetra, Karnal, Kaithal, Jind and Panipat districts in Haryana. In these districts watertable has fallen by 5–15 m over the last 20 years requiring lowering of centrifugal pumps in deeper pits or replacing them with submersible pumps imposing additional economic burden in addition to causing threat to sustainability of groundwater resources. This calls for urgent measures to be taken up for economic and sustainable utilization of groundwater resources both at field and regional scales.

In case of continuation of prevailing rice–wheat sequence due to specific regional conditions, the possible options to arrest declining watertable are (i) increase in groundwater recharge and (ii) decrease in groundwater withdrawal. Increase in groundwater recharge may be achieved through structural options, i.e. percolation tanks, check dams, recharge tubewells and management interventions, i.e. rainwater conservation in fallow land. The groundwater withdrawal may be decreased through water demand management by reducing number of irrigation or crop allocation interventions. Keeping in

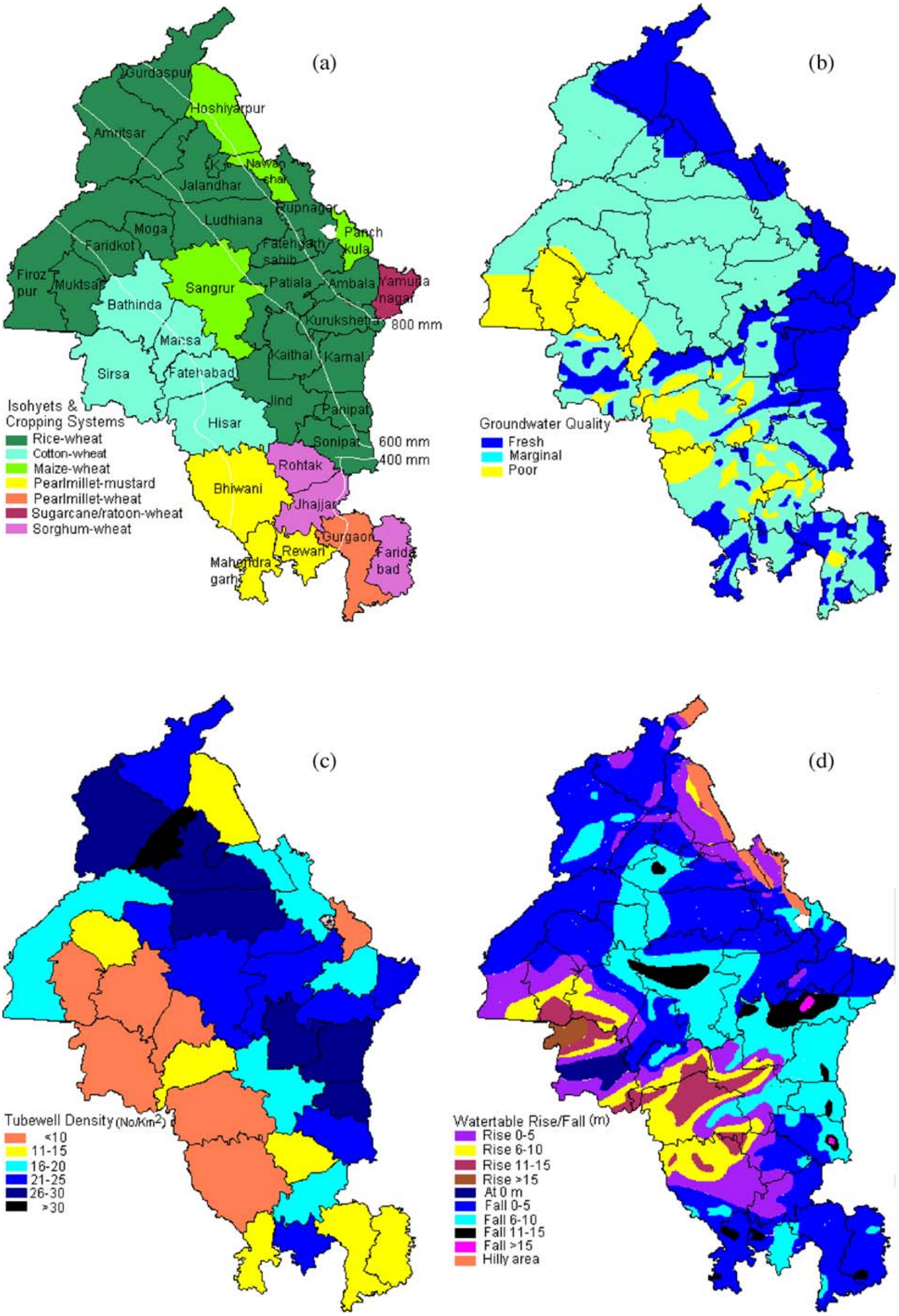


Fig. 3. District-wise (a) cropping system; (b) water quality; (c) tubewell density and (d) rise and fall of watertable in last 15 years in the Trans Indo-Gangetic Plain.

view the importance of such interventions, a feasibility study on artificial groundwater recharge through tubewell was undertaken in the Karnal district, Haryana. A study was also conducted for Kaithal and Karnal districts for stabilising watertable by changing land and water management practices.

3. Structural options of recharge

Artificial groundwater recharge through recharge structures may be the most effective means for increasing groundwater potential in the rapidly declining groundwater areas of trans IGP. Although the region has low average rainfall, each year there is short duration, high intensity rainfall creating flash floods that goes to sea as waste. Such flash floods need to be arrested at various locations for recharge at accelerated rate. In flat topography, where extensive groundwater development has taken place at shallow depth in the first aquifer of 10–60 m depth, recharge structures with tubewell are often better choice than surface storage. The transmissivity, hydraulic conductivity and specific yield of the alluvial aquifers that exist in 98% areas are ranging between 500 and 4000 m^2/day, 10–80 m/day and 10–18%, respectively (Tanwar, 1998). In such areas, recharge tubewells improve water quality and availability more quickly than gradual percolation from percolation tank or check dams. Moreover, good quality recharged water is protected from contamination on way through percolation. Surface drainage systems, which are generally constructed to control waterlogging and floods, alone or in conjunction with recharge tubewells, offer a good scope for groundwater recharge in this region.

3.1. Scope of harvesting water for recharge

In order to prevent further decline in groundwater that in-fact may initiate/accelerate the desertification process in the trans IGP, priority should be given to harvest the excess water. However, the availability of excess water and favourable geo-hydrological conditions are the pre-requisites for successful implementation of such a programme. In this region, rainfall runoff and limited canal water during lean periods of irrigation requirement may be utilised for artificial groundwater recharge (Table 1). In Punjab, the

Table 1
Availability of excess water for artificial recharge in trans IGP

Particulars	Punjab	Haryana
Area (M ha)	3.5[a] + 0.5[b]	1.75[a]
Average rainfall during monsoon (m)	0.50 + 0.76	0.50
Runoff coefficient[c]	0.10 + 0.25	0.10
Runoff volume (ha m)	175000 + 95000	87500
Average annual canal supply (m)	0.35	0.35
Annual surplus canal water at 5% of annual supply (ha m)	61250	30625
Available water potential for recharge (ha m)	200000	89000

[a] Irrigated area with fresh/marginal quality groundwater.

[b] Foothill area.

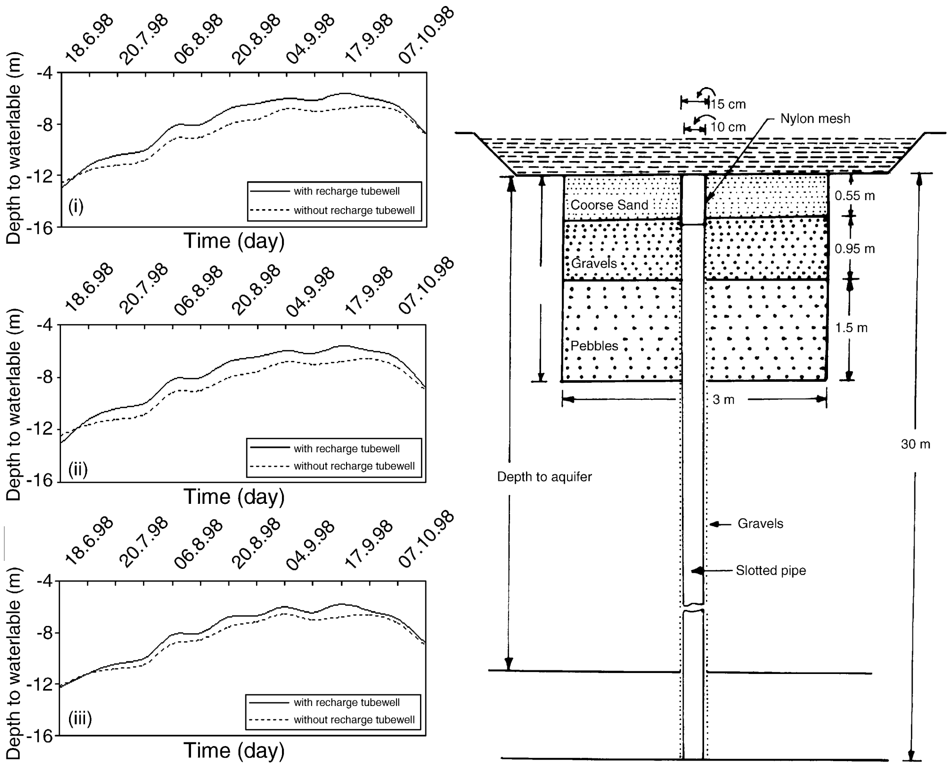
[c] Khepar (2001).

total available rainfall runoff is 0.27 M ha m, whereas the annual canal water surplus has been estimated as 0.06 M ha m. Considering the technical feasibility for exploiting the excess water in irrigated area at 75% and foothill area at 25%, the available water potential for recharge is estimated as 0.2 M ha m. Interestingly, recharge of this water (taking specific yield as 15%) will reduce the watertable decline in irrigated area of Punjab by 40 cm/year. Similarly, available rainfall runoff is estimated as 0.09 M ha m in the irrigated area with fresh/marginal quality groundwater, whereas the annual canal water surplus has been estimated as 0.03 M ha m in the State of Haryana. Considering technical feasibility for exploiting the excess water in irrigated area at 75%, the available potential for recharge is estimated as 0.09 M ha m. The artificial recharge in irrigated area of Haryana, where groundwater quality is fresh/marginal and watertable is falling, may lead to reduction in decline in watertable by 34 cm/year.

3.2. Recharge through tubewell

A study on feasibility of artificial groundwater recharge was conducted in Haryana (Singh et al., 1997). The Old Sirsa canal, a branch of Western Yamuna Canal runs only during rainy season (July–October) to carry surplus river water for kharif irrigation, passes through the fresh groundwater depleting areas of northeast Haryana. The static groundwater level in the area generally varies between 6 and 14 m. The seasonal fluctuation of groundwater is 1–3 m. On the basis of lithologs, declining watertable trend, availability of excess water and accessibility by the road, a site in the bed of Old Sirsa Branch Canal near village Manak Majara, Karnal was selected. Geo-electrical resistivity survey was carried out in the bed of canal to find out the potential recharge area. On the basis of probes, two recharge tubewells, at a distance of 50 m, were installed. Keeping recharge tubewell at the centre, a filter pit (6 m × 6 m × 4 m) was excavated and filled with filter material, i.e. sand, gravel and pebbles to prevent the entry of sediments and suspended solids in recharging water. Mechanical analysis of the base material (soil from the canal bed) was made for design of filter. A network of observation wells was provided to monitor the watertable change as a result of recharge through tubewells. A set of observation wells on the upstream side of the recharge tubewell were also drilled for monitoring recharge from canal and paddy fields under natural condition. The efficacy of recharge tubewell is estimated by comparing watertable fluctuations in the observation wells aligned with recharge tubewells with those located parallel on upstream side (Fig. 4a).

Higher watertable elevations at observation wells clearly indicated the increase in recharge due to recharge tubewell. The recharge tubewell admits water from the surface and conveys it to fresh water aquifer and its flow pattern is the reverse of the pumping tubewell pattern. On the basis of radial flow equation under steady state recharge condition in unconfined aquifers (Todd, 1980), an average rate of recharge is estimated at 11 l/s (Kaledhonkar et al., 2003), whereas the cost of artificially recharged water is estimated at INR 10/100 m^3 (1 US$ = 45 INR). The recommended design of recharge structure is shown in Fig. 4b and the estimate for recharge structure is given in Table 2 (Singh et al., 2002).



(a) (b)

Fig. 4. (a) Observed watertable at (i) 16 m (ii) 33 m and (iii) 88 m from the recharge tubewell (b) design of recommended recharge structure.

Table 2
Cost estimate for recommended recharge tubewell setup

Particulars	Quantity	Unit cost (INR)	Total cost[a] (INR)
1. Installation of pipe with boring (6" dia. bore and 4" dia. PVC pipe with perforations	1 No.	@ 8000	8000
2.Excavation & disposal of dug soil & refilling of pit with filter materials (3 m × 3 m × 3 m).	27.00 m^3	@ 50/m^3	1350
3. Procurement of filter material	4.95 m^3	@ 300/m^3	1485
(a) Coarse sand	8.55 m^3	@ 350/m^3	2993
(b) Gravel	13.50 m^3	@ 400/m^3	5400
(c) Pebbles			
Total cost			19230

[a] Based on 1999 price; (1US$ = 45 INR).

4. Management options

It is apparent that the present cropping pattern and intensity in trans IGP has created an unfavourable water balance, which is not sustainable in the long run. To have a sustainable system, either the present land and water management practices have to be modified or a new cropping pattern is to be evolved. However, there has to be some criterion on the basis of which changes are to be suggested. There are two possible options to bring watertable to the desired (6–7 m from the surface) level and stabilize it through management practices: (1) increase in groundwater recharge (2) decrease in groundwater withdrawal. Both the options have to be exercised to different degrees depending upon the existing water balance and watertable situation. To evolve suitable management options, groundwater balance, effect of irrigation water on crop yields and effect of watertable decline on pumping cost, etc. have been estimated for different management options. The general groundwater balance at any time is expressed as:

$$(\mathrm{RCD} + \mathrm{RTC} + \mathrm{RCF} + \mathrm{GWI}) - (\mathrm{GWO} + \mathrm{EVG} + \mathrm{GWW}) = \mathrm{GWB}$$

where RCD is the recharge from canal conveyance and distribution system, RTC is the recharge from tubewell conveyance system, RCF is the recharge from crop fields, GWI is the groundwater inflow from adjoining areas, GWO is the groundwater outflow to adjoining areas, EVG is the evaporation from groundwater storage, GWW is the groundwater withdrawal by tubewells and GWB is the groundwater balance. All components of the groundwater balance are expressed in ha m. Since groundwater recharge is a function of the total percolation losses, the recharge from different components of the water balance equation is estimated for computing the groundwater rise or fall (Fig. 5). Further, a computer program was developed in FORTRAN language to estimate different combinations of rice and wheat acreage for sustainable groundwater management in the study area (Fig. 6). In the present study, RCD is estimated by accounting transient losses at 28% and taking recharge factor as 0.8 measured for Jundla distributary of the system as applied by Tyagi et al. (1995). For estimation of RTC, seepage loss is taken at 7% for 100 m channel length and recharge factor is taken at 5.6% of water pumped. RCF is estimated by considering irrigation requirements of different crops, irrigation depth and the retained rainfall values. EVG from groundwater storage is considered negligible as watertable in the study area remain below 4 m from the soil surface except in some parts of Kalayat and Rajound block where watertable rises to 1 m. The subsurface flow may be estimated as function of hydraulic conductivity, depth to bedrock, hydraulic gradient and width of the flow area. Since the study area is a part of the large irrigation area under similar agro-hydro-geological conditions and mostly flat with gentle subsurface hydraulic gradients (about 5×10^{-4}), the subsurface inflow from the adjoining area has been taken as equal to the subsurface outflow to the adjoining area. Groundwater withdrawal is assumed for agricultural use only and is estimated as the difference of irrigation requirement of crops and annual canal water supply. Further, in this study the yield of rice is expressed in terms of equivalent wheat yield by considering the sale prices of both the crops for the year 1999–2000. The estimated cultivation costs (excluding irrigation) of rice and wheat crops are based on the practices followed at CSSRI, Karnal and the market prices of the different cultivation inputs. The cost

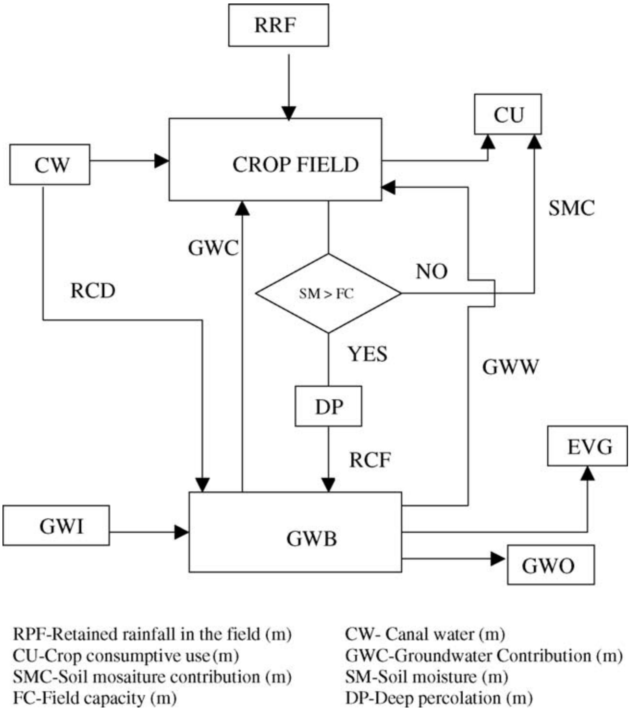


Fig. 5. A flow chart for estimation of groundwater rise or fall in different blocks.

of irrigation included the cost of canal water supply and the groundwater pumping only.

In the absence of other credible options to increase water supply, the option of keeping a fraction of cultivable area fallow for in situ conservation of rainwater to increase soils moisture storage and groundwater recharge during rainy season, is given consideration. It is postulated that, this practice would decrease load on groundwater and permit more recharge by ponding of rainwater, which is not permissible in case the land is put under upland crops. The conserved moisture in the soil profile would be useful for growing early sown crops like mustard and pulses solely on conserved moisture and winter rainfall during *rabi*. The area that should be put under this practice in different blocks has to be determined. The other option that would decrease load on groundwater is reduced pumping for irrigation of rice and wheat. Irrigations to rice in post planting phase range between 20 and 25 depending on the rainfall distribution. Most part of this water joins the groundwater system through deep percolation from ponded rice paddies and is re-circulated. Irrigation reduction would have impact on crop yields. Based on established crop-water-production functions of rice and wheat, it has been estimated that there would be reduction of 3.4% in rice and 11.8% in wheat, if the number of irrigation is reduced by one. It may be added that wheat receives only 4–5 irrigations, therefore, the scope for reducing irrigation is less. Looking at differential response of these crops, relative economic implication of a decision

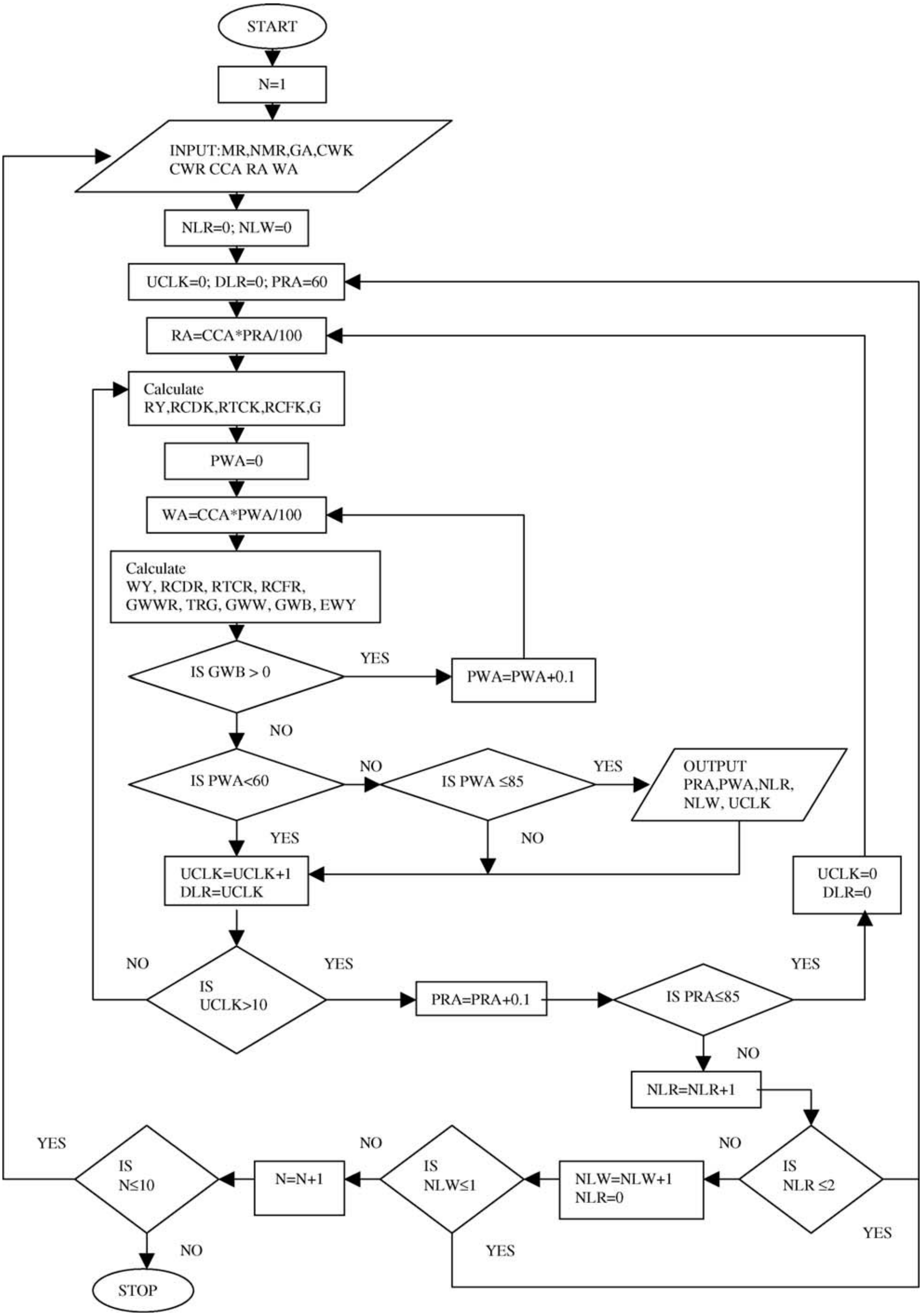


Fig. 6. A flow chart for estimation of rice and wheat area under different management options.

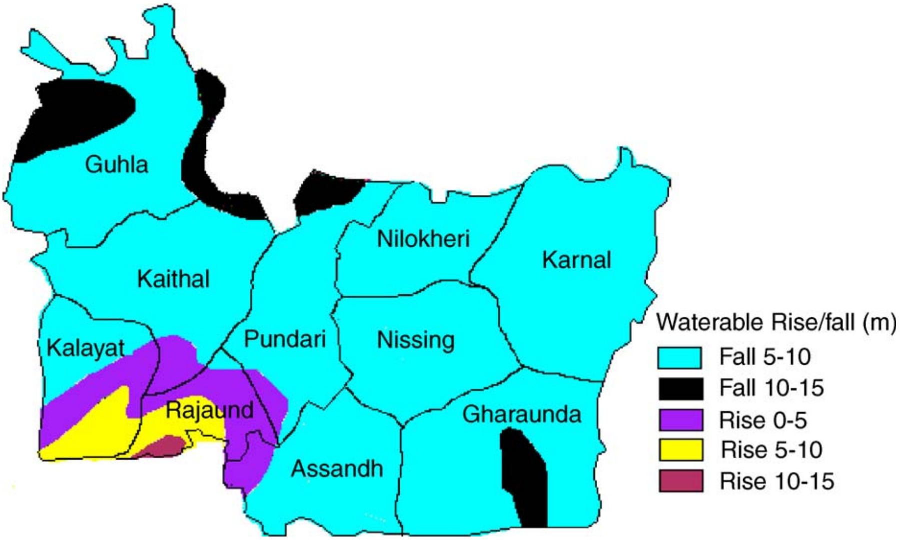


Fig. 7. Watertable rise/fall in different blocks of Kaithal and Karnal districts of Haryana.

is evaluated in terms of equivalent wheat yield. Both the options, i.e. (i) modifying land and water management that may help sustain the existing cropping and (ii) delve upon the possibilities of introducing changes in rice–wheat areas that would maximize the overall production, have been evaluated.

The analysis for land-water management options have been attempted with reference to Kaithal and Karnal districts in Haryana (Fig. 7), where rice and wheat are grown in more than 70% area. Rice and wheat together have an evapotranspiration demand of about 1000 mm and water requirement of about 1800 mm. In this part of the trans Indo-Gangetic plain, where rainfall is about 600 mm, large amount of water has to be supplied through surface water from canals and groundwater pumped through shallow tubewell (depth < 40 m). The contribution of groundwater use through tubewells, which primarily depends on groundwater quality (Table 3), accounts for 44% of irrigation in Kaithal and 84% in Karnal district. The groundwater is able to support such a high percentage of irrigation, largely due to recharge emanating from seepage losses from extensive canal system and the rice paddies that enable in situ harvesting of rainwater. It is estimated that rice-paddies enable harvesting of about 90% of the rainy rainfall (Tyagi, 1980). Although, the overall rainwater utilization due to rice cultivation is high, it has created an overall deficit in water balance resulting in decline of watertable (Table 4). It is estimated that the annual water deficit ranges from 4 to 14% creating a decline in watertable in the order of 0.2–1.1 m, which increases pumping cost and requires replacement of centrifugal pumps with more costly submersible pumps.

The blocks in both the districts can be grouped as (1) blocks with good quality groundwater and (2) blocks having saline/sodic waters. There seems to be a direct relationship between groundwater quality and the area under rice as blocks with good quality groundwater have high percentage of rice and wheat area (more than 70%),

Table 3
Blockwise average groundwater quality in Kaithal and Karnal districts

Block	EC (dS/m)	RSC ($\text{mmol}_c\,\text{l}^{-1}$)	pH	SAR ($\text{mmol}_c\,\text{l}^{-1}$)$^{1/2}$
Pundri	1.4	4.2	9.2	6.4
Guhla	1.2	3.8	9.0	6.4
Kaithal	1.4	4.1	8.6	6.3
Kalayat	2.9	4.7	9.0	15.3
Rajaund	2.5	1.7	8.9	9.8
Nissing	1.3	0.0	8.0	2.8
Nilokheri	1.2	0.3	8.0	3.1
Gharaunda	1.1	0.0	7.8	2.5
Karnal	0.8	0.0	7.8	1.4
Assandh	1.9	0.0	8.0	4.7

whereas blocks with marginal groundwater supports rice in less than 60% area. Wheat, which is relatively more salt tolerant than rice and requires less water, is supported at higher level (70%) even in blocks having water quality problem (Table 4). In all the blocks, groundwater development is more than recharge but the rate of fall in watertable is higher in freshwater quality zone. In poor groundwater quality blocks, the watertable though not rising, continues to be at higher level (3–4 m) but the overall productivity of rice–wheat in these blocks is lower by 5–10%. The watertable required to be lowered to keep it at safe distance during rainy period. It is projected that with the existing cropping and groundwater pumping rates, watertable would fall beyond 25 m in Guhla, 18 m in Gharaunda and Pundri, but will remain between 6 and 7 m in Kalayat and Rajaund blocks. The fall in watertable would increase pumping cost adversely affecting the economics of rice–wheat system. Estimates show that cost of production of rice–wheat excluding irrigation is INR 17725/ha (Raul, 2000). The total cost of cultivation including irrigation, ranges between INR 18920/ha in Kalayat block to INR 21488/ha in Guhla block. The contribution of irrigation to total cost of production is within 20%. It should however

Table 4
Blockwise rice–wheat area and groundwater situation in Kaithal and Karnal districts

Block	CCA (ha)	Area under		Annual deficit (%)	Watertable fluctuation (m/annum)	Watertable depth (m)		
		Rice (%)	Wheat (%)			Existing	After 5 year	After 10 year
Pundri	41855	94	89	13.8	−1.1	8.5	13.7	18.9
Guhla	49487	88	82	15.3	−1.1	15.7	21.1	26.4
Kaithal	51405	83	77	12.7	−0.9	9.3	13.6	17.9
Kalayat	32388	61	69	7.2	−0.4	2.9	5.0	7.0
Rajaund	26570	49	74	4.0	−0.2	4.0	5.1	6.1
Nissing	31212	77	80	10.1	−0.6	6.3	9.3	12.4
Nilokheri	36299	77	74	13.3	−0.9	7.3	11.8	16.4
Gharund	33562	75	80	12.4	−0.8	11.0	14.9	18.8
Karnal	38814	64	67	6.4	−0.4	7.2	8.9	10.7
Assandh	49327	57	57	4.6	−0.2	6.1	7.3	8.5

Table 5
Rice–wheat area (%) under normal irrigation for percentage fallow land in kharif

Block	CCA (ha)	Fallow land (% of CCA)											
		0, Area under		2, Area under		4, Area under		6, Area under		8, Area under		10, Area under	
		Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat	Rice	Wheat
Pundri	41855	60.0	68.4	60.0	79.2	61.9	85.0	66.0	85.0	70.1	84.9	74.2	84.9
Guhla	49487					60.0	65.0	60.0	75.5	60.3	85.0	64.0	84.8
Kaithal	51405					60.0	69.9	60.0	80.3	62.2	84.8	66.1	84.8
Kalayat	32388							60.0	63.6	60.0	74.5	60.2	84.8
Rajaund	26570									60.0	68.9	60.0	80.2
Nissing	31212			60.0	67.3	60.0	77.1	60.8	84.8	64.6	85.0	68.5	84.9
Nilokheri	36299									60.0	69.0	60.0	79.1
Gharaunda	33562							60.0	65.9	60.0	76.2	60.7	84.9
Karnal	38814					60.0	62.3	60.0	72.5	60.0	82.6	63.1	85.0
Assandh	49327									60.0	66.5	60.0	76.9

be realised that irrigation costs are low because the electricity charges are highly subsidized. The indirect cost, though not borne by the individual farmers, is borne by the society. In real term, the cost of pumping from deeper water levels are much higher and if electricity is charged at market rates, profitability of rice wheat cropping would be reduced.

4.1. Through in situ rainwater conservation

Since the existing level of rice–wheat cropping is causing secular fall in watertable, extent of areas that should be left fallow for conserving rainwater during *kharif* season has been estimated in terms of maximized equivalent wheat yield for different blocks. It may be mentioned that these fallow areas can be used for raising crops like gram, mustard and other pulse crops under rainfed farming during winter. Based on prevailing agro-climatic and economic conditions, 60% area is considered as the minimum area that should be put under rice. Water balance analysis shows that only Pundri block can support minimum rice area (60% of CCA) without any fallow land during *kharif* (Table 5). Nissing block require 2% fallow *kharif* area to support minimum 60%, whereas Guhla, Kaithal and Karnal require 4%. All other blocks require 8% *kharif* fallow to support 60% rice. It is estimated that 10% fallow area is necessary to support 60–75% rice and 75–85% wheat in all the blocks (Raul, 2000).

4.2. Through irrigation management

The effect of reduced irrigation on rice–wheat cropping for stabilized watertable conditions is estimated in terms of maximized equivalent wheat yield. The analysis indicated that no block, except Pundri, supports rice even at 60% under normal irrigation (Table 6). Guhla, Nissing and Kaithal require (NR-1) irrigation to support rice at 60% and

Table 6
Area under rice and wheat for different irrigation management options

Block	Irrigation management options											
	NR, NW		NR-1, NW		NR-2, NW		NR, NW-1		NR-1, NW-1		NR-2, NW-1	
	I	II	I	II	I	II	I	II	I	II	I	II
Pundri	60.0	68.4	60.5	84.8	69.1	84.9	69.9	84.6	78.6	84.7		
Guhla			60.0	61.7	60.0	79.2	60.6	84.7	67.4	84.7	75.9	84.8
Kaithal			60.0	66.6	60.0	84.2	62.5	84.6	70.1	84.8	79.9	84.8
Kalayat					60.0	66	60.0	61.6	62.3	85.0	70.4	85.0
Rajaund									60.0	82.7	67.6	84.7
Nissing			60.0	75.1	64.0	84.9	66.0	84.7	74.6	84.9		
Nilokheri					60.0	63.7			61.6	84.8	70.5	84.9
Gharaunda					60.0	69.9	60.0	69.6	64.5	85.0	74.5	84.8
Karnal					60.0	77.1	60.0	84.0	67.7	85.0	78.1	84.7
Assandh					60.0	60.1			60.0	85.0	69.0	85.0

NR: normal irrigation to rice; NW: normal irrigation to wheat; I: rice area (% CCA); II: wheat area (% CCA).

wheat between 60 and 75%. All other blocks require (NR-1, NW-1) or (NR-2, NW-1) irrigation to support higher rice and wheat areas.

4.3. Watertable control and stabilization with existing cropping

In the 10 administrative blocks, three types of situations prevail: high watertable (3–4 m), medium watertable (5–10 m) and deep watertable (>10 m) (Table 4). Under the existing rice–wheat cropping and management, watertable in Kalayat and Rajaund blocks is falling at the rate of 0.20–0.40 m/year. Since both the blocks have water quality problem, which is hazardous to soil health, it is required to be depleted to some extent to bring watertbale within desirable limits. This would take 10–15 years. Once the watertable reaches desirable levels, it would be maintained by resorting to rainwater conservation in 4–8% area. In medium watertable areas, the annual water deficit is of the order of 6–14% in different administrative blocks. The combined effect of rainwater conservation and irrigation reduction on watertable is analysed. It is seen (Fig. 8a) that in Kaithal NR-2 irrigation to rice and NW-1 to wheat raises the watertable by a maximum of 46 cm per year for 10% uncropped *kharif* area and brings it up to 8.85 m from the existing level of 9.31 m. It will take 5 years for the watertable to reach a desirable level of 6–7 m and once the watertable reaches desirable limit, it can be stabilized at that level by irrigation practice (NR-2) and uncropped area of 8.1%. It is further seen that irrigation practice (NR-2, NW-1) requires only 0.7% of CCA under fallow condition. But if the two strategies are compared in terms of productivity, the maximum equivalent wheat yield is obtained for irrigation practice (NR-2) and 9% fallow land during *kharif* season (Table 6).

Two blocks (Guhla and Gharaunda) fall in deep-water category (>40 m) and have a water deficit in the range of 12–15% with annual watertable fall of 0.80–1.10 m. To raise the watertable to desirable limit requires irrigation practice (NR-2, NW-1) along with 10% fallow during *kharif* (Fig. 8b) at the rate of 0.24 m/year over a period of next 40 years. Once

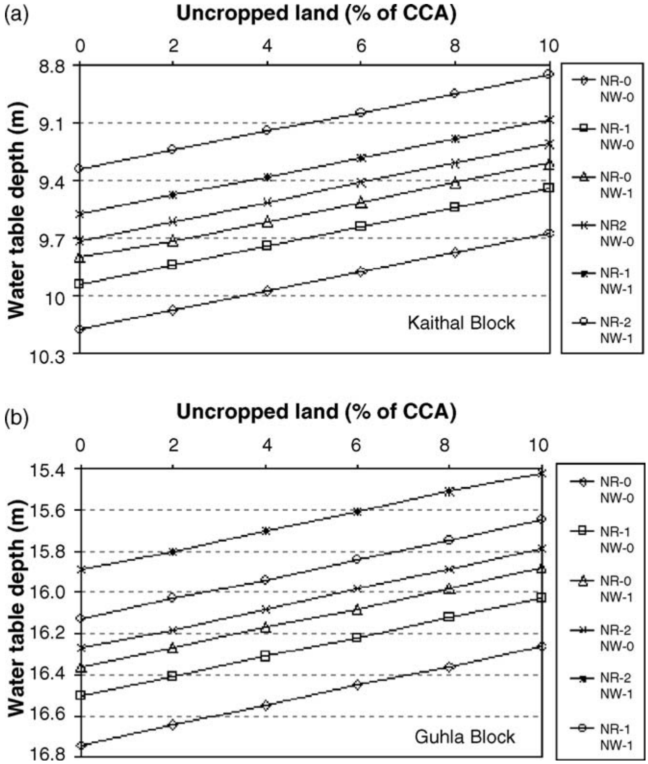


Fig. 8. Watertable behaviour for different options of fallow land (during kharif) and irrigation management.

it attains the desirable limit, further rise or fall can be checked by either irrigation practice NR-1, NW-1 with 9.9% fallow land or by irrigation practice (NR-2, NW-1) with 5% uncropped area. But the first option is better as the equivalent wheat yield is higher in this case.

4.4. Through modification in rice–wheat areas

Whereas both the practices help in sustaining higher percentages of rice and wheat area, but the combined effect of rainwater conservation and modified irrigation is more advantageous. The advantage of synergetic effect can be taken by designing a more profitable cropping pattern. As indicated earlier, the concept of equivalent yield can be used to decide the profitable cropping pattern. The effect of varying irrigation and fallow cropping on attainable yield was analysed and practices maximizing equivalent yield were determined (Table 7). It is seen that in Rajaund block maximum equivalent wheat yield (127.1×10^3 t) is attained when uncropped *kharif* area is 10% and (NR-2, NW), irrigation practice is adopted as compared to only 103.2×10^3 t in the existing situation. Thus, an increase of more than 23% is made possible by changing the land and water management practices.

Table 7
Rice–wheat areas, irrigation practices and uncropped area for rainwater conservation for maximum equivalent wheat yield

Block	Culturable command area (ha)	Required fallow area in kharif (%)	Area under crop % of CCA		Irrigation practice		Maximum equivalent yield, 10^3 tonnes		Increase in yield (%)
			Rice	Wheat			MC	PC	
Pundri	41855	10	83.4	85.0	NR-1	NW	212.9	209.7	11.5
Guhla	49487	10	80.0	85.0	NR-2	NW	255.2	235.3	8.4
Kaithal	51405	10	81.9	84.7	NR-2	NW	258.8	242.3	6.6
Kalayat	32388	10	67.1	84.9	NR-2	NW	157.1	130.5	20.3
Rajaund	26570	10			NR-2	NW	127.1	103.2	23.2
Nissing	31212	8	84.1	84.9	NR-2	NW	156.9	148.3	5.8
Nilokheri	36299	10	74.5	84.9	NR-2	NW	174.1	162.9	6.9
Gharaunda	33562	10	79.4	84.9	NR-2	NW	164.9	155.7	5.9
Karnal	38814	10	82.3	85.0	NR-2	NW	193.6	156.5	23.7
Assandh	49327	10	73.8	85.0	NR-2	NW	234.0	171.4	36.5

MC: modified cropping; PC: present cropping.

5. Conclusions

The indiscriminate use of groundwater, due to intensive cultivation of rice–wheat sequence evolved under specific regional climatic and geo-hydrological conditions, is leading to watertable decline at an alarming rate in fresh and marginal quality groundwater areas in the trans IGP in India. This calls for urgent measures to be taken up for economic and sustainable utilization of groundwater resources, both at field and regional scales. The situation is amenable to improvement through implementation of several feasible water supply and demand management interventions.

The hydrological water balance conducted for the trans IGP indicates availability of augmenting water supplies through artificial recharge to manage declining groundwater. Artificial recharge of aquifers through vertical shaft, with recharge rate almost equal to well discharge, in natural drains, abandoned canals and topographical depressions is the technically feasible and economically viable option.

Water management options in terms of in situ rainwater conservation, deficit irrigation and modifying rice–wheat areas are other possible interventions to be adopted for managing groundwater. The case study in the Kaithal and Karnal districts of trans IGP in Haryana suggests rainwater conservation in one-tenth fallow land during rainy season to induce recharge to support rice and wheat in minimum 60% and 75% CCA, respectively. Deficit irrigation by one to both rice and wheat is found necessary for sustaining minimum rice–wheat area. However, rainwater conservation appears to be better option. Situation specific strategies for existing cropping pattern in high, medium and deep watertable conditions have been suggested to bring and stabilize declining watertable within economic pumping depth. Options of modifying rice–wheat areas for different combinations of rainwater conservation and deficit irrigation are evaluated to subscribe optimal rice–wheat cropping pattern for maximizing equivalent yield and managing groundwater within economic pumping zone.

References

Abrol, I.P., 1999. Sustaining rice–wheat system productivity in the Indo-Gengetic plain: water management related issues. Agric. Water Manag. 40, 31–35.

Ambast, S.K., Tyagi, N.K., Agrawal, A., Sharma, D.K., Sakthivadivel, R., 2004. Analysis of water allocation and distribution on farm level productivity in marginal quality groundwater area under scarce canal water supply condition. In: Rathore, R.S., Singh, G.N., Tiwari, V.K. (Eds.), Proceedings of the International Conference on Sustainable Management of Sodic Lands, 9–14 February 2004, UPCAR, Lucknow (India), pp. 514–518.

Anonymous, 2003a. Statistical Abstracts of Haryana. Government of Haryana, Chandigarh, India.

Anonymous, 2003b. Statistical Abstracts of Punjab. Government of Punjab, Chandigarh, India.

Hira, G.S., Jalota, S.K., Arora, V.K., 2004. Efficient Management of Water Resources for Sustainable Cropping Punjab. Research Bulleting, PAU Ludhiana (India), 20 pp.

Kaledhonkar, M.J., Singh, O.P., Ambast, S.K., Tyagi, N.K., Tyagi, K.C., 2003. Artificial groundwater recharge through recharge tubewells: a case study. J. Inst. Eng. (India) 84, 28–32.

Khepar, S.D., 2001. Strategies for ensuring hydrological sustainability of rice–wheat cropping system in Punjab. ICAR-IWMI Groundwater Policy Initiative-2001, 5–7 Nov, 2001, CSSRI, Karnal (India), 119–137.

Jacobs, C., De Jong, J., Mollinga, P.P., Bastiaanssen, W.G.M., 1997. Possibilities and constraint to mitigate waterlogging in a socio-technical context. In: Proceedings of the ICID Workshop on Sustainable Irrigation in Areas of Water Scarcity and Drought, Oxford, UK.

Malhotra, S.P., 1982. Warabandi system and its infrastructure. Central Board of Irrigation and Power, Publication no. 146, New Delhi, India.

Raul, S.K., 2000. Sustainability implications of rice–wheat cropping in Haryana: analysis of salt and water balance implications, unpublished M.Tech. Thesis (unpublished) submitted to GBPUAT, Pantnagar (India).

Singh, O.P, Ambast, S.K., Kaledhonkar, M.J., Verma, A.K., Rani, M., 1997. Feasibility studies on artificial groundwater recharge in North-East Haryana, Annual Report-1997, Central Soil Salinity Research Institute, Karnal (India) 22.

Singh, O.P., Kaledhonkar, M.J., Ambast, S.K., Verma, A.K., Rani M., Tyagi, K.C., Tyagi, N.K., 2002. Feasibility studies on artificial groundwater recharge in North-East Haryana, Bull. No. 1/02, Central Soil Salinity Research Institute, Karnal, India, 66 pp.

Todd, D.K., 1980. Groundwater Hydrology. John Wiley & Sons, New York.

Tanwar, B.S., 1995. Disposal of drainage effluents-options for Haryana. In: Rao, K.V.G.K.,Agrawal, M.C., Singh, O.P., Oosterbaan, R.J. (Eds.), Proceedings of Reclamation and Management of Waterlogged Saline Soils, CSSRI, Karnal and HAU, Hisar (India), pp. 219–225.

Tanwar, B.S., 1998. Orientation in policy and plan to manage depleting groundwater reserves. Hydrology, INCOH & WRED of Punjab, Chandigarh (India), pp. 251–257.

Tyagi, N.K., 1980. Crop planning and water resources management in salt-affected soils-a systems approach. Ph.D. dissertation (unpublished) submitted to Jawaharlal Nehru Technological University, Hyderabad

Tyagi, N.K., Srinivasulu, A., Kumar, A. and Tyagi, K.C., 1995. Modelling Conjunctive Use of Water Resources: Hydraulic and Economic Optimization, Bull. No. 6/95, CSSRI, Karnal (India), 86 pp.

Tyagi, N.K., Agrawal, A., Sakthivadivel, R., Ambast, S.K., Sharma, D.K., 2004. Productivity of rice–wheat cropping system in a part of Indo-Gengetic plain: A spatial analysis. Irrig. Drain. Systems 18 (1), 73–88.

Yadav, R.L., Subba Rao, A.V.M., 2001. Atlas of Cropping Systems in India. Bull. No. 2001-2, Project Directorate for Cropping Systems Research, Modipuram, India, 96 pp.