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Optimal extraction of groundwater for irrigation: synergies from surface water bodies in tropical India

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Abstract

The synergistic effects of canals and tanks in groundwater recharge that contribute to an economically sustainable path of groundwater extraction are examined. Thirty farmers each with groundwater wells located in canal command (GWCI), in tank command (GWTI) and in solely well-irrigated areas (devoid of surface water bodies) (GWSI) are studied in Tumkur district of Karnataka.

Applying Pontryagin's maximum principle to find the economically sustainable path of groundwater extraction, results indicated that by following the optimal path, the life of groundwater wells will increase by an additional 8, 17 and 24 years, respectively in GWSI, GWTI and GWCI areas over myopic (or uncontrolled) extraction. The additional net present value of benefit realized is US$822, US$1,907 and US$3,636 by optimal extraction in the three well areas. GWCI farmers realized the highest net returns (US$255) per hectare of gross groundwater irrigated area followed by GWTI (US$227.5) and GWSI (US$162.5). In GWTI (GWCI) amortized cost per cubic metre of groundwater was lower by 33% (53%) compared with GWSI, which reflects positive externality owing to the synergistic role of canals and tanks in groundwater recharge.

Keywords: Economic access; Groundwater; Maximum principle; Sustainability; Synergy

1. Introduction

In India's agriculture, ever since the green revolution, groundwater has been a *sine quo non* in its contribution to agricultural growth and development. Karnataka state is no exception to this phenomenon, where groundwater is continuing to be explored and utilized for agriculture and allied activities. Apparent features in respect of groundwater are the receding groundwater levels, increasing depth of bore wells and gradual failure of open wells in different parts of Karnataka. These are indicators of economic scarcity as the real cost of extraction is increasing over time. According to hydrogeologists however, only 33% of groundwater is being extracted and utilized in Karnataka, the same percentage as in India as a whole, which *prima facie* belies the idea of physical scarcity. Thus, groundwater resource economists are faced with the challenge of testing the veracity of physical scarcity leading to economic scarcity. It should be noted that groundwater endowments are extremely site specific and hence attempted generalizations using inductive or deductive methods prove to be utopian. Thus, it is difficult to reach a conclusion regarding groundwater availability for one farmer, when considering the neighboring farmer/s whose irrigation well/s are successful. Similarly it is difficult to come to a conclusion on groundwater scarcity for one farmer considering his/her neighbor's well failure. The predicament is thus exacerbated in hard rock areas fraught with low recharge and secular overdraft of groundwater.

2. Groundwater endowment

Groundwater endowment is a function of recharge, degree of weathering, effective demand for groundwater produce and the resulting extraction. Hence, static and dynamic (flowing) surface water bodies play a vital role in determining the supply of groundwater. Karnataka state has the largest number of 34,249 static water bodies commonly referred to as irrigation tanks. Among these, there are 3,036 irrigation tanks with a command area of more than 40 hectares per tank and 31,213 irrigation tanks with a command area up to 40 hectares per tank. The estimated groundwater recharge from irrigation tanks varies between 15 and 21%.[1] However, owing to a declining number of rainy days, lack of desiltation efforts, encroachments and emergence of irrigation wells, the importance of surface water bodies has diminished. However, groundwater supply is dependent on the degree of recharge, which in turn depends on the quantum of rainfall received and the recharge efforts.

Optimal extraction of groundwater is crucial for groundwater resources, for society and posterity. Here optimal extraction of groundwater implies extraction of a specific volume of groundwater from an irrigation well from the specific level of depth that maximizes the net present value of benefits given the rainfall, recharge, aquifer area, storativity and scarcity rent caused by negative externality from groundwater extraction. As groundwater irrigation wells are mushrooming in places/areas where groundwater irrigation is apparent, the degree of initial/premature failure is increasing. For marginal and small farmers this is an equity issue since premature well failure imposes huge transaction costs on them.

3. Property rights to groundwater

Groundwater utilization is just one aspect of the general problem of common property resource. The right to percolating water is normally obtained by "capture" as farmers have an incentive to withdraw water at a rate greater than would otherwise be rational for the fear that the withdrawals of others will lower water levels in their own well. As each one has property rights that are valid in the future, individuals are not encouraged to maximize the present value of total extractions over time. Groundwater in India is a responsibility of the state. However, recognizing the need for regulation of this precious resource, the Government of India prepared a model groundwater regulation and control bill during 1970 and circulated it to all the states for adoption. Government of Karnataka prepared The

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[1] According to the lastest Minor Irrigation census (2000), in Karnataka, more than 90% of wells are located outside the command area of irrigation tanks. However, there are no estimates of groundwater abstraction from these wells.

Karnataka Groundwater (Regulation and Control) Bill, 1996.[2] According to this bill, no person shall sink a well or install devices to extract groundwater for any purpose either on a personal or community basis without obtaining the requisite "permit" from the groundwater authority. While considering the application for the permit, the authority considers (a) the purpose for which the water is to be used, (b) the existence of other competitive users, (c) availability of water and the need to conserve it and (d) any other factors relevant thereto. In the bill, it was proposed that all the existing users of groundwater should be registered. It was also proposed that the distance between two successful bore wells as well as between a bore well and a successful dug-cum bore well[3] should be maintained at 250 m and the distance between two dug wells should be 182 m. In surface irrigation command areas the distance between two dug wells is limited to 120 m. The Government of Karnataka has not yet implemented the groundwater regulation.

4. Optimal control model

Economists have recognized that failure to maximize income over time causes a serious misallocation of resources and have suggested approaches to optimal extraction and use of groundwater. The early studies by Feinerman & Knapp (1983) examined groundwater management using dynamic optimisation models. In optimal control theory, the dynamic allocation problem is that of finding the optimal extraction of groundwater over time that will maximize the net present value of benefits from groundwater extraction in consonance with the rainfall, recharge, aquifer area, storativity and scarcity rent. Here, in arriving at an optimal path for groundwater extraction, marginal returns are equated to marginal cost of extraction plus the scarcity rent or user cost of groundwater. Thus, externality cost is considered as scarcity rent. Changes in the stock of groundwater over time are thus a function of volume of groundwater extraction (control variable) and groundwater resource stock (state variable) in each period.

5. Myopic extraction of groundwater

In the case of a "no control" or "competitive" situation, the marginal returns are equated to the marginal cost of extraction alone, in determining the path of extraction, ignoring externality cost. This is often referred as myopic extraction, since externality cost is ignored. Thus, the myopia of ignoring scarcity rent or user cost of groundwater in the competitive regime leads to overexploitation of the resource in early periods, thus increasing the extraction cost for future resource users, which leads to intergenerational inequity in availability of the groundwater resource.

6. Objectives

According to the Department of Mines and Geology (Shyamasundar, 1996), Government of Karnataka, if the proportion of groundwater extracted from the groundwater recharge is above 85%, the area is categorised as "dark"; between 65 and 85% it is categorised as "grey" and below 65% it is

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[2] http://www.nlsenlaw.org/water/law/waterbill/document_view.

[3] A dug-cum-borewell is a borewell drilled inside a dug well.

"white" area. In the central dry agroclimatic zone of Karnataka, India (Fig. 1), Tiptur and Turuvekere taluks are characterized as "dark" implying that groundwater extraction is more than 85% of recharge. Groundwater extraction is subjected to tremendous pressure owing to overexploitation and inadequate recharge, thus jeopardizing present and future water supplies for agriculture and other uses. Overexploitation here connotes that groundwater extraction is more than 85% of the recharge. Accordingly there is a dire need for improved integration of both surface water and groundwater resources to improve supply reliability, quality and quantity in order to promote sustainable irrigation farming systems. The objective of this paper is to analyse the synergistic effects of canals and tanks in groundwater recharge and to estimate the optimal path of groundwater extraction by considering the factors governing the supply of groundwater for the benefit of farmers. For this purpose, three groups of farmers were interviewed depending on the degree of recharge their land received from surface water bodies. The sample size consisted of (i) 30 farmers with wells with no recharge from surface water bodies (GWSI) (in Rangapura), (ii) 30 farmers with irrigation wells under the command of an irrigation tank (GWTI) (in Dharmegowdara Palya) and (iii) 30 farmers with irrigation wells under the command of

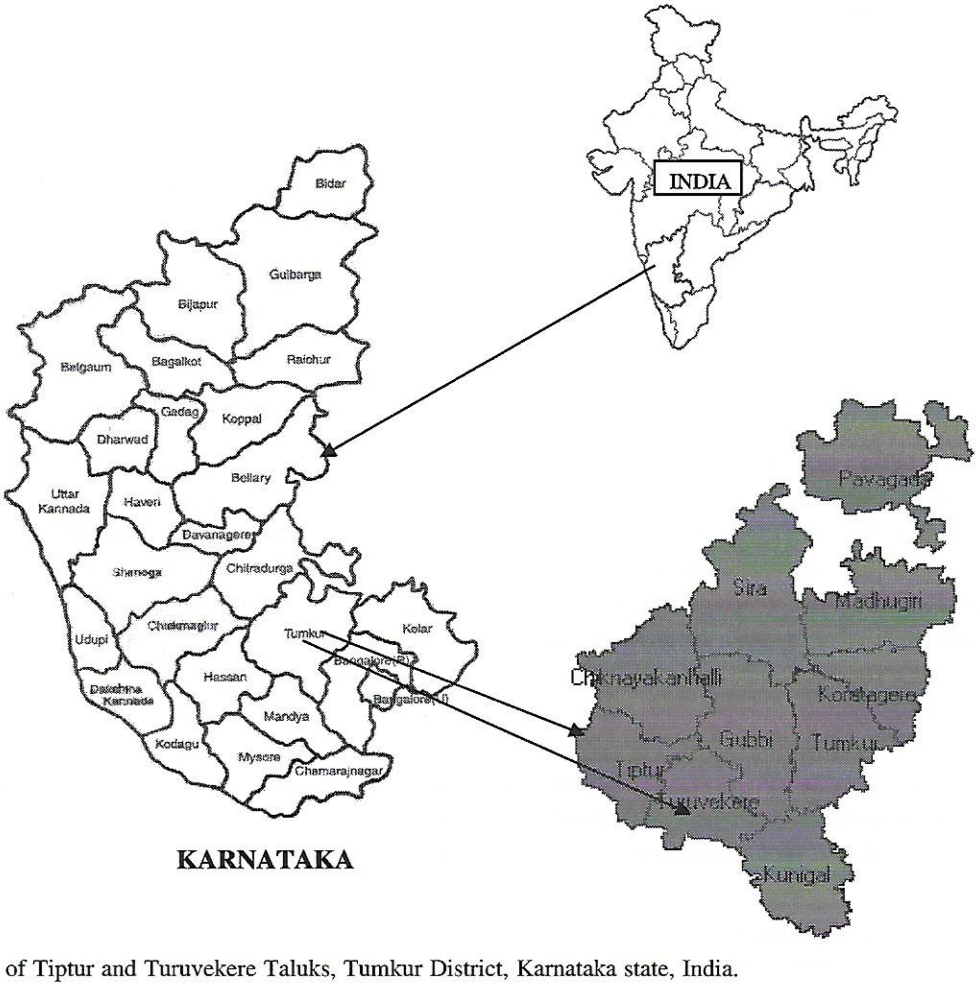

Fig. 1. Map of Tiptur and Turuvekere Taluks, Tumkur District, Karnataka state, India.

irrigation canals (GWCI) (in Dandinashivara and Ammasandra). Table 1 indicates the socio-economic conditions of the sample farms.

In the Rangapura village, there are no surface water bodies to facilitate recharge of groundwater in the irrigation wells. In The Dharmegowdara Palya village, the irrigation tank is the surface water body facilitating recharge of groundwater in the irrigation wells. In Dandinashivara and Ammasandra villages, irrigation canals facilitate the recharge of groundwater in the irrigation wells. This explains the selection of sample villages.

7. Empirical model

The objective is to maximize the present value of net social benefits from groundwater over time, given the stock of groundwater. Here, the state variable is the "stock of groundwater" in each period. The control variable is the volume of groundwater extracted in each period. Farmers with groundwater irrigation wells will benefit from the knowledge of the optimal path of groundwater extraction from their irrigation well over the expected average number of years of the life of the well, given the stock of groundwater. The empirical model used here is discussed in the light of optimization of time (dynamic optimization). The path of extraction prescribed by the optimal control model is compared with the myopic extraction of groundwater to estimate the differences in groundwater extraction between the two situations.

The objective function is given by:

$$\text{Max}\, NB = \sum_{t=0}^{n} \rho^t (TR - TC) \tag{1}$$

Subject to:

$$h_{t+1} - h_t = \{(1 - \theta)w_t - R\}/\{As\} \tag{2}$$

Here NB is the net benefit, TR is the total revenue (US\$ per well), TC is the total cost (US\$/m^3, per metre of lift) and ρ is the discount factor $\{1/(1 + r)\}$.

The volume of groundwater extracted for agriculture in time t is denoted as w_t. The height from which groundwater is pumped from the irrigation well in each time interval t is h_t. The net recharge to the aquifer from all sources except ground water return flows is given by "R". Here "θ" is the fraction of

Table 1. Socio economic conditions of the sample farms.

Particulars	GWSI (Rangapura)	GWTI (Dharmegowdarapalya)	GWCI (Ammasandra and Dandinashivara)
Average family size	6	4	5
Livestock population per farm (numbers)	5	3	3
Average size of land holdings (ha)	2.3	2.01	2.06
Modal number of wells per farm	2	1	1
Average annual net returns from agriculture (US$)	531	554	846
Average annual income from subsidiary occupation (US$)	250	135	183

groundwater irrigation returning to the aquifer. The value of θ lies between 0 and 1, implying that the fraction of groundwater applied which goes back as return flow varies between zero and one hundred percent. A is the average area of aquifer per irrigation well, taken as the total landholdings of sample farmers divided by the number of functioning wells. "s" is the specific yield (called the storativity), the proportion of groundwater held in one cubic unit of earth mass. Usually the value of "s" is around 2–3% for hard rock aquifers.

The variables used in the model are defined below.

7.1. Total revenue

The "total revenue" per well ($TR = aw_t - bw_t^2$) is defined as the annual gross returns from all crops cultivated using groundwater on the farm less all the costs of cultivation except the cost of groundwater. Here 'a' is the regression coefficient attached to w_t and 'b' *is the regression coefficient attached to* w_t^2. Thus, the total revenue as defined gives the gross return on groundwater used on the farm. This quadratic total revenue function with groundwater (w_t) and the square of the groundwater used (w_t^2) facilitates the estimation of optimal path of groundwater extraction. The total revenue per well thus depends on crops grown by the farmer, all variable costs incurred in the process and the volume of groundwater used.

7.2 Total cost

The total cost is the cost of electricity used in extracting groundwater and the cost of negative externality caused by over extraction of groundwater given by $K \times h_t \times w_t$.

Here $K = k_1 + k_2$, where k_1 is the electricity cost to lift 1 m^3 of groundwater by 1 m and k_2 is the cost of negative externality incurred per cubic metre of groundwater per metre of lift.

The cost k_1 is estimated as follows. By installing an electric meter to the groundwater well, it was estimated (by Sathisha, 1997) 42 KW h (kilowatt hours) are required to lift 102.66 m^3 (equivalent to one acre-inch of groundwater) from a depth of 25 m. Thus, the electrical power required to lift 1 m^3 of groundwater by 1 m lift is 0.0164 KW h. As mentioned above, the electricity cost to pump groundwater was estimated by installing an electric meter to a groundwater well. It was very difficult to get such data from a sizeable number of farmers, since farmers seldom cooperated in installing an electrical meter for fear of being charged. Hence a uniform pumping lift was used to obtain an estimate of the electricity cost of pumping.

In this study the optimal extraction of groundwater is compared across three situations with different degrees of recharge and other parameters.

k_1 is calculated at a cost of US$0.011 per KW h. Farmers using groundwater for irrigation have to invest in irrigation wells and also have to pay for electricity to pump groundwater for irrigation. On the other hand, farmers using surface water for irrigation do not incur any fixed cost and often they also do not pay the requisite water charges to the Revenue Department. Considering the anomalies in water charges, the norm of US$0.011 per KW h recommended by the National Council of Power Utilities, Government of India, was used for the cost of pumping.

k_2 is the negative externality suffered by farmer/s caused by overextraction of groundwater estimated as follows:

Negative externality cost per cubic metre of groundwater per metre of lift = (ACAW−ACFW)/TWU × (1/initial pumping lift)

Here, ACAW is the amortized cost of all irrigation wells constructed/drilled by farmers, ACFW is the amortized cost of functioning wells on the farm and TWU is the total groundwater extracted per year from functioning wells on the farm. Functioning well refers to the irrigation well, which was yielding groundwater at the time of the field data collection. Non-functioning well refers to the irrigation well, which is not yielding groundwater at the time of field data collection.

7.3. Recharge(R)

The groundwater recharge R is estimated as:

$$R = R_c \times A \times R_f$$

Here, R_c is the recharge coefficient ($0 < R_c < 1$), A is the average area of groundwater basin per irrigation well (in hectares) and R_f is the average annual rainfall (mm).

7.4. Pumping lift

Pumping lift is the vertical distance from the earth surface to the depth at which submersible pump is placed in the bore well. This is the average depth of pump placement from the earth surface.

The Hamiltonian for the above problem in Equations (1) and (2) is given by: $H = e^{-rt}\ (aw_t - bw_t^2 - Kh_tw_t) + \lambda\{(1-\theta)w_t - R\}/(As)$, treating time t as continuous variable.

Here, λ is the marginal user cost, implying reduction in the discounted future net benefit due to extraction of an additional unit volume of groundwater in the present period.

According to Pontryagin's maximum principle (Conrad & Clark, 1989), the necessary conditions to arrive at optimal path of extraction that maximize the net benefit from groundwater extraction are:

$$\delta H/\delta W = 0 \qquad \text{Condition (1)}$$

implies:

$$e^{-rt}(a - 2bw_t - Kh_t) + \lambda\{(1-\theta)/(As)\} = 0$$

or:

$$e^{-rt}(a - 2bw_t) = e^{-rt}Kh_t + \lambda\{(\theta - 1)/(As)\}$$

$$-\delta H/\delta h = \lambda_{t+1} - \lambda \qquad \text{Condition (2)}$$

implies:

$$\lambda_{t+1} - \lambda_t = e^{-rt}Kw_t$$

$$\delta H/\delta\lambda = h_{t+1} - h_tI \qquad \text{Condition (3)}$$

implies:

$$h_{t+1} - h_t = \{(1-\theta)w_t - R\}/\{As\}$$

8. Estimation of net benefit under myopic situation (no control)

Farmers usually do not internalize the negative externality imposed in the process of overextraction of groundwater. Thus, their extraction becomes myopic and they maximize their net benefit per annum subject to the availability of groundwater and other constraints. The resulting groundwater balance is the initial groundwater available for the next year. The recharge and return flows in the current year are added to the initial groundwater balance to estimate the total groundwater available in the current year. The annual net benefits were discounted and summed to estimate the present value of net benefits over the entire period.

8.1. Myopic rule

Marginal benefit = Marginal cost

$$a - 2bw_t = kh_t$$

or

$$w_t = B_0 - B_1 h_t$$

where

$$B_0 = a/2b$$

$$B_1 = k/2b$$

The economic and hydrological parameters used in the estimation of optimal path of groundwater extraction in three irrigation situations are given in Table 2. Here, *ceterus paribus*, it is assumed that the maximum depth the irrigation well can reach is 156 m, and that the negative externality cost would increase by 2.5% in GWCI, 7.5% in GWTI and 15% in GWSI according to the differential water recharge potentials. The optimal path of groundwater extraction is sensitive to these parameters and variables.

The field survey data were computerized using Microsoft-Excel. The optimal control model was implemented using the "solver option" available with Microsoft-Excel.

9. Results

The economic performance using groundwater as natural resource is reflected by the net returns realized per US dollar of groundwater extracted and used for irrigation. The cost per cubic metre of groundwater is estimated as the amortized cost of all irrigation wells on the farm (including functioning and non-functioning wells) considering the average age of all wells at a discount rate of 2%. The net

Table 2. Economic and hydrological parameters of optimal control model under three irrigation regimes.

Sl no.	Constants and variables	GWSI (sole well)	GWTI (wells under the tank command)	GWCI (wells under the canal command)
1	Aquifer area per functioning well (ha)	2.14	2.036	2.06
2	Initial pumping lift (m)	79	44	36
3	Storativity coefficient	0.025	0.025	0.025
4	Groundwater recharge (% rainfall)	5.0	7.5	10.00
5	Groundwater recharge (m^3)	806	1,158	1,431
6	Groundwater return flow coefficient (θ)	0.05	0.08	0.10
7	K_1 = Cost of electrical power (US\$/m^3, per metre of lift)	0.000 18	0.000 18	0.000 18
8	K_2 = Annual externality cost (US\$/m^3, per metre of lift)	0.000 77	0.000 219	0.000 118
9	Annual externality cost assumed to increase at the rate of (%)	15.00	7.50	2.50
10	Estimated regression coefficient of ground water extraction in quadratic function	549	460	543
11	Estimated regression coefficient of the square of groundwater extraction in quadratic function	−2.09	−1.54	−1.7
12	Discount rate chosen	0.02	0.02	0.02
13	Discount factor = 1/(1 + 0.02)	0.980	0.980	0.980
14	Annual rainfall (mm)	743.75	743.75	681.25

return per US dollar of groundwater extracted is the net return divided by the cost of groundwater as estimated (in Table 3). It is hypothesized that farmers who a have higher endowment of groundwater realize higher net returns per US dollar of groundwater.

The net return per cubic metre of groundwater reflects the farmer's management capacity in relation to physical availability of groundwater. The net return per US dollar of groundwater is an indicator of the management acumen of the farmer in relation to the Ricardian rent of groundwater. *Ceteris paribus*, if groundwater is scarce and farmers face significant externality, the cost of groundwater will be higher and net returns in relation to groundwater cost may be smaller and vice versa.

In order to compare the performance of sole well irrigation farmers and farmers using tank water with farmers using canal irrigation, the relative sustainability index is worked out as = (net returns per dollar (US$) of groundwater realized by a farmer)/(net returns per dollar (US$) of groundwater realized by a farmer in the high water user group in canal command).

The relative sustainability index is defined as the net returns per dollar (US$) of groundwater realized by a farmer in relation to the net returns per dollar (US$) of groundwater realized by a farmer in the high water user group in canal command.

Farmers with a sustainability index closer to zero have to cope with the predicament of low groundwater supply. Farmers who have irrigation wells without any recharge effect from irrigation tanks or irrigation canals, have low sustainability and need to be prudent in extracting and using groundwater compared with farmers whose groundwater is recharged by irrigation tanks/canals.

Table 3. Net returns/US$ of groundwater realized by farmers in different groundwater recharge situations in the central dry zone of Karnataka, India.

	Low water users ($< 4,080\,m^3/ha$)		Medium water users ($4,080–5,355\,m^3/ha$)		High water users ($>5,355\,m^3/ha$)	
Recharge situations	Net returns/US$ of groundwater	Relative sustainability index	Net returns/US$ of groundwater	Relative sustainability index	Net returns/US$ of groundwater	Relative sustainability index
GWSI	0.051	0.54	0.047	0.50	0.064	0.69
GWTI	0.076	0.80	0.059	0.63	0.073	0.78
GWCI	0.096	1.02	0.129	1.38	0.093	1.00

GWSI = groundwater using farmer with irrigation well/s with no recharge support from any surface water body. GWTI = groundwater using farmer with irrigation well/s with recharge support from irrigation tank. GWCI = groundwater using farmer with irrigation well/s with recharge support from irrigation canal. Relative sustainability index = (net returns/US$ of groundwater realized by a farmer)/(net returns/US$) of groundwater realized by a farmer in the high water user group in canal command). Relative sustainability index is defined as the net returns/US$ of groundwater realized by a farmer in relation to the net returns per dollar (US $) of groundwater realized by a farmer in the high water user group in canal command.

10. Myopic and optimal extraction of groundwater in GWSI

In myopic extraction, the volume of groundwater extracted in the initial year is 113% higher than optimal extraction. This exerts pressure on irrigation wells. In natural resource management, the initial years are crucial with reference to adoption of technology with conviction. Comparison of groundwater extracted between a myopic and an optimal regime is reflective of the externality in water extraction in the myopic over the control regime.

The net benefits realized by farmers in myopic extraction are not commensurate with the volume of groundwater extracted, as the discounted net benefit of myopic over optimal extraction is higher by a modest 30% even though water extraction is higher by 113% per well.

Extraction of groundwater beyond five years in myopic conditions results in economic scarcity owing to an increase in the cost of extraction of resource induced by increased pumping lift of the irrigation well (Tables 4 and 5).

11. Myopic and optimal extraction of groundwater in GWTI

The extraction of groundwater in GWTI using optimal extraction extends the modal life of well from six years (Table 6) to 23 years. In the initial period, optimal extraction was 4,998 m^3 (equivalent to grow 1 acre of paddy). The present value net benefits with optimal extraction are US$4,588 (Table 7). Thus, optimal extraction enhanced the well life by 17 years and the additional discounted net benefit by considering externality is US$1,907.

Extraction of groundwater becomes sustainable because of the extended life of irrigation wells, as a result of the enhanced recharge potential of the irrigation well provided by the presence of a surface water source, given the same pressure on groundwater extraction. Concern for wise use of groundwater, a fugitive resource, is crucial when the balance between demand for and supply of water in groundwater scarce areas is disturbed resulting in a decline of groundwater table. Efficiency is affected as

Table 4. Myopic extraction of groundwater, pumping lifts and discounted net benefits in GWSI.

Time (years)	w_t (m^3)	h_t (m)	PVNB (US$)
1	11,730	83	502
2	11,322	102	424
3	10,914	121	352
4	10,506	139	285
5	10,200	157	224
Total			1,784

Table 5. Optimal extraction of groundwater, pumping lift and discounted net benefits in GWSI.

Time (years)	w_t (m^3)	h_t (m)	PVNB (US$)
1	5,508	83	390
2	5,406	91	356
3	5,202	99	322
4	4,998	107	289
5	4,794	114	257
6	4,488	122	225
7	4,182	128	193
8	3,876	134	163
9	3,570	140	134
10	3,162	145	106
11	2,652	149	81
12	2,142	152	57
13	1,632	155	37
Total			2,610

w_t = ground water extracted; h_t = pumping lift; PVNB = present value of net benefits.

groundwater level drops, externality increases and surface water supplies are also limited, affecting recharge. Use of high power pumps to lift groundwater from deeper levels and neglect of traditional water sources like tanks in groundwater recharge have led to overexploitation of groundwater. Thus, optimal groundwater extraction is a vital strategy for water scarce areas to conserve groundwater and maximize net return per unit of groundwater as well as per hectare of irrigated area.

12. Myopic and optimal extraction of groundwater in GWCI

If farmer adopts myopic extraction, the life of irrigation wells becomes six years. In the initial period the farmer realizes a net benefit of US$844 by extracting 15,300 m^3 of water per well. Gradually the water level draw down and extraction beyond six years increases the cost induced by increased pumping lifts. Compared to a sole well regime, canal command farmers have additional access to groundwater to the tune of 34% and are realizing 68% additional present value of net benefits (PVNB). The total PVNB for the period of 6 years is US$3,889 (Table 8).

Optimal extraction extends the life of irrigation. In the initial period the optimal extraction recommends that 5,508 m^3 be extracted when compared with 15,300 m^3 under myopic extraction. Thus, optimal extraction conserves groundwater by reducing extraction to the tune of 177%.

Table 6. Myopic extraction of groundwater, pumping lifts and present value net benefits in GWTI.

Time (years)	w_t (m^3)	h_t (m)	PVNB (US$)
1	13,974	46	620
2	13,362	69	540
3	12,648	91	469
4	12,138	113	405
5	11,526	133	348
6	11,016	152	298
Total			2,681

Table 7. Optimal extraction of groundwater, pumping lifts and discounted net benefits in GWTI.

Time (years)	w_t (m^3)	h_t (m)	PVNB (US$)
1	4,998	46	371
2	4,896	53	350
3	4,794	59	329
4	4,692	66	310
5	4,590	72	292
6	4,488	78	274
7	4,386	84	258
8	4,182	90	242
9	4,080	95	227
10	3,978	101	212
11	3,876	106	199
12	3,774	111	186
13	3,672	115	173
14	3,570	120	162
15	3,366	124	150
16	3,264	128	140
17	3,162	132	129
18	3,060	135	119
19	2,856	138	110
20	2,754	141	101
21	2,652	144	93
22	2,448	147	84
23	2,346	149	77
Total			4,588

w_t = ground water extracted; h_t = pumping lift; PVNB = present value of net benefits.

Initially the extraction is lower and hence the PVNB also gains substantially owing to increased well life. Thus, farmers realize additional net benefits of US$3,636 (Table 9).

A major hypothesis underlined in the extraction of groundwater from the irrigation well in the three regimes is, in future, that there is no cumulative interference effect on the irrigation well in question.

In myopic extraction farmers invest in new well after six years or deepen the existing well as groundwater is overexploited, to remain on the original iso-revenue curve. Farmers cannot be expected to shift from farming, as they have no alternative. Rather than investment in new wells, strategies for saving water have to be encouraged and such strategies for saving water should not reduce income and employment. Thus, the optimal extraction extends well life by 24 years, giving farmers the potential to gain and realize additional net benefits of US$3,636 over myopic extraction.

13. Synergies and externalities in groundwater irrigation influenced by surface water bodies in the central dry zone, Karnataka, India

Owing to synergistic effect of recharge of groundwater from surface water bodies in GWTI and GWCI, the irrigation wells in GWTI (GWCI) yielded 39% (65%) higher groundwater compared with the wells without any recharge support from water bodies (Table 10). Correspondingly the cost per cubic metre of groundwater in GWTI (GWCI) was lower by 33% (53%) when compared with GWSI. Investment per successful well in GWTI (GWCI) was 27% (19%) lower compared with GWSI. Net return per hectare of gross irrigated area in GWTI (GWCI) was 41% (57%) higher than GWSI, while net return per cubic metre of water were 16% (17%) higher than GWSI. The economic access to groundwater in GWTI (GWCI) was 50% (118%) higher than GWSI. The net returns per US dollar of groundwater in GWTI (GWCI) was 75% (156%) higher when compared with GWSI.

14. Significance

The economics of groundwater extraction is handled independently for tank command, canal command and rain-fed lands. This study is comprehensive, considering all the three areas together for relative comparison in drawing policy implications.

15. Policy implications

1. As discounted net returns and well life improve in optimal extraction compared with myopic extraction, withdrawal of groundwater based on optimal control results in sustainable extraction.
2. Rainwater harvesting for recharging groundwater in non-tank or canal command reduces the groundwater extraction cost. Hence efforts should be made in this direction.
3. Farmers need to be motivated to invest in backstop technologies like drip irrigation rather than investing in new wells which is increasingly becoming a new venture.
4. Since installation of electrical meters on irrigation pump sets (IP sets) is meeting resistance from farmers, a water meter can be fixed initially to educate farmer regarding the volume of extraction of

Table 8. Myopic extraction of groundwater, pumping lifts and discounted net benefits in GWCI.

Time (years)	Wt (m^3)	Ht (m)	PVNB (US $)
1	15,300	38	844
2	14,688	63	755
3	14,178	86	674
4	13,566	108	602
5	13,056	129	536
6	12,546	150	477
Total			3,889

Table 9. Optimal extraction of groundwater, pumping lifts and discounted net benefits in GWCI.

Time (years)	W_t (m^3)	H_t (m)	PVNB (US$)
1	5,508	38	501
2	5,406	45	475
3	5,304	52	450
4	5,202	58	427
5	4,998	65	404
6	4,896	71	383
7	4,794	77	363
8	4,692	82	344
9	4,590	88	326
10	4,386	93	309
11	4,284	98	292
12	4,182	103	277
13	4,080	108	262
14	3,978	112	247
15	3,876	117	234
16	3,774	120	221
17	3,570	124	209
18	3,468	128	197
19	3,366	131	186
20	3,264	134	175
21	3,162	138	165
22	3,060	140	155
23	2,856	143	145
24	2,754	145	136
25	2,652	147	128
26	2,550	149	119
27	2,448	151	111
28	2,244	153	103
29	2,142	154	95
30	2,040	155	88
Total			7,525

groundwater on their farm. This helps in budgeting groundwater for different crops. Later, the farmer can be convinced to defray electrical charges.

16. Limitations of the study

The hydrological parameters such as storativity, recharge and return flow coefficients were not available for localized areas and thus the applications of the study had the corresponding limitations.

17. Advantages and applications of the study

1. The analysis in this paper helps in suggesting an estimation of the optimal path of groundwater extraction, which imperative in the context of groundwater over extraction.

Table 10. Externalities and synergies due to surface water bodies on groundwater irrigation in the central dry zone of Karnataka, India.

SL no.	Particulars	GWSI (sole well)	GWTI (wells in tank command)	GWCI (wells in canal command)
1	(a) Average yield of well (GPH)	1,692	2,360	2,794
	(b) Well Yield in relation to GWSI		+39%	+65%
2	(a) GIA per well (Ha)	2.72	2.04	3.2
	(b) GIA in relation to GWSI		−25%	+18%
3	Cropping pattern	Coconut, pulses, jowar, maize, ragi	Coconut, pulses, maize, paddy, vegetables, groundnut	Coconut, maize, paddy
4	(a) Amortized cost/m^3 of water (US$)	0.034	0.0225	0.015
	(b) Cost/m^3 in relation to GWSI		−33%	−53%
5	Modal number of wells per farm	2	1	1
6	Modal age of well (years)	9	14	16
7	(a) Investment per successful well (US$)	1,006	729	815
	(b) Investment in relation to GWSI		−27%	−19%
8	(a) Investment per well (US$)	779	694	770
	(b) Investment in relation to GWSI		−11%	−2%
9	(a) Net returns per hectare of GIA (US$)	162.5	227.5	255
	(b) Net returns in relation to GWSI		+41%	+57%
10	(a) Net returns/ m^3 of water (US$)	0.063	0.072	0.073
	(b) Net returns in relation to GWSI		+16%	+17%
11	(a) Economic access = m^{3}of water/US$ of amortized cost (m^3)	0.6528	0.9792	1.428
	(b) Economic access in relation to GWSI		+50%	+118%
12	(a) Net returns/US$ of groundwater	1.83	3.22	4.7
	(b) Net returns/US$ of groundwater in relation to GWSI		+75%	+156%

2. The suggested optimal path of groundwater extraction is of relevance in all three groundwater endowment areas of tank command, canal command and rain-fed land. Farmers can maximise their profits subject to the availability of groundwater on a sustainable basis.

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