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

ABSTRACT

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

Applying Pontryagin's maximum principle to find the economically sustainable path of groundwater extraction, results indicated that by following the optimal path, life of groundwater wells will increase by additional 8, 17 and 24 years respectively in GWSI, GWTI and GWCI areas over myopic (or uncontrolled) extraction. Additional net present value of benefit realized is US $ 822, US $ 1907 and US $ 3636 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 meter of groundwater was lower by 33 percent (53 percent) compared with GWSI which reflects positive externality due to synergistic role of canals and tanks in groundwater recharge.

Key words: Maximum principle, Synergy, Groundwater, economic access, sustainability.

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

B.S. Chaitra And M.G. Chandrakanth[1]

Preamble

For India's agriculture, ever since green revolution, groundwater has been *sine quo non* contributing 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. An apparent feature in respect of groundwater is the receding groundwater levels and increasing depth of bore wells and gradual failure of open wells in different parts of Karnataka. This is one indicator of economic scarcity as the real cost of extraction is increasing over time. According to hydro-geologists however, only 33 percent of groundwater is being extracted and utilized in Karnataka as well as in India, which *prima facie* belies physical scarcity. Thus, groundwater resource economists are faced with the challenge of testing the veracity of the physical scarcity leading to economic scarcity. It is in order to note that groundwater endowments are extremely site specific and hence, generalizations using inductive or deductive methods are utopian and lack generalization. Thus, it is difficult to conclude regarding groundwater availability for one farmer, considering the neighboring farmer/s whose irrigation well/s are successful. Similarly it is difficult to conclude 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.

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 supply of groundwater. Karnataka state has the largest number of 34249 static water bodies commonly referred to as irrigation tanks. Among these, there are 3036 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 percent.[2] However, due to declining number of rainy days, lack of desiltation efforts, encroachments and emergence of irrigation wells, the importance of surface water bodies is relegated. However, groundwater supply is

[1] Authors are respectively Senior Research Fellow, Department of Agricultural Economics, University of Agricultural Sciences, Bangalore-560 065, India
Professor, Department of Agricultural Economics, University of Agricultural Sciences, Bangalore 560 065, India

[2] As no official statistics are available regarding the number of irrigation wells located in the command area of irrigation tanks, there are no estimates of groundwater abstraction from these wells.

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 resource, for the society and posterity. Here optimal extraction of groundwater implies extracting 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 due to 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.

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 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 state subject and recognizing the need for regulation of this precious resource, the Government of India prepared the model groundwater regulation and control bill during 1970 and circulated to all the States. Government of Karnataka prepared THE KARNATAKA GROUNDWATER (REGULATION AND CONTROL) BILL, 1996[3], and has not yet been able to implement it. According to this Bill, no person shall sink a well or install devices to extract groundwater for any purpose either on personal or community basis without obtaining the requisite 'permit' from the Groundwater Authority. While considering the application for 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 is proposed to register all the existing users of groundwater. It is proposed to maintain distance between two successful Borewells and successful Dug-cum Borewell as 250 meters, between two dug wells as 182 meters. In surface irrigation command areas the distance between two dug wells is limited to 120 meters.

[3] www.ceeraindia.org

Optimal control Model

Economists have recognized that failure to maximize income over time causes a serious misallocation of resource and have suggested approaches to optimal extraction and use of groundwater. The early studies by Feinerman and Knapp (1983) and Allen and Gizzer (1984) examined groundwater management using dynamic optimisation models. In this regard optimal control theory, a dynamic allocation problem is one of the fundamental tools of analysis towards optimal extraction of groundwater over time that will maximize net present value of benefits from groundwater extraction in consonance with the rainfall, recharge, aquifer area, storativity and scarcity rent. Here, to arrive at optimal path of 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 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.

Myopic extraction of Groundwater

In the case of 'no control' or 'competitive' situation, the marginal returns are equated to 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 over exploitation of resource in early periods, thus increasing extraction cost for future resource users, which leads to intergenerational in-equity in availability of groundwater resource.

Objectives

According to the Department of Mines and Geology[4], Government of Karnataka, if the proportion of groundwater extracted out of groundwater recharge is above 85 percent, the area is categorised as 'dark'; between 65 and 85 percent categorised as 'grey' and below 65 percent is 'white' area. In the central dry agroclimatic zone of Karnataka, India (Figure 1), Tiptur and Turuvekere taluks are characterized as 'dark' implying that groundwater extraction is more than 85 percent of recharge. Groundwater extraction is subjected to tremendous pressure owing to over exploitation and inadequate recharge thus, jeopardizing the present and future water supplies for agriculture and other uses. Overexploitation here connotes that groundwater extraction is more than 85 percent 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 considering the factors governing the supply of groundwater for the benefit of farmers. For this purpose, three groups of farmers are interviewed depending on the degree of recharge from surface water bodies.

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[4] Quoted in M.S. Shyamasundar, Interplay of markets, externalities, institutions and equity in groundwater development – An economic study in the hard rock areas of Karnataka. Unpublished Ph.D thesis, Department of Agricultural Economics, University of Agricultural Sciences, Bangalore, 1996, Appendix 9, p. 198.

The sample size consisted of A. 30 farmers with wells with no recharge from surface water bodies (GWSI) (in Rangapura), B. 30 farmers with irrigation wells under the command of irrigation tank (GWTI) (in Dharmegowdara Palya) and C. 30 farmers with irrigation wells under the command of irrigation canals (GWCI) (in Dandinashivara and Ammasandra). The following table indicates socio economic conditions of the sample farms.

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 (Hectares)	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

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. Hence the selection of sample villages.

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 optimal path of groundwater extraction from their irrigation well over the expected average number of years of well life, 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

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

Subject to

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

Here,

NB= Net benefit

TR = Total revenue ($s per well)

TC = Total cost ($s per cubic meter per meter of lift)

ρ= Discount factor ={**1/(1+r)**}

The variables used in the model are defined below:

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. Thus, the total revenue as defined gives the gross return to groundwater used on the farm. A 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.

Total cost

The total cost is the cost of electricity used in extracting groundwater and the cost of negative externality due to over extraction of groundwater given by $K*ht*w_t$.
Here $K=k_1 + k_2$ where k_1 =electricity cost to lift one cubic meter of groundwater by one meter and k_2= cost of negative externality incurred per cubic meter of groundwater per meter of lift.

The cost k_1 is estimated as follows. By installing electric meter on groundwater well, it was estimated that[5] **42 Kwh (**Kilo watt hours) are required to lift 102.66 cubic meters (equivalent to one acre-inch of groundwater) from a depth of 25 meters. Thus, the electrical power required to lift one cubic meter of groundwater by one meter lift is 0.0164 Kwh. As mentioned above, the electricity cost to pump groundwater was estimated by installing electric meter on a groundwater well. It was very difficult to get such data from a sizeable number of farmers, since farmers seldom cooperated to install electrical meter, with the fear of being charged. Hence the 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 the cost of US $ 0. 011 per Kwh . Farmers using groundwater for irrigation have to invest on irrigation wells and also have to pay for electricity for

[5] Sathisha K.M. 1997, Resource Economics study of valuation of Well Interference Externalities in Central Dry zone of Karnataka, Unpublished thesis, Department of Agricultural Economics, UAS, Bangalore.

pumping groundwater for irrigation. On the other hand, farmers using surface water for irrigation do not incur any fixed cost and most often they do not pay the requisite water charges also to the Revenue Department. Considering the anomalies in water charges, it was considered to use the norm of US $ 0. 011 per Kwh recommended by the National Council of Power Utilities, Government of India, for cost of pumping.

k_2 is the negative externality suffered by farmer/s due to over extraction of groundwater estimated as follows**:**

Negative externality cost per cubic meter of groundwater per meter of lift
= (ACAW-ACFW)/TWU *(1/Initial pumping lift)

Here, ACAW -Amortized cost of all irrigation wells constructed/drilled by farmer
ACFW -Amortized cost of functioning wells on the farm
TWU - Total groundwater extracted per year from functioning wells on the farm.

Functioning well refers to the irrigation well, which is yielding groundwater at the time of field data collection. Non – functioning well refers to irrigation well, which is not yielding groundwater at the time of field data collection.

Recharge(R)

The groundwater recharge is estimated as: $R = R_c*A*R_f$,

Here, R_c is the Recharge coefficient ($0 < R_c < 1$)
A is the Average Area of groundwater basin per irrigation well (in hectare)
R_f is the Average annual rainfall (millimetres)

Pumping lift

Pumping lift is the vertical distance from 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 volume of groundwater extracted for agriculture in time ‘t’ is denoted as ‘w_t’. Height from which groundwater is pumped from irrigation well in each time 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 groundwater irrigation returning to 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 is) the proportion of groundwater held in one cubic unit of earth mass. Usually the value of ‘s’ is around two to three percent for hard rock aquifers.

The Hamiltonian for the above problem (Equation 1 and 2) is given by

$\mathbf{H = e^{-rt} (aw_t - bw_t^2 - Kh_t w_t) + \lambda\{(1-\theta)\, wt - R\}/(As)}$, 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 and Clark, 1989), the necessary conditions to arrive at optimal path of extraction that maximize the net benefit from groundwater extraction are:

Condition (1) $\boldsymbol{\delta H/\delta W=0}$ implies $\boldsymbol{e^{-rt}(a-2bw_t - Kh_t)+\lambda\{(1-\theta)/(As)\}=0,}$
or

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

Condition (2) $\boldsymbol{-\delta H/\delta h = \lambda_{t+1} - \lambda_t}$ implies $\boldsymbol{\lambda_{t+1} - \lambda_t = e^{-rt} Kw_t}$

Condition (3) $\boldsymbol{\delta H/\delta \lambda = h_{t+1} - h_t}$ implies $\boldsymbol{h_{t+1} - h_t =\{(1-\theta)\, wt - R\}/\{As\}}$

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 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.

Myopic rule: Marginal benefit =Marginal cost,

$$a-2bw_t = kh_t$$
$$\text{or } w_t=B_0-B_1 h_t$$

$$\text{where } B_0= a/2b$$
$$B_1=k/2b$$

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 156 meters, It is assumed that the negative externality cost would increase by 2.5 percent in GWCI, 7.5 percent in GWTI and 15 percent 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.

Results

The economic performance of using groundwater as natural resource is reflected by the net returns realized per US $ of groundwater extracted and used for irrigation. The cost per cubic meter 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 the discount rate of 2 percent. The net return per US $ of groundwater extracted is the net return divided by the cost of groundwater as estimated above (Table 3). It is hypothesized that, farmers who have higher endowment of groundwater realize higher net returns per US $ of groundwater.

The net return per cubic meter of groundwater reflects farmer's management capacity in relation to physical availability of groundwater. The net return per US $ 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, 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).

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 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.

Myopic and Optimal extraction of groundwater in GWSI

In myopic extraction, volume of groundwater extracted in the initial year is 113 percent 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 myopic and optimal regime is reflective of the externality in water extraction in the myopic over control regime.

Net benefits realized by farmers in myopic extraction arenot commensurate with the volume of groundwater extracted as the discounted net benefits in myopic over optimal extraction is higher by a modest 30 percent even though water extraction is higher by 113 percent per well.

Extraction of groundwater beyond five years in myopic condition results in economic scarcity due to increase in the cost of extraction of resource induced by increased pumping lift of the irrigation well. (Table 4 and table 5)

Myopic and Optimal extraction of groundwater in GWTI

The extraction of groundwater in GWTI according to optimal extraction extends the modal life of well from six years to 23 years. In the initial period, optimal extraction was 4998 cubic meters (equivalent to grow one acre of paddy). The present value net benefits with optimal extraction are US $ 4588. (Table 7) Thus, optimal extraction enhanced the well life by 17 years and the additional discounted net benefits by considering externality is US $ 1907.

Extraction of groundwater becomes sustainable due to extended life of irrigation wells as a result of enhanced recharge potential of irrigation well due to presence of surface water source, given the same pressure on groundwater extraction. Concern for wise use of groundwater, a fugitive resource is crucial, when balance between demand and supply of water in groundwater scarce areas is disturbed resulting in decline of groundwater table. Efficiency is affected as 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, negligence of traditional water source like tanks in groundwater recharge have led to over exploitation 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.

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 farmer realizes net benefit of US $ 844 by extracting 15300 cubic meters 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 sole well regime, canal command farmers, have additional access to groundwater to the tune of 34 percent and are realizing 68 percent additional PVNB. The total PVNB for the period of 6 years is US $ 3889. (Table 8)

Optimal extraction extends the life of irrigation. In the initial period the optimal extraction recommends 5508 cubic meters to be extracted when compared with 15300 cubic meters under myopic extraction. Thus, optimal extraction conserves groundwater by reducing extraction to the tune of 177 percent. Initially the extraction is lower and hence the PVNB too and gains substantially due to increased well life. Thus, farmers realize additional net benefits of US $ 3636. (Table 9)

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

In myopic extraction farmers invest on 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 on new wells, strategies for saving water have to be encouraged and such strategies of saving water should not reduce income and employment. Thus, the optimal extraction extends well life by 24 years from which farmers have potential to gain and realize additional net benefits of US $ 3636 over myopic extraction.

Synergies and externalities in groundwater irrigation influenced by surface water bodies in Central Dry Zone,Karnataka,India

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

Significance

Economics of groundwater extraction is handled independently for tank command, canal command and rainfed lands. This study is comprehensive considering all the three areas together for relative comparison for drawing policy implications.

Policy implications

1. As discounted net returns and well life are improving in the 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 be made in this direction.
3. Farmers need to be motivated to invest on backstop technologies like drip irrigation rather than investing on new wells which is increasingly becoming a new venture.
4. Since installation of electrical meter on IP sets is inviting resistance from farmer, water meter can be fixed initially to educate farmer regarding the volume of extraction of groundwater on their farm. This helps in budgeting groundwater for different crops. Later, farmer can be convinced to defray electrical charges.

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 has the corresponding limitations.

Advantages and applications of the study

1. The analysis in this paper helps in suggesting the estimation of optimal path of groundwater extraction, which is the need of hour in the context of groundwater over extraction.
2. The suggested optimal path of groundwater extraction is of relevance in all the three groundwater endowment areas of tank command, canal command and rainfed land. Farmers can maximise their profits subject to the availability of groundwater on sustainable basis.

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 (hectares)	2.14	2.036	2.06
2.	Initial pumping lift (meters)	79	44	36
3.	Storativity coefficient	0.025	0.025	0.025
4.	Groundwater recharge (percent of rainfall)	5.0	7.5	10.00
5.	Groundwater recharge (cubic meters)	806	1158	1431
6.	Groundwater return flow coefficient (Theta)	0.05	0.08	0.10
7.	K1 = Cost of electrical power (US $ per cubic meter, per meter of lift)	0.00018	0.00018	0.00018
8.	K2 = Annual externality cost (US $ per cubic meter per meter of lift)	0.00077	0.000219	0.000118
9.	Annual externality cost assumed to increase at the rate of (percent)	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 (milli meters)	743.75	743.75	681.25

Table 3: Net Returns per US $ of groundwater realized by farmers in different groundwater recharge situations in Central Dry Zone of Karnataka, India.

Recharge situations	Low water users (< 4080 m^3 / ha)		Medium water users (4080-5355 m^3 / ha)		High water users (>5355 m^3 / ha)	
	Net returns per dollar (US $) of groundwater	Relative Sustainability index	Net returns per dollar (US $) of groundwater	Relative Sustainability index	Net returns per dollar (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

Notes:
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 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).
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.

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

TIME (YEARS)	WT (CUBIC METERS)	HT (METERS)	PVNB (US $)
1	11730	83	502
2	11322	102	424
3	10914	121	352
4	10506	139	285
5	10200	157	224
Total			1784

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

TIME (YEARS)	WT (CUBIC METERS)	HT (METERS)	PVNB (US $)
1	5508	83	390
2	5406	91	356
3	5202	99	322
4	4998	107	289
5	4794	114	257
6	4488	122	225
7	4182	128	193
8	3876	134	163
9	3570	140	134
10	3162	145	106
11	2652	149	81
12	2142	152	57
13	1632	155	37
Total			2610

NOTE: WT = Ground water extracted
HT = Pumping lift
PVNB = Present value of net benefits

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

TIME (YEARS)	WT (CUBIC METERS)	HT (METERS)	PVNB (US $)
1	13974	46	620
2	13362	69	540
3	12648	91	469
4	12138	113	405
5	11526	133	348
6	11016	152	298
Total			2681

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

TIME (YEARS)	WT (CUBIC METERS)	HT (METER)	PVNB (US $)
1	4998	46	371
2	4896	53	350
3	4794	59	329
4	4692	66	310
5	4590	72	292
6	4488	78	274
7	4386	84	258
8	4182	90	242
9	4080	95	227
10	3978	101	212
11	3876	106	199
12	3774	111	186
13	3672	115	173
14	3570	120	162
15	3366	124	150
16	3264	128	140
17	3162	132	129
18	3060	135	119
19	2856	138	110
20	2754	141	101
21	2652	144	93
22	2448	147	84
23	2346	149	77
Total			4588

NOTE: WT = Ground water extracted
HT = Pumping lift
PVNB = Present value of net benefits

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

TIME (YEARS)	WT (CUBIC METERS)	HT (METERS)	PVNB (US $)
1	15300	38	844
2	14688	63	755
3	14178	86	674
4	13566	108	602
5	13056	129	536
6	12546	150	477
Total			3889

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

TIME (YEARS)	WT (CUBIC METERS)	HT (METERS)	PVNB (US $)
1	5508	38	501
2	5406	45	475
3	5304	52	450
4	5202	58	427
5	4998	65	404
6	4896	71	383
7	4794	77	363
8	4692	82	344
9	4590	88	326
10	4386	93	309
11	4284	98	292
12	4182	103	277
13	4080	108	262
14	3978	112	247
15	3876	117	234
16	3774	120	221
17	3570	124	209
18	3468	128	197
19	3366	131	186
20	3264	134	175
21	3162	138	165
22	3060	140	155
23	2856	143	145
24	2754	145	136
25	2652	147	128
26	2550	149	119
27	2448	151	111
28	2244	153	103
29	2142	154	95
30	2040	155	88
Total			7525

Table 10: Externalities and synergies due to surface water bodies on groundwater irrigation in 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)	1692	2360	2794
	(b) Well Yield in relation to GWSI		+39%	+65%
2.	(a) GIA per well (Hectares)	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 per cubic meter of water (US $)	0.034	0.0225	0.015
	(b) Cost per cubic meter in relation to GWSI		-33%	-53%
5.	(a) Modal No. of wells per farm	2	1	1
6.	(a) Modal Age of well (Years)	9	14	16
7.	(a) Investment per successful well (US $)	1006	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%

Contd…..

SL No.	Particulars	GWSI (Sole well)	GWTI (Wells in tank command)	GWCI (Wells in canal command)
10.	(a) Net returns per cubic meter of water (US $)	0.063	0.072	0.073
	(b) Net returns in relation to GWSI		+16%	+17%
11.	(a) Economic access= cubic meter of water per US $ of Amortized cost (cubic meters)	0.6528	0.9792	1.428
	(b) Economic access in relation to GWSI		+50%	+118%
12.	(a) Net returns per US $ of Groundwater	1.83	3.22	4.7
	(b) Net returns per US $ of groundwater in relation to GWSI		+75 %	+156%

References

Burt, O.R. (1966). Economic control of groundwater reserves. *Journal of Farm Economics*, **31** (51), 3315-3321.

Chandrakanth, M.G. and Arun, V. (1997). Externalities in groundwater Irrigation in hard rock areas. *Indian Journal of Agricultural Economics*, **52** (4): 761-770.

Chandrakanth, M.G. and Diwakara, H. (2001). *Synergistic effect of watershed treatments on farm economy through groundwater recharge- An Economic analysis*. Ford Foundation Report, Department of Agricultural Economics, University of Agricultural Sciences, Bangalore.

Conrad, J.M. and Clark, C.W. (1989). *Natural Resource Economics - Notes and Problems.* Cambridge University Press, Cambridge.

Conrad, J.M.(1999). *Resource Economics.* Cambridge University press, Cambridge.

Darrell L. Krulce, James A.Roumassest and Tom Wilson. (1997). Optimal management of a renewable and replaceable resource: The case of coastal groundwater. *American Journal of Agricultural Economics,* **79**: 1218-1228.

Eli Fierman and Keith C. Knapp. (1983). Benefits from groundwater management, magnitude, sensitivity and distribution. *American Journal of Agricultural Economics*, 703-710.

Hellegers Petra, Zilberman David and Ierland, E.V. (2001). Dynamics of agricultural groundwater extraction- Copyright 2001, downloaded from Internet.

Jay E. Neol, Delworth Gardner, B. and Charles V. Moore. (1980). Optimal regional conjunctive water management. *American Journal of Agricultural Economics*, 489-498.

Palanisami, K. and Easter, K. William. (1991). Hydro-economic Interaction between Tank Storage and Groundwater Recharge. *Indian Journal of Agricultural Economics*, **46**(2), 174-179,

Sathisha, K.M. (1997). *Resource Economic study of Valuation of Interference Externalities in Central Dry Zone of Karnataka*, M.Sc. (Agri.) thesis (unpublished), University of Agricultural Sciences, Bangalore.

M.S. Shyamasundar, (1996). Interplay of markets, externalities, institutions and equity in groundwater development – An economic study in the hard rock areas of Karnataka. Ph.D thesis (Unpublished), University of Agricultural Sciences, Bangalore,