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ARTICLES

Energy Costs and Groundwater Withdrawals: Results from an Optimal Control Model for North Gujarat

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I

INTRODUCTION

The sustainable use of water resources is key to food and ecological security. More so in India with its agrarian economy where more than half of the population's livelihood security is based on agriculture. India ranks first in irrigated agriculture with 21.7 per cent of the total global irrigated area. Groundwater plays an important role in Indian agriculture. In India, gravity systems dominated irrigated agriculture until 1970s, but by the early 1990s, groundwater irrigation had surpassed the use of surface irrigation (Debroy and Shah, 2003 and Shah *et al*., 2003). Between 55 and 60 per cent of India's irrigated lands is supplied with water from groundwater (Shah *et al*., 2003). Groundwater is gaining importance as a source to meet the needs of our ever-increasing population for drinking as well as industry and irrigation. Furthermore, recurrent droughts, advent of high-yielding varieties and introduction of an incentive oriented agricultural pricing policy paved the way for extensive use of ground water for irrigation. While groundwater development has had important implications for the economy, the over use of groundwater is emerging as a major concern.

Groundwater plays a critical role in the agricultural economy of Gujarat state. Over-exploitation and mismanagement of the resource have led to depletion and degradation of groundwater aquifers in the North Gujarat region of western India, particularly Mehsana and Banaskantha districts with high rates of over-exploitation. Mehsana and Banaskantha are the most intensively cropped districts of the Gujarat state. As there are no major or medium irrigation schemes in the area, more than 90 per cent of the net irrigated area is served by groundwater in these districts (Anonymous, 2000). During the last few decades, groundwater development in the area has been taking place in an exponential manner. High level of extraction of groundwater has caused substantial decline in water table. It is estimated that in Mehsana district, water table has been falling at the rate of 5 – 8 meters annually and

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that some 2,000 wells dry up every year (Moench and Kumar, 1997). The water level data indicate more than 130 meters water level in Mehsana district requiring nearly 70 to 85 H.P electric motor coupled with submersible pumps which is very expensive from installation, operation and maintenance point of view (Khan, 2000). The depletion of water table is chased by increasing the depth of wells, which increases the cost of pumping per unit volume of extraction as well as poor yield. Presently, groundwater is extracted from the C and D[1] confined aquifers.

Concern about the potential use of this resource mounts as water table drops, energy costs and investment on borewells increases. As a common property resource, groundwater use is likely to be inefficient without regulation. The chronic overdraft of groundwater in the region can be attributed directly to their common pool nature coupled with the highly subsidised power supply to the farm sector. The lack of explicit property rights to groundwater stocks results in individual users of the resource evaluating only their own private pumping costs in their decision framework and implicitly assigning a zero opportunity cost to the stock portion of the resource. Individual users have little or no incentive to consider the effect of their withdrawals on other users or on future water levels. Myopic behaviour by individual farmers thus leads to collective inefficiencies and externalities.

II

OBJECTIVES, SCOPE AND METHOD

Groundwater over-exploitation has become a major concern to sustain the agrarian economy of Gujarat state in general and North Gujarat region in particular. About 70 per cent area of the region is classified under ‘over-exploited’ (OE) category, implying that groundwater extraction is more than cent per cent of the recharge, while the rest comes under ‘dark’ category with more than 85 per cent of the recharge. Drawing attention to these unsustainable utilisation rates is critical to informing the decision makers and changing course towards sustainability. It is in this context, the study was conducted with the main objective of sustaining the groundwater resource in the region. Moreover, the study examines the impact of pro-rata tariff regime on the sustainability of groundwater resource. For this, Mehsana and Banaskantha districts were purposively selected as they represent highly over-exploited districts of the region. A total of 160 borewell farmers or shareholders in company borwells (80 from each district) were surveyed and necessary information was collected with the help of well-designed and pre-tested questionnaire.

III

OPTIMAL CONTROL MODEL

For the sustainable management of groundwater, optimal control theory model, a dynamic optimisation model is used which shows the optimal groundwater extraction path over the time. The earlier studies (Noel *et al.*, 1980; Feinerman and Knapp, 1983; Krulce *et al.*, 1997; and Hellegers *et al.*, 2001) 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 maximise the net present value of benefits from groundwater extraction in consonance with the rainfall, recharge, aquifer area and storativity. The model consists of hydrological and economic parameters. The model maximises the value of economic components subject to the constraints imposed by hydrological parameters, consistent with the optimal allocation of groundwater over the time horizon. The optimal use of natural resource under optimal control regimes arise from the fact that the farmer considers the user cost of the resource, unlike in competitive (no control) regime, where the marginal cost is equated to current marginal benefit in determining the optimal level of resource extraction. Hence, the myopia of ignoring user cost of groundwater under competitive regime leads to over-exploitation of the resource in early periods, thus increasing the extraction cost for future resource users, which leads to intergenerational inequity in the availability of the groundwater resource.

IV

EMPIRICAL MODEL

The objective is to maximise 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. The empirical model used here is discussed in the light of optimisation of time (dynamic optimisation). 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:

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

Subject to:

$$h_{t+1} - h_t = \frac{\left\{\left(1-\theta\right)w_t - R\right\}}{As} \qquad \text{....(2)}$$

Here, NB is the net benefit, TR is the total revenue and (Rs. per well), TC is the total cost (Rs. per 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 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 per cent. '*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. [2] "*s*" is the specific yield (called the storativity), the proportion of groundwater held in one cubic unit of earth mass.

The variables used in the model are defined below.

4.1 *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.

4.2 *Total Cost:*

The total cost is the cost of electricity used in extracting groundwater which is given by $kh_t\, w_t$.
where, k = electricity cost to lift one ha-cm of water by one metre of lift in Rs.

For the estimation of power cost, the reference of two studies is quoted. The power required to lift one ha-cm of water by one metre was found to range between 0.5 to 0.6 kWh (Patel, 1990) in the central Gujarat. Yet, in another study carried out in Mehsana area, 0.38 kWh of electricity was required to pump m^3 of groundwater (IRMA/UNICEF, 2001). Both the studies are based on pumping depths, pump capacities, etc. Based on both the studies, the power required to lift m^3 of water by one metre was worked out to be Re 0.00041 per kWh.

4.3 *Recharge*:

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 rainfall (mm).

4.4 *Pumping Lift*:

Pumping lift is the vertical distance from the earth surface to the depth at which submersible pump is placed in the borewell. 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:

$$H = e^{-rt}\left(aw_t - bw_t^2 - Kh_t w_t\right) + \lambda \frac{\left\{(1-\theta)w_t - R\right\}}{As},$$

treating time '*t*' as continuous variable.

Here, 'λ' is the 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, 1987), the necessary conditions to arrive at optimal path of extraction that maximize the net benefit from groundwater extraction are:

$$\frac{\delta H}{\delta w} = 0 \quad \text{---------------------------------> Condition 1}$$

implies: $$e^{-rt}\left(a - 2bw_t - Kh_t\right) + \lambda \frac{(1-\theta)}{A_s} = 0$$

Or

$$e^{-rt}\left(a - 2bw_t\right) = e^{-rt}Kh_t + \lambda \frac{(\theta-1)}{A_s} = 0$$

$$-\delta H/\delta h = \lambda_{t+1} - \lambda_t \quad \text{--------------------------------> Condition 2}$$

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

$$\delta H/\delta\lambda = h_{t+1} - h_t \quad \text{---------------------------------> Condition 3}$$

implies: $$h_{t+1} - h_t = \left\{(1-\theta)w_t - R\right\} \Big/ \left\{As\right\}$$

Estimation of Net Benefits Under Myopic Situation

Farmers usually do not internalise the negative externality imposed in the process of over-extraction 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 up to estimate the present value of net benefits over the entire period.

5.1 *Myopic Rule*:

Marginal benefit = Marginal cost

$$a - 2bw_t = kh_t \quad 3$$

or

$$w_t = B_0 - B_1 h_t$$

where, $B_0 = a/2b$ and $B_1 = k/2b$

V

MODEL PARAMETERS

The various economic and hydrological parameters used in the model and their values for the study area is presented in Table 1. The average aquifer area per well was found to be 8.87 hectare in Mehsana, whereas it was relatively less for Banaskantha district (5.19 ha). There are lot of limitations and practical problems in defining the area of aquifer. Here, we take the area of aquifer per well approximately as total land holdings by the number of functioning wells of sampled farmers, which is just as proxy for the aquifer area. The initial pumping lift is the placement of pumps from above the ground during survey period. The pumps are deeply placed in

TABLE 1. ECONOMIC AND HYDROLOGICAL PARAMETERS OF THE OCT MODEL

Sr. No. (1)	Constants and variables (2)	Mehsana (3)	Banaskantha (4)
1.	Aquifer area per functioning well (ha)	8.87	5.19
2.	Initial pumping lift (metre)	138	79
3.	Storativity coefficient	0.095	0.075
4.	Recharge coefficient (R_c)	0.2	0.2
5.	Long term annual rainfall (cm)	111.45	77.32
6.	Groundwater recharge (ha-cm)	197.63	79.87
7.	Groundwater return flow coefficient (θ)	0.001	0.001
8.	**k** = Cost of electrical power (Rupee per m^3, per metre of lift)	0.0004	0.0004
9.	Estimated regression coefficient of ground water extraction in quadratic function (a)	618	452
10.	Estimated regression coefficient of the square of groundwater extraction in quadratic function (b)	- 0.03	- 0.023
11.	Discount rate chosen	0.02	0.02
12.	Discount factor (=1/(1+0.02))	0.98	0.98

Mehsana as compared to Banaskantha district due to deeper water level. “The specific yield “s” or storativity is the proportion of groundwater held in one cubic unit of earth mass. The values of the specific yield range from 0.01 to 0.30 (1 to 30 per cent). The average specific yield of 9.5 per cent was considered for Mehsana aquifers, whereas for Banaskantha, it varies from 2 to 13 per cent. In the model we take the average specific yield of 7.5 per cent for Banaskantha district. The hydrological data used in the model is as per the data of Ground Water Resources Development Corporation (GWRDC), Gujarat state.

Recharge coefficient (R_c) is the fraction of total rainfall that percolates down to join water table or in other words as deposit to aquifer. The recharge coefficient varies from soil to soil. Recharge coefficient is found generally high for sandy alluvium soils and very low for clay and hard soils. For both the districts, with sandy alluvium soil, the recharge coefficient was chosen 20 per cent as per the available field tests of the soil scientists and groundwater engineers of the region. Groundwater return flow coefficient (θ) is the fraction of applied groundwater returning back to aquifer. In this case, θ is taken as near to zero ($0.001 \approx 0$), because presently, the farmers of the North-Gujarat region are drawing water from the C and D zones of the confined and semi-confined aquifers. The fraction of groundwater returning back to aquifer does not reach to D zone level. The OCT model was separately tried for the two districts due to difference in the hydrological parameters.

Optimum Control Model for Mehsana District

Under the myopic extraction rule, the life of well(s) gets limited to 3 years in Mehsana, even after crossing the maximum pump depth constraint of 366 metres (Table 2). The maximum limit of 366 metre pump depth was given on the basis of highest pump depth of the sampled borewell farmers in the area. The water extracted in the initial year (2003) is 9,96,289 m^3. The initial pump lift is taken 138 metres based on the average pump placement data of the borewell farmers during survey period. Instead of myopic rule, if water is extracted optimally as governed by optimal extraction rule; the benefits derived will be high not only from economic angle but also from sustainable point of view. Under optimal extraction regime, well life increases upto 15 years, which is 12 years more than that of myopic regime. The initial water extraction starts from 2,65,523 m^3 and the allocated quantum goes on decreasing till it reaches to the scale of 19,968 m^3 in the final year. After 15th year, the extraction path comes to steady state because of maximum pump depth constraint imposed in the model. The steady state is the state at which withdrawal rate gets balanced with the recharge rate. The present value net benefits (PVNBs) for the fifteen years period under the optimal extraction works out to the tune of Rs. 1,08,99,365 which is higher by 20.65 per cent than the PVNB under myopic extraction (Rs. 90,33,921).

TABLE 2. GROUNDWATER EXTRACTION, PUMPING LIFTS AND DISCOUNTED NET BENEFITS UNDER OPTIMAL AND MYOPIC REGIMES IN MEHSANA DISTRICT, GUJARAT

	Optimal Extraction			Myopic Extraction		
Time (Years) (1)	Water extraction (m^3) (2)	Pumping lifts (metre) (3)	PVNB (Rs.) (4)	Water extraction (m^3) (5)	Pumping lifts (metre) (6)	PVNB (Rs.) (7)
1	2,65,523	138	13,85,602	9,96,289	138	31,22,693
2	2,50,163	167	12,87,757	9,87,891	259	30,09,947
3	2,34,394	194	11,90,372	9,79,590	380	29,01,280
4	2,18,317	220	10,94,205			
5	2,01,933	243	9,99,164			
6	1,85,242	265	9,05,152			
7	1,68,243	284	8,12,077			
8	1,50,938	302	7,19,843			
9	1,33,325	318	6,28,354			
10	1,15,405	331	5,37,513			
11	97,075	343	4,47,223			
12	78,438	352	3,57,384			
13	59,392	359	2,67,895			
14	40,038	363	1,78,656			
15	19,968	366	88,168			
Total	22,18,394		1,08,99,365	29,63,770		90,33,920

Initial pump lift = 138 metres; Max. pump depth = 366 metres;
Power cost (k) = Rs. 0.5 per kwh; Discount rate = 2 per cent.
PVNB → present value net benefits.

In Table 1, we put the limit of 366 metres as maximum depth for well and also for pump placement upto which it can go on extracting water. The maximum pump depth constraint of 366 metres was given on the basis of highest depth of borewell in sample. But there are borewells in Mehsana district, which are operating beyond this depth. The highest depth of borewell in Manund village of Patan taluka is 550 metres deep. The technology also permits to go upto 610 metres well depth in the study area. Hence, when the limit of maximum pump depth was increased upto 610 metres, the life of well(s) extends to 22 years under optimal regime and 5 years under myopic regime. The optimal water extraction curve starts from 3,61,062 m^3 in the initial year and goes on continuously declining in the subsequent years with 19,763 m^3 in the 22nd year, beyond which the water extraction adopts steady state path. The total groundwater extraction under the optimal control regime came to be 4.41 million m^3 over the time horizon of 22 years period which was found to be 16.43 per cent less than that of water extraction under myopic regime (5.13 million m^3) that too within 5 year limited period. The values of groundwater extraction, pump lifts and PVNBs under myopic and optimal regime at 610 metre pump depth limit are given in Table 3.

TABLE 3. GROUNDWATER EXTRACTION, PUMPING LIFTS AND DISCOUNTED NET BENEFITS UNDER OPTIMAL AND MYOPIC REGIMES IN MEHSANA, GUJARAT AT HIGHER PUMP DEPTH

	Optimal Extraction			Myopic Extraction		
Time (Years) (1)	Water extraction (m^3) (2)	Pumping lifts (metre) (3)	PVNB (Rs.) (4)	Water extraction (m^3) (5)	Pumping lifts (metre) (6)	PVNB (Rs.) (7)
1	3,61,062	138	17,85,323	10,44,685	138	31,22,693
2	3,47,443	178	16,92,027	10,35,878	259	30,09,947
3	3,33,619	217	1,600,287	10,27,174	380	29,01,280
4	3,19,590	254	15,10,227	10,18,470	500	27,96,544
5	3,05,254	290	14,21,755	10,09,869	618	26,95,596
6	2,90,714	324	13,34,777			
7	2,75,968	356	12,49,205			
8	2,60,915	387	11,64,947			
9	2,45,658	415	10,81,916			
10	2,30,093	442	10,00,022			
11	2,14,323	467	9,19,179			
12	1,98,246	490	8,39,299			
13	1,81,862	511	7,60,294			
14	1,65,171	530	6,82,078			
15	1,48,173	548	6,04,564			
16	1,30,867	563	5,27,664			
17	1,13,254	576	4,51,293			
18	95,232	587	3,75,363			
19	76,902	596	2,99,787			
20	58,163	603	2,24,479			
21	39,117	607	1,49,352			
22	19,763	610	74,684			
Total	44,11,389		1,97,48,522	51,36,076		1,45,26,060

Initial pump lift = 138 metres; Max. pump depth = 610 metres.
Power cost (k) = Rs 0.5 per kwh; Discount rate = 2 per cent.

Optimum Control Model for Banaskantha District

In Banaskantha district, the hydrology differs and the well(s) are not so deep as compared to Mehsana district. There is hardrock bed beneath 137 to 198 metres, beyond which farmers cannot deepen wells to extract water. The hardrock bed therefore, becomes the limit for chasing water for this area. It was also found that the average bore yield was less in Banaskantha district as compared to Mehsana district. In Banaskantha, farmers draw water at an average level of 79 metres. The values of water extraction, pump lifts and PVNBs under myopic and optimal regime for Banaskantha district are shown in Table 4. The life of well(s) lasts for 6 years under myopic regime. The myopic water extraction path starts from 95,744 m^3 in the initial year and reduces to 94,720 m^3 in the final (6th) year. The total PVNBs of Rs.11,85,591 could be realised. As against the myopic regime, optimal extraction rule extends the well life upto 26 years with water extraction starting from 41,472 m^3 withdrawal in the first year which is about 130 per cent less when compared with the first year withdrawal under myopic regime. The optimal extraction path goes on declining and reaches to a level of 7,987 m^3 in the 26th year (2028) before reaching to steady state path. The total PVNBs realised under optimal rule was found 73 per cent higher than the total PVNBs under myopic rule.

TABLE 4. GROUNDWATER EXTRACTION, PUMPING LIFTS AND DISCOUNTED NET BENEFITS UNDER OPTIMAL AND MYOPIC REGIMES IN BANASKANTHA DISTRICT, GUJARAT

	Optimal Extraction			Myopic Extraction		
Time (Years) (1)	Water extraction (m^3) (2)	Pumping lifts (metre) (3)	PVNB (Rs.) (4)	Water extraction (m^3) (5)	Pumping lifts (metre) (6)	PVNB (Rs.) (7)
1	41,472	79	1,42,466	95,744	79	2,09,679
2	40,448	87	1,36,907	95,539	101	2,04,691
3	39,322	96	1,31,428	95,334	124	1,99,822
4	38,298	104	1,26,021	95,130	146	1,95,069
5	37,171	111	1,20,682	94,925	169	1,90,430
6	35,942	119	1,15,410	94,720	191	1,85,900
7	34,816	126	1,10,200			
8	33,587	133	1,05,050			
9	32,358	140	99,958			
10	31,130	146	94,921			
11	29,901	152	89,936			
12	28,570	157	85,000			
13	27,341	163	80,110			
14	26,010	168	75,265			
15	24,576	172	70,460			
16	23,245	177	65,694			
17	21,811	180	60,963			
18	20,378	184	56,265			
19	18,842	187	51,597			
20	17,408	190	46,957			
21	15,872	192	42,341			
22	14,234	194	37,746			
23	12,698	196	33,171			
24	11,059	197	28,613			
25	9,421	198	24,068			
26	7,987	198	20,301			
Total	6,73,897		20,51,530	5,71,392		11,85,591

Initial pump lift = 79 metres; Max. pump depth = 198 metres;
Power cost (k) = Rs. 0.5 per kwh; Discount rate = 2 per cent.

Comparing the water extraction paths of the two districts from Tables 2 and 4, it is seen that, despite high bore yield and almost double the maximum pump depth limit in Mehsana, the life of well(s) is near to half as against to that of Banaskantha district. This is due to the current high extraction state at which farmers are drawing water. The farmers in Mehsana district are extracting water at an exorbitant rate. Even if the demand of well owner(s)/shareholders is met, he/they continue to draw to enter in the water market trade which is most prevalent in the region and thereby keeping no regard for the future. Though the water market reduces the inequity as proposed by a number of researchers, it adversely affects the sustainability of the resource.

The groundwater extraction paths and PVNBs under optimal and myopic regimes were estimated for Banaskantha district at an average specific yield of aquifers of 7.5 per cent. As already explained in the previous sections, the specific yield varies from 2 to 13 per cent in the district. The specific yield of aquifers is generally found less for hardrock areas and high for sandy alluviums. The OCT model was run at these two extreme values to see the change in the water extraction paths as well as PVNBs and well life which is depicted in Figure 1. At a specific yield of 2 per cent, the life of well was found to be 14 years under optimal regime and only two years under myopic regime. On 13 per cent value of specific yield, the well life extends for a period of 35 and 10 years under optimal and myopic regimes, respectively. The water extraction path under optimal regime at 2 per cent specific yield starts with 26,112 m^3 in the initial year and reaches at withdrawal level of 7,987 m^3 in the 14th year, whereas optimal water extraction path at 13 per cent specific yield starts at a level of 50,176 m^3 in the initial year and goes on declining steadily for subsequent periods, ending at withdrawal level of 7,987 m^3 in the 35th year. It is thus concluded from the graph that specific yield of an aquifer has a greater bearing on borewell yield and its life. The difference in the total PVNBs realised under optimal regime at two different specific yield levels was very high (Rs. 21,44,153). The results are supported by the findings of Renshaw (1963), where he found the net benefits from groundwater management to the tune of $100 per acre and observed that these benefits would increase with the increase in yield coefficient of aquifer.

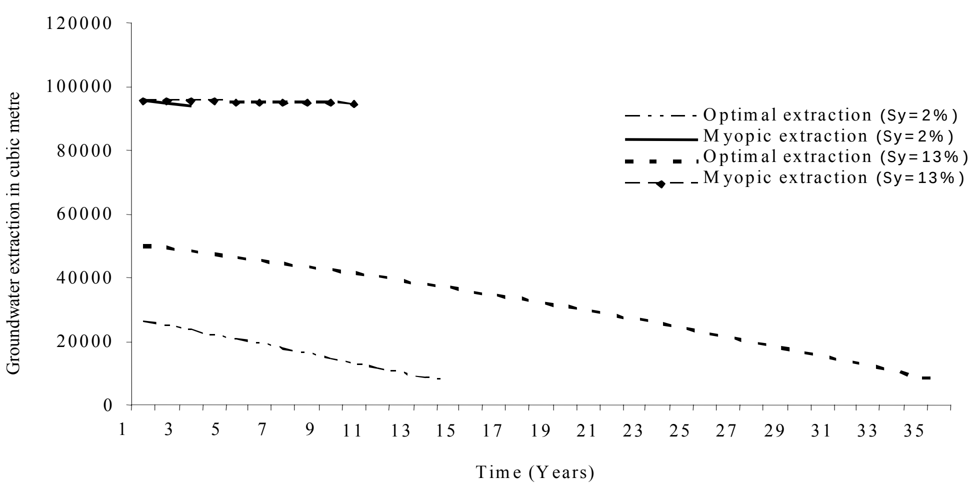

Figure 1. Groundwater Extraction Paths under Optimal and Myopic Regimes in Banaskantha at Two Specific Yield Levels.

Initial pump lift = 79 metres; Maximum pump depth = 198 metres;
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2 per cent.
Specific yield (Sy) = 2 to 13 per cent.

Sensitivity Analysis for Power Cost

The electricity supplied to the farmers is at a highly subsidised rate ranging between Re 0.50-0.70 per kWh as against the supply cost of Rs. 2.50-Rs.3.80 per kWh. The new connections to the farm sector for the extraction of groundwater are being metered on pro-rata tariff base in Gujarat state. The normal agricultural connection with meter is charged at Re 0.50 per kWh and those with *Tatkal* (emergency) agricultural connection at Re 0.70 per kWh. The sensitivity analysis was carried out at different power cost rates for the extraction of groundwater, keeping other parameters of the model constant, to see the change in the benefits realised from groundwater management (GWM) through optimum control rule and effect of different power tariff rates on the behaviour of groundwater extraction paths over the time horizon. The results from sensitivity analysis are presented in Tables 5 and 6 and water extraction curves (WEC) or paths are shown in Figures 2 and 3. The results indicated that the life of borewell increases at higher tariff rate in both the districts mainly because of lower withdrawals at higher pumping costs in the initial years. However, the higher pumping costs have had no effect on borewell life under myopic rule. The benefits realised from groundwater management through optimal extraction are significantly higher for both the areas under different tariff rates. Sensitivity analysis results further reveal that the magnitude of benefits realised from GWM increases with increase in energy tariffs.

TABLE 5. SENSITIVITY ANALYSIS FOR ENERGY COST AND BENEFITS REALISED FROM GROUNDWATER MANAGEMENT (GWM) THROUGH OPTIMAL CONTROL FOR MEHSANA DISTRICT OF GUJARAT

	Optimal extraction			Myopic Extraction			
Power tariff (Rs./kWh) (1)	Well life (Years) (2)	PVNB (lakh Rs.) (3)	Water withdrawal (m^3) (4)	Well life (Years) (5)	PVNB (lakh Rs.) (6)	Water withdrawal (m^3) (7)	Benefits from GWM (lakh Rs.) (8)
0.50	15	108.99	22,18,394	3	90.34	31,07,700	18.65
0.75	16	108.82	22,38,193	3	88.74	30,79,800	20.08
1.00	16	107.76	22,38,464	3	87.10	30,51,100	20.65
1.50	16	105.74	22,38,193	3	84.09	29,97,000	21.66
2.00	16	103.70	22,38,193	3	81.11	29,42,600	22.59
2.50	16	101.65	22,38,193	3	78.23	28,88,900	23.42
3.00	17	100.34	22,57,963	3	75.44	28,35,800	24.90
3.50	17	98.27	22,57,963	3	72.74	27,83,300	25.54

TABLE 6. SENSITIVITY ANALYSIS FOR ENERGY COST AND BENEFITS REALISED FROM GROUNDWATER MANAGEMENT (GWM) THROUGH OPTIMAL CONTROL FOR BANASKANTHA DISTRICT OF GUJARAT

Power tariff (Rs./kWh) (1)	Optimal extraction Well life (Years) (2)	Optimal extraction PVNB (lakh Rs.) (3)	Optimal extraction Water withdrawal (m^3) (4)	Myopic Extraction Well life (Years) (5)	Myopic Extraction PVNB (lakh Rs.) (6)	Myopic Extraction Water withdrawal (m^3) (7)	Benefits from GWM (lakh Rs.) (8)
0.50	26	20.52	6,73,894	6	11.86	5,71,400	8.66
0.75	26	20.36	6,73,981	6	11.71	5,67,600	8.65
1.00	27	20.39	6,82,011	6	11.56	5,64,000	8.83
1.50	27	20.07	6,82,011	6	11.27	5,56,800	8.80
2.00	27	19.75	6,82,011	6	10.99	5,49,600	8.76
2.50	28	19.61	6,90,040	6	10.71	5,42,600	8.90
3.00	28	19.29	6,90,040	6	10.44	5,35,600	8.85
3.50	29	19.13	6,98,070	7	11.60	6,12,200	7.54

An important finding from the curves of optimal water extraction paths at different pumping costs emerged with regard to inter-temporal allocation of water or inter-generational equity. It is evident from the Figures 2 and 3 that the water extraction paths at higher tariff rates start from lower water extraction levels in the initial years and all curves converge over a time (i.e., 2011th year for Mehsana and 2016th year for Banaskantha district). After that, the water extraction curves at higher pumping costs get over and above to that at lower tariff rates. Hence, in the later years, the water allocated would be more at higher tariff rates to that of lower tariff rates.

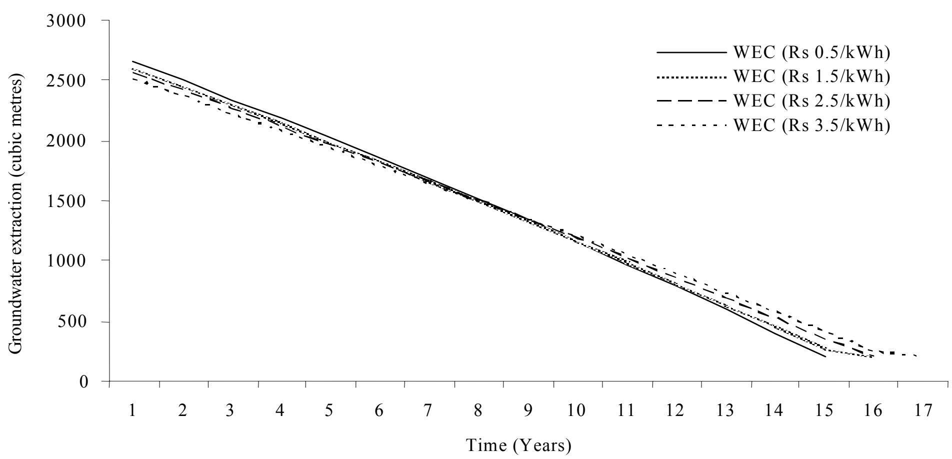

Figure 2. Optimal Groundwater Extraction Paths at Different Energy Tariffs for Mehsana District.

Initial pump lift = 138 metres; Maximum pump depth = 366 metres;
Power cost (k) = Rs 0.50-3.5 per kWh; Discount rate = 2 per cent.

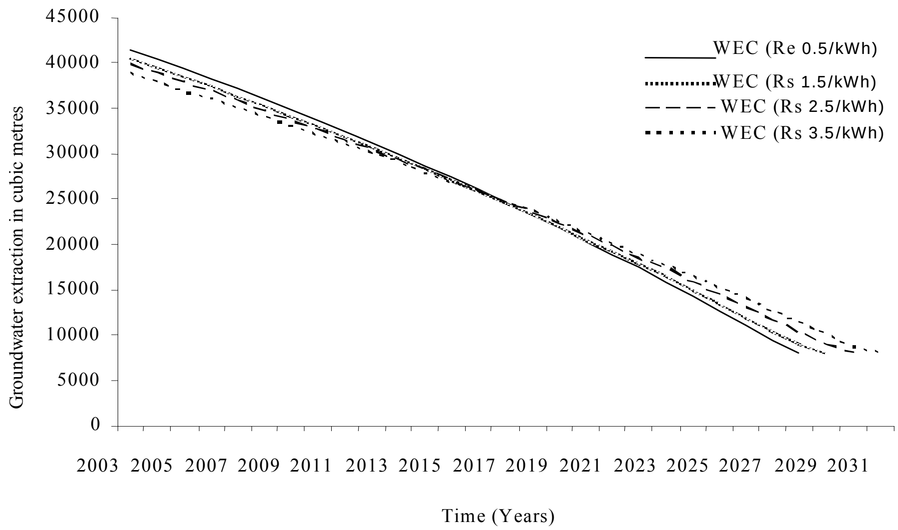

Figure 3. Optimal Groundwater Extraction Paths at Different Energy Tariffs for Banaskantha District

Initial pump lift = 79 metres; Maximum pump depth = 198 metres;
Power cost (k) = Rs 0.50 to 3.5 per kWh; Discount rate = 2 per cent.

VI

CONCLUSION AND POLICY IMPLICATIONS

The problem of inter-temporal groundwater management has played an important role in the development of resource economics. The sustainability of the resource becomes more important when it is under threat. It is argued that the subsidised energy regime is the main culprit for the over-exploitation of the resource as the marginal energy cost for groundwater extraction is near zero. The highly subsidised energy regime to the farm sector is making viability of power sector unreliable on the one hand and threatening the groundwater sustainability on the other. The amount of budgetary subsidy to farm sector for energy in Gujarat was to the tune of Rs. 1100 crore as per Gujarat Electricity Board (GEB), Gujarat for the year 2004-05. The paper has proposed an optimal control model framework for optimal allocation of groundwater resource over the time horizon. In this paper, we investigated the magnitude of benefits from groundwater management (i.e, control of quantities extracted), their sensitivity to various parameters, and related welfare effects on groundwater users.

Groundwater basins were found to react differently to alternative economic and hydrological parameters. The benefits from the groundwater management under optimal control regime are higher than that of myopic regime. The optimal control model takes care of the sustainability aspect of the resource, besides inter-generational equity in the resource availability. The optimal rates of groundwater pumping over the time horizon were sensitive to increasing energy costs. From the policy point, the energy costs had a great bearing on the farmers' behaviour of groundwater extraction. Higher energy tariffs were found to be more effective in sustaining the resource as well as taking care of inter-generational equity. The study presents a beginning for a wise and useful policy in formulating the pro-rata energy tariff policy which can sustain the resource as well as improve the power sector viability. Though, the farmers are very much reluctant to pay on pro-rata tariff rate and the ruling party to implement it, as the farming community forms the major share of vote bank. This synergy of groundwater politics leads to a vicious cycle of groundwater politics – energy subsidy – energy and groundwater unsustainability. In order to break this vicious circle, the government should implement the pro-rata tariff regime at a low tariff rate initially and withdraw the subsidy in a phased manner. The withdrawal of subsidy in a phased manner on the one hand and provision of subsidy on water saving technologies on the other hand may serve the purpose. Such a policy at the macro level will make the farmers to extract groundwater optimally and efficient use of water by investing in water saving technologies thereby, sustaining energy as well as resource sustainability.

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NOTES

1. North Gujarat region is characterised by multi-layered phreatic aquifer systems with A, B, C and D layers. These zones are classified in terms of depth. With high over-exploitation of the resource; A, B and in some areas C layers had got exhausted and farmers are drawing water from C and D zones of confined aquifers.

2. There are lot of limitations and practical problems in defining the area of aquifer. Here, we take area of aquifer per well approximately as total land holdings by the number of functioning wells of the sampled farmers, which is just as proxy for the aquifer area.

3. $TR = aw_t - bw_t^2$ and $TC = kh_t w_t$; Marginal Benefit (MB) = $\partial TR/ \partial w_t = a - 2bw_t$; similarly, Marginal Cost (MC) = $\partial TC/ \partial w_t = kh_t$

REFERENCES

Anonymous (2000), *District Statistics for Mehsana and Banaskantha Districts.*

Conrad, J.M. and C.W. Clark (1987), *Natural Resource Economics-Notes and Problems*, Cambridge University Press, Cambridge.

Debroy, A. and Shah, T. (2003), "Socio-Ecology of Groundwater Irrigation in India", in R. Llamas and E. Custodio (Eds.) (2003), *Groundwater Intensive Use: Challenges and Opportunities*, Swet and Zetlinger Publishing Company, The Netherlands.

Feinerman, Eli and K.C. Knapp (1983), "Benefits From Groundwater Management, Magnitude, Sensitivity, and Distribution", *American Journal of Agricultural Economics*, Vol. 65, No. 4, pp. 703-710.

Hellegers, P.; Zilberman, D. and Ekko van Ierland (2001), "Dynamics of Agricultural Groundwater Extraction", *Ecological Economics*, Vol.37, pp. 303-311.

Institute of Rural Management (IRMA) and UNICEF (2001), *White Paper on Water in Gujarat*, submitted to Government of Gujarat.

Khan, A.A. (2000), "Groundwater Development and Artificial Recharge in North Gujarat Region", Report of Groundwater Resources Development Corporation Ltd., Gandhinagar, Gujarat.

Krulce, D.L.; Roumasset, J.A. and Tom Wilson (1997), "Optimal Management of a Renewable and Replaceable Resource: The Case of Coastal Groundwater', *American Journal of Agricultural Economics*, Vol. 74, No. 4, pp. 1218-1228.

Moench, M. and Dinesh Kumar (1997), "Distinction Between Efficiency and Sustainability: The Role of Energy Prices in Groundwater Management", in Anil Agarwal (Ed.) (1997), *The Challenge of Balance: Environmental Economics in India*, Centre for Science and Environment, New Dehli.

Noel Jay E.; Gardner, B.D. and C.V. Moore (1980), "Optimal Regional Conjuctive Water Management", *American Journal of Agricultural Economics*, November, pp.489- 498.

Patel, S.M. (1990), "Conservation of Energy in Agricultural Pumpsets", Report submitted to Gujarat Agricultural University, Sardar Krushinagar, Banaskantha, Gujarat.

Renshaw, E.F. (1963), "The Management of Groundwater Reservoirs", *Journal of Farm Economics*, Vol. 45, pp. 285-295.

Shah, T.; Scott, C.; Kishore, A. and Sharma, A. (2003), "Energy-Irrigation Nexus in South Asia: Improving Groundwater Conservation and Power Sector Viability', Research Report 70, International Water Management Institute, Colombo, Sri Lanka.