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Sustaining Water and Energy Use in Semi-Arid Agriculture Region in Gujarat, India: Application of Optimal Control Model

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Abstract: An optimal control model is used to determine the socially optimal and temporal allocation of groundwater for agriculture in the over-exploited areas of western India. The dynamic optimization model shows the optimal extraction path over the time horizon. The benefits from the groundwater management by optimal control regime were significantly higher than that of myopic regime. Optimal rates of groundwater pumpage over the time horizon were sensitive to increasing energy costs. Sensitivity analysis revealed that the lower interest rates take more care of inter-generational equity of the resource. Groundwater basins were found to react differently to alternative economic and hydrologic parameters.

Key words: Groundwater management · Semi-Arid agriculture · Optimal control model · Resource optimization · Energy pricing · Sustainability · Intergenerational equity

INTRODUCTION

The sustainable use of water resource is key to food and ecological security. In fact, livelihood security is critically linked with water security. Water security means 'some for all and forever' [1]. Water security should ensure equity and sustainability. There have been many attempts in defining the sustainability. The most commonly used definition is the one provided by the World Commission on Environment and Development [2]: "Progress that meets the needs of present without compromising the ability of future generations to meet their own needs". For any given technology, preference structure and known resource base, there are some utilization rates that cannot be sustained [3]. Such unsustainable utilization rates are most prevalent in the highly developed, over-exploited groundwater regions of India.

The use of groundwater in India for irrigation has been in vogue since time immemorial. It forms the most important and reliable source of irrigation. The contribution of groundwater to irrigated agriculture is more than 50 per cent [4] and also meets a major part of our drinking and industrial needs. The occurrence of recurrent droughts, advent of high yielding varieties and introduction of an incentive oriented agricultural pricing policy paved the way for extensive use of groundwater for irrigation [5]. India's groundwater resources are almost ten times its annual rainfall. It forms the most important and reliable source of irrigation in India. According to the Central Groundwater Board [6] of the Government of India, the country has an annual exploitable groundwater potential of 26.5 million hectare metres. Like surface water, nearly 85 per cent of the currently exploited groundwater is used only for irrigation. The importance of groundwater in Indian economy can hardly be overemphasized. According to researcher Marcus Moench [7], groundwater accounts for as much as 70 – 80 per cent of the value of farm produce attributable to irrigation. It contributes enormously to crop production and Indian economy (9% of GDP). With agriculture contributing roughly 25 per cent of India's GDP and the production from irrigated land claims the lion's share, a large percentage of the country's GDP is closely tied to availability of groundwater. In case of drought, it is the most dependable source for irrigation and plays a critical role in maintaining production.

There has been over-exploitation of this resource in various parts of the country, which is a matter of great concern, as it is closely related to food security. While developing groundwater resources, promises to help alleviate poverty in many areas, the most formidable

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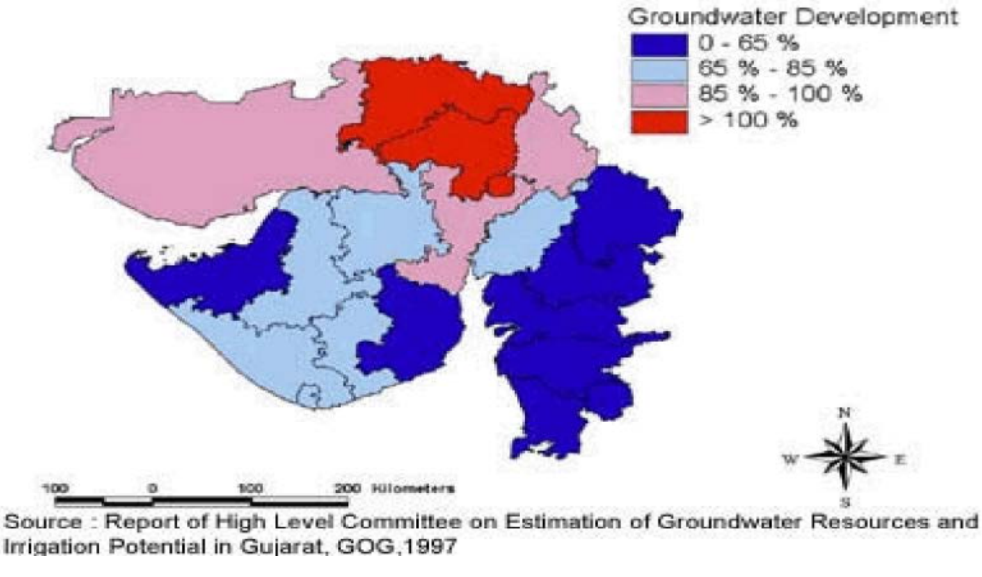
groundwater challenge is to attain the sustainable use and management of groundwater in vast and growing regions where the resource is under threat. According to Sandra Postel [8], the world overdraws 200 cubic km of its global groundwater ‘bank account’ every year. Probably more than 66 per cent of the overdraft occurs in India, placing the country’s food and livelihood security at great risk. As water crisis deepens, states fail to take a long term perspective to tackle the problem. In fact, the share of water management in the total budgetary allocation of India has steadily declined from 8.21 per cent in 1995-96 to 5.55 per cent in 2002-03. The worst case is Gujarat state of western India, which reeled under severe water crisis only four years ago, the state’s budgetary allocation on water management and irrigation declined by a massive 5.81 percentage points during the last seven years from 15.31 per cent in 1995-96 to 9.5 per cent in 2002-03 [9].

Groundwater Scenario in Western India: Groundwater plays a critical role in the agricultural economy of western India. The state of Gujarat lies on the western coast of India between 26º6’ to 24º42’N and 68º10’E to 74º28’E. Over-exploitation and mismanagement of the resource have led to depletion and degradation of groundwater aquifers in North Gujarat region of western India, particularly Mehsana and Banaskantha districts with high rates of over-exploitation. The North-Gujarat region falls under arid and semi-arid climate regime. Mehsana and Banaskantha districts of the North Gujarat region are the most intensively cropped districts of the Gujarat state. As there are no major or medium irrigation schemes existing in the area, more than 90 per cent of the net irrigated area is served by groundwater in these districts [10]. 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 water table declines. It is estimated that in Mehsana district, water table has been falling at the rate of 5 – 8 meters annually and that some 2,000 wells dry up every year [11]. 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 [12]. 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 confined aquifers. The extent of groundwater development and its over-exploitation in the state is depicted in Map 1.

Concern about the wisely 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 subsidized power supply to farm sector. The lack of explicit property rights to groundwater stocks results in individual users of

MAP 1.

Level of Ground Water Development in Gujarat



Source : Report of High Level Committee on Estimation of Groundwater Resources and Irrigation Potential in Gujarat, GOG,1997 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. Drawing attention to these unsustainable utilization rates is critical to informing 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. For this, Mehsana and Banaskantha districts were purposively selected as they represent highly over-exploited districts of the region. A total of 160 farmers (80 from each district) were surveyed and necessary information was collected with help of well-designed and pre-tested questionnaire during the agricultural year 2002-03.

For the sustainable management of groundwater, optimal control theory model, a dynamic optimization model is used which shows the optimal groundwater extraction path over the time. The model consists of hydrological and economic parameters. The model maximizes the value of economic components subject to the constraints imposed by hydrologic parameters, consistent with the optimal allocation of groundwater over the time horizon. The objective of optimal control problem is to arrive at temporally optimal allocation of groundwater over time horizon that will maximize the net present value from extracting the resource over the entire period. A typical problem is that of choosing optimal levels of decision variables over time. These variable(s) are called control variable(s). The state of the system at any point of time is characterized by state variable(s). Changes over time in the state variable(s) are represented by the equations of motion, which are assumed to be the functions of the state variable, control variable and random variable(s) at the moment of change.

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 under competitive regime leads to over exploitation for future farmer causing intergenerational inequity in resource availability with respect to groundwater resource. The control variable (decision variable) is the quantity of water to be pumped in each period.The state variable is the groundwater resource stock in each time period. The objective function is the net social benefit for the given ground water.

The Model: Consider an agricultural area relying on an aquifer for its water withdrawal in time period 't' are denoted 'w_t', pumping lifts by 'h_t' and net recharge to the aquifer from all sources except groundwater return flows by 'R'. Under these assumptions, annul pumping lifts are given by:

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

where 'θ' is the fraction of applied groundwater returning to aquifer ($0 \leq \theta \leq 1$), A is the area of the aquifer, 's' is the specific yield (storativity) is described as the proportion of groundwater held in one cubic unit of earth mass and the initial lift h_t is given. Benefits from the groundwater withdrawal are assumed to be given by the area under the demand curve. Total pumping cost is $K*h_t*w_t$, where 'K' denotes the cost of energy need to lift one hectare centimeter (ha-cm) of water by one meter.

The inverse demand function is given by:

P = a-2bw,

where,

P = price of water in Rs.

W = water demanded in ha-cm.

The total revenue is given by the area under the demand curve, estimated by integrating the water demand function. Hence, the annual total benefit from groundwater use is given by:

$$TB_t = \sum_{t=0}^{n} \int (a - 2bw)\,dw$$

$$TB_t = \sum_{t=0}^{n} (aw - bw^2)$$

Thus the net benefit (NB) is given by

$$NB = \sum_{t=0}^{n} (aw_t - bw_t^2 - Kh_tW_t)$$

Thus, the dynamic optimization problem is to maximize present value of net benefit as:

Max NB = $\sum_{t=0}^{n} e^{-rt}\left(aw_t - bw_t^2 - Kh_t w_t\right)$

Subject to

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

where, ‘r’ is the discount rate.
The Hamiltonian for the above problem is given by:

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

Where λ is the marginal user cost or shadow price or opportunity cost or royalty is the reduction in the discounted future net benefits from withdrawal of one additional unit volume of water in the current period.
Necessary conditions for optimality are

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

Or

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

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

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

The empirical model used below in the present problem is discussed below in the light of the above methodology of dynamic optimization.

The objective function in the present study is given by:

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

Subject to

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

where,
TR = Total revenue (Rs/well)
TC = Total cost (Rs/ha-cm of water/meter of lift)
ρ = Discount factor ={1/(1+r)}

The variables used in the model are defined below:

Total Revenue: The revenue variable is estimated considering the revenue per well as a quadratic function of water used per well with zero intercept. The hypothesis is that total revenue per well varies directly with water used and varies inversely with the square of water used.

$$TR = aw_t - bw_t^2$$

Here intercept is assumed zero because in irrigated land, without water, revenue is zero.

Given, the diversity of crops grown in the study area, it is not practically feasible to estimate individual production function and then plugging the production function coefficient into the model. Therefore water revenue function was estimated instead of production function.

Total Cost: Another important input for the model is the total cost which is estimated using formula

$$Kh_t w_t$$

where,

k = electricity cost to lift one ha-cm of water by one meter 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 through one meter was found to range between 0.5 to 0.6 kWh [13] in the central Gujarat. Yet in other study carried out in Mehsana area, 0.38 kWh of electricity was required to pump 1m^3 of groundwater [14]. Both the studies are based on pumping depths, pump capacities etc. Based on both the studies, the power required to lift one ha-cm of water through one meter was worked out to be Rs 0.04185 kWh.

Recharge(R)

$$R = R_c A R_f$$

R_c- Recharge coefficient ($0 < R_c < 1$)
A-Area of ground water basin per well in acres.
R_f-Rainfall (inches). Here, recharge coefficient of 0.20 is taken for the study area with sandy loam soil. This figure was arrived by using official estimates of gross annual recharge; the geographical area and the average (spatial) mean annual rainfall values.

Pumping Lift: It is the distance from land surface to the water table or the depth at which the pump is placed in the well. It is obtained from primary data of the pump placement depths of the farmers. A close approximation to this is the average depth of pump placement from the earth.

Area of Aquifer per Well: The area of aquifer per well is approximately obtained as

= Total Land holdings/Number of functioning wells.

Estimation of Net Benefit under Myopic (No Control): The path under myopic extraction was estimated by maximizing the net benefit per annum subject to the water availability and other constraints. The resulting water balance is introduced as the initial water availability for the next year and the recharge and return flows during the year were added to the initial water balance to estimate the total water availability in current year. This procedure is repeated for all the years of horizon. The individual year wise net benefit was discounted and summed up to estimate the sum of present value of net benefits over the entire period.

Myopic rule

Marginal benefit = Marginal cost

$$a - 2bw_t = Kh_t$$

or

$$W_t = B_0 - B_1 h_t$$

where $B_0 = a/2b$ and $B_1 = K/2b$

Software: The data were computerized using Microsoft Excel. The statistical analysis was performed using Microsoft excel. The optimal control model was implemented using the solver option available with Microsoft excel.

Economic and Hydrological Parameters of Model: 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 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 area of aquifer per well approximately as total land holdings by number of functioning wells, 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 Mehsana as compared to Banaskantha district due to deeper water level. The specific yield or storativity is the volume of water that an aquifer releases from storage per unit surface of aquifer per unit decline of the water table [15]. The values of the specific yield range from 0.01 to 0.30 (1 to 30%). 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 model we take average specific yield of 7.5 per cent for Banaskantha district. The hydrological data used in model is as per the data of Ground Water Resources Development Corporation (GWRDC), Gujarat state.

Recharge coefficient 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. Groundwater return flow coefficient (θ) is the fraction of applied groundwater returning back to aquifer. In this case, θ is taken as zero, because presently, the farmers of the North-Gujarat region are drawing water from the C and D zones of the 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.

Table 1: Economic and Hydrological parameters of the OCT model

S.No	Constants and variables	Mehsana	Banaskantha
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	0
8.	k = Cost of electrical power (Rupee per ha-cm, per metre of lift)	0.00108	0.00108
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	0.020.02	
12.	Discount factor (=1/(1+0.02))	0.98	0.98

OCT 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 meters (Figure 1). The maximum limit of 366 meter 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 9963 ha-cm. 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 not be high 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 2655 ha-cm and the allocated quantum goes on decreasing and reaches to 200 ha-cm in 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 rule works out to the tune of Rs. 1,08,99,365 which is higher by Rs. 18,65,444 than the PVNB under myopic rule (Rs 90,33,921). The water extraction and the PVNB under two regimes shown in Figure 1 and 2, respectively are arrived when the power cost is taken at the rate of Rs. 0.5 per kWh (Case 1).

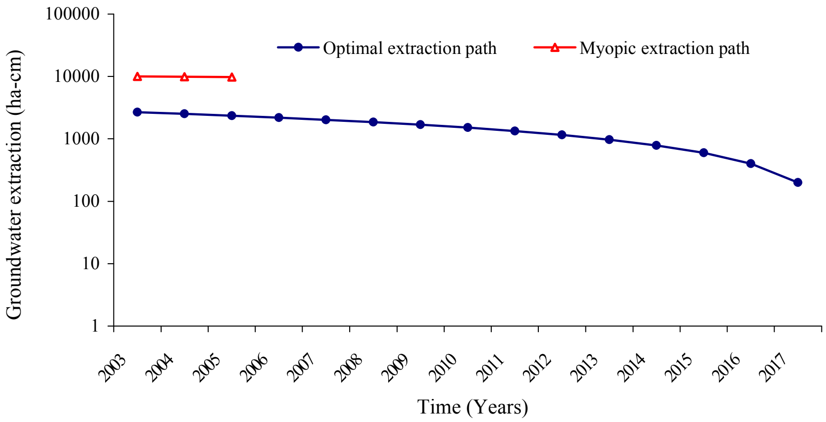


Fig. 1: Groundwater extraction paths under optimal and myopic regimes in Mehsana
Initial pump lift = 138 meters; Maximum pump depth = 366 meters
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2%

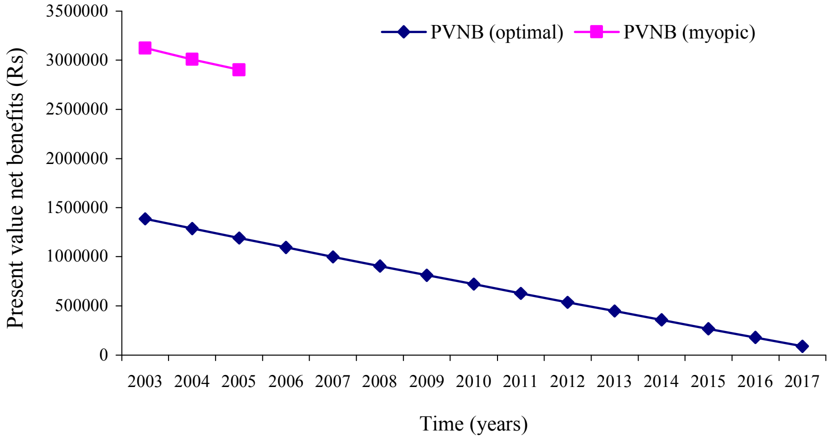


Fig. 2: Present value net benefit curves under optimal and myopic regimes in Mehsana
Initial pump lift = 138 meters; Maximum pump depth = 366 meters
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2%

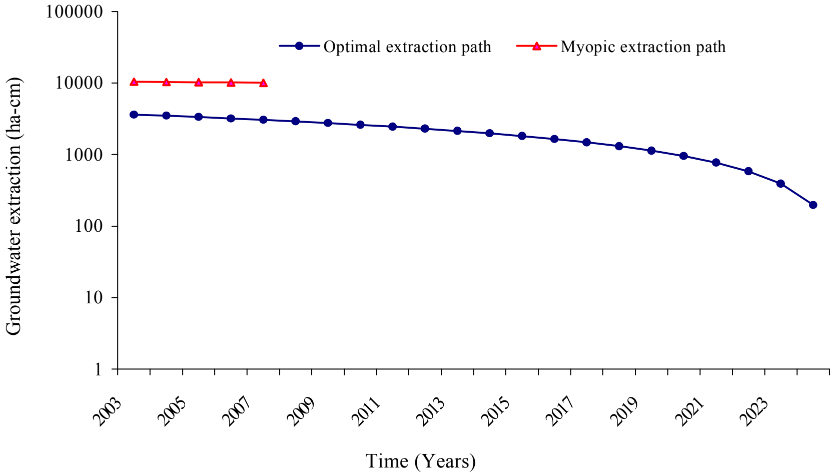


Fig. 3: Groundwater extraction paths under optimal and myopic regimes in Mehsana
Initial pump lift = 138 meters; Maximum pump depth = 610 meters
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2%

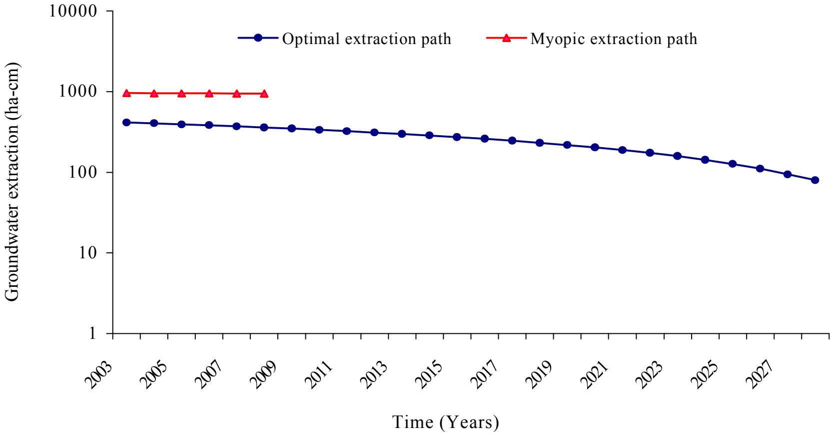


Fig. 4: Groundwater extraction paths under optimal and myopic regimes in Banaskantha
Initial pump lift = 79 meters; Maximum pump depth = 198 meters
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2%

On increasing the power cost from Rs 0.5 per kWh to Re 1.0 per kWh (Case 2), the water extraction path curve as well as pumping lifts and PVNB curves change. The life of well(s) increases by one more year under the optimal regime, whereas it remains same in myopic regime. The water extraction starts from 2632 ha-cm in the initial year, which is slightly lower by 23 ha-cm when power cost is considered at the rate of Rs 0.50 per kWh. Though the well life increases by one year in second case but the total PVNB for 16 years period gets reduced by Rs. 1,23,594 as against Case-1, which is directly attributed to increase in the power cost. In Case 1 and 2, 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 (Case-3), 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 3611 ha-cm in the initial year and goes on continuously declining in the subsequent years with 198 ha-cm in 22nd year, beyond which the extraction adopts steady state path. The graphs of water extraction paths at 610 metres pump depth constraint is given in Figure 3.

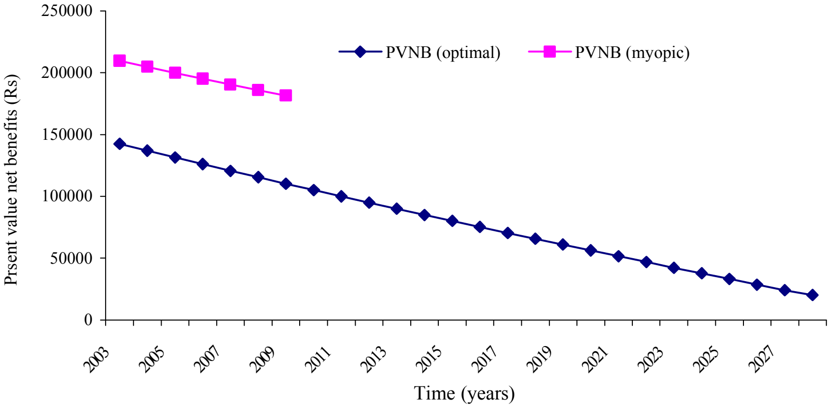


Fig. 5: Present value net benefit curves under optimal and myopic regimes in Banaskantha
Initial pump lift = 79 meters; Maximum pump depth = 198 meters
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2%

OCT 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 beyond which farmers cannot move 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 curves for water extraction and PVNB under myopic and optimal regime for Banaskantha district are depicted in Figure 4 and 5, respectively. It is observed from the graph that the life of well(s) lasts for 6 years under myopic regime. The myopic water extraction path starts from 957 ha-cm in the beginning and reduces to 947 ha-cm in the 6th year. The total PVNB of Rs.11,85,591 could be realized. As against the myopic regime, optimal extraction rule extends the well life upto 26 years with optimal water extraction path starting from 415 ha-cm 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 curve goes on declining and reaches to a level of 80 ha-cm in the 26th year before reaching to steady state path. Total PVNB realized under optimal rule (Rs 20,51,530) is higher Rs 8, 65,939 than the total PVNB realized under myopic rule.

There is no much change in the water extraction path as well as PVNB when power cost is increased to Re. 1 per kWh. The life of well(s) remains same under both the regimes. The increase in the power cost slightly shifts the water extraction path below. Total PVNB under optimal rule decreases by Rs 32,494. Comparing the water extraction curves of the two districts, 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 PVNB 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 previous sections, the specific yield varies from 2 to 13 per cent in the area. The specific yield of aquifers is generally found less for hard rock 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 PVNB and bore-well life. At a specific yield of 2 per cent, the well life was found 14 years under optimal regime and only two years under myopic regime. On the other extreme value of specific yield (13%), the well life was found to last for 35 years under optimal regime. The water extraction path under optimal and myopic regimes at two specific yield levels is given in Figure 6. The water extraction path under optimal regime at 2 per cent specific yield starts with 261 ha-cm in initial year and reaches at withdrawal level of 80 ha-cm in the 14th year, whereas optimal water extraction path at 13 per cent specific yield starts at 502 ha-cm and goes on declining steadily for subsequent periods, ending at withdrawal level of 80 ha-cm (steady state extraction rate) in the 35th year. It is thus, concluded from the graphs

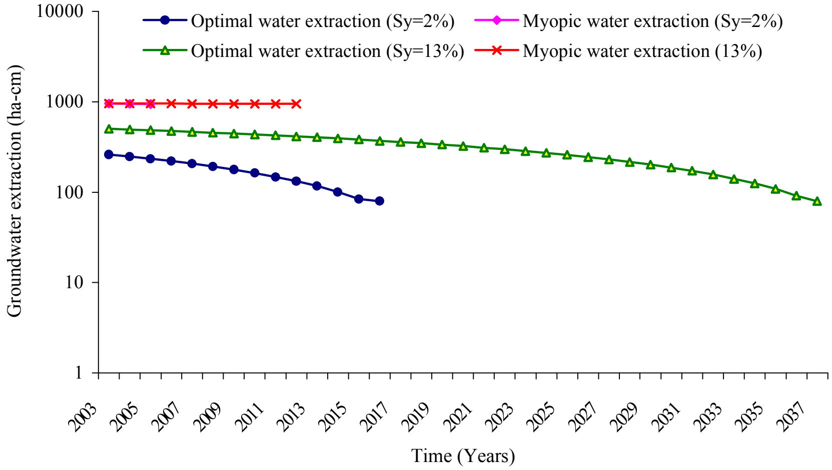


Fig. 6: Groundwater extraction paths under optimal and myopic regimes in Banaskantha at two specific yield levels
Initial pump lift = 79 meters; Maximum pump depth = 198 meters
Power cost (k) = Rs 0.5 per kWh; Discount rate = 2%; Specific yield (Sy) = 2 to 13%

that specific yield of an aquifer has a greater bearing on borewell yield and well life. The difference in the total PVNB realized under optimal regime at two specific yield levels was very high (Rs 21,44,153). The results are supported by the finding of Renshaw [16] 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.

The conclusion emerged from the optimal extraction is that the benefits to optimal groundwater management were higher than the myopic or no control regime. An increase in the power cost reduces the water extraction as higher power tariff increases the marginal cost of pumping and induces the farmers to reduce the over pumping.

OCT Sensitivity for Power Cost: The electricity supplied to farmers is at a highly subsidized rate ranging between Rs 0.50-0.70 per kWh as against the supply cost of Rs 2.50-3.80 per kWh. The new connections to 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 Rs 0.70 per kWh. The sensitivity analysis was carried out at different power cost rates for extraction of groundwater, keeping other parameters of the model constant, to see the change in the benefits realized from groundwater management through OCT rule and effect of different tariff rates on the behaviour of groundwater extraction paths over the time. The results of sensitivity analysis are presented in Table 2 and 3. In Table 2, the well life under myopic regime is considered as three years for Mehsana, inspite of crossing maximum pump depth constraint which imposes the break on the life of well. Likewise, Table 3, depicts the sensitivity analysis for Banaskantha district. The graph of optimal extraction paths at different power tariff rates is shown in Figure 7 and 8 for Mehsana and Banaskantha districts, respectively. 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 initial years. However, the higher pumping costs have found no effect on borewell life under myopic rule. The benefits realized from groundwater management through optimal extraction are significantly higher for both the areas under different tariff rates.

An important finding from the curves of optimal water extraction paths at different pumping costs was emerged with regard to inter-temporal allocation of water or inter-generational equity. It is evident from the graph that the water extraction paths at higher tariff rates start from lower water extraction levels during initial years and then all the curves converge over a time (i.e, 2011th year for Mehsana and 2016th year for Banaskantha). After that, the water extraction curves at higher pumping costs get over and above to that at lower tariff rates. Hence, in latter years, the water allocated would be more at higher tariff rates to that of lower tariff rates. Likewise, the graphs of PVNBs were observed to depict the same picture.

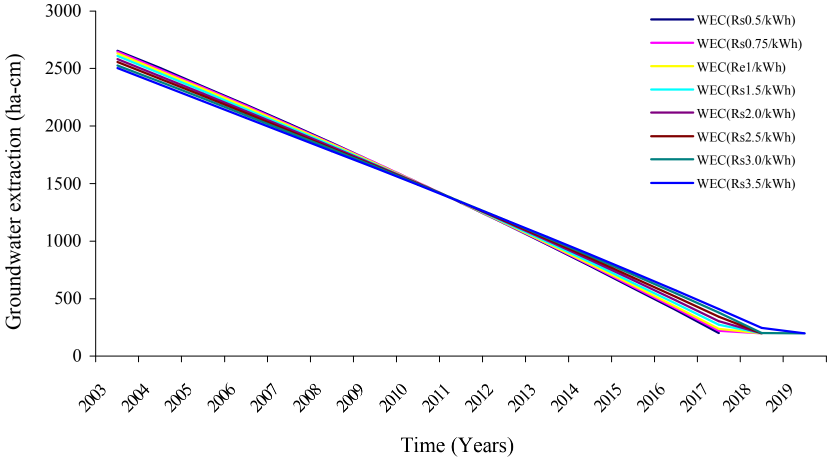


Fig. 7: Optimal groundwater extraction paths under different tariff rates for Mehsana
Initial pump lift = 138 meters; Maximum pump depth = 366 meters
Power cost (k) = Rs 0.50-3.5 per kWh; Discount rate = 2%

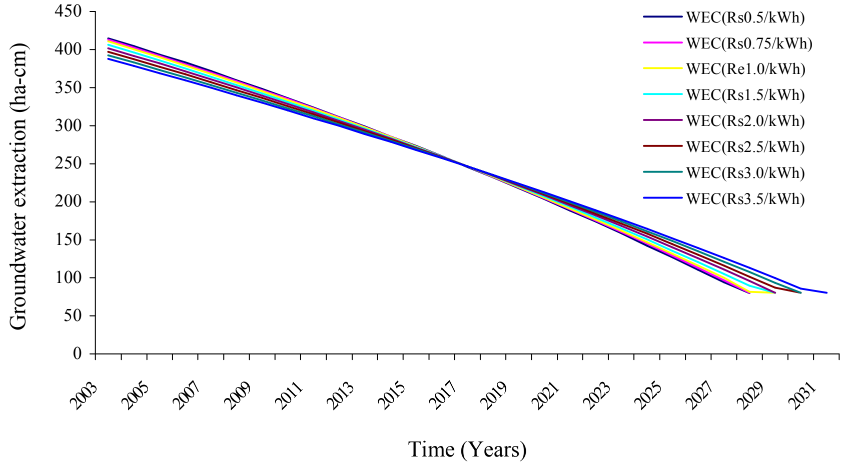


Fig. 8: Optimal groundwater extraction paths under different tariff rates for Banaskantha
Initial pump lift = 79 meters; Maximum pump depth = 198 meters
Power cost (k) = Rs 0.50 to 3.5 per kWh; Discount rate = 2%

Table 2: Benefits from groundwater management through optimal control for Mehsana (Sensitivity analysis)

	Optimal extraction			Myopic Extraction			
Power Tariff	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Benefits from GWM (Lakh Rs)
Rs. 0.50/kWh	15	108.99	22184	3	90.34	31077	18.65
Rs. 0.75/kWh	16	108.82	22382	3	88.74	30798	20.08
Rs. 1.00/kWh	16	107.76	22385	3	87.10	30511	20.65
Rs. 1.50/kWh	16	105.74	22382	3	84.09	29970	21.66
Rs. 2.00/kWh	16	103.70	22382	3	81.11	29426	22.59
Rs. 2.50/kWh	16	101.65	22382	3	78.23	28889	23.42
Rs. 3.00/kWh	17	100.34	22580	3	75.44	28358	24.90
Rs. 3.50/kWh	17	98.27	22580	3	72.74	27833	25.54

Table 3: Benefits from groundwater management through optimal control for Banaskantha (Sensitivity analysis)

	Optimal extraction			Myopic Extraction			
Power Tariff	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Benefits from GWM (Lakh Rs)
Rs. 0.50/kWh	26	20.52	6739	6	11.86	5714	8.66
Rs. 0.75/kWh	26	20.36	6740	6	11.71	5676	8.65
Rs. 1.00/kWh	27	20.39	6820	6	11.56	5640	8.83
Rs. 1.50/kWh	27	20.07	6820	6	11.27	5568	8.80
Rs. 2.00/kWh	27	19.75	6820	6	10.99	5496	8.76
Rs. 2.50/kWh	28	19.61	6900	6	10.71	5426	8.90
Rs. 3.00/kWh	28	19.29	6900	6	10.44	5356	8.85
Rs. 3.50/kWh	29	19.13	6981	7	11.60	6122	7.54

OCT Sensitivity at Different Discount Rates: A major debate in natural resource economics centres on the determination and use of methodology in discounting and selection of a discount rate. If the economies were optimal and all the society's wishes were reflected in financial markets, the determination of discount rate would be straight forward. It would be related to some financial rate such as interest on bank deposits. However, the economy is "non-optimal" or "second best" [17]. Furthermore, determining society's preference and how these are reflected through government spending is difficult and the subject of much controversy in economic literature [18]. Arguments center on whether discounting should occur at a social rate of time preference (the social discount rate) or at a marginal rate for private investment (the private discount rate). It is generally argued that society is more concerned with the future, especially with negative natural resource and environmental consequences, than the individual or private firms. Consequently, the social discount rate will be lower; some writers, however, support the notion that private and social rates do not differ [19, 20]. In case of natural resources, however, private decisions are central to the problem of resource exploitation [21].

Sharma *et al* [22] found the social discount rate in India to be 2.0 per cent using an annual growth rate of per capita real consumption of 1.5 per cent. This compares to the estimates of the social discount rates of slightly over 4 per cent in the United States and Canada using the same methodology [23]. The lower rate in India reflects the country's population pressure, natural resource scarcity and low levels of capital accumulation. A higher growth rate in consumption would result in a higher social discount rate. The disadvantage of using a predefined interest rate is that it may differ from the social discount rate, causing natural resource decisions to be less than optimally efficient.

Discount rates can also be limited in their ability to account for inter-generational equity [24, 25]. This notion refers to the rights of future generations to use resource relative to the present generations. Notions of inter-temporal justice require the present generation to consider equally those demands of the future. The OCT model was run at a discount rate of 2 per cent in all the above combinations. In the foregoing discussion, it was observed that it is too much difficult to determine the proper discount rate at which natural resources should be discounted. Hence, the sensitivity analysis was again carried out to see the change in the natural resource allocation over the time horizon, *ceterus paribus*, at different discount rates.

The water extraction paths were obtained by running OCT model at different discount rates, ranging from 2-7 per cent, which are depicted in Figure 9 and 10 for Mehsana and Banaskantha districts, respectively. It is observed from the graphs that lower interest rate encourages resource conservation and keeps more regard for the future generations. The results of sensitivity analysis are shown in Table 4 and 5 for Mehsana and Banaskantha districts, respectively. It was also found from the figures as well as tables that the well life decreases at higher interest rates, as the higher interest rates encourage the exploitation of resource. Furthermore, benefits from groundwater management were found to decline with the increase in interest rate. The sensitivity results obtained at different interest rates were found in accordance with the studies of Bredehoeft and Young [26] and Fienerman and Knapp [27].

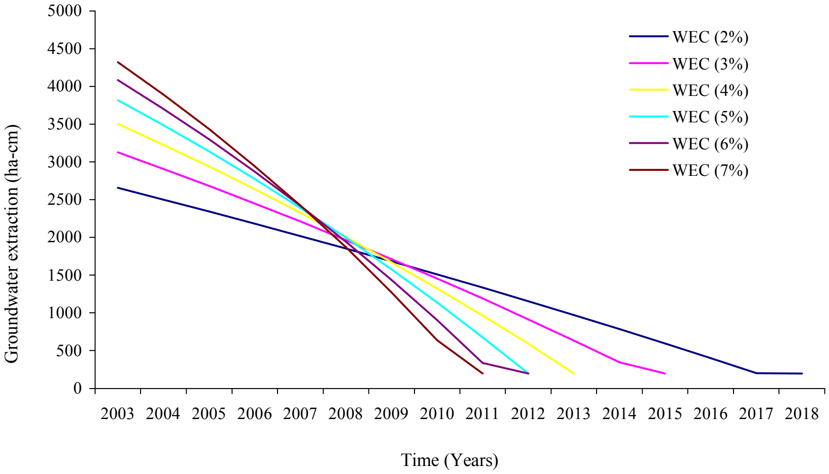


Fig. 9: Optimal groundwater extraction paths under different discount rates for Mehsana
Initial pump lift = 138 meters; Maximum pump depth = 366 meters
Power cost (k) = Rs 0.50 per kWh; Discount rate = 2 to 7%

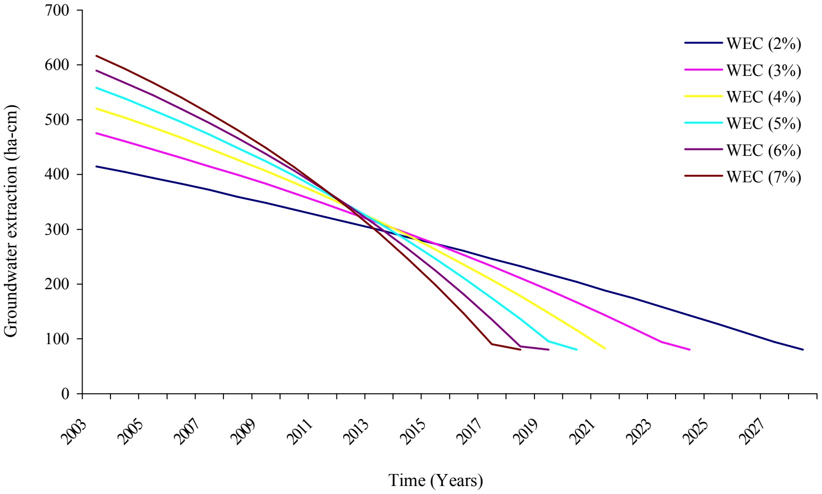


Fig. 10: Optimal groundwater extraction paths under different discount rates for Banaskantha
Initial pump lift = 79 meters; Maximum pump depth = 198 meters
Power cost (k) = Rs 0.50 per kWh; Discount rate = 2 to 7%

Table 4: Benefits from groundwater management through optimal control for Mehsana (Sensitivity analysis)

	Optimal extraction			Myopic Extraction			
Discount Rate	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Benefits from GWM (Lakh Rs)
2%	16	109.85	22382	3	90.34	31078	19.51
3%	13	103.06	21789	3	89.49	31078	13.57
4%	11	98.18	21393	3	88.66	31078	9.52
5%	10	94.71	21196	3	87.85	31078	6.86
6%	10	92.35	21196	3	87.06	31078	5.30
7%	9	89.63	20998	3	86.28	31078	3.34

Table 5: Benefits from groundwater management through optimal control for Banaskantha (Sensitivity analysis)

	Optimal extraction			Myopic Extraction			
Discount Rate	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Well life (Years)	PVNB (Lakh Rs)	Water withdrawal (ha-cm)	Benefits from GWM (Lakh Rs)
2%	26	20.52	6739	6	11.86	5714	8.66
3%	22	18.24	6418	6	11.58	5714	6.66
4%	19	16.61	6179	6	11.32	5714	5.29
5%	18	15.55	6096	6	11.06	5714	4.49
6%	17	14.66	6017	6	10.82	5712	3.84
7%	16	13.89	5937	6	10.59	5712	3.30

CONCLUSION

'Water' is one of the most important resources of a country. The resource becomes more important and central point of policy and development when its economy is typically an agrarian based with about two-thirds of its population derive their livelihood from farming occupation. India ranks first in irrigated agriculture with 21.7 per cent of the total global irrigated area. Between 55 and 60 per cent of India's irrigated lands is supplied water from groundwater. While groundwater development has had important implications for the economy, the over use of it is emerging as a major concern. Groundwater plays a critical role in the agricultural economy of western India. During the last few decades, groundwater development in the area has been taking place in an exponential manner. Over-exploitation and mismanagement of the resource have led to depletion and degradation of groundwater aquifers. Mehsana and Banaskantha districts of North Gujarat, western India are the most severely affected. The heavily subsidized power supply on flat tariff rate to lift groundwater is one of the major factors for the chronic over draft. To sustain the resource in the region, the optimal control theory framework is applied which shows optimal extraction path over the time horizon. The benefits from the groundwater management under optimal control regime are higher to 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. Optimal rates of groundwater pumpage over the time horizon were sensitive to increasing energy costs. Sensitivity analysis revealed that the lower interest rates take more care of inter-generational equity of the resource. Groundwater basins were found to react differently to alternative economic and hydrologic parameters.

The results of research study emphasize on groundwater regulation through pricing regime on pro-rata basis and phased withdrawal of energy subsidy. For the long term sustainability of resource in the region as well as to increase the water use efficiency, subsidies on water and energy saving technologies may be encouraged by the government.

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