Sustainable path of extraction of groundwater for irrigation and Whither Jevons paradox in hard rock areas of India

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Selected Paper prepared for presentation at the 2015 AAEA & WAEA Joint Annual Meeting, San Francisco, California, 26-28 July 2015

Sustainable path of extraction of groundwater for irrigation and Whither Jevons paradox in hard rock areas of India[1]

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Abstract

More than 65 percent of the geographical area in India comprise the hard rock areas where the recharge of groundwater is meagre (5 to 10% of the rainfall), while the extraction for irrigation has exceeded the recharge in several areas, leading to secular overdraft. Neither the farmers nor the policy makers have paid adequate attention towards sustainable path of extraction. This article is a modest attempt to demonstrate the sustainable path using Pontryagin's optimal control application in order to impress upon the policy makers the need for groundwater regulation. This study is based on primary data obtained from farmers with groundwater irrigation in hard rock areas of Deccan Plateau. Results indicated that discounted net benefit realized per well at steady state equilibrium on borewell recharge farms was Rs. 97201 ($1620) reached in 25 years; on drip irrigation farms cultivating broad spaced crops was Rs. 163347 ($2722) reached in 17 years. Thus, farmers who recharge borewell on the farm realize the service of borewell for larger number of years realizing sustainable incomes than their counterparts using drip irrigation, without performing on farm recharge. However the economic performance of both types of farms are substantially superior over farms adopting myopic extraction. The study disproved the operation of Jevons paradox.

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[1] Paper submitted for consideration for presentation at AAEA Annual Meeting in San Francisco, CA July 26–28, 2015, requesting for travel grant for the senior author from Developing country participant. This article is from the PhD thesis of the senior author entitled "Economics of coping mechanisms in groundwater irrigation: role of markets, technologies and institutions", Unpublished PhD thesis, submitted to the Department of Agricultural Economics, University of Agricultural Sciences, Bangalore, July 2014

Preamble

With increase in the demand for food, horticulture crops and dairy products, India's dependence on water resources is increasing exponentially, more so on groundwater resources, since surface water resources are limited by their proximity and seasonal nature, except for rivers in Indo Gangetic plains. Currently, India is the largest pumper of groundwater in the world next to United States and Europe. India pumps twice the groundwater pumped in the US, and six times that pumped in the Europe Union. With 65 per cent of the geographical area marked as hard rock areas, the rate of recharge ranges from five to ten percent of the rainfall. In this regard, efforts are being made towards soil and water conservation through Watershed Management Projects of State and Central Governments such as Sujala, National Watershed Development Projects, as an ongoing process. However, there have been massive initial and premature well failures in hard rock areas of Karnataka, rendering virtual disappearance of dug / open wells. Only in exceptional circumstances dug /open wells still functioning can be found, else, a majority of them have failed and farmers continue to burn their fingers by investing in irrigation wells including borewells as the depths of drilling have surpassed 1000 feet in many areas and the investment per borewell have exceeded Rs. 0.3 million ($50000). In many areas, drip irrigation is slowly catching up as a response to economic scarcity of groundwater and labor.

This study is a modest attempt to explore the sustainable path of groundwater extraction for irrigation in hard rock areas of India and to test the existence of Jevons paradox, since the area under drip irrigation is increasing over time. The major hypothesis of this study is that the economic benefits from supply side groundwater intervention such as on farm groundwater recharge efforts as well as the institution of sharing well water outweigh the economic benefits from demand side groundwater intervention such as use of drip irrigation. Due to drip irrigation, whether there is efficiency in natural resource use, or further over-exploitation is a concern. In this regard, it is hypothesized that the farmers using drip irrigation on the one hand achieve efficiency in water use, but on the other hand, expand area irrigated due to saved groundwater.

Sampling

The study focuses on the resource economics of supply side of groundwater recharge technologies and compares with parallel demand side technological efforts of using drip irrigation in Central Dry Zone of Karnataka, India (Chitradurga district). Accordingly, a snow ball sample of 30 farmers who have undertaken artificial on-farm borewell recharge and a random sample of 30 farmers with drip irrigation for broad spaced crops (arecanut, coconut, banana, pomegranate and other crops) were selected. The data on costs incurred and returns realized from various crop and livestock enterprise were elicited for the year 2012. The partial budgeting technique was employed to assess the economic impact of borewell recharge per well per year.

Methodology

Following Fienerman and Knapp (1983), Micha and David (1980) and Chaitra and Chandrakanth (2005), the inverse demand function of groundwater is given by

$$P_w = a - b\, w_t \qquad \ldots\ldots\ldots\ldots (1)$$

Where, P_w is the pumping cost or price per acre inch or ha cm of groundwater, w_t is the volume of groundwater extracted or pumped from an irrigation well in acre inches, a and b are the parameters of inverse demand function.

Gross revenue or the total benefit from groundwater use is given by the area under the inverse demand curve, expressed as:

$$GR_t = \int (a - bw_t)\, dw_t = aw_t - bw_t^2/2 \qquad \ldots\ldots\ldots (2)$$

Here, GR_t is the returns to groundwater obtained as (annual gross revenue from all crops on the farm cultivated using groundwater minus all costs of cultivation except cost of groundwater). The gross revenue function is estimated as a quadratic function by regressing returns to groundwater on volume of groundwater extracted. The hypothesis for estimating revenue function is that revenue per borewell varies directly with groundwater used and varies inversely with the square of groundwater used and hence with zero intercept. The coefficients ‘a’ and ‘b’ are the regression parameters of revenue function. As the crops grown by the sample farmers are diverse, revenue function (from all crops) on groundwater used (on all crops) is estimated, instead of estimating production function for each crop.

Cost function

The cost of pumping groundwater from the aquifer to the surface is assumed to be a linear function of pumping height and is represented as:

$$TC_t = (I + E * P_t)\, w_t \qquad \text{.............}(3)$$

Where, TC_t is the total cost of groundwater which includes irrigation cost and energy cost, w_t = total groundwater extracted in acre inches, P_t = depth of the groundwater table which is equal to the vertical distance between ground level and pump placement inside the borewell. It represents the initial pumping height or lift, P_t at t=0 and E is the estimated energy cost of lifting one acre inch of groundwater by one inch up.

Farmers are not paying for electricity as this is a subsidy. Studies conducted in the Department of Agricultural Economics, indicated that in order to pump on acre inch of water 80 kilo watt hours of electricity were used (Chandrakanth *et al.* 2001). According to WM Shivakumar (Karnataka Electricity Board, Research Wing, Bangalore, lecture presented to Department of Agricultural Economics, UAS Bangalore, dated 19/10/2004), the electricity used by irrigation well is 6532 kilo watt hours per year. Usually irrigation well yields around 1500 gallons per hour. With an estimated six hours of pumping per day for about 250 days in a year, the total water extracted is around 100 acre inches per well. Thus 65 kilo watt hours are used to lift around 100 acre inches of water, according to this estimate. Thus the electricity used to lift one acre inch of groundwater ranges from 42 to 65 kilo watt hours. The cost of generation of power varies according to the source, ranging from 8.78 paise per kilo watt hour from hydro electric power to Rs. 7.6 per kilo watt hour from Thermal, the average being Rs. 3 per kilo watt hour, considering an average of 50 kilo watt hours to lift one acre inch of groundwater, it costs Rs. 150.

I is the total cost of irrigation groundwater, which comprises of both variable and fixed cost component.

$$\mathrm{I} = \left(\frac{\mathrm{TAC}}{\mathrm{TWU}}\right) \times \left(\frac{1}{\mathrm{P}_{\mathrm{t=0}}}\right) \qquad \text{……... (4)}$$

Where, TAC is the total amortized cost of irrigation investment on all borewell, TWU is the total groundwater extracted from all the borewells in acre inches. Dividing TAC by TWC gives the irrigation cost per acre inch of groundwater and this is further divided by initial pumping lift to get I. The economic and hydrological parameters essential for optimal control theory is provided in Table 1.

Following (Micha and David, 1980 and Feinerman and Knapp, 1983), the hydrological behavior of groundwater is given by the difference equation which relates depth of groundwater table to time. The corresponding differential equation is derived by equating groundwater outflows and groundwater inflows to the aquifer.

$$\mathrm{P}_{\mathrm{t+1}} - \mathrm{P}_{\mathrm{t}} = \frac{\{(1-\theta)\mathrm{w}_{\mathrm{t}} - \mathrm{R}\}}{\mathrm{AS}} \qquad \text{……… (5)}$$

Where, $\mathrm{w_t}$ is the extracted groundwater in farming (acre inches), $\mathrm{w_t} * \theta$ is the return flow from the applied groundwater in farming in acre inches, so that $(\mathrm{w_t} - \mathrm{w_t} * \theta)$ represents groundwater used in the farming (acre inches). ‘R’ is the recharge from rainfall in acre inches. R is computed using the formula ‘R’ = R_c *A * R_f (equation 6) where ‘R’$_c$ is the recharge coefficient which ranges from 0 to 1, ‘A’ refers to aquifer area in acres and ‘R_f’ refers to rainfall in inches. Groundwater recharge is assumed to be eight per cent across all categories of sample farmers. The extraction of groundwater is greater than recharge if the difference $\{(1-\theta)w_t - R\}$ is positive. W_0 is the initial groundwater extraction in the year 2013 in acre inches. P_{t+1} is the depth of groundwater table in the next year t+1, P_0 is the initial depth of the groundwater table in the year 2013 t=0.

Burt (1966) found that in a shallow groundwater table situation, the recharge is probably a decreasing function of height. In the case of over exploited aquifers, the groundwater table is at a critical level at which height does not make much difference on recharge rates.

Total recharge from rainfall is estimated as:

$$R = F \times R_f \times A \qquad \text{……... (6)}$$

Where, R is the total recharge of groundwater to the aquifer from rainfall (acre inches), F is the annual rainfall (inches), R_f is the recharge coefficient of rainfall taken as eight per cent.

θ is the return flow coefficient which represents the percentage of groundwater applied for the crops which percolates back to the aquifer considered as two per cent (Chaitra and Chandrakanth, 2005).

A is the area of the aquifer or recharge area, which is approximately the total geographical area of the representative sample village.

S is the storativity coefficient that indicates the groundwater holding capacity of soils in one cubic meter of mass considered as 2.5 per cent (Chaitra and Chandrakanth, 2005)

Sustainable path of extraction

The Pontryagin’s optimal control theory is used to derive the optimal path of extraction of groundwater, since at present all farmers are myopically extracting and hence the OCT path is derived. Hence the purpose is to demonstrate, the optimal path of extraction of groundwater and not to compare the existing path, since the existing path is non optimal due to farmers' myopia as reflected in high externality costs. OCT model is run under several assumptions as required to be made for relevant models.

The results of the optimal control path of extraction are applicable with the assumption that all the farmers in the aquifer will follow the optimal path. The Optimal control path of groundwater extraction for farmer who has undertaken artificial borewell recharge, indicates that the steady state equilibrium is achieved over 25 years since the steady state pumping height is attained. In the case of farmers with borewell irrigation with drip irrigation for broad spaced crops the steady state is attained at 17 years. The discounted net benefit realized per well at steady state equilibrium on borewell recharge farms was Rs. 97201 and on drip farms serving broad spaced crops was Rs. 163347 (Table 2). The farmers who performs on farm borewell recharge enjoys longer well life which is almost twice of that on drip farms.

Sustainable groundwater extraction volume and depth for drip farms serving broad spaced crops in Central Dry Zone

Wt = $-5004.65 + e^{0.0199t} + 6914.2\, e^{0.00000468t} + 4490.44$

Pt = $3600 + 0.001071[-251489.95(e^{0.0199t} - 1) + 1477393162\, (e^{0.00000468t} - 1)]$

Sustainable groundwater extraction volume and depth for farms with on-farm borewell recharge in Central Dry Zone

Wt = $-4657.77 + e^{0.0199t} + 7563.42\, e^{0.0000202t} + 3814.35$

Pt = $3660 + 0.00133[-234058.79(e^{0.0199t} - 1) + 374426931\, (e^{0.0000202t} - 1)]$

Jevons paradox

Technology in general contributes to improved efficiency of input use. Further, this should result in overall conservation of the scarce input. This phenomenon was seen in the case of rise in the price of fossil fuels during 1973. The rise in the price of fossil fuels results in two types of response over time. The short run response was from users of vehicles, who reduced the travel by cutting down on fossil fuel expenditure. The long run response was from manufacturers of vehicles, who drastically brought in technological improvements in the size of vehicles and contributed to increase in efficiency of use of fossil fuel. However, the increase in efficiency of fossil fuel use was also coupled with the reduction in the cost of vehicles. This enabled a large number of consumers to purchase new small sized efficient vehicles, at the cost of over utilization of fossil fuel resource rather than its conservation, the Jevons' Paradox (JP).

With the improvement in groundwater efficiency due to the adoption of drip irrigation / micro irrigation in farming, leads to 'more crop per drop' – i.e. higher output can be obtained per unit volume of groundwater. In economic terms, this can be translated as higher net return per rupee value of groundwater. This results in groundwater use efficiency as well as sustainable use. According to Jevons Paradox, the technological improvements in the form of "efficiency" can also result in both intensive / extensive cultivation. Intensive cultivation refers to savings in groundwater due to water use efficiency and extensive cultivation refers to enhancing the area under cultivation, by using the 'saved' groundwater. Therefore groundwater use efficiency, in effect may result in 'over exploitation' or 'overdraft' of groundwater instead of 'conservation' or wise use. Thus, due to drip irrigation, efficiency of groundwater use which results in 'more crop per drop' or higher net return per rupee of groundwater, which should result in groundwater conservation, on the other hand, motivate farmer/s to expand the area under cultivation and in fact 'over draft' groundwater. Since, this hypothesis can then be tried for each crop output; it is convenient to estimate the groundwater use efficiency for the entire farm by considering gross returns per acre inch of groundwater or net returns per acre inch of groundwater as the dependent variable. Irrigation intensity measured as the quotient of gross irrigated area to net irrigated area, expressed in percentage, also reflects efficiency of groundwater use in physical terms, since marginal productivity of groundwater and elasticity of production have already been estimated to reflect economic efficiency.

In this study, JP was attempted by regressing groundwater used per farm (as volume of water in acre inches) as a function of adoption of drip irrigation (dummy variable to represent technology), gross area irrigated (to represent intensive cultivation) and the interaction of drip irrigation and gross area irrigated (represent extensive cultivation on the drip irrigation farms).

$$Y = \beta_0 + \beta_1 X + \beta_2 D + \beta_3 D^*X + \varepsilon \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1A)}$$

where,

Y represents the groundwater used per farm in acre inches

X represents the gross irrigated area per farm in acres per year. The Gross Irrigated Area (GIA) is the sum of irrigated area under all crops in all seasons.

D represents dummy variable for adoption of Drip technology. It takes the value 1 for farms with drip irrigation for both narrow spaced crops (in Eastern Dry Zone) and broad spaced crops (in Central Dry Zone) and takes the value 0 for farms without drip irrigation technology (in both the zones)borewells.

D*X represents the slope dummy variable representing interaction between gross irrigated area and the technology of drip irrigation. The coefficient β_3 captures the rate of increase in use of groundwater on drip irrigation farms due to increase in gross irrigated area resulting in extensive cultivation if any.

ε: represents stochastic error term

The presence of Jevons Paradox was also tested on regressing groundwater used per farm in acre inches on adoption of drip irrigation technology on farm (represented through dummy variable, dummy takes the value 1 for farms with drip irrigation and 0 for farms with farms without drip), net returns realized per farm in rupees and interaction slope dummy (dummy for drip and net returns per farm). The regression model is specified as below

$Y = \beta_0 + \beta_1 X + \beta_2 D + \beta_3 D^*X + \varepsilon$ ……… (1B)

where,

Y represents the groundwater used per farm in acre inches

X represents the net returns per farm in Rs.

D represents dummy variable for adoption of Drip technology. It takes the value 1 for farms with drip irrigation for both narrow spaced crops (in Eastern Dry Zone) and broad spaced crops (in Central Dry Zone) and takes the value 0 for farms without drip irrigation technology (in both the zones)borewells.

D*X represents the slope dummy variable representing interaction between net returns per farm and the technology of drip irrigation. The coefficient β_3 captures the rate of increase in use of groundwater on drip irrigation farms due to increase in net returns resulting in extensive cultivation if any.

ε: represents stochastic error term

Whither Jevons Paradox?

The Jevons Paradox estimation (model 1A) was statistically significant at one per cent level of significance. The adjusted coefficient of determination was 0.62. The regression coefficients for gross irrigated area and interaction slope dummy are statistically significant at five per cent level (Table 3). The results of regression indicated that the groundwater used per farm (in acre inches) increases by 9.13 acre inches for every one acre increase in gross area irrigated per farm and are statistically significant. The intercept dummy coefficient reflecting drip irrigation technology indicates that the groundwater use increases by 3.22 acre inches above the threshold or base level of groundwater use of 17 acre inches. However, the intercept dummy coefficient was not significant. For every acre of increase in gross irrigated area on drip irrigation farms, water used reduced by 3.76 acre inches and is statistically significant. The average gross irrigated area was 8.13 acres; hence, the amount of groundwater conserved is substantial. Therefore, the analysis disproves the hypothesis that Jevons' Paradox is operating in Eastern and Central Dry Zone of Karnataka with regard to use of groundwater resource.

The Jevons Paradox on drip irrigation farms was also tested by model 1B. The results indicated that the groundwater used could be reduced by 17 acre inches due to adoption of drip irrigation, which results in conservation of groundwater resource. However, for each rupee of net return realized on drip irrigation farms, the groundwater use increases by 0.0000187 acre inch. Since, the average net return per farm for farmers who have drip irrigation is Rs, 5, 91,974, the total groundwater use on drip irrigation farm increases by 11.06 acre inches (Table 4). However, the coefficient of the slope dummy variable which indicates the interaction of net returns with the adoption of drip irrigation (0.0000187) was statistically non-significant; the existence of Jevons Paradox cannot be proved. For each rupee increase in net return, the groundwater use increases by 0.0000727 acre inch on an average farm (with or without drip irrigation). Therefore, for the average level of net return of Rs. 3, 21,893 for control farmers with conventional irrigation, the groundwater use increases by 43.21 acre inches. Even the coefficient for net returns (0.0000727) was not statistically significant and hence, the existence of Jevons Paradox cannot be proved using net returns as an explanatory variable to reflect expansion of area on the farm. Thus, using both models, it was proved that there is no Jevons' paradox and hence, groundwater is being conserved on drip farms rather than expended. The results obtained are in contradiction with the results of Pfeiffer and Cynthia (2013). The likely reason for absence of Jevons paradox in drip irrigation in Central and Eastern Dry Zone of Karnataka would be the power (electricity) constraints as expressed by sample farmers during field survey.

Summary

The annual reciprocal negative externality in borewell irrigation was modest for farms borewell recharge (Rs.3386, USD 56) while it was substantial (Rs. 25223, USD 420) for those who did not have on farm recharge. The net return per rupee of cost of irrigation was substantial for farmers recharging their borewell (Rs. 8.17, USD 0.14). Drip irrigation shifted marginal productivity of groundwater by Rs. 4335 per acre inch (USD 72) from threshold level of Rs. 3814 per acre inch (USD 64). Due to on-farm borewell recharge the years of successful functioning of borewells was 26 years yielding annual net return of Rs 1,97,583 per well (USD 3293). Drip irrigation conserved groundwater and farmers did not expand their area irrigated Hence Jevons paradox is disproved. Pontryagin’s optimal groundwater extraction demonstrated that farmers who recharged borewells can extract groundwater for 25 years, a substantial welfare gain for the society.

Table 1: Economic and Hydrological parameters of optimal control model

Particulars	Borewell Recharge farms, CDZ	Drip farms serving broad crops, CDZ
Annual rainfall in inches	15.86	15.04
Natural recharge from rainfall in per cent	8	8
Storativity coefficient (S)	0.25	0.25
Percolation coefficient from crops in per cent (ϴ)	0.02	0.02
Real interest rate (r)	0.02	0.02
Total aquifer area (A)	2945	3657.6
Number of functioning well	120	200
Total recharge from natural rainfall in acre inches (R)	3738	4400.64
Initial pumping height in inches (P_0)	3660	3600
Initial water extraction in acre inches (w_0)	6720	6400
Annual energy cost per acre inch per inch of lift (E)	0.08	0.08
Annual irrigation cost per acre inch per inch of lift (I)	0.160	0.39
Annual gross revenue function parameter (a)	5130	10309
Annual gross revenue function parameter (b)	-5.50	-19.1

Exchange rate: 1 USD = Rs. 60 INR (Indian Rupees)

Table 2: Sustainable volume and depth of groundwater extraction across institutions and technologies

Categories of sample farmers	Steady state equilibrium attained at time t in years	Steady state level of ground water extraction (acre inches)	Steady state pump height (ft)	Net present value at the steady state equilibrium (Rs.)	Nominal investment on irrigation well per farm (Rs.)
Borewell recharge farmers	25	30.88	309	97201	494169
Drip farms connected to broad spaced crops	17	21.87	301	163347	406917

Exchange rate: 1 USD = Rs. 60 INR (Indian Rupees)

Table 3: Estimation of Jevons paradox in Drip irrigation (Dependent variable: Water used per farm in acre inches) (n=90)

Particulars	Magnitude
Intercept	17.65 (1.38)
Gross area irrigated in acres (X)	9.14** (4.99)
Dummy for Drip technology (D) (1 for drip farms,0 for control farms)	3.22 (0.23)
Slope dummy (Dummy for Drip technology * Gross irrigated area) [DX]	-3.76* (-1.98)
Adjusted R Square	0.62
F statistic	49.92**

Exchange rate: 1 USD = Rs. 60 INR (Indian Rupees)

Note 1: figures in the parenthesis indicate‘t’ value

* indicates 5 per cent level of significance of the estimates

** indicates 1 per cent level of significance of the estimates and the model

Note 2: $Y = \beta_0 + \beta_1 X + \beta_2 D + \beta_3 DX + \varepsilon$

Note 3: D represents dummy variable to capture the influence of drip technology, which takes the value ‘0’for farms with conventional irrigation and ‘1’ for farms with drip irrigation

Note 4: DX represent slope dummy which captures the rate of increase in water use per farm for every increase in area irrigated on drip farms

Table 4: Estimation of Jevons paradox in Drip irrigation (Dependent variable: Water used per farm in acre inches) (n=90)

Particulars	Magnitude
Intercept	51.76 * (3.71)
Net returns Per farm in Rs. (X)	7.27E-05 (1.91)
Dummy for Drip technology (D) (1 for drip farms, 0 for control farms	-34.76* (-2.16)
Slope dummy (Dummy for Drip* Net returns per farm) [DX]	1.87E-05 (0.47)
Adjusted R Square	0.45
F statistic	24.83**

Exchange rate: 1 USD = Rs. 60 INR (Indian Rupees)

Note 1: figures in the parenthesis indicate‘t’ value

*indicates 5 per cent level of significance of the estimates

** indicates 1 per cent level of significance of the estimates and the model

Note 2: $Y = \beta_0 + \beta_1 X + \beta_2 D + \beta_3 DX + \varepsilon$

Note 3: D represents intercept dummy variable to capture the influence of drip technology, which takes the value ‘0’ for farms with conventional irrigation and ‘1’ for farms with drip irrigation

Note 4: DX represent slope dummy which captures the rate of increase in water use per farm for every rupee increase in net returns per farm on drip farms

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