When cutting subsidies increases farmers' profits.

A case study of groundwater management in India

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Abstract

India is the largest groundwater user in the world and most of its aquifers are overexploited. Politically motivated subsidies for electric power in India led to a stronger decline of groundwater tables compared to the case of no subsidies. The farmers' dynamic decisions problem is formulated as a distributed optimal control problem since the age-structure of perennial crops has to be taken into account. For the solution of this problem the study proposes the predictive control approach to account of the farmers' strategic decision problem that operate either small, medium, and large-sized farms. Besides the dynamics of the water table the study takes account of the possibility that farmers invest in the depth of their well. Based on a case study of a region in Karnataka, India, the study determines and compares the efficiency and distributional effects of different policy instruments on private profits and social welfare. The complete elimination of subsidies cuts the aggregate farm benefits over 30 years by 5.4% but increases social benefits by 13.1%. Partial elimination of subsidies increases social benefits by very similar percentages. However, they allow reducing the government costs, and lead either to slight drop of the farm-benefits or some policies may even lead to an increase in the farm-benefits. This counter-intuitive result can be explained by the fact that some policies reduce the severity of the common tragedy problem by limiting the farmers' capacity to extract. Moreover, the partial elimination of subsidies favours farmers of small or medium-sized farms and disfavours farmers of large-sized farms. This result is important for evaluating the political acceptability and their potential for avoiding social unrest of new policies.

JEL Codes: Q18, Q25

Keywords: Groundwater management, water-energy nexus, subsidies, aquifer dynamics.

1. Introduction

Given the limited availability of global freshwater, predicted increases in future water consumption present a serious challenge for many countries.[1] The problem is especially severe in India, which is the largest groundwater user in the world, with an estimated usage of around 251 billion of cubic meters per year – more than double the extraction level of the United States or China (NGWA, 2016; Parikh, 2013) and more than a quarter of the worldwide extraction (World Bank, 2010). To accelerate the Green Revolution, the government constructed public tube wells and channels to deliver groundwater into the fields (Shah et al., 2007). Moreover, government subsidies for electricity, where farmers received power either free of charge or in exchange for the payment of a flat rate (Scott & Sharma, 2009), encouraged millions of farmers to construct private wells (World Bank, 2010). These subsidies led to a frequent overdraft of aquifers (Vaux, 2011), aggravated by the fact that aquifer depletion incentivises farmers to invest in deepening wells (Sayre & Taraz, 2019).

Currently groundwater extraction exceeds recharge in more than half of Indian wells (Shiao et al., 2015). If the current trends of groundwater extraction continue, the aquifers located in 60 percent of India's districts will reach a critical condition within 20 year, putting at risk at least 25% of the country's agriculture production (World Bank, 2019). The current pattern of groundwater extraction has many side effects. Firstly, it increased the burden of power subsidies on public finances. Secondly, albeit the payment of subsidies the financial performance of electricity has been stressed and led to the rationing of power supply. Thirdly, subsidies have also aggravated the problem of greenhouse gas emissions, since 14 million out of 20 million operating wells in India, rely on electricity for pumping (Prayas (Energy Group), 2018). Mishra et al (2018) estimated that groundwater pumping activity is responsible for 2 - 7% of CO_2 emissions of India (Mishra et al., 2018).

A field study by Fishman et al. (2016) shows that the capacity of voluntary approaches to address India's groundwater crisis is very limited. Thus, a substantial improvement of groundwater management necessarily has to include other policy instruments, like the pricing of electricity or quantitative restrictions on water extraction.

Our study determines the optimal behaviour of heterogeneous farmers that employ a common property aquifer to irrigate their agriculture land. The farmer's decision problem is modelled as a dynamic optimization problem. However, farmers also cultivate perennial crops whose yields vary with the age of the crop. Taking account of the age distribution of the perennial crops leads to the formulation of a distributed optimal control problem. The consideration of perennial crops is important

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[1] A forecast of the International Renewable Energy Agency estimates that the global freshwater demand will increase by 50% from 2015 to 2050 (Ferroukhi et al., 2015).

as it influences the farmer planning horizon. Besides the dynamics of the aquifer dynamics, we also allow for the possibility that farmers invest in well depth.

The objective of our study is to determine and compare the efficiency and distributional effects of different policy instruments on private profits and social welfare. For the evaluation of the different policy instruments, we use a case study of the Indian region of Karnataka. The model developed allows determining the privately and socially optimal intensive and extensive margin, i.e., the optimal allocation of land, labour, energy, water and fertilizer to a variety of crops. The unrealistic assumption of closed loop solutions that farmers fully commit to the optimal trajectory that is determined at the beginning of the planning horizon suggests analysing feedback loop solutions. They consider that each farmer takes the current state of the aquifer as a reference point for the determination of their current optimal behaviour. Feedback loop solutions are implemented by using the predictive control approach – a technique widely used in Operations Research (Dombrovsky et al., 2006; Ellis et al., 2014; Goodwin & Medioli, 2013).

The results of the study show that the complete or partial elimination of subsidies curb the extraction of the aquifer significantly. The complete elimination of the subsides leads to increases of 13% in the aggregate social benefits over 30 years but to a decrease of 5.4% in the aggregate farm benefits over 30 years. A partial elimination of the subsidies allows reducing the government costs and depending on the form and scale of the partial elimination, leads either to a slight drop of the farm benefits or even to an increase in the farm benefits.

This counter-intuitive result can be explained by the fact that certain reductions of the farmers' subsidies is overcompensated by cost savings. Subsidy-reducing policies lessen the severity of the tragedy of the common property since they increase the farmers' pumping costs per *m* of lift. Consequently, agricultural production and private agricultural profits decline. However, subsidy-reducing policies not only contribute a decline in agricultural profits but also to a reduction in the costs of well deepening and the overall pumping cost since farmers extract less water in comparison with the case of fully subsidized electricity prices. Thus, for some subsidy-reducing policies the decline in private agricultural profits is overcompensated by the decrease in the cost of well deepening and the overall pumping cost. In other words, for a specific range of reduced-price support of the electricity price private agricultural profits increase. Moreover, the results of the study show that the partial elimination of subsidies favours farmers of small or medium-sized farms and disfavours large farms. These two findings are important for the political acceptance of subsidy-reducing policies. The joint emergence of social and private gains may contribute to their acceptance and decrease the potential for social unrest. The finding of this study also offers a new direction for applied research and policy design since the determination of the range of reduction of subsidies where private and social benefits emerge is challenging.

The remainder of the paper proceeds as follows: Section 2 provides a review of the literature related to our study. Section 3 presents the structure of the model and its different elements. Section 4 describes the study area, data collection, calibration and parameterization of the model. For the policy analysis we define different policy instruments in Section 5, a numerical approximation method for solving the model in Section 6 and present the results of the policy analysis in Section 7. Section 8 evaluates the sensitivity of the results of the policy analysis with respect to variations of key parameters of the model. Section 9 compares and evaluates our findings with the findings of the previous literature. The last section closes the article with the main conclusions drawn from the analysis.

2. Literature review

Several approaches have been identified for groundwater management, that reach from the maintenance of current subsidies to a complete market solution (Kumar, 2005; Kumar et al., 2011; Tushaar Shah et al., 2012). In the first approach subsidies are considered as a means of intersectoral income redistribution between the non-agricultural and the agricultural sectors and efficiency considerations are not taken into account. In the second approach – the market solution – farmers face the full cost of electricity so that water is used more efficiently and there are incentives to adopt water saving irrigation technologies. There exist a considerable number of studies that compare flat rates with metered tariffs based on the amount of electricity used and confirm the responsibility of the former in the groundwater depletion problem (Kumar, 2005; Mukherji & Das, 2014; T. Shah & Chowdhury, 2017; Tushaar Shah et al., 2004; Tushaar Shah & Verma, 2008; Sidhu et al., 2020). However, the literature that analyses and compares the efficiency of different policies including full or partial elimination of subsidies, or the use of subsidies decoupled from the energy use is scarce. Similarly, the literature that analyses not only the efficiency of policies but also its distributional effects is scant. The latter aspect is highly important as it shed some light on the potential political acceptability of policies. The model proposed by Sayre and Taraz (2019) shares some important characteristics with our model. They assume that farmers grow a single generic crop and are myopic with respect to the impact of their pumping decision on the future evolution of the water table but farsighted with respect to their investment decision for deepening the well. The farmers' farsightedness is not based on the observed evolution of the water table but on an expected rational evolution of the stock. In other words, the shadow price of water is zero with respect to pumping and greater than zero but exogenous with respect to investment decisions. In our model farmers choose between different crops with different vegetation periods and all shadow prices are endogenous. Sayre and Taraz (2019) found a 66% increase in social benefits from eliminating subsidies. Their study focuses on the comparison of two policies: fully subsidized electricity price (flat rate) and non-subsidized electricity prices, but do not analyse the effects of other policies, for example policies where subsidies are only granted up to a given amount of water, or where the complete elimination of subsidies is compensated by lump-sum transfers.

The study by Ryan and Sudarshan (2022) found that the change from a rationing regime of electricity to the case with no subsidies increases social benefits by 12%. A direct comparison of the findings of these two studies with results of our study is difficult since the evaluated policies of the two studies – subsidies vs no subsidies without equity consideration (Sayre & Taraz, 2019) and rationing vs no subsidies with equity consideration (Ryan & Sudarshan, 2022) are different. Both studies find that the shadow price of water is important and thereby do not confirm the Gisser Sanchez effect (Gisser & Sánchez, 1980; Esteban & Albiac, 2011; Koundouri, 2004; Pfeiffer & Lin, 2012; Rubio & Casino, 2001). To shed more light on these divergent results we develop a more detailed model for analysing efficiency and equity concerns of different policies. In other words, we aim to contribute to the literature by presenting a study that compares the distributional impact and efficiency of various policies where both, the shadow price of the water in the aquifer and of the well depth are determined endogenously. Moreover, we analyse the effects of policies that are in between the cases of non– and fully subsidized electricity prices, for example policies where electricity prices are partially subsidized, or fully subsidized electricity prices are only granted up to a certain amount of water.

3. Model

In this section we present the building elements of a dynamic groundwater model. It is based on the net benefit functions of farmers who use the groundwater of an aquifer to irrigate their land. We consider $j = 1, 2, \cdots, N$ farmers that are differentiated according to the size of their cultivated land. The length of the planning horizon is given by T years. Farmers can cultivate i different crops with $i \in \{1, 2, 3, 4\}$. Crops 1 and 2 are seasonal crops like millet or tomato, and crops 3 and 4 are perennial crops like mulberry or grapes.

We assume that farmers maximize their net benefits by taking decisions at the intensive and extensive margins – in particular with respect to the allocation of inputs such as land, labour, energy, water, and mineral and organic fertilizers. Additionally, if the availability of the input is limited, we consider this restriction either in form of a static constraint (e.g., land, labour) or a dynamic constraint (e.g., water table, well bore depth, age of the perennial crops). We assume that each farmer constructs and maintains its own well (Badiani-Magnusson & Jessoe, 2019), and all wells share the same aquifer.

Agricultural inputs are denoted by $h, l, c, o, w,$ and indicate the size of the cultivated land, the amount of labour, chemical or organic fertilizer, and water respectively. Thus, making use of our previously introduced notation the variable $w_i^j(t)$ denotes the amount of water applied by farmer j to crop i at calendar time t. Similarly, the variable $c_i^j(t)$ denotes the amount of chemical fertilizer applied by farmer j to crop i at time t. Moreover, we denote by $W^j(t)$ the amount of water extracted by farmer j.

In the following we discuss each of the static and dynamic constraints together with the objective function.

3.1 Static constraints

Land and labour endowment

Each farmer j is endowed with H^j hectares of land. Since it is possible to raise more than one seasonal crop i per year, the variable μ_i expresses the length of the vegetation period of a seasonal crop as the proportion of the calendar year, and the variable $h_i^j(t)$ denotes the size of the cultivated land by farmer j with crop $i, i = 1, 2,$ at time t. In the case of perennials, we need to take account of its age distribution. Thus, $h_i^j(t,\alpha)$ denotes the size of the cultivated land by farmer j with crop $i,\ i = 3, 4,$ with age $\alpha \in [0, \bar{\alpha}]$ at time t.

To guarantee that farmer $j's$ land allocation decisions do not exceed their[2] land endowment it has to hold that

$$\sum_{i=1}^{2} \mu_i h_i^j(t) + \sum_{i=3}^{4} \int_0^{\bar{\alpha}} h_i^j\left(t,\alpha\right) d\alpha \leq H^j. \tag{1}$$

Moreover, it has to hold that each farmer j does not employ more hours of labour than the given hours of their family labour endowment L^j, i.e.,

$$\sum_{i=1}^{2} l_i^j(t) + \sum_{i=3}^{4} \int_0^{\bar{\alpha}} l_i^j(t,\alpha)\, d\alpha \leq L^j, \tag{2}$$

3.2 Dynamic constraints

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[2] Instead of the gender-specific pronouns, his or her we use the gender-neutral form “their”.

Evolution of the water table

We assume that water for irrigation is only available from an underlying single-cell aquifer that is not connected to any other water mass. In addition to natural recharge from rainfall per acre r the aquifer is also fed by the return flow, i.e., the fraction, ψ_i, of applied water $w_i^j(t)$ used for the irrigation of crop i that percolates back to the aquifer. The available groundwater decreases with the distance between the ground and the water table, denoted by $S(t)$. Thus, changes in the available groundwater can be expressed by the change in the distance between the ground and the head of the aquifer (water table), $dS(t)/dt$. Changes in the water table are the result of the extraction of water and the inflow given by the return flow and natural recharge. Since all these changes are measured volumetrically (cubic meter) we need to introduce the parameter ϕ that translates the extraction or inflow of groundwater to changes in the distance between the water table and the ground. Thus, the groundwater balance is given by

$$\frac{dS(t)}{dt} = \phi \sum_j \sum_i (1-\psi_i) w_i^j(t) - \phi\tau[r]A, \tag{3}$$

where τ is the percolation coefficient of rainfall and A denotes the size of the hydrologic catchment area of the aquifer.

Evolution of the well depth

The well bore depth $D^j(t)$ of farmer j is measured by the distance from the ground to the bottom of the well, and farmer j can only extract water as long as the water table is above or equal to the bottom of the well. Mathematically, this technical restriction is expressed by the condition

$$D^j(t) \geq S(t). \tag{4}$$

Once inequality (4) holds as a strict equality farmers have two options: a) to extract only up to the inflow of water or b) to invest in the construction of a deeper well. Consequently, the model considers investment in well bore depth and takes account of the evolution of the groundwater table $S(t)$ and the well bore depth $D^j(t)$. The evolution of the depth of the well can be described by

$$\frac{dD^j(t)}{dt} = I^j(t), \tag{5}$$

where $I^j(t)$ indicates the additional depth of the well bore. Drilling deeper wells often involves higher costs due to a number of factors, including specialized drilling equipment, skilled labour and materials. In addition, the need for more powerful pumps to extract resources from these deeper wells further increases the overall capital expenditure. (Raghunath, 1982; Sekhri, 2014). Therefore, for each farmer

j the costs per each additional meter of the well bore depth, $CI\left(D^j(t)\right)$, are given by the quadratic function $CI\left(D^j(t)\right)=\omega_1 D^j(t)+\omega_2\left(D^j(t)\right)^2$, where $\omega_1>0$ and $\omega_2>0$ are given coefficients. Hence $CI\left(D^j(t)\right) I^j(t)$, provides the cost of deepening the well by $I^j(t)$. *Evolution of perennial stands*

For perennial crops like mulberry trees or grapevines we need to keep track of their transitions from year to year in order to portray their age distribution over time. At every moment of time farmers have to decide whether it is optimal to clear land occupied by mulberries or grapevines with age α or to maintain their cultivation. Hence the evolution of the perennial stand is governed by

$$\frac{\partial h_i^j(t,\alpha)}{\partial t}+\frac{\partial h_i^j(t,\alpha)}{\partial \alpha}=-u_i^j(t,\alpha),\ i=3,4\,. \tag{6}$$

Equation (6) is subject to the initial age distribution and the boundary condition of newly planted sapling of perennials $n_i^j\left(t\right)$ of age 0. These conditions are stated as

$$h_i^j\left(0,\alpha\right)=h_{i0}^j\left(\alpha\right),\ \alpha\in\left(0,\bar{\alpha}\right),\ h_i^j(t,0)\ =n_i^j\left(t\right),t\in\left(0,T\right),i=3,4\,, \tag{7}$$

where $u_i^j(t,\alpha)$ denotes the area cleared from mulberry trees and/or grapevines of age α.

Additionally, the modelling requires that the cleared area of a particular perennial crop does not exceed its cultivated area, i.e.,

$$u_i^j(t,\alpha)\le h_i^j(t,\alpha),i=3,4. \tag{8}$$

3.3. The objective function

The objective of the model is to maximize the net present value of profits of a farm community cultivating annual and perennial crops over a given time horizon. To delineate the net benefit function, we define the production, cost and revenue functions of farmer j.

Production function

For the production of seasonal and perennial crops we use a Mitscherlich-Baule function. It depicts the physical relation between inputs and crop output per acre of land. This function is superior to the quadratic production function in the sense that in the quadratic formulation some inputs are dispensable for production while for the Mitscherlich-Baule formulation all inputs are indispensable for production.

The production F_i^j of crop i for farmer j is given by

$$F_i^j(t,\alpha)=M_i\left(\alpha\right)h_i^j(t,\alpha)(1-e^{(\frac{-\beta_i^w w_i^j(t,\alpha)}{h_i^j(t,\alpha)})})(1-e^{(\frac{-\beta_i^l l_i^j(t,\alpha)}{h_i^j(t,\alpha)})})(1-e^{(\frac{-\beta_i^c c_i^j(t,\alpha)}{h_i^j(t,\alpha)})})(1-e^{(\frac{-\beta_i^o o_i^j(t,\alpha)}{h_i^j(t,\alpha)})})\,, \tag{9}$$

where $M_i(\alpha)$ stands for the maximum attainable yield of crop i with age α per acre of land. Since seasonal crops, $i=1,2$, are not age-structured the outputs and inputs in equation (9) are given by $F_i^j(t), M_i$ and $h_i^j(t)$, $w_i^j(t)$, $l_i^j(t)$, $c_i^j(t)$ and $o_i^j(t)$ respectively. The parameters $\beta_i^w, \beta_i^l, \beta_i^c, \beta_i^o$ allow to calibrate the production function of each crop i by scaling the effect of the inputs water, labour and chemical and organic fertilizer respectively.

Cost functions

The required electrical energy $e(t)$ for lifting a cubic meter of groundwater is a function of the depth of the water table. As the depth of the well increases, the power requirement of the pump tends to rise due to the greater effort needed to overcome the additional pressure and lift the water to the surface (Sekhri, 2014). Consequently, the electricity required to lift one cubic meter of groundwater also tends to rise. It can be presented by

$$e(t)=\varepsilon_1 S(t)+\varepsilon_2\left(S(t)\right)^2, \tag{10}$$

where $\varepsilon_1>0$ and $\varepsilon_2>0$ are given coefficients.

Besides the determination of the required electricity to lift the water one needs to specify the costs per unit for all inputs. Let denote p_o, p_c, p_m, p_e, p_u the costs per unit of organic fertilizer, chemical fertilizer, maintenance of the well, electricity, and cleared land respectively.[3] Hence, the expenditures for organic fertilizer are $p_o\, o_i^j(t)$, for chemical fertilizer $p_c\, c_i^j$ and for well maintenance $p_m w_i^j(t)$. Expenditures for the lifting of groundwater are $\left(1-\gamma\right) p_e e(t) w_i^j(t)$, where γ is the subsidized percentage of the electricity price. The costs for the clearing of land are given by $\int_0^{\bar{\alpha}} p_u\, u_i^j(t,\alpha)\, d\alpha,\ i=3,4$, and for deepening the well by $I(t)CI\left(D^j(t)\right)$.

Given this notation the aggregated cost function for farmer j is given by

$$\begin{aligned}C^j(t,\bar{\alpha}) &= I^j(t)CI\left(D^j(t)\right)+\left(\left(1-\gamma\right)p_e e(t)+p_m\right)W^j(t)+\sum_{i=1}^{2}\left(p_o o_i^j(t)+p_c c_i^j\right)+\\ &\sum_{i=3}^{4}\int_0^{\bar{\alpha}}\left(p_o o_i^j(t,\alpha)+p_c c_i^j(t,\alpha)+p_u u_i^j(t,\alpha)\right)d\alpha\end{aligned} \tag{11}$$

Revenue function

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[3] Cleared land incorporates the costs of clearing and replanting.

Farmer's j revenues $R^j(t)$ are the result of the sale of annual crops and perennial crops, which leads to the following equation

$$R^j(t,\bar{\alpha}) = \sum_{i=1}^{2} p_i F_i^j(t) + \sum_{i=3}^{4} p_i \int_0^{\bar{\alpha}} F_i^j(t,\alpha)\, d\alpha \,, \tag{12}$$

where $p_i, i = 1,2,3,4$ denotes the product prices of the corresponding crops.

Social Optimum

After having defined the revenue and cost functions we can state the objective function for a regional planner. She maximizes the discounted profits of all farmers over the planning horizon of T years given the vector of policy parameters $\bar{\upsilon}$ whose elements indicate policy variables, for example the degree of price support or the severity of restrictions on water consumption. The maximized profits yield the value function $J_{SOC}(\bar{\upsilon})$ that is given by

$$J_{SOC}(\bar{\upsilon}) \equiv \max_{\left\{\bar{x}_i^j(t), I^j(t)\right\}_{i=1,\dots,4,\, j=1,\dots,N}} \int_0^T e^{-\varphi t} \left(\sum_{j=1}^{N} \left(R^j(t,\bar{\alpha}) - C^j(t,\bar{\alpha}) \right) \right) dt + \sum_{j=1}^{N} \int_0^{\bar{\alpha}} V^j\left(T, S(T), h_3^j(T,\alpha), h_4^j(T,\alpha)\right) d\alpha$$

(13)

subject to the equations (1) - (8), where the vector $\bar{x}_i^j = \left(h_i^j, l_i^j, w_i^j, c_i^j, o_i^j\right), \forall i = 1,2$ denotes inputs or activities related to agricultural production of seasonal crops, and $\bar{x}_i^j = \left(n_i^j, l_i^j, w_i^j, c_i^j, o_i^j, u_i^j\right), \forall i = 3,4,$ the corresponding inputs for perennials.[4] The residual value of the stock variables at time T is presented by the sum of the functions $V^j(\cdot)$ over all farmers. The integral in equation (13) reflects the stream of farmer's j profits, $R^j(t,\bar{\alpha}) - C^j(t,\bar{\alpha})$, over time discounted at the rate φ.[5]

Private Optimum

Similarly, each farmer j maximizes her private profits over the planning horizon of T years. The maximized discounted profits of farmer j over the entire planning horizon given the vector of policy parameters $\bar{\upsilon}$ yield the value function $J_{PRIV}^j(\bar{\upsilon})$ that is given by

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[4] For notational convenience we suppress the argument t and α of control and stock variables whenever the notation is unambiguous.

[5] We assume that the farmers and the social planner use the same discount rate. Moreover, as discussed in Section 6 the choice of the discount rate has only minor impact on the private or social value function if farmers frequently update their behaviour in accordance with the evolution of the water table.

$$J_{PRIV}^{j}\left(\overline{\upsilon}\right)=\max_{\left\{\overline{x}_i^j(t)\right\}_{i=1,\dots,4},I^j(t)}\int_0^T e^{-\varphi t}\left(R^j(t,\overline{\alpha})-C^j(t,\overline{\alpha})\right)dt+\int_0^{\overline{\alpha}}V^j\left(T,S(T),h_3^j\left(T,\alpha\right),h_4^j\left(T,\alpha\right)\right)d\alpha \qquad (14)$$

subject to the equations (1) - (8). Yet, in contrast to the optimization problem of the regional planner, individual farmers only consider the effect of their water extraction on the evolution of the water table, but not that of all other farmers. Since individual farmers have no information about other farmers' extraction they take them as given. Thus, in the case of the farmers' optimization problem the summation sign in equation (3) over the index j does not exist. Finally, like in equation (13) the function $V^j\left(\cdot\right)$ takes account of the residual value of farmer j's stock variables at time T.

Since all farmers share the same aquifer, their net benefit functions are interdependent, and therefore, the N optimization problems formulated in equation (14) have to be solved simultaneously. It constitutes a challenge that can be solved using the predictive control approach, as proposed in Section 5.

The corresponding distributed Hamiltonian function $\mathcal{H}$ (Feichtinger et al., 2003; Goetz et al., 2010; Hritonenko et al., 2008) for an interior solution of the control variables is given by

$$\begin{aligned}\mathcal{H}^{PRIV} &= R^j(t,\overline{\alpha})-C^j(t,\overline{\alpha})-\lambda_{h_3}^j\left(t,\alpha\right)u_3^j\left(t,\alpha\right)-\lambda_{h_4}^j\left(t,\alpha\right)u_4^j\left(t,\alpha\right)+\lambda_S\left(t\right)\left(\phi\sum_i(1-\psi_i)w_i^j(t)-\phi\tau\left[r\right]A\right)\\ &\quad+\lambda_I\left(t\right)\left(I(t)\right)+\lambda_H\left(t\right)\left(H^j-\sum_{i=1}^{2}\mu_i h_i^j(t)-\sum_{i=3}^{4}\int_0^{\overline{\alpha}}h_i^j\left(t,\alpha\right)d\alpha\right)\\ &\quad+\lambda_L\left(t\right)\left(L^j-\sum_{i=1}^{2}l_i^j(t)-\sum_{i=3}^{4}\int_0^{\overline{\alpha}}l_i^j(t,\alpha)\,d\alpha\right),\end{aligned}$$

(15)

where $\lambda_{h_3}^j\left(t,\alpha\right),\lambda_{h_4}^j\left(t,\alpha\right),\lambda_S\left(t\right),\lambda_I\left(t\right),\ \lambda_H\left(t\right),\lambda_L\left(t\right)$ denote the shadow prices of the cultivated land for the crops mulberry and grapes, the water table, the depth of the well, the available land and the available labour. Equation (15) has to be complemented with the initial and boundary Hamiltonians given by

$$\begin{aligned}\mathcal{H}^{Initial} &= \sum_j\lambda_{h_3}^j\left(0,\alpha\right)h_3^j\left(0,\alpha\right)+\lambda_{h_4}^j\left(0,\alpha\right)h_4^j\left(0,\alpha\right)+\int_0^T e^{-\varphi t}\left(\sum_j R^j(t,\overline{\alpha})-C^j(t,\overline{\alpha})\right)dt\\ \mathcal{H}^{Boundary} &= \sum_j\lambda_{h_3}^j\left(t,0\right)n_3^j\left(t\right)+\lambda_{h_4}^j\left(t,0\right)n_4^j\left(t\right).\end{aligned}$$

For the policy analysis we study the comparative dynamics of equation (15). In particular, we study how policies affect the farmer's behaviour by evaluating the following terms

$$\frac{\partial J_{PRIV}}{\partial \upsilon_k} = \int_0^T e^{-\varphi t} \frac{\partial \mathcal{H}^{PRIV}}{\partial \upsilon_k} dt \,. \tag{16}$$

They describe the influence of the k^{th} element of the vector $\bar{\upsilon}$, i.e., the influence a particular policy has on the stream of the aggregate discounted profits of all farmers within the region. Our analysis allows us to rank the different policies with respect to their efficiency. Moreover, we test for the stability of the ranking by evaluating the policy instruments for different values of the policy variables, for instance a variation of the subsidized percentage of the electricity price. For this purpose, we determine how the value function J^j_{PRIV} changes with variation of the subsidized percentage of the electricity price. Moreover, the analysis allows us to compare different policies not only in terms of its efficiency but also in terms of to their incidence on the profits of poorer and wealthier famers.

4. Study area, data collection, calibration and parameterization of the model

To analyse the energy water nexus within the context of the Indian situation described above we collected data from two villages that water management options are representative for the situation of Eastern Dry Zone of the Indian state of Karnataka. The two villages Patrenahalli and Thandramaradahalli are located in the Chikkaballpur District of this state (see Figure 1). The Eastern Dry Zone of Karnataka is considered an overexploited groundwater region characterized by low rainfall (847.4 mm p.a.), available surface water is nearly negligible and therefore crop production relies by more than 90% on groundwater (Government of Karnataka, 2008-09; Nagaraj et al., 1999).

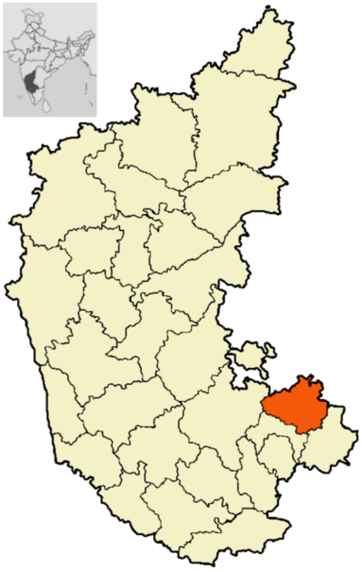

Figure 1. Map of the location of the study area, Chikkaballpur District, in the Indian state of Karnataka.

The data for the model was collected from primary and secondary sources. The primary data was collected from 132 groundwater dependent farmers located in the two villages. Detailed information was elicited from the respondents with the aid of structured and pre-tested schedules of personal interviews, covering the following aspects: (i) socioeconomic information about the farm family, including the size of the family the education level of the household head, the size of the land holdings etc., (ii) information regarding irrigation practices, details about the type of and investment in the wells, and information about the cost and revenues of cultivated crops. The two villages cover a total area of 241.03 hectares of which around 80% of the land is allocated to agriculture. Secondary data about geographic, demographic, economic and hydrological conditions was collected from different government bodies (Department of Agriculture & Farmers Welfare).[6] Additional hydrological information was elicited by consulting an engineering bureau specialized in hydrology.

To keep the model manageable, the N farmers were categorized into three farm types based on the size of their land endowments: small, medium, and large, respectively. Additionally, it is assumed that all farms within each farm type are homogeneous. Likewise, we restricted the number of crops to four that are representative for the local agricultural production context: millet, tomato, mulberry and grapevine. Millet does not require irrigation and presents a cereal crop, tomato presents a vegetable crop and mulberry and grapevine present the most widely grown perennial crops in the area. As a result of the meteorological conditions – heavy rainfalls – vegetables cannot be grown all year around. Thus, we limited the cultivation of tomatoes by requiring that tomatoes do not occupy more than 2/3 of the land cultivated with tomatoes and millets.[7]

Moreover, the production of grapes requires some initial investments which often cannot be financed by small and intermediate farms. Therefore, in accordance with the observation of the current cultivation practices in the studied regions, we restrict the option to cultivate grapes to large farmers.

Both primary and secondary data were used for the specification of the parameters of the model and are summarized in Table 1 to facilitate the reading.

Table 1. Summary of the variables and parameters of the model

Arguments of the variables and functions	
$j = 1, \cdots, N$	Individual farms, which are categorized into subsets of small, medium, or large, based on the size of their land endowment.

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[6] https://agricoop.nic.in/en, accessed on October 20th, 2022.

[7] The corresponding constraint is given by 0.5 (cultivated land with tomatoes) < 1 (cultivated land with millet).

$i = 1, \cdots, 4$	Crop type.
$i = 1, 2$	Subset of i: Seasonal crops, tomato and millet.
$i = 3, 4$	Subset of i: Perennial crops, mulberry and grapevine.
$t = 0, ..., T$	Time horizon of the economic analysis.
$\alpha, \; \bar{\alpha}$	Current age and maximal age of the perennial crops.
Variables and functions	
$h_i^j(t), h_i^j(t,\alpha)$	Size of the land cultivated by farmer j with seasonal and/or perennial crops.
$u_i^j(t,\alpha), \; i = 3, 4$	Size of the area cleared from mulberry trees and/or grapevine.
$n_i^j\left(t\right), \; i = 3, 4$	Size of the area planted of mulberry trees and/or grapevine.
$c_i^j(t), c_i^j(t,\alpha)$	Amount of chemical fertilizer applied by farmer j to crop i at time t.
$o_i^j(t), o_i^j(t,\alpha)$	Amount of organic fertilizer applied by farmer j to crop i at time t.
$l_i^j(t), l_i^j(t,\alpha)$	Amount of labour used by farmer j to cultivate crop i at time t.
$w_i^j(t), w_i^j(t,\alpha)$	Amount of water applied by farmer j to crop i at time t.
$W^j(t)$	Amount of water applied by farmer j across all crops at time t.
$\bar{x}_i^j$	Vector of activities and inputs $(h_i^j, u_i^j, n_i^j, c_i^j, \sigma_i^j, l_i^j, w_i^j)$.
$\lambda_{h_3}^j\left(t,\alpha\right), \lambda_{h_4}^j\left(t,\alpha\right),$ $\lambda_S\left(t\right), \lambda_I\left(t\right),$ $\lambda_H\left(t\right), \lambda_L\left(t\right)$	Shadow prices of the stock variables and the available land and labour endowment
$S(t)$	Distance from the ground to the water table at time t.
$D^j(t)$	Depth of the well bore.
$I^j(t)$	Investment, additional depth of the well.
$CI\left(D^j(t)\right)$	Costs per each additional meter of the well bore depth.
$e(S(t))$	Required electric energy to lift the water per cubic meter to the surface.
$E(t)$	aggregate electricity consumption at time t.
$F_i^j(\cdot)$	Production function, yield of crop i.
$C^j(\cdot)$	Aggregated cost function for farmer j.
$R^j(\cdot)$	Aggregated revenues from crop sale for farmer j.

Parameters		
φ	Discount rate.	4%
γ	Energy subsidy rate.	0 to 100%
p_e	Price for electricity.	5.87 Indian rupee (INR)/kWh
p_o	Price of organic fertilizer.	1229 INR/t
p_c	Price of chemical fertilizer.	32789 INR/t
p_m	Price of maintenance.	0.004 INR/m^3
p_i	Price of crops.	tomato 13870; mulberry 16000; grape 27310; millet 23280 INR/t
p_u	Price for tree/bush clearing.	77072.168 INR/ha
ϕ	Change in m of the water table.	$5.6834*10^{-6}$ per m^3 of extraction
ψ_i	Percolation rate for crop i.	tomato 0.3; mulberry, grapevine, millet 0.1
μ_i	Relative length of the cultivation season.	tomato 0.33; millet 0.5; mulberry and grapevine 1 yr.
ε_1, ε_2	Coefficients of the energy function for lifting.	$5.43*10^{-4}$; $7.04*10^{-9}$
ω_1, ω_2	Coefficient of the drilling cost.	322.8346457; $3.93701*10^{-4}$
L^j	Family labour for farmer j.	29.5; 29.1; 333 days/yr.
H^j	Land endowment for farmer j.	0.8; 1.6; 9.6 ha
r	Average rainfall.	6350m^3/ha per year
τ	Percolation rate.	0.25
A	Catchment area.	127.84 ha
$\beta_i^w, \beta_i^l, \beta_i^c, \beta_i^o$	Coefficients of the production function.	water (0.000689 – 0.001126); labour (0.000205 – 0.000453); organic (0.000925 – 0.004134); chemical (0.006496 – 0.248031)
M_i	Maximum attainable yield of crop i.	tomato 74.13; millet 4.94; mulberry 19.77 (9.88 in year 15); grapevine 49.42 (24.71 in year 15)

5. Policy scenarios

We use the model formulated in equation (13) subject to the equations (1) - (8) for a policy analysis of different available policy measures. For the specification of the policy scenarios, it seems reasonable to assume the farmer's planning horizon covers at least the economically viable lifespan of perennial crops of 15 years. Moreover, given that the farmers on average are 50 years old and likely remain active for 15 years, we set the planning horizon equal to 15 years, i.e., $T = 15$.

For the analysis of the different policy measures we need to calculate the private optimum for each type of farmer j, taking into account the type of policy to be implemented. Thus, the calculations of the private outcome differ from the calculation of the social outcome not only with respect to the length of the planning horizon but also with respect to the objective function. The objective function for farmer j is given by

$$\max_{\left\{\bar{x}_i^j(t)\right\}_{i=1,\dots,4},\, I^j(t)} \int_0^T e^{-\varphi t}\left(R^j(t,\theta)-C^j(t,\theta)\right)dt + V^j\left(T, S(T,\theta), h_3^j\left(T,\alpha,\theta\right), h_4^j\left(T,\alpha,\theta\right)\right) \tag{17}$$

subject to the equations (1) - (8) for a given j, where θ is the specific implemented policy.

For the policy analysis we consider the following six scenarios. The name in brackets indicate the shortened title of the policy scenario.

i. Fully subsidize price of the electricity (baseline scenario)
ii. No subsidy of the electricity price (market outcome)
iii. Partially subsidized price of the electricity (partially subsidized price)
iv. Two-tier price subsidy of the electricity (two-tier price subsidy)
v. Partial compensation of the cost of electricity consumption completely independent from the actual electricity consumption (lump-sum transfer)
vi. Social optimum

The first scenario is taken as the baseline. It is the based on the current situation, i.e., none of the policy measures is implemented and electricity consumption is fully subsidized. With an electricity price p_e equal to zero there are no costs for lifting the water so that farmers only have to defray the costs of maintaining or deepening the well bore. At the initial year and with a fully subsidized price of electricity farmers consume $E(0)$ kwh, extract $W(0)$ cubic meters of water, and thus, the subsidies amount to $p_e E(0)$. While scenario i) avoids any metering devices, scenarios ii) to v) require the installation of a metering device that allows controlling the consumption of electricity for groundwater pumping. In the second scenario farmers pay the market price for electricity, i.e., p_e is equal to 5.87 INR/kWh.

Scenarios iii) to v) are less disruptive than the second scenario as they maintain 50% of the support but differ in the reference point for the calculation of the subsidy. In the third scenario the electricity price is subsidized by 50%, i.e., $\gamma = 0.5$. Thus, the farmer's electricity expenditure is equal to $(1-\gamma)\, p_e E(t) = 0.5 p_e E(t)$.

The policy support for scenarios iv and v is based on the amount of water extracted and the scope of price support in the first year of the baseline scenario respectively. This support is maintained throughout the time horizon of the model. In the fourth scenario, the price of electricity is fully subsidized (first tier) up to 50% of $W^j(0)$. For extraction beyond this limit, farmers are charged the market price of the electricity (second tier). In the fifth scenario, the farmers receive a lump-sum payment of $0.5 p_e E(0)$, i.e., the subsidy is independent from their energy consumption.

Finally, in the sixth scenario we assume that a social planner with a planning horizon of 30 years maximizes the aggregate net benefits of all farmers. The resulting social optimum presents the most efficient solution. The evaluation of the policy scenarios (i) to (v) is based on the maximization of the individual farmer's net benefits as specified in equation (17).

6. Numerical approximation

The complexity of the analytical model presented in Section 3 and specified in Section 4 does not allow to solve it analytically. Thus, we need to resort to numerical techniques for solving the model. As a first step for finding a numerical solution of the distributed optimal control problem, we formulate the ordinary differential equations (ODEs) represented by equations (3) and (5), as well as the partial differential equation (PDE) shown in equation (6), as difference equations in time and also in age in the case of the perennial crops. It is important to note that each of the three types of farmers has a specific depth of the well, 15 different vintages of mulberry and grapes, and the water table is identical for all three types. Thus, once discretized the model defined in equation (17) subject to the equations (1) – (8) has 94 state variables and 39 decision variables. The nonlinearity of the model and the high number of state variables suggests that a numerical solution of the model based on dynamic programming is likely not feasible. Alternatively, to the approach by Sayre and Taraz (2019) we do not reduce the dimensionality of the model by redefining the model but apply a different numerical technique known as Nonlinear Model Predictive Control (NMPC) or Receding-Horizon Control

(Faulwasser et al., 2018; Fele et al., 2018; Grüne & Pannek, 2017). Since this technique only calculates one optimal trajectory at a time the computational demand is much lower than for dynamic programming (Grüne et al., 2015). This approach is well established in the engineering literature (Ellis et al., 2014; Xiao et al., 2022) and has also found its way into the economic literature (Bréchet et al., 2014; Grüne et al., 2015). Theoretical and numerical analysis of different optimization problems by Grüne and Pannek (2017), Faulwasser et al. (2018) and by Fele et al. (2018) showed that the solutions obtained via the NMPC technique approximate well the true solution of the optimization problems. The NMPC technique basically consist in an iteration of closed-loop solutions where the values of the state variables in year one of the optimal trajectory become the starting values of the following closed-loop solution. The length of the planning horizon is identical for all closed-loop solutions, but the starting time is receding by one year with each new iteration.

Let us denote the solution of the model defined in equation (17) subject to the equations (1) – (8) as $\left(\bar{x}^{*j}(t;\overline{X}^{*j}(0)), I^{*j}(t;\overline{X}^{*j}(0))\right), \forall t \in [0,T]$, where $\overline{X}^{*j}(t)$ denotes the vector of all state variables evaluated at time t of the optimal trajectory. However, at time one all state variables have changed from $\overline{X}^{*j}(0)$ to $\overline{X}^{*j}(1)$. In particular, they are modified as a result of the overall water abstraction $\sum_{j}^{N} W^{*j}(t;\bar{X}^{*j})$, where $W^{*j}(t;\bar{X}^{*j}(0))$ indicates farmer's j privately optimal water extraction given stock $S(0)$. As a result of the change in the water table, the optimal solution $\left(\bar{x}^{*j}(t;\bar{X}^{*j}(0)), I^{*j}(t;\bar{X}^{*j}(0))\right)$ is not optimal anymore from $t=1$ onwards. Hence, farmers will consider the new value of the water table, $S(1)$, as the initial value and repeat the optimization that yields $\left(\bar{x}^{*j}(t;\bar{X}^{*j}(1)), I^{*j}(t;\bar{X}^{*j}(1))\right), \forall t \in [1, T+1]$. The iteration of this optimization problem with horizon T for the observed values of the water table $S(0),\cdots,S(30)$ allowed us to take account of the interdependence between the farmers' decision problems. At the same time, the repeated iteration of the optimization problem not only reduces the computational burden but also avoids the difficult specification of the terminal value functions of the stock variables, $V(T,\bar{X}(T)),\cdots,V(T+30,\bar{X}(T+30))$. The iteration of the closed loops is based on the values of the state variables in year $t+1$ so that the terminal value function of the state variables at time $t+T$ has hardly any influence on the $t+1$ values. Likewise, one would expect that the discount rate has little importance for the farmer's decisions since discounting from $t+1$ to t has only minor importance compared to discounting from T to t. Our numerical analysis confirmed this expectation and therefore, we do not present an analysis of the effect of a variation of the discount rate on the farmers' behaviour.

For the determination of the socially optimal outcome, we also employ the NMCP technique. However, since the interdependence of the farmers' decision problem is already taken account for by maximizing the aggregate net benefits of all farmers, the optimal solution found at time t remains valid for the subsequent periods. Thus, NMPC is employed for the social planner problem only in order to avoid the difficulty of determining the terminal value function.

Our modelling approach is based on the annual revision of the optimal trajectories $\left(\overline{x}^{*j}(t;\overline{X}^{*j}(t)), I^{*j}(t;\overline{X}^{*j})\right), \forall t \in \left[t, T+t\right], t = 0,\cdots,30$, once the farmers observe $S(t+1)$. We have chosen at least a one-year period of the iteration intervals as it predominantly corresponds with the cultivation period for seasonal crops. Shorter iteration intervals are difficult to justify since farmers have little margin to adjust once crops are planted. At the same time, we did not opt for iteration intervals larger than one year since the water table may reach the bottom of the well.[8] Thus, if the current trajectories $\left(\overline{x}^{*j}(t;\overline{X}^{*j}(t)), I^{*j}(t;\overline{X}^{*j}(t))\right), \forall t \in \left[t, T+t\right]$ do not foresee investments in deepening the well in year $t+1$, farmers may have no access to the groundwater. This situation is avoided by the setup of one-year iteration intervals. It implies that farmers investments in well depth are perfectly malleable as reflected in the formulation of the costs of investment function $CI(D^j)$ of our model.

The articles by Sayre and Taraz (2019) and by Ryan and Sudarshan (2022) are based on very distinct modelling approach. Based on an annual revision interval of the water table, Sayre and Taraz (2019) calculate the optimal trajectory of the decision variables. However, the evolution of the water table is not obtained endogenously as it depends on the evolution of the depth well that in turn is stipulated exogenously. The study by Ryan and Sudarshan is not dynamic as it focuses on the current situation. However, like Sayre and Taraz (2019), Ryan and Sudarshan (2022) infer the water table from the observed evolution of the well depth. These modelling approaches are probably a good approximation for determining the losses of social welfare if electricity prices are fully subsidized compared to case if electricity prices are not subsidized at all. However, for analysing a wider set of policies, their approaches would require the derivation of reliable estimates of the evolution of the water table for each policy. In the absence of endogenous shadow prices of the remaining stock of water this

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[8] Jasechko and Perrone (2021) found that 6% to 20% of wells are no more than 5 meters below the water table. As such, these wells run a high risk of running dry if the iteration interval were extended.

requirement might be an obstacle for a correct ranking of policies that are in between the two extreme cases – subsides or no subsidies.

The model was coded in the GAMS programming language (Brooke et al., 1998), and solved using the IPOPTH solver, which implements an interior point optimization algorithm suitable for large-scale nonlinear programming problems.

7. Results of the policy analysis

For each of the policy scenarios we present the evolution of the groundwater table, the depth of the bore well, and the key inputs; electricity and water. Moreover, we portray the evolution of the investments in the well and the profit for each type of farm along with the aggregate profit of all farmers. A noteworthy result of the policy analysis is that the "market outcome" and "social optimum" are very similar, that is, there are only small percentage gains in social welfare by switching from the maximization of private profits to the maximization of social welfare in the absence of subsidies. This finding suggests that the tragedy of the common problem has very little influence on the farmers' behaviour and is line with the Gisser-Sanchez result (Gisser & Sánchez, 1980). As a result of the very close similarity between the market outcome and socially optimal outcome we only include the market outcome in the legend of the Figures 2 – 9 in order to facilitate their apprehension.

Figure 2 shows the evolution of the water applied per hectare for each type of farm in the baseline scenario (fully subsidized electricity price). During the initial years, farmers maintain a constant level of water use per hectare; more precisely, 8375.62, 8247.37 and 10172.00 m^3/ha corresponding to small, medium and large farms respectively. This is the result of the fact that the price of electricity is fully subsidized, and farmers do not consider the shadow price of water. Only when the water table reaches the bottom of the well, they start extracting less water. After 30 years, farmers apply 6493.67, 6365.29 and 7949.10 m^3/ha for small, medium and large farms respectively, which represents a decrease of more than 20% compared to their initial water consumption.

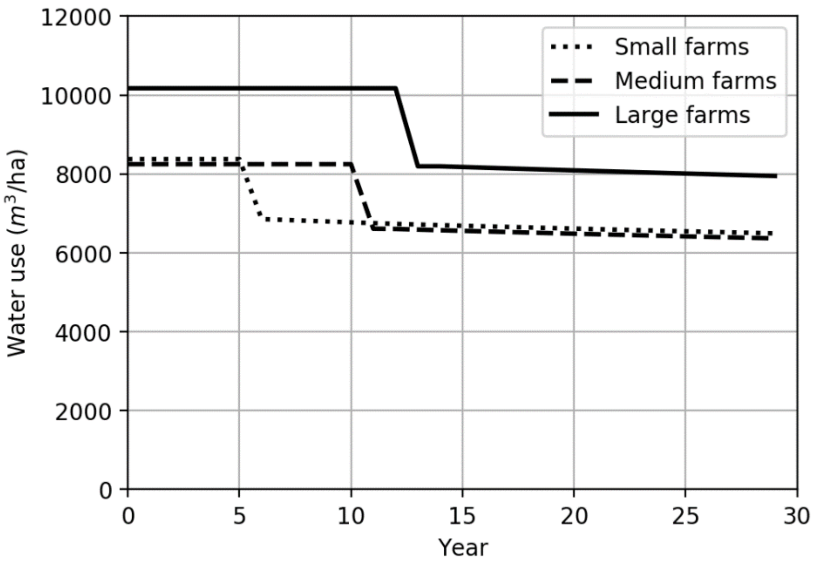

Figure 2. Evolution of the applied water in the baseline scenario

Figure 3 depicts, for each policy, the evolution of water applied per hectare as a percentage of the baseline (for each type of farm (panels a – c) and in aggregate (panel d)). It illustrates that changes in the subsidy regime led to considerable changes in the water extraction. In particular, the two-tier price is not as effective as the complete elimination of the subsidies, the partially subsidized price, or lump-sum transfers. This is because 50% of the farmers' water consumption in the baseline is free of charge, and therefore, they extract initially exactly this amount and have no incentive for additional reductions of water consumption.

However, after 30 years the farmers' reduction in water consumption compared to the baseline has decreased to 35% (see Table 2). Further reduction in water consumptions, compared to the two-tier price can be achieved by the partially subsidized price. As shown in Table 2 and Figure 3, the reduction in the water consumption compared to the baseline scenario is 57.85% at the beginning and 47.25% at the end of the planning horizon respectively. As expected, market outcome and lump sum transfers yield nearly identical reductions in water consumption. Moreover, these reductions cannot be achieved by any of the other polices.

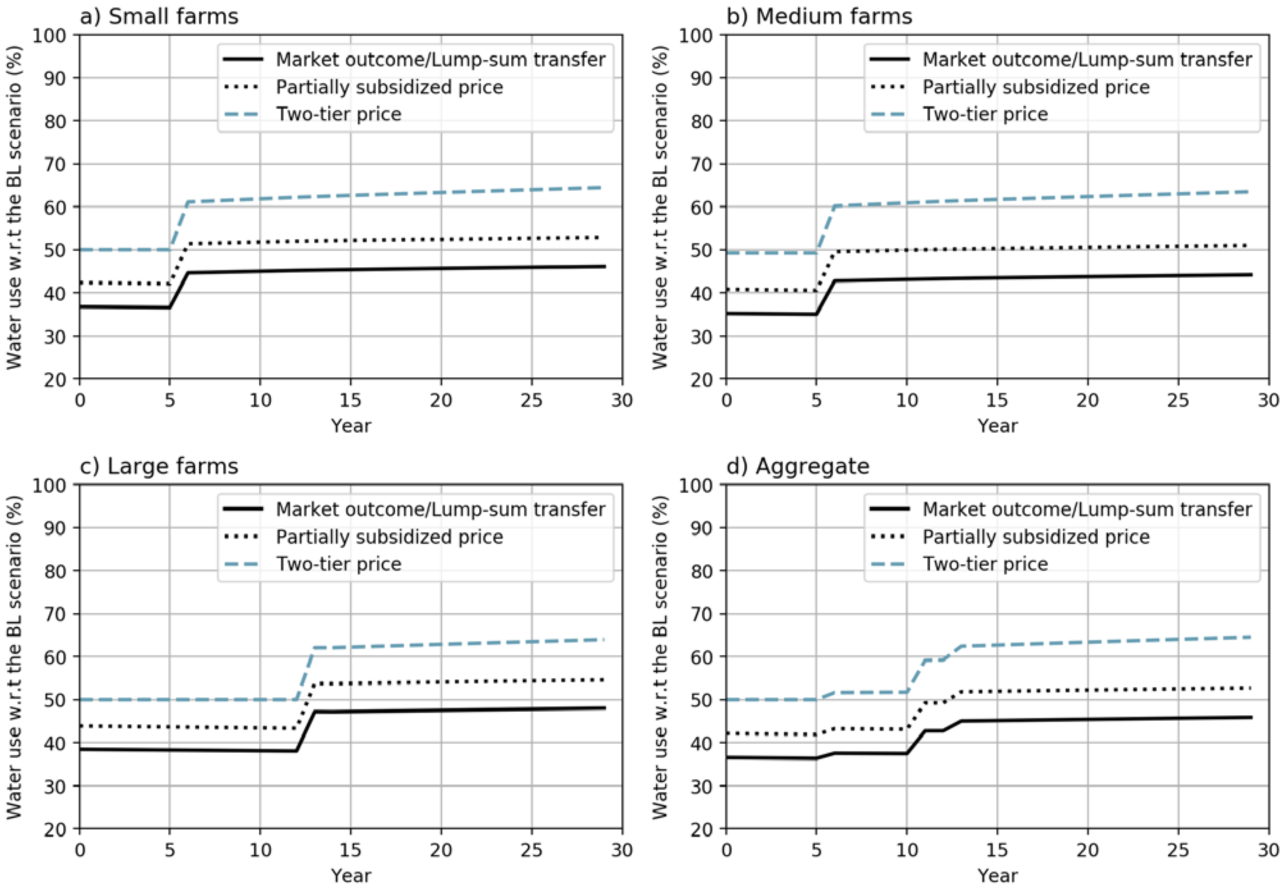

Figure 3. Evolution of the applied water induced by the policies analysed, in percentage over the baseline scenario

Table 2. Aggregate water use and groundwater depth.

Scenario	Aggregate water use at year 0 (hm^3)		Aggregate water use at year 30 (hm^3)		Groundwater depth at year 30 (m)	
Baseline (fully subsidized price)	3.66		2.83		116.07	
Market outcome	1.34	(63.47)[1]	1.30	(54.09)	85.55	(26.29)
Partially subsidized price	1.54	(57.85)	1.49	(47.25)	88.84	(23.46)
Two-tier price	1.83	(50.00)	1.83	(35.44)	93.96	(19.05)
Lump-sum transfer	1.34	(63.47)	1.30	(54.09)	85.55	(26.29)
Social optimum	1.31	(64.26)	1.28	(54.96)	85.11	(26.67)

[1] Values in parenthesis represent the percentage change with respect to the baseline scenario.

The result of the different policies on the evolution of the water table is shown in Table 2 and Figure 4. For the case of the baseline scenario, Figure 4 (panel a) shows that the depth of the water table declines within 30 years from 76.2 m to 116.06 m, i.e., a decline of more than a meter per year. This result is consistent with the findings of Fishman et al., (2016) who reported declines of even 3 meters per year over the last decades. In contrast, Figure 4 (panel b) shows that the policies where subsidies are reduced lead to a significantly lower decline of the water table. After 30 years, depending on the considered policy, the depth of the water table ranges between 85.55 and 93.96 m, i.e., the depth of water table reaches between 73.7% - 81% of that of the baseline scenario (Table 2).

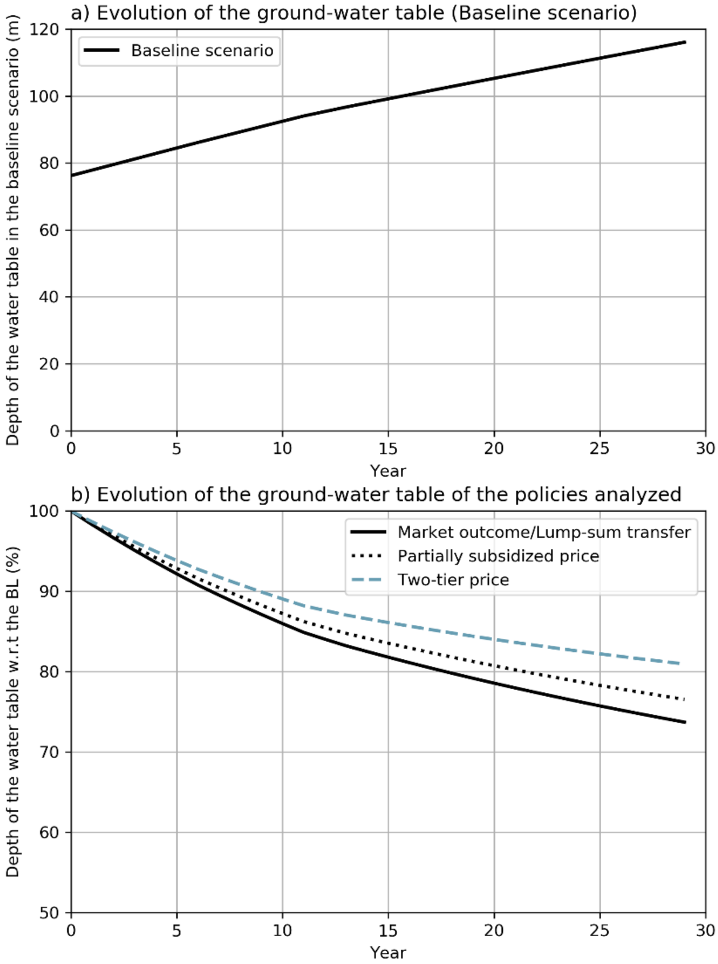

Figure 4. Evolution of the groundwater table

As the water table decreases it eventually reaches the bottom of the well and farmers need to invest in deepening their well bores if they want to extract more water than the water inflow of the aquifer. Figure 5 illustrates the evolution of the bore well depth for each type of farm. For the baseline scenario it shows that the bore well depth of small (medium, large) farms increases from 84.73 to 116.08 (93.55 – 116.08; 96.82 – 116.24) meters respectively.

Figure 5 illustrates how policies affect farmers' investment behaviour. Panel a) shows that small farms have the highest need for investing in deepening their wells while medium-sized and large farms can continue to extract water with almost no need for investing in deepening their wells (Figure 5, panels b-c). In contrast, with the two-tier price for electricity small farms deepen their bore well up to 93.97 m, and with a partially subsidized price up to 88.76 m.

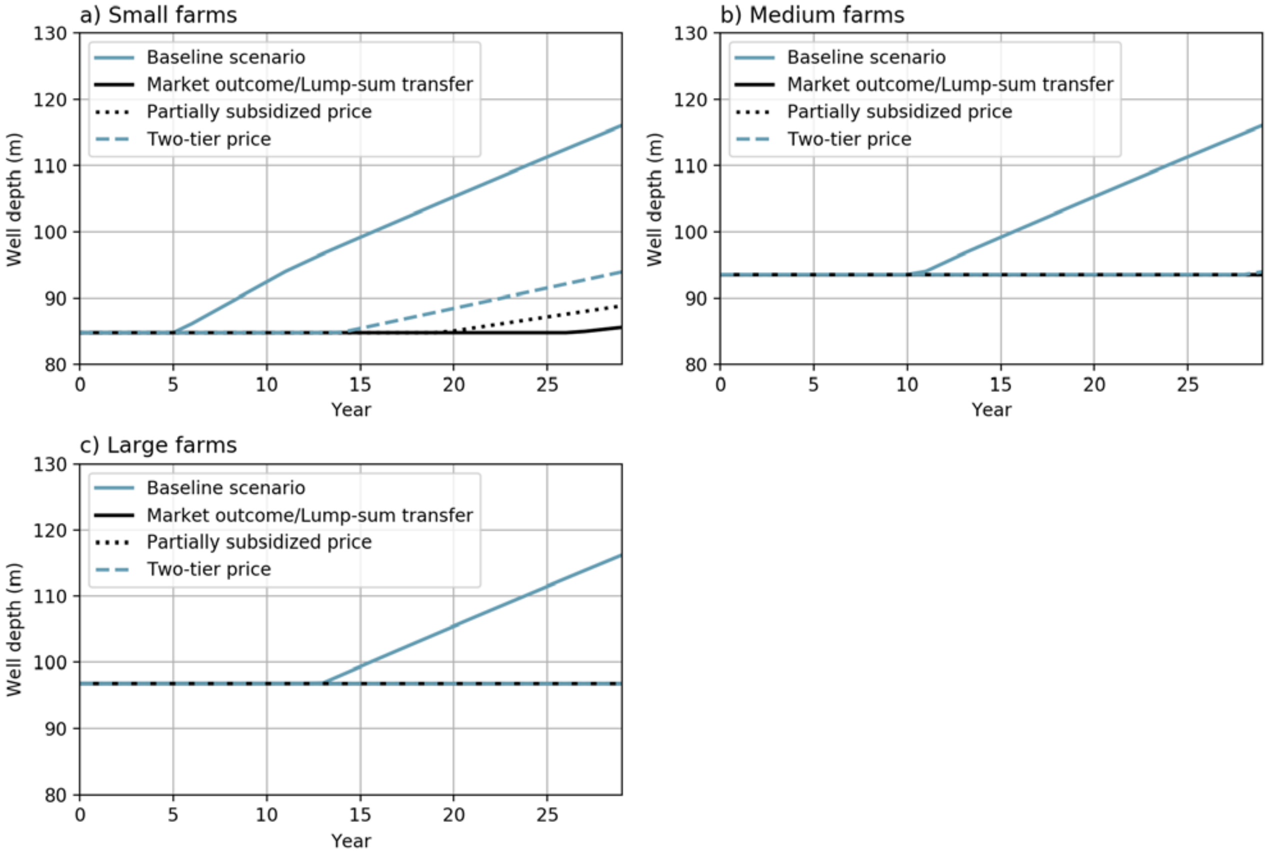

Figure 5. Evolution of the bore well depth

Investing in well depth has a direct impact on electricity consumption due to the need to extract water from a greater depth. In the baseline scenario, farmers' electricity consumption increases over time. However, if the water table gets close to bottom of the well the readily available water of the well becomes scarce and farmers start extracting less water. Their water extraction and energy consumption drops before investing in the depth of the well and is resumed after the investment in the well depth has been realized, (see the Appendix, Figure A.1). Figure A.2 of the Appendix shows that subsidy-reducing policies prompt significant savings in electricity-consumption. In particular, for the market outcome and lump-sum transfers, farmers consume only between 31.97% and 36.52% of the baseline electricity. Slightly higher is the electricity consumption in the case of partially subsidized prices and two-tier prices (37.39% - 43.65% and 45.84% - 54.02%).

In summary, the complete or partial elimination of subsidies curb the extraction of the aquifer significantly. The market outcome and lump-sum transfers are the most effective and obtain equivalent results with respect to the water table, bore well depth and electricity use, followed by the partially subsidized prices and the two-tier prices. However, the different policies have unlike effects on the farmers' profits and government spending. Figure 6 shows for the case of the baseline that the farmers' profits per hectare are fairly stable over time. Moreover, it shows that the profits of large farms plunge temporarily between 8 - 9% since they clear land and replant grapes in the years 14 and 28 that causes one-time costs.

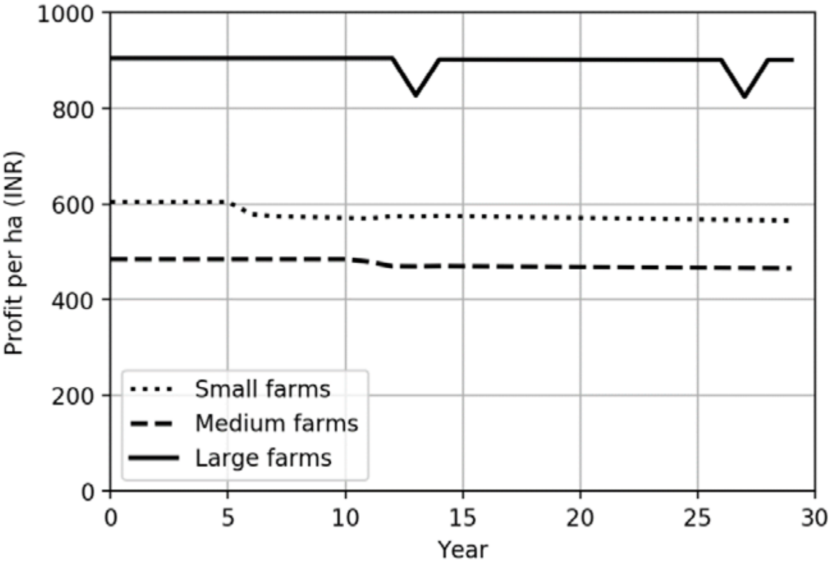

Figure 6. Evolution of farm profits per ha in the baseline scenario

Figure 7, (panels a - d), illustrates the profits for each type of farm, and the aggregate profits of all N farmers in the region as a percentage of the baseline. It shows that the farmers' aggregate profits are lowest when farmers do not receive any subsidies at all (market outcome). Compared to the baseline scenario the farmers' aggregate profits decrease initially from 247.5 to 239.17 million INR (6,55%) and to 229.7 million INR in year 30 (4.14%). In contrast, the aggregate profits of lump-sum transfers are higher than those of the baseline scenario. Compared to the baseline it allows to increase the profits initially up to 249.6 million INR (0.78%) and to 247.33 million INR (3.46%) in year 30. This can be explained by the fact that fully subsidized price of electricity of the baseline scenario aggravate the overexploitation of the aquifer since variable water extraction costs are zero.[9] However, if farmers receive a lump-sum payment equivalent to 50% of the subsidies of the baseline scenario, the electricity price is not subsidized at all. Lump-sum transfers imply higher water extraction costs so that it is optimal for farmers to extract less water and consequently, less investments in well depth are required. Since the lower investment costs and the received lump-sum payments overcompensate the higher extraction costs the farmers' profit increase. Moreover, small and medium-sized farmers benefit more from the instalment of lump-sum payments than large farmers (Figure 7, panels a-c). In the case partially subsidized prices of electricity and two-tier prices, the farmers' profits are in between those of the baseline scenario and the market outcome.

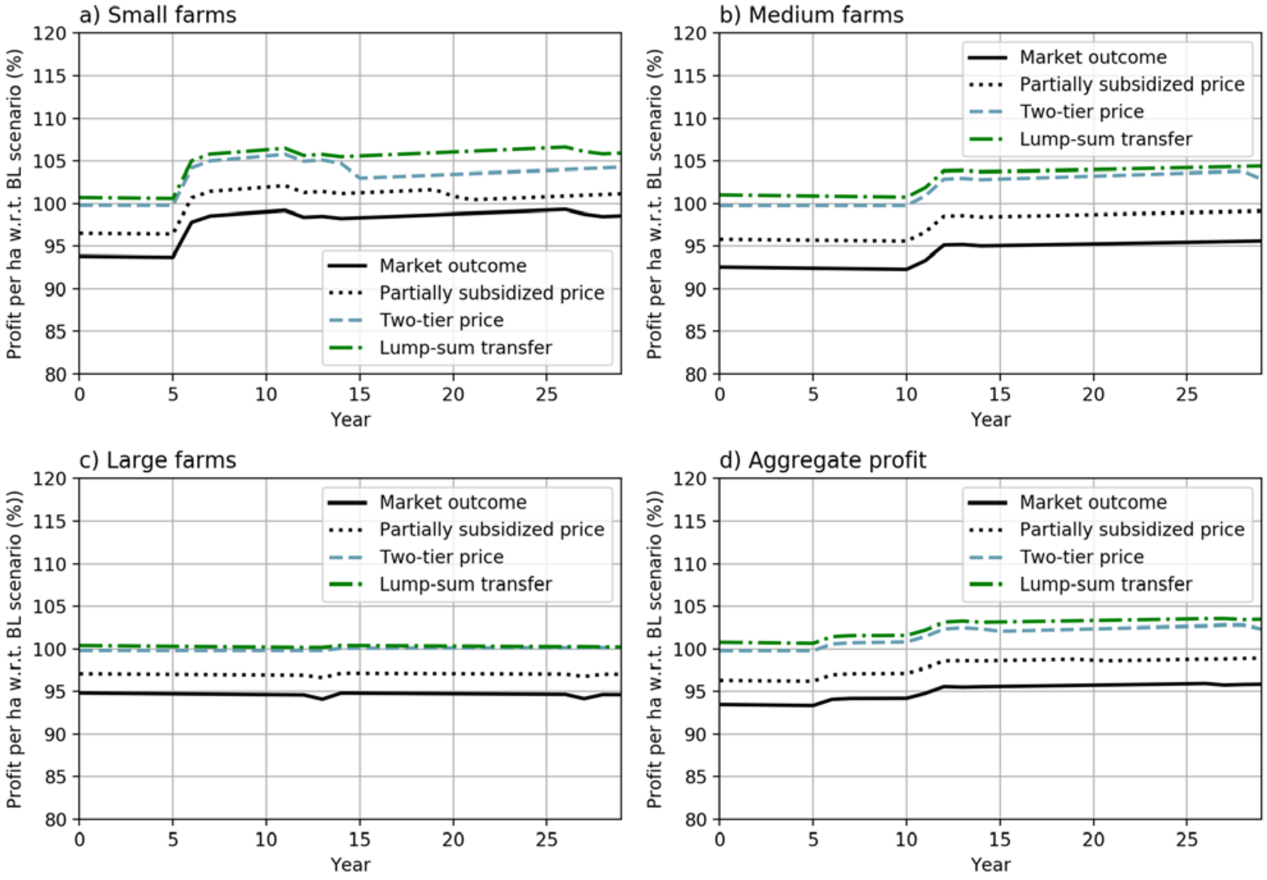

Figure 7. Evolution of farm profits per ha, in comparison with the baseline scenario.

Table 3 complements the results shown in Figures 6 and 7 and presents, for each policy scenario, the discounted sum of the farms' profits, aggregate profits, government expenditure (subsidies) and

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[9] Lower extraction costs make the extracted water more valuable, i.e., the in-situ value of the water in the aquifer increases, and moreover, the pumping externality decreases. The latter externality results from the fact that each farmer's extraction leads to a drop in the water that inflicts additional extraction costs on all other farmers.

social net benefits (farm profits minus subsidies) over 30 years. It reveals that the market outcome cuts the aggregate farm net benefits by 5.4% (23.44 M INR), government expenditures by 100% (71.43 M INR) but increases social net benefits by 13.1% (47.99 M INR). The partially subsidized price, two-tier price and lump-sum transfer allow to obtain almost the same social net benefit, i.e., an increase by 12.6%, 11.2% and 13.1% respectively. However, the policies affect farm profits and government expenditures differently. Switching from a fully to a partially subsidized price decreases farm profits by 2.4%, while, a two-tier price and lump-sum transfers are even able to increase farm profits. Thus, they can be considered as less distorting policies, since farm profits do not decrease, and over-extraction can be reduced.

A remarkable result is that policies have unequal effects on the different types of farmers. The market outcome and the partially subsidized price lead to losses in farm profits in all type of farms. The market outcome generates the greatest losses in profits, since farmers do not receive any kind of subsidies. While the farm profits of small farms decrease by 2.9% medium-sized and large farms suffer profit losses of 6.3% and 5.3% respectively. Profit losses as a result of the implementation of partially subsidized prices are relatively moderate and range between 0.2% and 3%. On the other hand, the application of two-tier prices leads to an increase in the profits of small and medium-sized farms (2.9% and 1.3%, respectively), while profits of large farms decrease minimally (0.1%). Finally, a lump-sum transfer is able to increase the profits of small farms by 4.3% which is nearly twice as much as the profit increases of the medium-sized and large farms.

The results indicate that the reduction of subsidies often leads to an increase in social net benefits and to a decrease in farm profits. However, depending on the implemented subsidy-reducing policy, social welfare and farmers' profits increase simultaneously. This somehow counter-intuitive result can be explained by the fact that reductions in subsidies lead to higher expenditure on electricity and to cost savings at the same time. For a certain range of subsidy-reducing policies the cost savings overcompensate the higher expenditure on electricity that corresponds to the cut-back in subsidies. Subsidy-reducing policies reduce the in-situ value of the water in the aquifer so that farmers extract less water compared to the case where the price of electricity is fully subsidized. Hence, the water declines less rapidly and farmers save on overall pumping costs and investment for deepening well. Thus, there may exist subsidy-reducing policies where the loss of subsidies weights less than the gains from costs-saving. The two driving factors are separated by a line that may be drawn by a very fine or very thick brush. In the case of a very thin (thick) line the interval of reduced-price support that generate an increase in farm profits is very narrow (wide). Yet, depending on the economic, agronomic, and hydrologic data of the study area this interval may have the width zero. In this case subsidy reducing policies always lead to a decrease in farm profits. The determination of the width of the interval is basically an empirical question and presents an interesting challenge for future research in the field of applied economics. The existence of this interval is, however, not only interesting for the design of policies but also for their acceptance by farmers. Gains in social welfare and private profits contribute to their acceptance by all stakeholders and decrease the potential for social unrest.

8. Discussion

Our analysis shows that subsidy-reducing policies induce substantial cutbacks in water extraction, which moderate the decline of the water table. The results of this study are qualitatively similar to those obtained by Sayre and Taraz (2019), who found that flat rate tariffs provide incentives for well deepening, which is responsible for the accelerated decline of the water table. Our qualitative findings of the welfare analysis are also consistent with previous research (Ryan & Sudarshan, 2022; Sayre & Taraz, 2019). However, our quantitative results diverge from the existing literature. Sayre and Taraz (2019) find that the difference between the private and social optimum is 66% while our study reports 13.1%. This discrepancy could be explained by several factors. Firstly, their analysis is based on the cultivation of a single crop, rice, which has 4 to 6 times higher water requirements than the crops analysed in our study. Secondly, they assume that the investment decisions are based on rational expectations about the evolution of the water table and not on the observed evolution of the water table. Rational expectations are formed exogenously but not endogenously. Thirdly, the authors' study is based on a substantially smaller aquifer where the same amount of water extracted leads to a 13 times higher drop in the water table than in our aquifer. As a result, the numerical results are not strictly comparable. The findings of Ryan and Sudarshan (2022) are more similar to ours. Specifically, they found that moving from a rationed electricity system to a subsidy-free system increases annual income by 12%, and social welfare by 47%. It's worth noting, however, that their analysis is static and the current electricity rationing constitutes their baseline. These two distinct elements make a direct comparison of the results difficult.

Nevertheless, both studies highlight the inefficiency of electricity subsidies and the potential of high social welfare gains if price support were completely withdrawn. Implementing the socially optimum by eliminating all subsidies, however, may be politically infeasible. The complete elimination of subsidies leads to a significant fall in farmers' profits that may provoke social unrest.

Table 3. Discounted value of aggregate farm profits, government expenditures and social net benefits.

Scenario	**Small farm profits (%)**		**Medium farm profits (%)**		**Large farm profits (%)**		**Aggregate farm profits (%)**		**Governmental subsidies (%)**		**Social net benefits (%)**	
Baseline (fully subsidized price)	3388[1]	-	5623	-	62852	-	437567	-	71433	-	366134	-
Market outcome	3291	**(-2.9%)**[2]	5271	**(-6.3%)**	59513	(-5.3%)	414124	(-5.4%)	0	(-100%)	414124	(13.1%)
Partially subsidized price	3380	**(-0.2%)**	5460	(-2.9%)	60991	**(-3.0%)**	426960	(-2.4%)	14542	(-79.6%)	412418	(12.6%)
Two-tier price	3486	**(2.9%)**	5699	(1.3%)	62801	**(-0.1%)**	442909	(1.2%)	35854	(-49.8%)	407054	(11.2%)
Lump-sum transfer	3533	**(4.3%)**	5754	**(2.3%)**	63043	(2.7%)	446795	(2.1%)	34961	(-54.3%)	414124	(13.1%)
Social optimum	3293	**(-2.8%)**	5271	**(-6.3%)**	59517	(-5.3%)	414193	(-5.3%)	0	(-100%)	414193	(13.1%)

[1] Absolute values are given in thousand INR.

[2] Values in parenthesis represent the percentage change with respect to the baseline scenario.

Studies by Sidhu et al. (2020), Bhattacharyya & Ganguly (2017) and Mitra et al. (2022) are aware of the social and political difficulties of implementing the social optimum and therefore, they propose intermediate policies, e.g., a flat rate of electricity based on the power of the pump or financial reward for reductions in electricity consumption. Although the three studies propose different subsidy schemes, they have in common that subsidies are not completely eliminated but are maintained to some degree. Table 3 shows that a 100% price support for 50% of the baseline water consumption, $W^j(0)$ and 0% price support of any water consumption beyond $W^j(0)$ (two-tier price) increases farmers' profits while a policy where 50% of the electricity price is subsidized does not. Thus, the question arises to what extent different policies and different degrees of price support of electricity consumption affect farms profits and social welfare. Figure 9 displays the discounted value of aggregate farm profits over a 30-year period as a function of two different subsidy schemes. The **dotted black line** indicates the farmers' profits as a function of the share of the electricity price that is subsidized and the **dotted blue line** denotes the farmers' profit as a function of the share of $W^j(0)$ up to that 100% of the electricity price is subsidized and 0% beyond. If the subsidy rate is 100% the farmers' profits are 414124 x 10^3 INR (Table 2). Any decrease of the share of the subsidized price up to 98% leads to an increase of the farmers' profits. A further decrease of the share of the subsidized price up to 86% leads to decrease of the farmers' profits but maintain its level above the baseline value of 414124 x 10^3 INR. Thus, the "line" where the loss of subsidies weights less than the gains from costs-saving has a width of 14%. Similarly, we observe for the case of the share of two-tier price that the width of the line where the loss of subsidies weights less than the gains from costs-saving is limited below by 35% and above by 100%. The discontinuous line peaks at 51%. Thus, a two-tier price where 51% of $W^j(0)$ is granted for free is the most beneficial for farmers. Yet farmers are likely to be indifferent between the current situation (baseline), a 86% share of the subsidized price or a 35% share of $W^j(0)$. Yet, from the government perspective the 35% share of $W^j(0)$ is preferential since the social net benefits are 414120 thousand INR compared to 405700 thousand INR for the 86% share of the subsidized price and 366134 thousand INR for the baseline scenario.

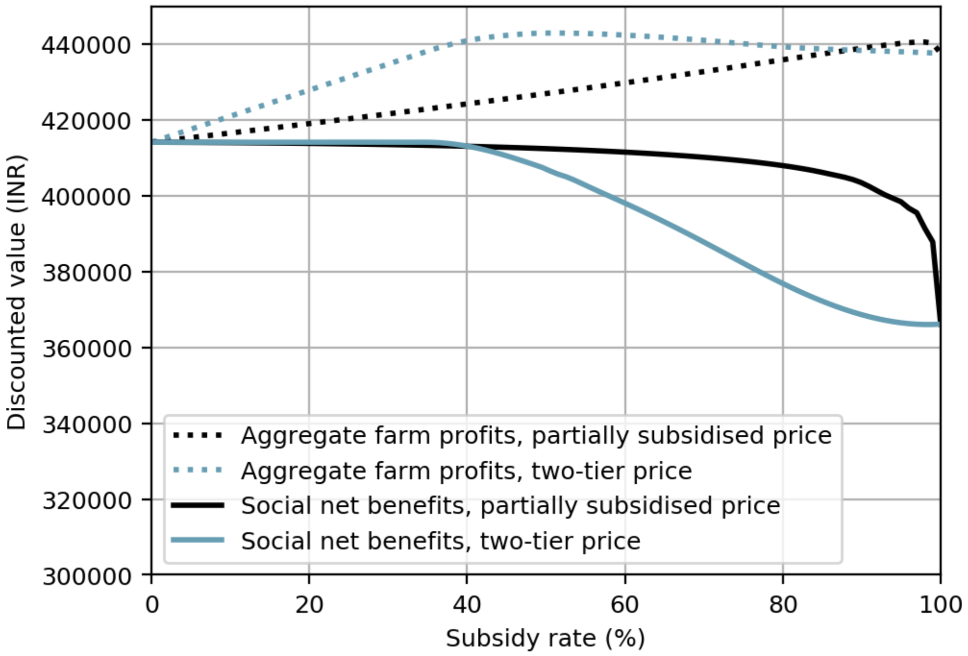

Figure 9. Aggregate farm profits and social net benefits as a function of subsidy rate

10. Conclusions

In many regions of India groundwater has become the primary source of freshwater. If the rate of groundwater extraction is above the natural recharge of the aquifer the extraction of water is not sustainable since water tables decline continuously and may lead to a complete depletion of the aquifer. Since the Indian government heavily subsidized the price of electricity farmers constructed in the past millions of private wells that contributed even more to the overexploitation of aquifers. Therefore, any policy designed to improve groundwater management necessarily has to address the energy water nexus, in particular the price of the electricity that is used for the extraction of groundwater.

This paper presents a distributed optimal control model that allows to analyse the efficiency of different policy instruments to reduce water extraction, and to evaluate their distributional effects on farmers’ profits. The policy analysis is based on a case study located in the district of Chikkaballpur in the Indian state of Karnataka. It considers three types of farms that differ by the size of their land endowment (small, medium and large), and use land, labour, energy, water, and mineral and organic fertilizer to produce seasonal crops (tomato and millet) and perennials (grape and mulberry). Moreover, farmers have the option to deepen their well. For the numerical solution of the model, we rely on the Nonlinear Model Predictive Control. This numerical technique avoids the “curse of dimensionality” so that a reduction of the dimensionality is not necessary, and the complexity of the model can be fully maintained.

The study analyses the effects of five different policy options: (i) 100% of the price of electricity is subsidized (baseline, status quo), (ii) 0% of the price of electricity is subsidized (market outcome), (iii) 50% of the price of electricity is subsidized, (iv) a two-tier price where 100% of the price of electricity is subsidized up to 50% of the quantity of water that is extracted in the baseline scenario (first tier) and non-subsidized for any quantity of extracted water beyond this tier and (v) non-subsidized prices of electricity coupled with a lump-sum payment equivalent to 50% of the subsidy that is paid in the baseline scenario.

First, the results show that the payment of subsidies exacerbate stress on groundwater resources since the initial water table of 76.2 m goes after 30 years, depending on the policy instrument, down to 85.55 (lump-sum transfer) – 116.07 m (fully subsidized price). Yet, the market outcome (85.55m) and lump-sum transfers are very close to the social optimum of 85.11m. A little further distant are the partially subsidized price (88.84 m) and the two-tier price (93.96 m). A shift from fully subsidized prices of electricity to the social optimum increases social welfare by 13.1%. Subsidy reducing policies increase social welfare by 11% – 12% and lump-sum transfer even by 13.1%. Thus, their welfare increases are nearly comparable to that of the social optimum, however, they come at the costs of a decline in the farmers' profit. The social optimum, the market outcome or partially subsidized prices of electricity leads to a reduction in the farmer's profit by 5.3%, 5.4% and 2.4% respectively. Thus, the political acceptance of the market outcome and partially subsidized prices is likely to be low because farmers may be unwilling to accept income losses. Moreover, cuts in farmers' profits may jeopardize social peace. Since income losses and social unrest are likely to be costly for politicians in terms of rural votes one expects that politicians are neither supportive of these policies. In contrast, two tier prices and lump-sum transfer are likely to be accepted by politicians and farmers since they increase social net benefits, and also the farmers' profits by 1.2% and 2.1% respectively.

The results also show that the social optimum, the market outcome or partially subsidized price of electricity lead to losses of medium and large farms that in percentage are twice as large as the losses of small farms. However, two-tier prices or lump-sum transfer result in gains of small farms that in percentage are significantly higher than the gains of medium and large farms. These distributional effects of the different policies are very important for the evaluation of their political acceptance by farmers and politicians since two-tier prices and lump-sum transfers support the most unfavoured group of farmers (small) and at the same time the largest group of farmers (medium-sized farms). Lump-sum transfers are the only policy that benefits all groups of farmers.

The gains and losses of subsidy-reducing policies vary with the degree of price support of electricity consumption. Weighing the loss of subsidies and the gains of cost saving for different degrees of price support may either lead to losses or gains in farm profit. Our results determine for partially subsidized price and two-tier prices the minimum and maximum degree of price support that leads to an increase farms profits and social welfare. They show that any degree of price support between 86% and 100% in the case of partially subsidized prices and between 35% and 100% for the case of two-tier prices form intervals that lead to an increase in farm profits in comparison with a full subsidy of electricity. The highest social welfare is obtained for the lower bounds of these intervals but the highest increase in the farms profits is obtained for intermediate values of the intervals.

The precise determination of the size of the intervals for the different subsidy-reducing policies is an empirical question and a challenge for applied research as it depends on the policy design and the agronomic, hydrological and economic parameters that are determined by the context of the study. Nevertheless, we think that it is an interesting perspective for future research as it not only allows to identify win-win situations for the environment, farmers and society but also to evaluate the political acceptance of subsidy reducing policies.

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Appendix

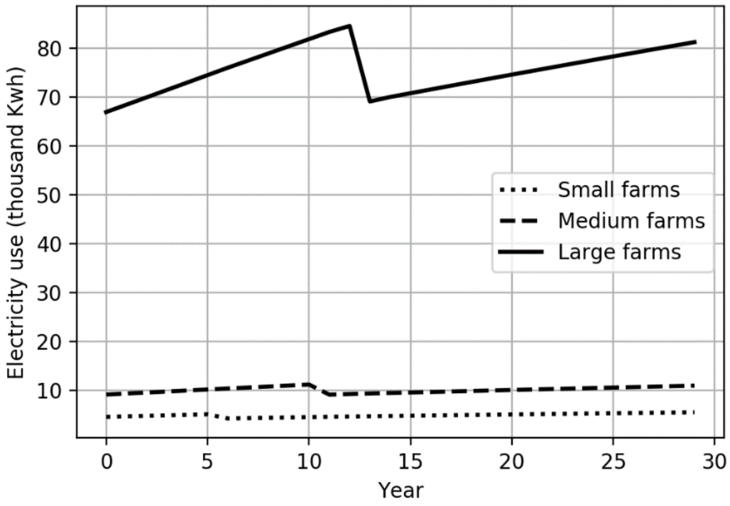

Figure A.1. Evolution of the total electricity consumption of each farmer in the baseline scenario

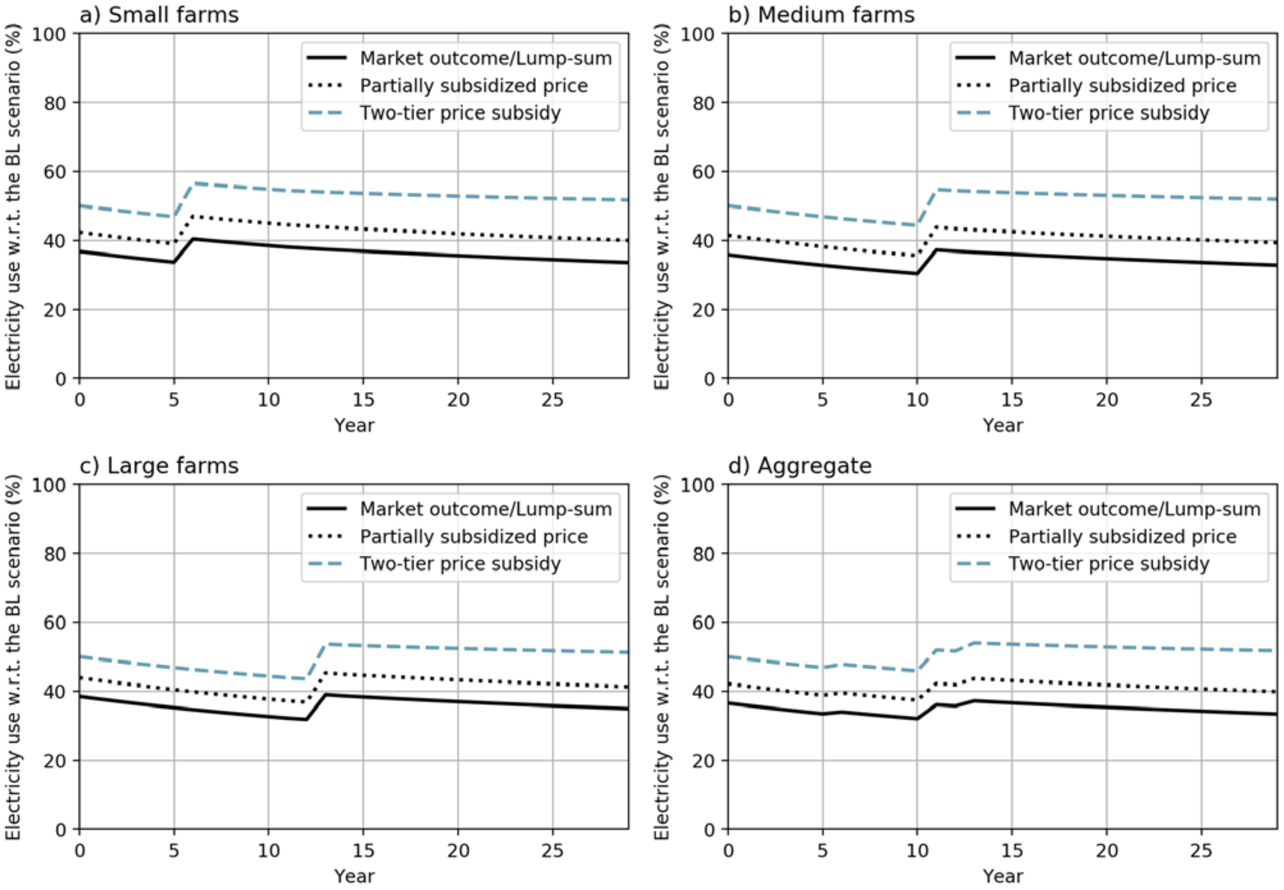

Figure A.2. Evolution of the total electricity use of the policies analysed, in comparison with the baseline