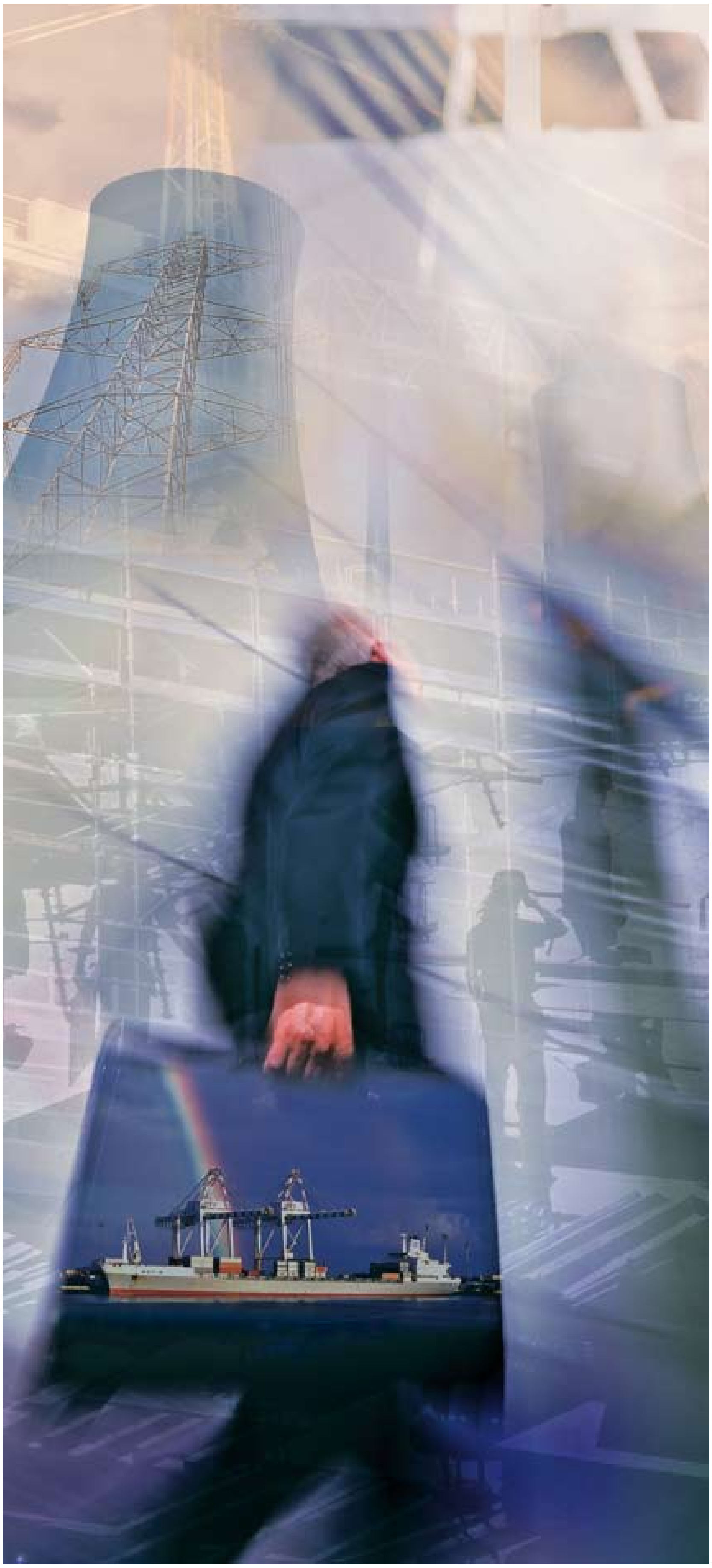

Queensland

The Economic Society of Australia Inc.

Proceedings of the 37th Australian Conference of Economists

Papers delivered at ACE 08

30th September to 4th October 2008
Gold Coast Queensland Australia

ISBN 978-0-9591806-4-0

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The Paper following forms part of - *Proceedings of the 37th Australian Conference of Economists*
ISBN 978-0-9591806-4-0

Groundwater Extraction Externalities: Accounting for Quantity Depletion and Quality Deterioration Simultaneously

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Abstract:

Over extraction of groundwater in many parts of the world is common and such practices have led to negative externalities. Numerous studies have examined quantity depletion and quality deterioration issues and have prescribed optimal policy instruments such as imposing a tax which is equated as the shadow price of groundwater. However, the literature reveals that no study has dealt with both quantity depletion and quality deterioration externalities at the same time. As a result these studies have underestimated the shadow price of groundwater, and, therefore, the solutions suggested do not turn out to be optimal. The low estimated shadow price in turn has resulted in the overexploitation of groundwater resources. The main objective of this paper is to derive the costs of groundwater extraction externalities, both quantity depletion as well as quality deterioration simultaneously. The results show that when both externalities are taken into account, the shadow price is higher than that calculated by previous studies and hence lead to a reduction in groundwater extraction to an optimal level. The results suggest that by considering the impact of groundwater extraction quantity and quality externalities in a resource management model it is possible to achieve the optimum outcomes by preserving the steady state quantity as well as the quality of groundwater. The theoretical arguments are tested empirically using data collected from onion production in Sri Lanka.

Keywords: Groundwater; steady state; quantity and quality externalities, onion production

1. Introduction

Increasing demands for groundwater and its over extraction pose new challenges to water resources managers. Owing to its importance, the sustainable use of groundwater has been extensively studied during the last two decades (cf. Yeh, 1992; Seward et al. 1996; Takahashi and Peralta, 1995; Roseta-Palma, 2002). As evidenced from these studies, groundwater abstraction can cause, directly or indirectly, changes in groundwater quantity as well as quality. However, an examination of the literature shows that water quantity and its quality externalities are examined separately thus preventing an optimal abstraction solution. For example, Brown and Mcguire, 1967; Bhatia et al. 1992; Bill and Oscar, 1993 focus on water quantity depletion externalities and unit cost increasing externalities and emphasise that these externalities can be corrected by using a simple tax or charge. On the other hand Larson et al. 1996; Fleming and Adams, 1997 focus on water quality deterioration externalities due to pollution and siltation and analyse non-point pollution as an externality imposed by agricultural production activities. They also emphasise that these externalities can be corrected by using a simple tax or a charge. A few studies (cf. Dinar and Xepapadeas, 1998; Roseta-Palma, 2002), however, have attempted to include the quality component into the quantity model, but these models do not fully address the quantity depletion and quality deterioration externalities and the models contain a number of unrealistic simplifications with respect to the hydrological component. The aim of this paper is to examine the socially optimal groundwater extraction levels and to demonstrate how the socially optimal is affected by changing both the quantity and quality of groundwater simultaneously.

The remainder of the paper is set out as follows. Section 2 discusses the relevant groundwater literature while Section 3 describes how the traditional economic literature incorporates the groundwater extraction externality problems in their models. Section 4 shows how changes in stock quantity and quality over time can be modelled and how it changes the traditional optimal solution. Section 5 demonstrates the importance of incorporating the quality component into the existing models in an empirical setting. The final section summarises and concludes.

2. A discussion of the relevant groundwater literature

The economic literature on groundwer extraction literature dates back to the 1970s. Brown (1974) was one of the earliest to derive an optimum program for managing a common-property natural resource where the rate of growth of the resource stock depends on the resource stock level and the current rate of extraction. According to this model if the resource stock is sufficiently small it will be socially optimal to have a period of no extraction. This is because the rate of extraction is faster than the increase in resource stock. Since then, economists have extensively analysed different aspects of groundwater extraction which includes the economic value of groundwater extraction, setting prices on groundwater extraction, inter-temporal allocation, scarcity value and environmental impacts groundwater use, property right issues and pollution of groundwater (cf. Gisser and Sanchez, 1980; Knapp and Feinerman, 1987; Bhatia et al. 1992; Lee and Howitt, 1996; Hellegers et al. 2001; Rubio and Casino, 2003). More recently, economists have analysed the sustainability of groundwater extraction (cf. Loaiciga and Leipnik, 2001; Alley and Leake, 2004; Devlin and Sophocleous, 2005). As defined in the literature, sustainable groundwater exploitation occurs when the rate of groundwater extraction is equal to or less than the natural rate of groundwater replenishment for any level of aquifer storage (Loaiciga and Leipnik, 2001). Since climatic factors affect sustainable groundwater exploitation Loaiciga and Leipnik, (2001) have analysed different strategies for sustainable groundwater exploitation. They identify the market price of groundwater, cost of groundwater extraction, aquifer storage and natural replenishment characteristics, intuitional and environmental regulations on groundwater extraction and the real discount rate as the key factors affecting sustainable exploitation strategies.

Another area of groundwater use that has been examined is the problem of water allocation. The allocation issues have been analyzed using static optimization or dynamic optimization methods (cf. Knapp and Feinerman, 1987; Sun and Zheng, 1999; Hsiao and Chang, 2002). Young (1996) has shown that the characteristics of groundwater and the economic allocation problems make it well suited to dynamic forms of analysis However, dynamic efficiency conditions require that all water users achieve the same marginal welfare gain for each unit of water and equalisation of the net marginal benefit from using the resource and the inter-temporal cost[1]. Knapp and Feinerman (1987) while solving a problem of steady-state allocation of groundwater argue that the dynamic steady-state is a concept that has limited applicability in ground-water management. According to them in cases where the optimal steady state is indeed useful, the dynamic solution is often identical to the static solution

Furthermore, the divergence between myopic and optimal control strategies of groundwater extraction have been explored extensively in the economic literature. Studies conducted by Gisser and Sanchez (1980); Bill and Oscar (1993); Rubio and Casino (2001) have focused on the sign and magnitude of the welfare improvement between the myopic and social equilibrium levels. Bill and Oscar (1993) distinguish between efficient groundwater allocation following a myopic strategy that accounts only for private costs/benefits and efficient allocation following an optimal control strategy that accounts for all costs/benefits to society. Private extraction strategies cause divergence between private and social welfare because of the negative externalities. In their analysis Bill and Oscar (1993) describe various types of externalities[2] such as stock externalities, cost externalities and risk externalities. According to Santiago et al. (1999) the inefficiency of private exploitation is caused by pumping cost externalities and strategic externalities. The cost externality appears because the pumping cost increases with pumping lift, so that a withdrawal by one farmer lowers the water table thus increasing the pumping costs for all farmers operating over the aquifer. The strategic externality arises from competition among farmers to appropriate groundwater through pumping since property rights over the resource are not well defined (Santiago et al. 1999). Related to groundwater extraction externalities, Chermak et al. (2005) presents a general model of optimal groundwater management under cooperative, non cooperative and myopic management approaches. Comparing the results from the approaches, they find that the cooperative solution results provide the highest level of net social welfare.

In relation to examining the costs and benefits of groundwater over exploitation Ratna reddy (2005) has estimated the costs of groundwater over exploitation and the costs and benefits arising from groundwater replenishing mechanisms in different ecological contexts in India. This study argues that the over extraction and the resultant environmental

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[1] The inter-temporal cost is defined as the marginal private cost of current period extraction and the present value of externalities resulting from current consumption, most notably the user cost resulting from using the resource now instead of saving it for the future (Zachariah, 1999).

[2] Externalities occur when the activities of one economic agent impact on the activities of another agent in ways that are not reflected in market transactions. Externalities can take either positive or negative values.

degradation of groundwater is a direct consequence of policy failure for managing groundwater resources. Diwakara and Chandrakanth (2007) show that the negative externalities arising from groundwater irrigation in India is due to groundwater overdraft leading to premature well failure and reduced yield.

In the presence of externalities economic analysis suggests that markets will operate inefficiently. In such situations resources will not be allocated for a use that provides the greatest welfare gain, because private agents equate private marginal benefits with private marginal costs and thus fail to include marginal social costs or benefits in their analysis (Freeman, 1993). In the case of a negative externality, the agent's failure to internalize the external impacts of their activity results in over-allocation of resources. In these conditions, the underlying resource stock is depleted at a rate faster than the social optimal. Groundwater abstraction can cause, directly or indirectly, changes in groundwater quality as shown by studies in India. Intensive agriculture[3] has steadily increased the demand for water resources on the one hand and negatively affected the quality of water on the other. Many studies have been conducted on the value of water quality changes over the years. Most of these studies have focused on specific sites or local water quality issues (cf. Lee and Howitt, 1996; Fleming, and Adams, 1997; Lee, 1998). Some studies have concentrated on ways to reduce nonpoint pollution based on relatively easily observed factors such as ambient water quality (cf. Sims, 1979; Larson et al. 1996). For instance, Larson et al. (1996) recognize that water as the best single input to regulate its non-point source pollution externalities by using second-best tax policies. However, as pointed by Roseta-Palma (2002) the value of water as a resource depends as much on the quantity available as on its quality, so that both aspects should be considered simultaneously for adequate management. During the last decade several papers have been published that take into account quality as well as quantity aspects of groundwater (cf. Zeitouni and Dinar, 1997; Dinar and Xepapadeas, 1998; Roseta-Palma, 2002). However, these models do not accurately address the resulting externalities and they include a number of unrealistic assumptions with respect to the hydrological component. In the next two sections we show the socially optimal groundwater extraction patterns and show how the social optimal is affected by changing both the quantity and quality of groundwater simultaneously.

[3] The increasing use of agricultural chemicals i.e. fertilisers and pesticides are a major cause of deterioration of the quality of both surface and under groundwater.

3. Traditional economic analysis of optimal groundwater use

The economic approach to decide on the most desirable allocation of water is to use the principles of economic efficiency to ensure that water is supplied to its most valuable uses. Hence it is necessary to develop a theoretically sound approach of analysing the impacts of groundwater extraction externalities. Although herein we are considering only the use of groundwater for agriculture, the same economic principles can be used to explain the use of groundwater for other purposes such as drinking. In the economic literature simple models have been used to determine the socially optimum price for groundwater (Brown and Mcguire, 1967; Bhatia et al. 1992; Bill and Oscar, 1993). In these models the steady state conditions have been assumed for groundwater conditions and water demand functions. According to them, the social optimum could be achieved by an appropriately conceived tax policy. One of the most commonly used models in the economics literature for analyzing groundwater extraction effects is explained below. In this model we assume that there is an N number of identical farmers engaging in production in a particular region. In each period, each user withdraws W_t units of groundwater. The objective functions represent that the farmers are trying to maximize their profits. We also assume that farmers sell their production in competitive markets so that the price of water is equal to the value of the marginal product of water. Hence, the social planners objective function is as follows:

$$\text{Maximize } \Pi = \int_{t=0}^{T} \{N\,[P_Q Q - (PC)] + \lambda \dot{D}\}\ e^{-rt}\,dt \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The first term and the second term of Equation (1) is the total revenue of agricultural production and total costs while the third term describes the constraints of the optimization problem. For simplicity, we have assumed that production (Q) is a function of water (W) and that diminishing marginal returns exist for water *($f_w > 0$ and $f_{ww} < 0$).* Hence, we have assumed that P_Q is the price of the agricultural product and PC is the pump cost. In case of groundwater, pump cost basically depends on groundwater depth as well as the amount of groundwater extraction. A commonly used cost function in the literature, (Brown and Mcguire, 1967; Huang and Mayer, 1997) is used in this paper which can be explained as follows: Assume that D_t is the groundwater depth (lift in feet at t), W_t is the groundwater extraction in the well or basin at time t for each extractor and A is the fixed cost. Then the cost equation becomes $PC_t = C\,(A_t, D_t, W_t)$. We assume a linear cost function which is $PC_t = A + bD_t + cD_tW_t$.

In the above equation we assume two types of variable costs: The first variable cost is bD_t which shows how total costs vary with groundwater depth and the second variable is cD_tW_t which shows that the variable costs depend on the amount of water pumped and groundwater depth. A physical balance equation (dD/dt) is used as the constraint and it has been included in the groundwater quantity change (stock change) overtime. If we assume that R as the amount of water recharged, then the quantity constraint equation can be written as $dD/dt = R - NW_t$.

In the steady state $D_t = D_{t-1}$ and $W_t = R / N$ are assumed as the safe groundwater yield. Accordingly, the lagrangian objective function of social planners including all the relevant variables is as follows:

$$\text{Maximize } \Pi = \int_{t=0}^{T} \{N [P_Q f(W) - (A + bD_t + cD_tW_t)] + \lambda (R - NW_t)\} e^{-rt} dt \quad \ldots(2)$$

And the current Hamiltonian function is:

$$H = N [P_Q f(W) - (A + bD_t + cD_tW_t)] + \lambda (R - NW_t) \quad \ldots\ldots\ldots\ldots(3)$$

The first order conditions gives:

$$dH/dW = 0 : \quad N(P_Q MP_w - cD_t) - N\lambda = 0$$

$$P_Q MP_w = cD_t + \lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where the value of marginal product of water is equal to marginal cost plus the shadow price of water.

The behaviour of the opportunity cost or shadow price of water along the optimal extraction path can be obtained using Equation (2) and through the equation of motion to give:

$$\text{Equation of motion: } \dot{\lambda} = r\lambda - [dH/dD] \text{ or } \dot{\lambda} = r\lambda + N (b + cW) \quad \ldots\ldots\ldots\ldots (5)$$

Where in steady state $\dot{\lambda} = 0$ and $r\lambda + N (b + cW) = 0$

$$\lambda = - (N/r) (b + cW) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

By substituting λ into equation (1) we obtain the following steady state solution:

$$P_Q MP_w = cD_t + (N/r) [b + cR/N] \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Private equilibrium occurs where the marginal value product equals the marginal private costs ($P_Q MP_w = cD_t$). Following a private strategy, the individual user does not consider the effect of their pumping on other users' costs. This results in each individual extracting too much groundwater per period. However, at the social optimal level the value of the marginal product of water should be equal to marginal private cost plus the external cost. According to Equation 6 the external cost equals the shadow value of water [λ or (N/r) (b + cW)]. Comparing the results of the social planner and the individual, we see that the social planner takes full account of the impact of withdrawing water today on future costs. Theoretically, we know that by imposing a tax or a charge which is equivalent to the shadow value of water [λ or (N/r) (b + cW)], social optimal can be achieved.

The social optimal level is where the value of the marginal product of water equals the marginal private costs plus the external costs and if tax rate equals the external cost or the value of the marginal product of water equals the marginal private cost plus the tax rate. This situation can be analyzed by using a simple graph. This is shown in Figure 1.

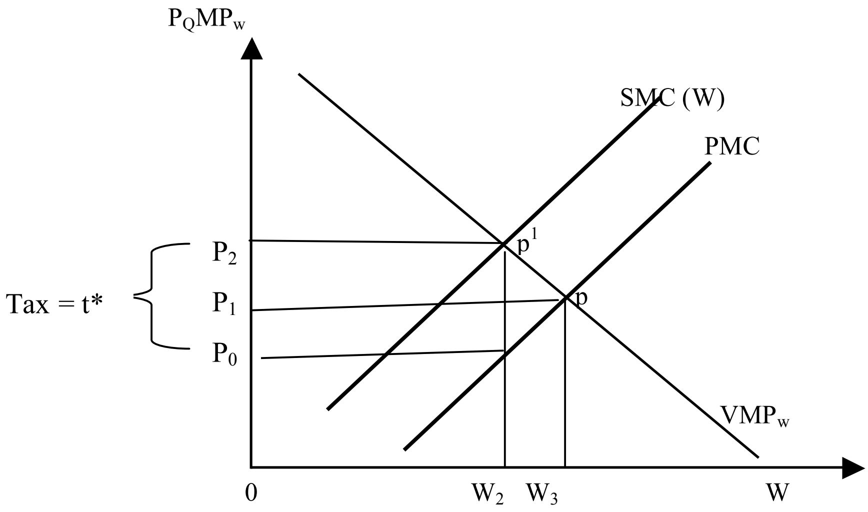

Figure 1: The theoretical optimal solution shown in the literature

The divergence between private and social welfare maximization occurs because private users view their water allocation strategy as a single period optimization problem equating marginal private benefits with marginal private costs. In contrast, the optimal control problem seeks dynamic efficiency equating inter-temporal marginal social costs and benefits where the inter-temporal marginal social cost consists of aggregate marginal costs for the current period. Figure 1 shows market equilibrium at point ‘p’ characterized by a situation in which the externality is not priced. In the absence of a regulatory authority the market will be guided by the marginal cost curve that reflects the private marginal cost of groundwater extraction, leading to an extraction level given by W_3. The socially optimal level of groundwater extraction, however, is at W_2. The prevailing private market price for water is given by P_1. According to the economic literature, to achieve efficient pricing by incorporating externalities, what is required is a charge that will raise the price of water from P_1 to P_2. Accordingly, optimal pricing can be achieved by using a simple tax or a charge which is equivalent to *t**. However, is this sufficient? In the next section we show that targeting quantity alone is insufficient. In other words we also have to consider quality aspects since the quality of water has a bearing on agricultural productivity for many crops.

4. New economic model of optimal groundwater extraction

A methodology is developed for determining a robust optimal groundwater extraction level by using the same farmers' objective function used in Section 3 but adding the impact of water quality changes on agricultural production[4]. Accordingly the quality change constraint can be introduced into the above model. Assume that S is water quality and dS/dt indicates that changes in groundwater quality over time and it is comprised of initial quality of the groundwater stock plus quality changes due to recharge flows. As a quality indicator we can use nitrate concentration as an example. Assume that S^* is the existing nitrate concentration level in the groundwater stock and $g(W_t, R_t)$ is the nitrate concentration due to recharge flows. Here nitrate concentration in recharge flows depends on ground water extraction (W_t) and total amount of water recharge (R_t). Groundwater quality will deteriorate if recharge flows are of a lower quality (higher nitrate concentration) than extraction flows.

$$dS/dt = (S_t - S_{t-1}) = S^* + g(W, R) \quad \ldots\ldots(8)$$

As can be seen from Equation (8) production is a function of two variables namely water quantity as well as quality. Assume that $f_w > 0$, $f_s > 0$ and $f_{ww} < 0$, $f_{ss} < 0$. The social planners objective function includes the quantity as well as quality depletion externalities where:

$$\text{Maximize } \Pi = \int_{t=0}^{T} \{ N[P_Q f(W,S) - (a + bD_t + cD_tW_t)] + \lambda_1 (R - NW_t) + \lambda_2 [S^* + Ng(W, R)] \} e^{-rt} dt$$

The new current value Hamiltonian function is:

$$H = N[P_Q f(W,S) - (a + bD_t + cD_tW_t)] + \lambda_1 (R - NW_t) + \lambda_2 [S^* + N g(W, R)] \ldots\ldots(9)$$

The first order conditions are:

$$dH/dW = 0 : \quad N(P_Q MP_w - cD_t) - N\lambda_1 - N\lambda_2\, dg/dW = 0 \quad \text{as } dg/dW < 0$$

[4] One of the important on-farm effects of poor quality groundwater irrigation is lower yield of crops.

$$P_Q\, MP_w = cD_t + [\lambda_1 + \lambda_2\, dg/dW] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.... (10)$$

The new social optimal is where the valve of the marginal product of water equals the marginal cost plus the shadow price of water. The behaviour of the shadow price of water along the optimal extraction path is described by Equation (11) and (12).

Equation of motion 1: $\dot{\lambda}_1 = r\,\lambda_1 - [dH/dD]$ and $\dot{\lambda}_1 = r\,\lambda_1 + N\,(b + cW)$

Steady state $\dot{\lambda}_1 = 0$ and $r\,\lambda_1 + N\,(b + cW) = 0$

$$-\,(N/r)\,(b + cW) = \lambda_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (11)$$

Equation of motion 2: $\dot{\lambda}_2 = r\,\lambda_2 - [dH/dS]$ and $\dot{\lambda}_2 = r\,\lambda_2 - [\,N(P_Q\, f_s)\,]$

Steady state $\dot{\lambda}_2 = 0$ and $r\,\lambda_2 - [\,N(P_Q\, f_s)\,] = 0$ or $[\,(N/r)(P_Q\, f_s)\,] = \lambda_2$ .. ……….... (12)

By substituting Equations (6) and (7) into Equation (10) we have:

$$P_Q\, MP_w = cD_t + (N/r)\,(b + cW) + [\,(N/r)(P_Q\, f_s)\,]\, dg/dW \quad \ldots\ldots.(13)$$

The left hand side of the Equation (13) shows the marginal value product of water when both quantity and quality depletion externalities are taken into account. There are three components in the right hand side of the equation, namely the marginal private costs, external costs of scarcity rent and external costs of quality deterioration respectively. Accordingly, at the social optimal level, value of the marginal product of water should be equal to marginal private cost plus the external cost of scarcity rent as well as quality deterioration. As mentioned above, the external costs have two components namely externalities due to scarcity rent and quality deterioration externalities. As a result external cost in this case are greater than the previous case. To achieve the optimal solution an instrument such as a tax or a charge can be used to cover both externalities. This new situation is illustrated in Figure 2. Figure 2 shows that private market equilibrium occurs at point ‘p’ in a situation in which the externality is not priced. The PMC is the private marginal cost, and the MSC (W) is the marginal social costs associated with quantity depletion externalities. The MSC (W+ S) is the marginal social costs associated with quantity as well as quality depletion externalities.

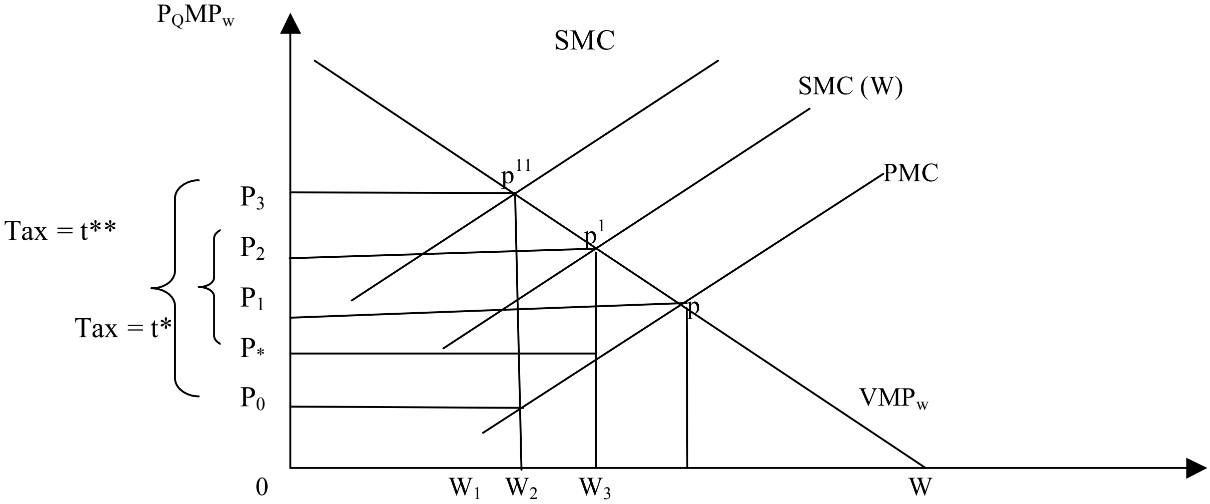

Figure 2: Comparing the social optima's

level of water extraction is W_2 and the optimal price is at P_2. The optimal was achieved by using a tax or a charge which is equivalent to t*. However, when calculating the social marginal cost, we need to take into account quality deterioration as well. Hence, the optimal quantity and price become W_1 and P_3 respectively. We see that the SMC has now moved leftwards to SMC (W+S). The tax or a charge used, t**, is greater than t*. Accordingly, to achieve efficient pricing for groundwater by incorporating the extent of the full external costs, social planners need to take into account, not only quantity extraction externalities but also quality deterioration externalities. Here what is required is a charge that will raise the price of water to the amount to P_3. The difference between the two solutions is significant.

5. Empirical results showing the impact of quality deterioration on production

The model developed in Section 4 is applied to the Anuradapura district in Sri Lanka. In this district there is a heavy reliance on groundwater to meet water demand for farming in the dry season and overdraft levels typically have been severe. The cultivation of onion in Anuradapura illustrates the analytical framework perfectly. At least three factors motivate the selection of onions as a representative commodity. First, onion is largely produced extracting groundwater from agro-wells in the dry zone of Sri Lanka. Second, it is a highly sensitive crop to water quality (salination/nitrate concentration) changes. Third, cultivation different types of minor crops including onion is spreading rapidly in many districts in the dry zone leading to a rapid deterioration in groundwater in the region. The data used for the empirical analysis is from a survey that was conducted among 144 Onion farmers in Anuradapura district in 2003. In addition to this primary data some secondary data published by the Central Bank as well as the Department of Sensus and Statistics in Sri Lanka are used in the analysis. Since there is no data available on crop losses due to Salinity the estimation of yield reduction for different salinity levels is undertaken by data published by Soltanpour and Follett (1995). However like most other empirical studies certain value judgements and assumptions were also made. The primary purpose of the study is to investigate quantity depletion as well as quality deterioration rather than to undertake a valuation study.

In spite of the rapid diffusion of agro-wells and pumps in Sri Lanka, there is no evidence of the existence of a water market as in other countries in the region (Kikuchi et al. 2003). The investments in agro-wells and pumps began to increase rapidly after the mid-1980s in many districts, including Anuradapura. It is apparent that the commencement of the government subsidy program for lined wells had significant impacts on farmer investments in pumps as well as in agro-wells (Kikuchi et al. 2003). However, such indiscriminate construction of new agro-wells can lead to serious environmental problems (De Silva, et al. 1999). The introduction of agro-wells has changed the cropping pattern in the dry zone of Sri Lanka. Minor cash crops such as onions, chilli and many kinds of vegetables is widespread. The number of farmers cultivating big onion has continued to increase from 2,515 in 2000 to 4,495 in 2006 in Anuradapura (Department of Census and Statistics, 2007). Total local production in Anuradapura district has increased from 8255 metric tons in 2000 to 11,256 metric tons in 2007.

Since water is a free commodity in the agriciultural sector in Sri Lanka water conservation is almost non-existent. Most farmers assume that if they apply more water they can get a larger yield. As a result farmers often waste valuable water, which could be used by them or others to produce additional crops. On the other hand the value of water may impact both the choice of technology and the level of substitution (Salman and Al-Karablieh, 2004). At present farmers in the dry zone are reporting that they don't have any water for their crops at the end of the growing season because over extraction has dried out aquifers. More agro-wells tapping into the same limited resource, and more intensive agriculture, is likely to mean that shallow groundwater resources will become further depleted and more severely polluted(IWMI, 2002).

In order to provide the numerical example for the model we first calculate the value of the externalities associated with common property extraction of groundwater at the steady state. For this purpose two functions are estimated using the survey data. They are for pump cost and output. For this purpose we run an Ordinary Least Squares (OLS) regression. The estimated cost function for pumping water and production function for onion is shown in Table 1. As can be seen the 'well-depth' variable is not significant in the cost function while capital is not significant in the production function[5].

Table 1: Estimated coefficients of the cost and production functions

Independent Variables	Pump Cost (PC)	Production(Y)
Intercept	682.5127(2.91)*	1.5259(2.11)*
Water quantity(W)		0.2012(3.35)*
Well-depth(WD)	10.6650(1.21)	
Water quantity*well depth	0.0072(4.46)*	
Labour(LA)		0.6221(7.33)*
Capital(CA)		0.0119(0.22)
R^2	0.31	0.54
DW	2.07	1.91

Note: The relevant t values are given within brackets. * denote significant variables. The production function was estimated using logs.

Using the estimates in Table 1 and average prices we calculated the shadow value of the groundwater defined in equation (11). Accordingly the present value of the cost of groundwater extraction for cultivation Onion is estimated at US$ 0.048 per cubic meter. However, at present water is being pumped at a cost of US$ 0.008 per cubic meter. Hence, cost of extraction is substantially below the price of water. However this calculation omits the impacts of climate change on rainfall patterns and subsequent recharge. If rainfall is decreasing, renewable recharge may drop subtantially and depleation will accelerate, leading to a higher shadow value than presented in this study. If groundwater level is to maintain at the optimum level over extraction has to stop. In order to acheive this optimum, the cost of extracting groundwater should be at least equal to US$ 0.048 per cubic meter.

In addition to quantity depletion, the problem of saline intrusion starts with heavy abstraction of groundwater from aquifers. Generally, saline water is drawn up towards the wells and this disturbs the equilibrium between fresh and saline water. Saline

[5] Many farms are small in size and most activities are labour intensive. As a result their capital expenditure is not very high.

water intrusion leads to the pollution of water and once it happens, it is very difficult to control and reverse[6]. Table 2 summarises the possible costs of salinity accumulation due to excess groundwater extraction[7]. The estimated cost of yield reduction[8] due to exceeding the threshed level of salinity is shown in Table 2.

Table 2: Estimated cost of yield reduction

Salt level (mmhos/Cm)	1.2	1.8	2.8	4.3
Percentage yield reduction with salt levels	0	10	25	50
2006 average yield per hectare (***Metric Tons)***	10.7	10.7	10.7	10.7
Yield reduction per hectare (***Metric Tons)***	0	1.07	2.67	5.35
Cost of yield reduction per hectare (US $) (2006 Onion prices are used)	0	404	1010	2020
Number of cultivated hectares	0	940	940	940
Total cost in the district (US $)	0	470,965	1,177,413	2,354,825

At the equilibrium the value of the marginal product of water should be equal to the marginal private cost plus the scarcity value. The estimated value of the marginal product of water under different equlibria are repoted in Table 3. It also shows how the marginal value of water differs under different salinity levels. We also calculated the total benefits of groundwater management in the area. In general the benefits of groundwater extraction are given by the area under the demand curve. But here we estimated the benefits of using avoidance cost of increasing water salinity level to 1.8 (mmhos/Cm) which is the lowest risk level in the above schedule. The corresponding present value of total benefits of managing both quality as well as quantity is US$ 18. 4 per acre.

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[6] According to Thiruchelvam et. al. (1994), over pumping is one of the major causes of salt-water intrusion into groundwater that affects agricultural production in the Jaffna peninsula of Sri Lanka.

[7] Salt accumulation reduces the osmotic potential of the soil, harming a plant's ability to absorb water. This effect is measured from crop salt tolerance. Mass and Hoffman (1977) developed the following relationship to estimate the osmotic effects of plant growth.

$$1 - Y_2/Y_1 = b(EC_e - A)$$

$1 - Y_2/Y_1$ = relative yield decrease from nonsaline to saline conditions

b – percentage yield decrease from a one unit increase in electrical conductivity above threshold limit

EC_e = the mean electrical conductivity of a saturated paste taken from the rootzone

A = salinity threshold (mmhos/cm or dS/m)

[8] Excessive soil salinity (salt) reduces the yields of many crops. This may range from a slight loss to complete crop failure, depending on the crop and the severity of the salinity problem (Soltanpour and Follett).

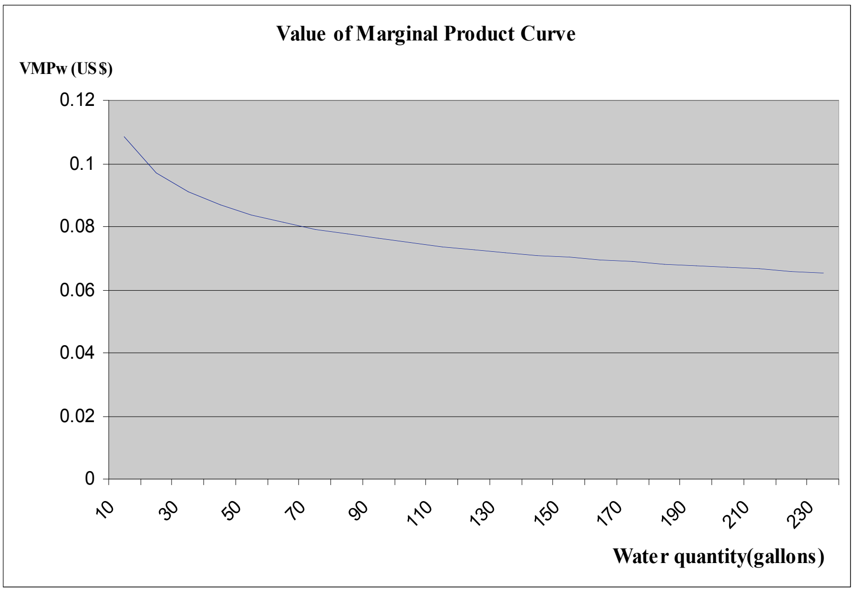
Table 3: Value of marginal product of water (US $/m^3) under different equilibrium scenarios[9]

Different equilibria	MV_w US $	Salinity level(mmhos/Cm) 1.8	2.8	4.3
Private equilibrium	0.187			
Social planers:				
Quantity decreasing	0.235			
Quality deteriorating		0.047	0.118	0.237
Both quantity decreasing and quality deteriorating		0.282	0.401	0.638

Using the estimated production function we can easily obtain the marginal product curve (MP_w) and value of the marginal product of water as follows:

$$MP_w = 0.31L^{0.62} W^{-0.79}$$

$$VMP_w = 11.9L^{0.62} W^{-0.79}$$



As our VMP curve is relatively elastic, internalisation of both quantity and quality externalities from groundwater extraction into the price of groundwater can easily be achieved without distorting other variables in the market.

The results in this study clearly imply that moves toward a market with low/free water charges could lead to large quantities being extracted and quality deterioration. In general this cost occurs only if the rate of water use is greater than the rate of replenishment. Under this situation, water becomes a depletable resource[10]. The basic

[9] Marginal value of water (US $) was calculated in terms of yield loss under different salinity levels.

[10] Mean annual rainfall in Anuradhapura District has been decreasing from 1,284 mm in 2000 to 1,098 by 2005. In general annual average recharge was only 10-15 per cent of the annual rainfall. Accordingly, it becomes clear that annual recharge level is decreasing in the area by increasing the shadow value of water.

idea here is to charge an extra price so that the rate of water used will diminish and the depletion of the water source will be delayed. Accordingly, the optimal paths of the state variables can be achieved by imposing a tax that takes into account the full resource cost. In any event, it is evident that the current extraction rates cannot be allowed to continue, and pricing commensurate with full resource costs could well provide a mechanism to adopt water allocation policies favouring conservation and efficient use. Furthermore, the policy of the unregulated groundwater extraction does not provide incentives to water users to adopt water saving technologies.

In this study we made a number of restrictive assumptions. These assumptions include economic and hydrologic factors. The included economic assumptions are constant variables like prices, interest rates and production technology. Furthermore, it was also assumed that consumers, producers and institutions work with perfect knowledge. The hydrologic assumptions that were included were constant rainfall and recharge patterns.

6. Conclusions

Efficient pricing requires that true marginal costs be used, including opportunity cost and externalities involved in the use of a resource. Groundwater extraction can result in stock depletion as well as in the degradation of quality. Both externalities are not considered when groundwater extraction patterns are being determined. In contrast to the economic literature, a simple model is developed to study socially optimal agricultural groundwater extraction patterns. It becomes clear that the current price of groundwater recommended in the existing economic literature is inefficient and does not reflect the true cost of externalities. This study shows the importance of bringing the joint quantity and quality groundwater extraction externalities into a resource management model. It becomes clear that the current low price of agricultural groundwater use in various countries (where a market operates) is the result of not taking into account both externalities simultaneously. This is inefficient and provides fewer incentives to conserve groundwater. The key finding from this theoretical derivation and empirical estimations are as follows: Various groundwater depletion studies in the economic literature have provided a misleading optimal as a result of not incorporating externalities in a correct way in their models. This has resulted in a low price charged for groundwater use resulting in over extraction of the resource. By incorporating quality changes to quantity deterioration we can achieve the most efficient social optimal. Our empirical results clearly show that the marginal value of water is higher than what is estimated in traditional models. In the private equilibrium decreases in quantity will be greater than what is implied by the social planners solution. This kind of input market distortion may create economic distortions in other markets as well resulting in welfare losses.

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