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The Full Economic Cost of Groundwater Extraction

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Abstract

When a groundwater basin is exploited by a large number of farmers, acting independently, each farmer has little incentive to practice conservation that would primarily benefit other farmers. This can lead to excessive groundwater extraction. When farmers pay less than the full cost of electricity used for groundwater pumping, this problem can be worsened; while the problem can be somewhat relieved by rationing the electricity supply. The research in this paper constructs an analytical framework for describing the characteristics of economically efficient groundwater management plans, identifying how individual water use decisions by farmers collectively depart from efficient resource use, and examining how policies related to both water and electricity can improve on the efficiency of the status quo. It is shown that an optimal scheme for pricing electricity used for pumping groundwater includes two main elements: 1) the full (marginal) economic cost of electricity must be covered; and 2) there must be an extra charge, reflected in the electricity price, corresponding to the externality cost of groundwater pumping. The analysis includes a methodology for calculating the latter externality cost, based on just a few parameters, and a discussion of how electricity pricing could be modified to improve efficiency in both power and water use.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the department toanalyze relationships between electricity pricing and groundwater extraction. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at jstrand1@worldbank.org.

The Full Economic Cost of Groundwater Extraction

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1. Introduction

The purpose of this note is to consider certain analytical aspects of optimal, and sub-optimal, management of groundwater in a water basin, where groundwater is pumped to the surface using electrical pumping equipment, and subsequently utilized as an input in agricultural production. We ask the following questions:

1) What are the characteristics of socially optimal water management for such a basin?
2) What are the characteristics of privately optimal groundwater extraction behavior?
3) Can the socially optimal allocation be implemented, and what electricity price must then be charged to farmers for this purpose?
4) What is the value of the standing groundwater as such, in both an overall optimal allocation, and when the groundwater allocation is not optimal (the water table is too low)?

The concrete reference and background for our interest in this issue is the serious problem of excessive groundwater extraction facing a number low-income and emerging economies. Recent prior analyses of the problem include World Bank (2010); IFPRI (2010); and Msangi (2010). Excessive groundwater extraction can involve serious negative externalities due to the common-pool nature of groundwater: When a given groundwater basin is exploited by a large number of independent farmers, each farmer has little incentive to conserve the groundwater stock, since such conservation confers future benefits largely upon other farmers, and not oneself. This general topic has recently been studied extensively inside and outside of the Bank, by Briscoe and Malik (2006), Dubash (2005), Ray (2008), Reddy (2005), Shah et al (2000), Shah (2009), World Bank (2005, 2010), Vaidyanathan (2006), Jessoe (2010), and Birner et al (2010), among others.

The overall consensus from this literature is that the current situation is non-sustainable in many countries and regions, in the sense that the amount of extracted groundwater is greater than the water replenishment, with falling water tables as a consequence. A leading prevailing view is that a main factor contributing to excessive groundwater extraction in many locations is low-priced electricity to farmers, given that this electricity is largely used for pumping from common-pool groundwater basins. When farmers pay little (or in some cases, even zero) at the margin for electricity used for pumping, basically all available electricity will be expended for groundwater pumping, and pumping is done regardless of the water table level and thus the distance any unit of water must be pumped (which in turn defines the electricity cost of pumping per water unit).[1]

The problem can however be said to be two-pronged. Since basic electricity consumption is not charged at the margin, there is the potential for excessive pumping even if groundwater had no standing value. This amplifies the problem that the value of standing groundwater is not priced nor charged. In principle, in the absence of direct pricing of groundwater to

[1] Note that while this is the main view, it is not the only view of the current groundwater situation in many locations. Some observers take an alternative view, that even when electricity prices are low, rationing of electricity supply to farmers can be sufficient to constrain agricultural water use to a level that would have been experienced, had farmers faced “correct” electricity and water prices, in the absence of rationing. This would in case imply that it is the basic increasing demand for water from agriculture that is the main culprit, not low electricity prices. See, in particular, the extensive discussion in Birner et al (2010).

internalize the open-access problem, correct pricing of electricity for pumping, in a situation where pumping costs are the only costs expended by farmers to withdraw groundwater, would imply an electricity price with two components. The first component reflects the basic electricity provision cost; and the additional component reflects the marginal value of (remaining) standing groundwater. Pricing electricity correctly then requires that both these components be calculated, and charged to users.[2]

The first component, true (social) electricity costs of pumping, should in principle be straightforward to measure. The second component, marginal groundwater value, is more complex. The perhaps most extensive treatment of this issue to date is found in National Research Council (1997). This report makes a very useful distinction, between two value components related to standing groundwater, namely 1) extractive value, and 2) "in situ" value. The former is the value of the standing groundwater for the purpose of future use of this water; in our context, this value mainly reflects use of irrigation water for agriculture given the focus on India. This is the value notion we will have in mind with our analysis in the following. The latter represents other services rendered by standing groundwater. "In situ" groundwater services can also include a) the buffer value against future possible shortages; b) less subsidence of the land surface due to ground water withdrawals; c) protection against sea water intrusion; d) protection of general groundwater quality; e) habitat and ecological diversity considerations; and f) providing discharge to support recreational activities. These services may in aggregate be important, but they will not be part of the analysis in this note.

There already exists a long-standing and sizeable literature on the general topic of optimal groundwater value and extraction policy. Early contributions to this literature include Burt (1967), Brown and Deacon (1972), Brown (1974), and Gisser and Mercado (1973), Gisser and Sanchez (1980), Gisser (1983); among more recent contributions we may mention Burness and Martin (1988), Provencher and Burt (1993), and Boyle and Bergstrom (1994). The current presentation builds in part on the analysis from these contributions, but goes further in certain respects, in particular by focusing much more directly on the basis for an intuitive understanding of the basic principles of the problem as they pertain to the Indian situation. We strip away what are unnecessary and complicating elements for our purposes and focus on the relationship between current extraction and future costs.

Work on this topic also exists with specific reference to specific countries. Banerji et al (2006) provide a derivation of the shadow price of groundwater, with an attempt to calibrate the model to the concrete groundwater situation in India. The calibration of their model to the Indian economy indicate a positive, but rather small, mark-up on basic electricity cost, approximately 15 percent. Another recent paper modeling such costs is IFPRI (2010). One purpose of this note is in this context to provide an analytical framework, and ultimately our own independent calibration to the Indian situation, that may be compared to the results obtained in that report, and hopefully useful in its own right.

2. Simple model for deriving the true economic value of groundwater

Consider an agriculturally productive region, with a large number of small farmers, where groundwater is extracted (pumped) to service agricultural needs. We set the amount of groundwater existing in (at the end of) a given period equal to G_t which is at the same time

[2] The literature also recognizes a third possible inefficiency, what is called a "strategic externality", not discussed here; see Negri (1989), Provencher and Burt (1993), Rubio and Casino (2003).

the height of standing groundwater above the basin floor of unit depth. The distance from the ground to the level of the groundwater table (equal to necessary pumping distance) then equals 1-G_t. For reasons of simplicity, we assume that the groundwater basin has flat bottom and vertical walls, and that its volume is unity.[3] Define R as the degree of replenishment of the basin in (at the start of) any given period. Assume that a fraction a < 1 of water withdrawal E_t in period t flows back to the aquifer at the start of the next period. We also assume that there is a periodic water loss from the aquifer which equals a fraction q of the standing amount of water at the beginning of the period. Assume also that an amount of water E_t is extracted in (at the end of) period t. This leads to the following equation of motion for the aquifer's groundwater stock:

(1) $$G_t = (1-q)(G_{t-1} + R + aE_{t-1}) - E_t .$$

G_t is here the level of the water table at the end of the extraction regime in period t. The relationship between steady-state values of E and G (regardless of whether or not they are optimal) is then given by

(2) $$(1-(1-q)a)E = (1-q)R - qG .$$

Assume that pumping cost per water unit per unit of pumping height is constant and equal to p.[4] Assume also that the value of agricultural output is a concave and increasing function of extracted water (on a particular relevant domain), and given by the function F(E_t), where consequently F' > 0, F'' < 0 (primes denoting derivatives). Net returns (profits) in period t are then given by the value of agricultural outputs minus pumping costs, defined as follows:

(3) $$\Pi_t = F(E_t) - \left[1-(1-q)(G_{t-1} + R_t + aE_{t-1}) + \frac{1}{2}E_t\right] pE_t .$$

The term $E_t/2$ in the square bracket in (3) represents the average value of the amount of extracted water during the extraction phase in period t, (starting at zero and ending at E_t), and the way that this component, on the average, contributes to extraction cost (as marginal costs are increasing with greater extraction).

Define the continuation value from (indefinite) agricultural production, starting from period t, by V_t, given recursively by

(4) $$V_t = \Pi_t + \delta V_{t+1} = \Pi_t + \delta\Pi_{t+1} + \delta^2\Pi_{t+2} + ...$$

Given a steady-state solution, with constant (sustainable) G over time, V_t is given by

(5) $$V_s = \frac{1}{1-\delta}\Pi_s$$

[3] This corresponds to assumption made by Banerji et al (2006); as noted in the final section, however, the assumption is not necessarily fully realistic.
[4] It is not always reasonable to assume full smoothness of the pumping cost function, as I do. As pumping depths increase, one may need, at some point, to switch from simple (surface) pumps to much more expensive submerged pumps, this increasing the overall pumping cost drastically at one (or more) discrete point(s). This complication is ignored here.

where "s" denotes a steady-state solution.

We are interested in the level of steady-state groundwater G_s that maximizes (4) with respect to G_t, or rather, the steady-state value of $G_t = G$ that corresponds to such a solution.

(6)

$$L_t = F(E_t) - pE_t\left[1-(1-q)(G_{t-1}+R+aE_{t-1})+\frac{1}{2}E_t\right]+\lambda_t[(1-q)(G_{t-1}+R+aE_{t-1})-G_t-E_t]$$

$$+\delta\left\{F(E_{t+1}) - pE_{t+1}\left[1-(1-q)(G_t+R+aE_t)+\frac{1}{2}E_{t+1}\right]+\lambda_{t+1}[(1-q)(G_t+R+aE_t)-G_{t+1}-E_{t+1}]\right\}$$

$$+\delta^2 L_{t+2}$$

Maximizing (6) with respect to E_t and G_t yields the following set of first-order conditions:

(7) $$\frac{\partial L}{\partial E_t} = F'(E_t) - p[1-(1-q)(G_{t-1}+R+aE_{t+1})+E_t]-\lambda_t+\delta[(1-q)apE_{t+1}+\lambda_{t+1}(1-q)a]=0$$

(8) $$\frac{\partial L}{\partial G_t} = -\lambda_t+\delta(1-q)pE_{t+1}+\delta(1-q)\lambda_{t+1}=0.$$

Solving a similar problem for all time periods t, t+1, t+2 etc, we obtain a family of solutions E_t, E_{t+1}, ..., G_t, G_{t+1}, ..., and Lagrange multipliers λ_t, λ_{t+1}, ... , that constitute an overall optimal solution, from an arbitrary set of starting values (G_{t-1}, E_{t-1}).[5] Such an infinite regress is not necessary for our purposes as we are basically only interested in the steady state, where all the E_{t+i}, G_{t+1}, and λ_{t+i} take common values E, G and λ. An approximate common value of the multipliers, out of steady state, can here be described by invoking this common value of $\lambda_t = \lambda_{t+1} = ... = \lambda$. This yields

(9) $$\lambda = \frac{\delta(1-q)pE}{1-\delta(1-q)}.$$

The optimal steady-state solutions for E and G (denoted E_{opt} and G_{opt}) are characterized by the following relationship:

(10) $$F'(E_{opt}) = p[1-(1-q)(G_{opt}+R+aE_{opt})]+\frac{1-\delta a(1-q)}{1-\delta(1-q)}pE_{opt}.$$

Alternatively, we can write, invoking the steady-state relationship (2):

(10a) $$F'(E_{opt}) = p(1-G_{opt})+(1-a)\frac{\delta(1-q)}{1-\delta(1-q)}pE_{opt}$$

[5] For mathematically more complete solutions, see Bellman and Kalaba (1965), and Beckman (1968).

From (10a), at a steady-state optimum the marginal productivity of groundwater used as an agricultural input, F', equals the sum of two terms (under certain conditions discussed below).[6] The first of these two terms represents the direct marginal cost of water extraction (marginal pumping costs at the equilibrium steady-state depth of the water table, equal to 1-G_s). The second term also represents a cost related to extraction, except that it expresses how optimal extraction cost (which is not exogenous in the model) is affected by a change in E_s. A greater E in any given period (and E_s in the steady-state solution) lowers the water table, and consequently increases the extraction costs for all units of water to be pumped in the future. The latter term then represents an "externality" related to groundwater extraction that a social planner, seeking a socially optimal solution, will consider.

It is here not sufficient to consider the *level of extraction costs* in the steady-state: one also needs to consider *how marginal extraction costs in the future are increased by more extraction today*. When q and a are small (there is a low rate of natural turnover of the water in the pool), and δ close to unity (the discounting interest is small), the steady-state effect of this latter factor is large. Again, for q, and δ, this is because future groundwater availability, and future discounted extraction costs, are then more highly affected by current extraction (or put otherwise, concentrating on q, there is then better control of future groundwater availability through the extraction policy). When the parameter a is large, most of the extracted groundwater runs back to the basin and little is lost by current extraction.

It is here interesting to note that *the marginal externality cost of groundwater extraction does not depend on the current level of the groundwater table as such*. Thus, the marginal externality cost of additional groundwater extraction is the same, regardless of whether the water table is currently high, or low. The reason is that the only externality at work in this model is the one that affects future extraction costs. Given the assumed features of the groundwater basin (as being rectangular with straight walls and flat bottom), the table level falls by a constant amount for given extraction, regardless of the starting point; and this yields a constant externality cost of extraction.[7]

(10a) illustrates a feature that is important to stress once more: the marginal standing value of groundwater is a reflection of how marginal extraction costs are affected *in all future periods*, by a marginal extracted unit today; when this is corrected for recharge a and water loss q. The way to intuitively understand this feature of the solution is to depart from a steady-state equilibrium strategy, and consider a small (marginal) increase in extraction in period t only, while extraction in future periods is kept at the initial equilibrium level. Given such a strategy profile, marginal extraction costs will be affected in all future years when one unit is extracted today.

We also see that the optimal steady-state value of F', derived from (10a), is directly proportional to the price of electricity for groundwater pumping, p. Thus in particular, in an extreme case with zero pumping cost, (10a) ascribes an optimal value of zero to F': water ought to be used in a steady-state amount sufficient to drive the marginal return from water in agriculture to zero. But here there is a catch: it is far from certain that sufficient water amounts would exist to drive F' to zero in a steady state. This reflects a limitation on the

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[6] A similar result is derived by Banerji et al (2006), but for a somewhat simpler situation with no water loss from the groundwater basin.

[7] We note that, with other shapes of the water basin, the marginal extraction, cost, and thus the marginal stock value of standing groundwater, is not necessarily constant; it could be falling or increasing. Other fundamental aspects of the model however do not change. See also section 5 below.

model in its current formulation: it needs to have an interior optimum. Note that, from (2), (1-q)R is the theoretically maximal level of water extraction at a steady state solution. Thus when F'((1-q)R) > 0, the first-order condition (10a) cannot be fulfilled with equality. Our solution would (technically speaking) prescribe $G_s < 0$ which is not an economically meaningful solution. The economically meaningful solution is then $G_s = 0$, and $E_s = (1-q)R$. We will however argue that such a case is not very realistic or perhaps interesting for our purposes. We have no intention to apply the (real optimality) model to such a case, recognizing that the real extraction cost is substantial and would then not allow for a very low (optimal) equilibrium water table.

We find, interestingly, that the steady-state level of E (denoted E_{ss}) is greater under discounting than without discounting (considering the steady-state directly, in (10a)). But, note, a greater steady-state E corresponds to a smaller steady-state groundwater stock G_{ss}. In the case of discounting, more groundwater will be extracted each period, but from a smaller overall stock, which corresponds to a lower water table and higher pumping costs.[8] Overall, the steady-state value of the groundwater stock will be lower under discounting as the negative effect of greater pumping costs overwhelms any positive effect of more groundwater extracted.

3. Market implementation in a steady state

Consider now the privately optimal solution in this model. Individual farmers cannot be expected to consider effects of their own water extraction on costs for others, and when there are many small farmers utilizing a common water pool, each will take the level of the water table as exogenously given. Assume also that each of these faces an exogenously given pumping (or electricity) price h. The private profit function can be written, assuming that the representative farmer selects a groundwater extraction level $E_{i,t}$ (and where we now assume that extraction is done at the "end" of the period, so that overall extraction has already reached a level E_t):

$$\Pi_{i,t} = F(E_{i,t}) - \left[1-(1-q)(G_{t-1}+R+aE_{t-1})+E_t\right]hE_{i,t}. \tag{11}$$

In expression (11), the expression in the square bracket is the height of the water table in the final situation, at the end of period t (when all water has been extracted for the period). (11) is now maximized with respect to the individually determined $E_{i,t}$, where all other magnitudes in (11) are taken as given, and where the number of farmers is normalized to unity:

$$\frac{d\Pi_{i,t}}{dE_{i,t}} = F'(E_{i,t}) - h[1-(1-q)(G_{t-1}+R+E_{t-1})+E_t] = 0. \tag{12}$$

A steady-state equilibrium here corresponds to $E_{i,t} = E_t$.[9] The private steady-state solution can then be expressed as follows (h representing the decentralized farmer solution)

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[8] Intuitively, when the groundwater stock is lower, less water is by assumption lost from the aquifer in the steady state, and a larger fraction of the periodic water replenishment R can be extracted in a steady state.

[9] This implies formally that all farmers are assumed to have the same electricity consumption. This need not be taken literally, and is not essential for the analysis in the following. What is essential is that all farmers face the same (optimal) electricity price, and that all choose to operate such that the marginal return to water as an agricultural input is the same for all farmers.

(13) $$F'(E_h) = h[1-(1-q)(G_h + R + aE_h) + E_h] = h(1-G_h)$$

(13) gives the steady-state market solution to this problem regardless of whether this solution is optimal or not. In a similar way as for the socially optimal solution, characterized by (10a), the choice of E (=E_h) is significantly affected by the private price that is paid per unit of pumping, h, and is generally higher when h is lower. Since a high E corresponds to a low level of the groundwater pool, G, in a steady-state, from (2), a low pumping cost results in a low standing groundwater. But under the model's assumptions (that the periodic water loss from the aquifer is smaller for a smaller standing amount of water), this then also leads to to a high level of extracted groundwater per period, in a long-run equilibrium solution.

Assume now that our goal is to implement the optimal steady-state solution (10a). Comparing (10a) and (13), we see that such implementation requires h to exceed p. In other words, to implement the efficient solution, it is required that *the cost of groundwater pumping charged to farmers must exceed marginal pumping cost*. This is due to the externality caused by current pumping on future pumping costs, which must be charged and thus corrected at the optimal solution.

Which price h should be charged of farmers per unit of pumping (identified here with the private electricity price), so as to implement the optimal solution? Invoking (10a) as optimal, we find

(14) $$h_{opt} = p + (1-a)\frac{\delta(1-q)}{1-\delta(1-q)}\frac{pE_{opt}}{1-G_{opt}} = p + t_{opt}$$

Here t_{opt} denotes the optimal "tax" (or "shadow value") related to electricity used for pumping of groundwater left in the ground, that must be charged to farmers in order to implement the optimal solution. It has several interesting characteristics, including the following:

1) *The groundwater shadow value per unit of electricity consumption, t, is higher when the optimal steady-state groundwater level, G_{opt}, is higher.* With high standing groundwater level, pumping costs at the margin are small, and the incentive for extracting water correspondingly great. This may appear surprising: when the water table is lower, and the problem of heavily extracted resources seemingly greater, the marginal charge for this externality, in terms of a mark-up on the (we assume, otherwise competitive) electricity price, ought to be less. However, when the water table is low, many units of electricity are required to pump one unit of water. Thus the (constant) extraction externality needs to be distributed over a large number of electricity units. Note that the pumping price is here the only mechanism by which the water resource is managed. The pumping price must then be high for the true water value to be reflected in farmers' extraction decisions; and this pumping price greater when less electricity is used. This can also be understood in an alternative way: the common pool problem associated with groundwater extraction is more serious the smaller is 1-G_s, since uncontrolled extraction is then cheaper due to basic extraction costs being lower. This requires a higher charge t_{opt} to implement the optimal solution.

2) *t is higher when the amount of water to be extracted per period at a steady-state equilibrium, E_{opt}, is greater*. This is due to the main externality at play here: namely,

from a greater stock of groundwater G, to pumping costs in subsequent periods. When more water, E_{opt}, is pumped per period in equilibrium, his externality is proportionately more significant. The reason is that one unit of extra groundwater in the basin, at the start of a period, then reduces extraction costs over a larger number of extracted units during the period.

3) *t is higher when there is less discounting (the rate of interest, r, is lower; and δ = 1/(1+r) is higher, and closer to unity).* The reason is that the reduction in future extraction costs, resulting from a higher water table, which must be counted for all future periods, then has a higher present value.

4) *t is higher when q is smaller, and thus less water lost from the system every period*. When less water is lost, a current amount of groundwater has a more persistent effect on extraction costs, in all future periods.

5) *t is higher when the rate of direct recharge of the groundwater from currently extracted water, a, is lower*. When a is high, there is relatively little water loss from the system resulting from water withdrawal, since much of the initially withdrawn water runs back to the aquifer. This leads to a less serious groundwater depletion problem and consequently a lower optimal tax on water withdrawal.

Note that t is not in itself the shadow value of in-ground groundwater. This shadow value is given by the last main term in (10a), which is independent of G_t. It must also be stressed that, in contrast to the optimal shadow cost of pumping, the equilibrium shadow value of the standing groundwater as such is in our model not related to the level of the groundwater at equilibrium. The reason is that the externality cost of a lower groundwater table on future extraction cost (which gives rise to the shadow value of standing water) has no relation with the level of the water table as such; it only depends on the amount of water pumped each period.[10]

The equilibrium marginal value of groundwater, F', however depends on the groundwater level, via the first term in (10a) which represents marginal social groundwater pumping costs.

4. Market implementation outside of the steady state

Consider now a market solution with a lower than optimal marginal pumping cost, h, charged to farmers. This cost may be low but generally positive. It consists of two parts, namely a variable electricity cost, and a cost related to purchase, rental and operation of pumping equipment. While marginal electricity cost may be zero, equipment costs will be positive. Assume now also, as different from in section 3, that we are not in a steady state, but rather at a case with a groundwater pool in the process of being reduced. This seems to characterize the current situation in India, where an increased recent pressure on groundwater pumping has led to a gradually falling water table in many parts of the country.

Relation (4) can then be invoked as the basis for an optimization concept. A key issue here is that in period t, G_{t+1}, and $V_i(G_{t+1})$ (using again subscript i to denote the individual farmer's variables, here his value function), can be taken as exogenous by farmers in period t.

[10] On the other hand, when the water basin has a shape different from that assumed here, the groundwater value is instead typically variable; see the final section for further discussion.

Essentially, the farmer still maximizes (3) with respect to E_{it}, the only difference being that we now assume that G_{t-1}, and consequently E_{it}, are not at a steady state, but that G_{t-1} can be higher or lower than this level.

We here have the general result, also outside of a steady state, that private pumping costs are given by h(1-G_t). Marginal social costs of water extraction are, in the general case with varying extraction levels, found by taking the infinite recursion by solving for all Lagrange multipliers λ_t, λ_{t+1}, ... , to the problem of maximizing (6), as follows:

$$(15) \qquad MC_t = p(1-G_t)+(1-a)\sum_{k=1}^{\infty}(\delta(1-q))^k pE_{t+k} \,.$$

(15) holds also for solutions where the groundwater table G_t is not necessarily optimal nor stationary, nor needs the process for the E_{t+k} to be stationary or optimal. The value of standing groundwater is affected by a change in G_t only through the first term on the right-hand side of (15), which represents extraction costs: these costs increase when G is reduced. The standing value represented by the second main term in (15) is not affected (apart from an effect from a steady-state change in E).

We are here particularly interested in cases where G_t is sub-optimal, which is probably a realistic description of major parts of India today. In this case, F' will be higher than its steady-state value, and E_h lower. A first question is then, what is required of the pumping price h, for G_h not to fall further (stay constant at its initial lower-than-optimal level)? We are thus initially not concerned with attempting to increase G_h over time (which might be the optimal strategy in this case).

Consider then any level of G to be kept at the steady state, implying that E (= E_{ss}) and G (= G_{ss}) are both stationary, and related by (2). Departing from the steady-state relationship of form (14), and inserting for E from (2), we find the steady-state relationship determining the necessary tax on pumping as a function of G_{ss} a s follows:

$$(16) \qquad h_{ss} = p+(1-a)\frac{\delta(1-q)}{1-\delta(1-q)}\frac{(1-q)R-qG_{ss}}{1-G_{ss}} = p+t_{ss}$$

Taking the derivative of h_{ss} with respect to G_{ss} yields

$$(17) \qquad \frac{dh_{ss}}{dG_{ss}} = (1-a)\frac{\delta(1-q)}{1-\delta(1-q)}\frac{(1-q)R-q}{(1-G_{ss})^2} > 0$$

This expression must be positive since we must have (1-q)R – q > 0 (this expression measures net steady-state extraction from a full water basin, with G = 1, which must be positive). We thus find that the price h that must be charged to farmers for electricity used in groundwater pumping, in order to keep the groundwater level, G, constant in this case, is reduced when G is lowered.

We conclude from this section that when the groundwater level is already reduced below its optimal level, the price of electricity for pumping, required to keep the groundwater stable at this (inefficiently low) level, is also reduced. The reason is not a reduction in the value of remaining groundwater at the margin, as one might first tend to think. The reason is rather that pumping costs per unit of groundwater extracted are greater when the water table is lower. A given amount of groundwater then requires more pumping and thus more electricity consumption for its extraction. This reduces the necessary tax per unit of pumping effort. Note however that the marginal value of remaining groundwater is constant in this model, independent of the level of the groundwater table. Thus the optimal tax per unit of groundwater extracted is a constant, equal to this value. The optimal tax per unit of electricity is then lower when the groundwater table is lower, just because the tax per groundwater unit is spread over a larger number of electricity units.

5. Some possible extensions

The above model is highly simplified, and unrealistic in some respects. Below we mention a few points that may require amendments of the basic structure, and indicate how such extensions could be handled.

Even in view of these weaknesses, we will still however argue that the model is rather robust and may be practically useful for illustrating numerically likely actual levels of externality costs. In particular, the model is easy to parameterize. The main parameters, needed for calculating the relevant cost variables, are the distance from the surface to the water table; and pumping costs per pumping distance and water unit.

5.1 The groundwater basin has different shape

We have above assumed that the groundwater basin has vertical walls and a flat bottom. As a consequence, the effect of current extraction on future extraction costs is always the same and independent of groundwater height, since the water table would always fall by a given amount, for any given amount of additional water pumped. In reality water basins do not have this shape. Most basins have less surface farther down so that a given amount of additional pumping would reduce the table by more when the starting level is low.

The main implication of such a modification of the model is to increase the (present discounted) future pumping costs related to a given current amount of water being pumped, when the water table is already low. This would imply that the marginal value of standing water in the groundwater basin is higher when the table is low. Such a factor in turn contributes to a higher optimal tax on pumping efforts, when the current water table is low. This factor may overturn the result from (17) above (where it was found that the tax on groundwater pumping, required to keep the groundwater table at a constant level, is reduced when the water table falls).

It is however in principle conceivable that the groundwater basin has a wider “bottom” than “top”. In such cases, the typical situation is that once the water table has fallen to a low level, it falls more slowly from then on. In such cases we will find that the marginal value of groundwater left in the basin is reduced. These cases are not very common, but may occur for some very large aquifers (in particular, those containing “fossil water”, sometimes in very large amounts).

5.2 The return flow rate to the water basin is endogenous, and variable

We have so far assumed that a constant fraction of current water extracted always flows back into the basin. Clearly this is not always the case. The flow-back rate is likely to depend on the care with which water is managed, and general scarcity of water including the level of extraction. In particular, when less water is extracted from the basin, a smaller fraction of this extracted water is likely to flow back, as most water is then either absorbed by plants or lost to evapo-transpiration.

5.3 Stochastic recharge of the water basin, and water demand

There is no uncertainty in the model as applied so far. In reality, for India and elsewhere, the recharge rate R can be highly variable. It is pointed out (e g by Banerji et al (2006)) that some water basins in India are replenished only every 10 years or so. Additionally, water demand may vary with the amount of natural rainfall, thus leading to variable values of F' in our model and putting different pressures on extraction over time.

Uncertainty will tend to put an extra premium on groundwater value as one recognizes that groundwater will be pumped in some future scarcity situations, at high pumping cost (low water table). Indeed, groundwater may have a large fraction of its value in the form of a buffer against variations in rainfall and other factors affecting water demand. Some indications exist that such motivations can constitute a large fraction of its value. (Tsur and Graham-Tomassi (1991), for example, calculate in some of their examples that the buffer stock value of groundwater can constitute more than 80 percent of its total value.)[11]

In the context of the model above, such concerns can partly be accommodated directly, and may in part require model extensions. In my model, an effect of stochastic supply and demand could be to increase externality costs of water withdrawals, perhaps dramatically, as one gets close to emptying the aquifer (with costs of further withdrawals approaching infinity as the basin becomes empty). In theory these costs can be avoided by simply not withdrawing water in such cases. But this raises the need for additional demand-side considerations. When one cannot withdraw water, its marginal value in agriculture can be very high (a likely outcome in a drought). This opportunity cost of not withdrawing "normal" quantities is then part of the cost of current withdrawals.[12] This can be a substantial factor in particular when aquifer dry-out and water value are highly correlated, which is of course highly likely.

A separate aspect of this issue is that some aquifers are more complex as there may be restrictions on the water flow across the aquifer. Athanassoglou et al (2010) combine this assumption with an assumption that extracting agents are heterogeneous. On this basis they claim to show that a socially optimal policy (implemented as a Markov perfect equilibrium) takes a quite similar form to that of an aquifer with perfect flow. Since this work is preliminary, more research is here clearly needed.

5.4 Groundwater value has additional components

So far we have concentrated on the productive value of water as an input in agriculture. Water may have other values or uses as described e g in National Research Council (1997) and as presented above. These arguments tend to enhance the net groundwater value whenever they are significant. They of course include the general extractive supply value of water to households and industry. But they also include other in situ value items such as supporting

[11] Tsur and Zemel (1995) model implications of uncertainty for groundwater valuation, focusing on the possibility of aquifer "rundown" due to over-exploitation.
[12] This factor is largely what drives the main result in Tsur and Graham-Tomassi (1991).

local biodiversity, preventing saltwater intrusion, and preventing subsidence.[13] In particular accommodating the latter arguments would require a reformulation of our basic model. We will come back to such extensions in future work.

[13] See also Tsur and Zemel (1995) for more discussion of such value items.

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