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FOI Working Paper

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2011 / 3

FOI Working Paper 2011 / 3

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Regulating Groundwater Use in Developing Countries: A Feasible Instrument for Public Intervention

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Keywords: Developing countries, groundwater use, moral hazard problems, taxes.

Abstract: In many developing countries, groundwater is a common pool resource which is potentially subject to the tragedy of the commons if water extraction is not adequately regulated. However, in these countries, the regulatory infrastructure is often too weak to allow detailed monitoring of individual groundwater extraction. For this reason, classical public intervention instruments, such as consumption fees or tradable quotas, are infeasible. Here we present a theoretical foundation for a new public regulatory instrument that can potentially generate the same efficiency inducing incentives as fees and tradable quotas, but without their information and monitoring requirements. The instrument we propose is a tax based on aggregate extraction, rather than individual extraction measures.

1. Introduction

The world's population is projected to reach almost 8 billion by 2025 (UN (1999)) and concerns are often voiced that the future may bring food and resource shortages which will affect poor populations (Rosegrant *et al*. (2001) and Scanes and Miranowski (2004)). An area of major concern is the growing demand for water in developing countries. Water is an inherently local good and substantial local differences in cost and accessibility may develop and persist with potentially far-reaching consequences for the affected populations. Today, more than 1 billion people live without access to clean water and the number of developing countries classified as water scarce is expected to rise in the future (UN (1999)).

Finding sound solutions to the task of protecting and allocating water resources will be a challenge of growing importance in the 21st Century for many developing countries. At the same time, the regulatory options which developing countries have to meet the challenge are not abundant. With increasing water shortages, traditional mechanisms for water allocation and conflict resolution may not be sufficiently efficient, while classic public regulatory instruments which focus on consumption tariffs or markets for water quotas may not be feasible due to a weak public regulatory infrastructure. Taking a weak public regulatory infrastructure as the premise, a number of researchers (Ostrom *et al* (2002), Lam (1999), Dittz *et al* (2003) and Dolsak and Ostrom (2003)) suggest that systems of self governance may be a way to address the increasing need for regulating water use. The idea behind this is to use the self-interest in regulating water use to facilitate water allocation agreements among users. Potentially, such agreements could be enforced through social control without the need for public regulation and enforcement. Clearly, the efficiency of self-governance critically depends on the existing social infrastructure and on the type of allocations that self-governing actors can agree on.

In this paper, we take a weak public regulatory infrastructure as our premise and suggest an alternative approach to public water regulation that is less administratively demanding than existing mechanisms such as fees and tradable permits. Both require the measurement and control of each individual's water use, something that may be difficult and/or very costly in many developing countries. What we suggest is that all water users pay a fee based on the same *aggregate* measure of water use. Therefore, the mechanism does not require the monitoring and control of each individual's water use. This makes its implementation more feasible and potentially attractive for regulating water use in developing countries. In the following, we show that the proposed mechanism has the potential of allocating water efficiently. This depends on the perception that water users have of their interaction with other water users. The main objective of the paper is to make the workings of the suggested mechanism transparent and to clarify the assumptions needed for it to induce an efficient allocation of water use. Several examples of how the mechanism can be relevant in practice exist. One example could be a common water resource used by several villages. Within each village, social control mechanisms may be actively regulating the use of water, whereas such mechanisms may be lacking between villages[1]. One could imagine the implementation of incentives at the village level with our mechanism. Another possible application could be the regulation of large farms using a common water resource. Without the mechanism, each farm or village may extract water without regard for the effects this has on other villages or farms. However, with the mechanism (approximate) social optimal incentives could be generated.

The paper is organised as follows. Section 2 discusses the relevant literature, while in section 3 a model of ground water extraction is formulated and the social optimum is found. Section 4 describes individual behaviour, while section 5 introduces the proposed regulating tax mechanism. Section 5 concludes the paper.

2. Existing models of groundwater regulation in developing countries

The core of the allocation problem is that water in many developing countries is a common pool resource, which is potentially subject to the tragedy of the commons (Hardin (1968) and (1998)). Water is typically available from commonly accessible streams, lakes or ground water with a limited supply. When there is unregulated access to the resource, each user´s water demand will only be constrained by the user's private costs. If water is scarce, unregulated competition among users will generally result in an inefficient increase in these private costs because lower ground water levels necessitate deeper and more expensive private wells, or because nearby springs run dry so that water must be collected from more distant springs[2]. A potentially more critical consequence of open access may result if over exploitation of the resource damages its regenerative ability (e.g. lowering of the ground water table increases the risk of contamination). Thus, when

[1] For example, Lam (1999) studies common resource water supply in Nepal with this two level structure and finds that there is little social control across village groups.

[2] In both cases, water demand is constrained as private users are forced to expend more resources on water access. However, an agreement among users to use less water would be more efficient achieving the same reduction, but saving water users the increased access costs.

common pool water resources become scarce, unregulated extraction results in excessive use and a stock externality problem arises (see Neher, 1990).

Conflicts between users in the face of water scarcity are not new to developing countries and such conflicts have traditionally been settled by local authorities in accordance with one of two dominating approaches (Ambec and Spurmont (2002)). The *Riperian allocation approach* allots land owners the right to extract water resources accessible on his land and, thereby, also the right to inflict negative external costs on other users of the same water source. The *prior allocation approach* gives the first user the right to uninhibited continued use, so that a land owner, who is the second user, only has the right to use water accessible from his land to the extent that this does not inhibit the first user (say a neighbouring land owner who was the first to start using the common ground water or stream). Prior allocation, in principle, prohibits new users from inflicting negative externalities on the first user of the resource. This approach, however, is inefficient, but more importantly, the approach is used to resolve conflicts between individuals and not as the basis of a general regulatory system. This means that in practice, only large and easily identifiable externalities originating from new users will be curtailed. Diffuse externalities, which affect many users, as well as effects of which the cause is not easily identified by victims, remain unregulated. Thus, even though water scarcity does result in the regulation of water extraction in many developing countries, none of the traditional conflict resolution approaches have been able to ensure efficient allocation or effective resource conservation (see Zilberman and Lipper (2000)), Ambec and Spurmont (2002) and Burness and Quirk (1979)).

Another line of research has suggested that ‘self-governance’ within the community may be an alternative to traditional conflict resolutions and (presumably inefficient) public regulation (Ostrom *et al* (2002), Lam (1999), Dittz *et al* (2003) and Dolsak and Ostrom (2003)). The idea is to develop and implement more efficient regulation of water users at the local level, building on traditional social structures that support collective decision-making. The attraction is that collective decision-making is better suited to recognise and to take the common pool externality problem into account than conflict resolution between individual water users. In addition, empirical studies show that self-governance is possible. For example, in Nepal where rural populations have a long tradition for collective action, Lam (1999) reports that self-governance has worked better than (notoriously ineffective) government intervention. However, many authors (e.g. Lam (1999) and Ostrom (2002)) also point out that a number of tough conditions must be fulfilled for self-governance to be a feasible alternative. Also, as scarcity increases, so may the forces that destabilise the coalition. Furthermore, even though the resulting regulations may be an improvement on traditional conflict resolution, they may still be far from optimal. In fact, Lam (1999) shows that there is a considerable welfare loss associated with self-governance in Nepal. One reason for this is that the necessary negotiations are very time consuming (see Berkes (2006)) so that they often stop short of the optimal result. Another reason is that regulations are typically applied to easily observable actions that are often only imperfectly correlated with water extraction (Ostrom *et al* (2002)). Thus, self-governance has the potential to outperform traditional conflict resolution. However, self-governance is only feasible under favourable conditions and yet probably far from optimal.

The classical policy recommendation from economists for water resource regulation problems is public intervention so that resource access is regulated by a public authority e.g. through taxes (Neher (1990)), or tradable quotas (Zilberman and Lipper (2000) and Becker *et al* (2001)). In theory, this type of regulation is able to conserve the resource effectively and to ensure efficient allocation. However, these types of public regulations require an efficient enforcement system that can produce dependable measures of each individual user's water extraction. In developing countries, evasion possibilities and an ineffective public administration often make it unrealistic, or too costly to base regulation on this kind of detailed information about individual water user´s extraction. For this reason, many authors have argued that public intervention of this type is not a feasible alternative in the context of developing countries (see Saliba and Bush (1987) and Colby (1990)).

This is our point of departure from the existing literature. It seems that self-governance is not universally applicable and often far from efficient, while public regulation through fees or tradable quotas is potentially efficient, but infeasible in many developing countries because of unrealistic information requirements. Here we present the theoretical foundation for a new public regulatory instrument that generates the same efficiency inducing incentives that fees and tradable quotas would ideally generate, but without the information and monitoring requirements that are necessary for the functioning of these instruments. Drawing on the ambient pollution tax literature (see Segerson (1988) for an original contribution) and the literature on stock taxes for fisheries regulation (see Hansen *et al* (2006) for a recent contribution), we propose a tax based on a measure of aggregate extraction, rather than individual extraction measures. The model we develop applies to a common pool ground water resource, but the basic idea of basing regulating taxes on aggregate extraction measures carries over to other common water resource settings.

3. A model of ground water extraction

In this section, we develop a model of a common pool groundwater resource with *n* users that we suggest is applicable in a developing country setting. Each user derives benefits from groundwater extraction and incurs costs of extraction. The common pool externality arises because extraction costs depend on the available stock of water. Thus, intensive extraction may lower the stock of water and, thereby, increase extraction costs.[3] The model is developed for continuous time, assuming an infinite time horizon, no uncertainty and an exogenously determined natural recharge of ground water stocks[4].

Let x_t be the stock of groundwater at time t , h_{it} user i's rate of water extraction at time t and $H_t = \sum_{i=1}^{n} h_{it}$ the aggregate rate of all groundwater extraction at time t. Furthermore, let F_t be the natural growth or recharge rate of the resource which is stock independent. The rate of change of the stock of groundwater at time t ,denoted $\dot{x}_t$, is thus:

$$\dot{x}_t = F_t - H_t \tag{1}$$

We assume a standard specification of the water extraction cost functions (see Hellegers *et al* (1999)). Letting c_{it} denote user i's extraction costs at time t, we thus have:

$$c_{it} = c_i(h_{it}, x_t) \tag{2}$$

whereby the costs are increasing in extraction ($\frac{\partial c_i}{\partial h_{it}} > 0$) and decreasing in stock size ($\frac{\partial c_i}{\partial x_t} < 0$).

Following Neher (1990), we assume positive, but decreasing marginal individual benefits of water

[3] We may think of a lower groundwater level forcing users to use deeper and/or more distant wells.

[4]Note that the analysis easily carries over to discrete time and a finite time horizon. Recharge through rainfall is typically stochastic and endogenous to some extent (e.g. lower groundwater stocks may reduce natural leakage to streams) and the incorporation of endogenous regeneration is straight forward. However, allowing for stochastic and endogenous recharge would not qualitatively change the results in the following, but it would complicate derivations and presentation substantially.

extraction $\tilde{b}_i(h_{it})$ where $\tilde{b}_i'(h_{it}) > 0, \tilde{b}_i''(h_{it}) < 0$. Furthermore, we define the *net* benefit function for user *i* by (see Hellegers *et al* (1999)):

$$b_i(h_{it}, x_t) = \tilde{b}_i(h_{it}) - c_i(h_{it}, x_t) \qquad (3)$$

Where $\frac{\partial b_i}{\partial h_{it}} > 0$ for some values of h_{it} and $\frac{\partial^2 b_i}{\partial h_{it}^2} < 0$

Hence, to determine the socially optimal individual water extraction paths over time, we maximise the sum of all *n* users current and discounted future net benefits subject to the resource restriction i.e.:

$$\underset{h_{1t}...h_{nt}}{Max} \int_{t=0}^{\infty} \left[\sum_{i=1}^{n} b_i(h_{it}, x_t) \right] e^{-\rho t} dt \qquad (4)$$

s.t.

$$\dot{x}_t = F_t - H_t, x_0 = a \text{ given} \qquad (5)$$

whereby ρ is the discount factor. In (4) $h_{1t}...h_{nt}$ are the control variables, while x_τ is the state variable. $x_0 = a$ is an initial condition. There is no terminal condition because we have an indefinite time horizon. Instead, there are two transversality conditions (see (11) and (12) below).
In the next subsection, the model is solved and the solution is interpreted.

Model solution

The standard way of solving (4) and (5) is to formulate a Hamiltonian function corresponding to the maximisation problem:

$$L = \left[\sum_{i=1}^{n} b_i(h_{it}, x_t) \right] e^{-\rho t} + \lambda_t \left[F_t - H_t \right] \qquad (6)$$

whereby λ_t is the shadow price of the resource restriction i.e. the marginal social value of ground water stocks.

The optimality conditions for this problem are:

$$\frac{dL}{dh_{it}} = \frac{\partial b_{it}}{\partial h_{it}} e^{-\rho t} - \lambda_t \frac{\partial H_t}{\partial h_{it}} = 0 \text{ for } i = 1,...,n \tag{7}$$

$$\frac{dL}{dx_t} = \left[\sum_{i=1}^{n} \frac{\partial b_{it}}{\partial x_t} \right] e^{-\rho t} = -\dot{\lambda}_t \tag{8}$$

$$\frac{dL}{d\lambda_t} = F_t - \sum_{i=1}^{n} h_{it} = \dot{x}_t \tag{9}$$

Let $(h_{1t}^*,...,h_{nt}^*,x_t^*,\lambda_t^*)$ be the solution to the social planners problem at t=0 giving us the socially optimal time path of all water users' extraction from t=0 and so on. This is the solution that a regulator with perfect information about the net benefit functions would like to implement.

Interpretation

The shadow price, λ_t, aggregates all the current and discounted future social net benefits of a marginal increase in ground water stock. Recognising that $\frac{\partial \mathrm{H}_t}{\partial \mathrm{h}_{it}} = 1$, the maximum conditions (7) state that, in optimum, the discounted marginal net private benefit of extraction derived by each water user

($\frac{\partial b_{it}}{\partial h_{it}} e^{-\rho t}$) must equal the shadow price of the water stock. Equation (8), the so called adjoint equation, states that this shadow price must fall over time, as cost reducing benefits from water stocks are reaped by water users, since the shadow price captures the aggregate of discounted remaining future benefits. Finally, the state equation (9) defines water stock changes over time as a function of recharge and extraction.

Letting $\lambda_\infty^* = \lim_{t\to\infty} \lambda_t^*$ we have the following definition:

$$\lambda_t^* = \lambda_\infty^* - \int_t^\infty \dot{\lambda}_\tau^* d\tau \tag{10}$$

In addition, we have two transversality conditions (see Neher, 1990):

$$\lim_{t\to\infty} L(t) = 0 \tag{11}$$

$$\lim_{t\to\infty} \lambda_t h_{it} = 0 \qquad \text{for } i = 1,\ldots,n \tag{12}$$

After inserting (6) equation (11) implies that $\lim_{t\to\infty} \lambda_t \left[F_t - H_t\right] = 0$ so that either $\lim_{t\to\infty} \lambda_t = 0$ or $\lim_{t\to\infty} \left[F_t - H_t\right] = 0$. In the latter case, since $F_t > 0$ we must have $\lim_{t\to\infty} H_t > 0$. Since (12) implies that $\lim_{t\to\infty} \lambda_t H_t = 0$ we must have $\lim_{t\to\infty} \lambda_t = 0$. Thus, the transversality conditions imply that:

$$\lim_{t\to\infty} \lambda_t = 0 \tag{13}$$

Intuitively, at 'the end of time,' water stocks have no value since no benefits are reaped from them beyond this point.

Inserting (13) and (8) into (10) we have:

$$\lambda_t^* = \int_t^\infty \left[\sum_{i=1}^n \frac{\partial b_i}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \tag{14}$$

By (3) this equals the value that water stocks have in reducing current and discounted future extraction costs incurred by user *i as well as* by all other water users (i.e. $\lambda_t^* = \int_t^\infty \left[\sum_{i=1}^n \frac{\partial c_i}{\partial x_\tau} \right] e^{-\rho\tau} d\tau$). If users are myopic, this is the external effect that users do not take into account and for which regulation must compensate.

Now define the optimal aggregate extraction of groundwater at time t as $H_{it}^* = \sum_{i=1}^n h_{it}^*$ and the optimal allocation aggregate net benefit function as $B(H_t, x_t) = \sum_{i=1}^n b_i(h_{it}^{H_t}, x_t)$ where ($h_{1t}^{H_t}$,..., $h_{it}^{H_t}$,..., $h_{nt}^{H_t}$) is the optimal allocation of aggregate extraction H_t across users. This implies that $H_t = \sum_{i=1}^n h_{it}^{H_t}$ and $\frac{\partial b_i(h_{it}^{H_t}, x_t)}{\partial h_{it}} = \frac{\partial b_j(h_{jt}^{H_t}, x_t)}{\partial h_{jt}}$ for all $i \neq j$, (stating that marginal net benefit should be the same for all users). This then means that $\frac{\partial B(H_t, x_t)}{\partial H_t} = \frac{\partial B(H_t, x_t)}{\partial h_{it}} = \frac{\partial b_j(h_{jt}^{H_t}, x_t)}{\partial h_{jt}}$ for all i and j. Thus, the effect on aggregate benefit of a marginal change in any water user's extraction is equal to the water user's own marginal benefit of extraction. Conditional on a current level of ground water stock and aggregate extraction, this function issues aggregate net benefits of all users if aggregate extraction is allocated optimally across users. It is obvious that: $B(H_t^*, x_t) = \sum_{i=1}^{n} b_i(h_{it}^*, x_t)$ and $B(H_t^*, x_t^*) = \sum_{i=1}^{n} b_i(h_{it}^*, x_t^*)$ and so also that $\dfrac{dB(H_t^*, x_t^*)}{dx_t} = \sum_{i=1}^{n} \dfrac{db_i(h_{it}^*, x_t^*)}{dx_t}$. Therefore, the marginal aggregate benefit of stock size is equal to the sum of individual benefits of stock size. Thus, we may write (14) as :

$$\lambda_t^* = \left(\int_t^{\infty} \left[\frac{\partial B(H_\tau^*, x_\tau^*)}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \right) \qquad (15)$$

Using (15) and that $\dfrac{\partial H_t}{\partial h_{it}} = 1$ we may write the key optimality for the socially optimal solution (7) as:

$$\frac{\partial b_j}{\partial h_{jt}} e^{-\rho t} - \left(\int_t^{\infty} \left[\frac{\partial B}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \right) = 0 \text{ for } i = 1, \ldots, n \qquad (16)$$

Next we turn to a description of user behaviour.

4. User behaviour

In the previous section, we found the socially optimal set of extraction paths that a regulator with perfect information would like to implement. Here we consider the extraction paths that the water users consider optimal to implement. However, it is not realistic to assume that water users have perfect information when they solve their optimisation problems, so let us initially make our assumptions about this clear.

Users are characterised by their net benefit functions $b_i(h_{it}, x_t)$ and it seems reasonable to assume that water users know this function. Users can ascertain benefits and costs and they are typically able to observe how changes in the ground water level (a proxy for stocks) affect their extractions costs. However, water users do not typically know other users' net benefit functions, nor do they typically observe the other users' level of water extraction. Thus, water users may not perfectly realise how their own or aggregate water extraction affects water stocks, i.e. they often underestimate this effect, or they may not even perceive that there is such an effect[5], thus, acting completely myopically. Furthermore, water users must base their plans on their own estimates of future aggregate extraction and derive from this their own expectations about future water stocks. We assume that water users have point expectations about future aggregate water extraction and derive from this point estimates of ground water stocks. We let x_{it}^{e} denote user *i*'s expectation of the ground water stock at time t and H_{it}^{e} the corresponding expectation of aggregate water extraction at time *t*[6]. User *i* maximises the discounted value of all future benefits and incorporates the expected future stocks and resource restrictions. With this objective, the maximisation problem of user *i* at time *t*=0 is:

$$\underset{h_{it}}{Max} \int_{t=0}^{\infty} \left[b_i(h_{it}, x_{it}^{e}) \right] e^{-\rho t} dt \tag{17}$$

s.t.

$$\dot{x}_{it}^{e} = g_i(F_t - H_{it}^{e}), x_0 = a \text{ given} \tag{18}$$

whereby $\mathrm{g_i}$ is a constant characterising user *i*'s perception of how extraction affects water stocks. If $\mathrm{g_i} = 0$, water user i acts myopically and does not recognise any stock changes or stock effects arising from his own and others' extraction behaviour. On the other hand, if $\mathrm{g_i} = 1$, water user i does correctly recognise such effects. Furthermore, we generally assume that the individual water user recognises that his extraction at date *t* influences aggregate extraction at date *t*.

Solving the users' problem

Following the steps developed in the previous section, the Hamiltonian function corresponding to the above maximisation problem is:

$$L_i = \left[b_i(h_{it}, x_{it}^{e}) \right] e^{-\rho t} + \lambda_{it} \left[g_i\, (F_t - H_{it}^{e}) \right] \tag{19}$$

[5]For parsimony we have assumed exogenous and deterministic recharge. However, in stochastic environments with endogenous recharge and many other users, it may be difficult to ascertain how one's own extraction affects the ground water stock.

[6] To simplify derivations in the following, we assume point estimates. This assumption is not critical and all results carry over qualitatively if we assumed that users held non-degenerative distributions over future water stocks.

The optimality conditions:

$$\frac{dL_i}{dh_{it}} = \frac{\partial b_{it}}{\partial h_{it}} e^{-\rho t} - \lambda_{it} g_i \frac{\partial H^e_{it}}{\partial h_{it}} = 0 \tag{20}$$

$$\frac{dL_i}{dx^e_{it}} = \left[\frac{\partial b_{it}}{\partial x^e_{it}}\right] e^{-\rho t} = -\dot{\lambda}_{it} \tag{21}$$

$$\frac{dL}{d\lambda_{it}} = g_i(F_t - H^e_{it}) = \dot{x}^e_{it} \tag{22}$$

Again λ_{it} is the shadow price of the resource restriction reflecting the marginal value of ground water stocks, but now only *to user i*. The solution to this problem gives us the privately optimal time path of water user *i*'s extraction from *t*=0, *conditional on* water user *i*'s expectations about the present and future aggregate extraction at time *t*=0 and derived from this, his expectations about present and future water stocks. Before continuing, it is important to note that the water users' expectations are not necessarily consistent with each other. Thus, as time progresses, some water users may be surprised about the development in current water stocks that they observe and may, as a consequence, revise their expectations and extraction plans. However, at any given point in time (here *t*=0), all water users have (possibly inconsistent) point expectations about all future aggregate extraction levels and so are able to solve (17) and (18) as indicated and undertake current extraction in accordance with this plan.

Condition (20) states that in optimum, the discounted marginal net private benefit of extraction derived by each water user ($\frac{\partial b_{it}}{\partial h_{it}} e^{-\rho t}$) must equal the 'private' shadow price of water stock *multiplied by* the marginal effect that user *i* expects his extraction will have on aggregate extraction ($g_i \frac{\partial H^e_{it}}{\partial h_{it}}$). Below we will consider more carefully what expectations water users might have about this. Equation (21) states that the 'private' shadow price must fall over time, but since the shadow price only captures future benefits reaped by water user *i* , it only falls with the benefits from water stocks that are reaped by water user *i* ($\frac{\partial b_{it}}{\partial h_{it}} e^{-\rho t}$). Finally, the state equation (22) defines how water user *i* expects the water stock to change over time, as a function of recharge and the expectations of aggregate extraction.

Again we let $\lambda_{i\infty}^{*}=\lim_{t\to\infty}\lambda_{it}^{*}$, using the transversality conditions, (11) and (12), and following the same steps as in the last section we have:

$$\lambda_{it}^{*}=-\left(\int_{t}^{\infty}\left[\frac{\partial b_i}{\partial x_\tau}\right]e^{-\rho\tau}d\tau\right) \qquad (23)$$

Thus, the ‘private’ shadow price of water stock is the value that water stocks have in reducing current and discounted future extraction costs incurred by user *i* (i.e. the cost reductions reaped by other water users are disregarded).

Using (23) we may write the key first order conditions for the privately optimal solution (20) as:

$$\frac{\partial b_{it}}{\partial h_{it}}e^{-\rho t}-\left(\int_{t}^{\infty}\left[\frac{\partial b_i}{\partial x_\tau}\right]e^{-\rho\tau}d\tau\right)g_i\,\frac{\partial H_{it}^{e}}{\partial h_{it}}=0\ \text{ for }\ i=1,\ldots,n \qquad (24)$$

User expectations

The expectations users may have regarding how their own extraction affects water stocks ($g_i\ \frac{\partial H_{it}^{e}}{\partial h_{it}}$) are not obvious. First, considering g_i , it is possible that the users do not perceive an important connection between water extraction and water stock costs (i.e. that $\mathrm{g_i}=0$). This is the myopic user’s assumption, which is customary in the literature (see e.g. Neher, 1990, Hellegers *et al* 2004), and for which there is some empirical support regarding Nepal (Lam, 1999). In this case, the individual simply assumes the marginal extraction cost is equal to marginal benefit at each instant of time and no water rent is recognised. Presumably, this ($g_i=0$) is one outer bound regarding perceptions with the other outer bound being the correct perception of the effect on ground water stocks ($g_i=1$)[7].

Now consider how user *i* expects a change in his own extraction to affect aggregate extraction. It seems natural to assume that $\frac{\partial H_{it}^{e}}{\partial h_{it}}=1$, i.e. a change in individual extraction will change aggregate extraction by the same amount. This corresponds to the standard assumption of Nash conjectures (i.e. that users do not expect other users to react to one’s own change in

[7] Users could, in theory, also perceive exaggerated effects of extraction on stocks. However, the consensus in the literature seems to be that there is a downward bias in misperceptions i.e. that users need to see evidence of effects before taking them into account.

extraction) and this seems well founded here, since users do not typically observe other users' extraction. However, consider a water user who, on the one hand, perceives that his extraction increase affects the water stock ($g_i = 1$) and also realises that this affects his own extraction costs. Such a water user might also realise that other users' extraction costs will be affected and he may reasonably also expect them to react to this by reducing their extraction. He would then logically expect $0 \le \frac{\partial H_{it}^e}{\partial h_{it}} < 1$.[8] In the following, we will look at regulation under three assumptions about user perceptions:

$$\begin{array}{llll} \text{Myopic Nash Perception:} & g_i = 0,\ \frac{\partial H_{it}^e}{\partial h_{it}} = 1 & \text{implying} & g_i \frac{\partial H_{it}^e}{\partial h_{it}} = 0 \\ \text{Correct Nash Perception:} & g_i = 1,\ \frac{\partial H_{it}^e}{\partial h_{it}} = 1 & \text{implying} & g_i \frac{\partial H_{it}^e}{\partial h_{it}} = 1 \\ \text{Non-Nash Perception} & g_i = 1,\ 0 < \frac{\partial H_{it}^e}{\partial h_{it}} < 1 & \text{implying} & 0 < g_i \frac{\partial H_{it}^e}{\partial h_{it}} < 1 \end{array} \tag{25}$$

Clearly Myopic and Correct Nash perceptions are boundary cases. Non-Nash perceptions result in a perceived effect within this bound. However, as we will see in the following, Non-Nash perceptions differ crucially in another dimension, which turns out to be important when considering the type of regulatory instruments we propose in the following.

5. Regulating extraction

We now consider how regulation might be imposed in order to secure optimality. The regulator wants to implement the social optimum characterised by optimality conditions (16), but is faced with unregulated users setting extraction according to (24). From (16) the social shadow price is $\left(\int_t^\infty \left[\frac{\partial B(H_\tau^*, x_\tau^*)}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \right)$ capturing the stock effect on net benefits of all users. In (24), the 'private' shadow price as perceived by the individual user is $\left(\int_t^\infty \left[\frac{\partial b_i}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \right)$. Thus, the individual user at

[8] Standard convexity conditions imply that $0 \le \frac{\partial H_{it}}{\partial h_{it}}$ and it also seems reasonable to assume this of expectations.

best (when $g_i \dfrac{\partial H_{it}^e}{\partial h_{it}} = 1$) only takes account of the stock effect on his own net benefits and does not take account of the net benefit effect he has on other users. In general therefore, the private and social shadow prices differ and this is the externality that makes regulation necessary.

However, even if we assume that the regulator can estimate the optimal aggregate net benefit function $B(.,.)$, implementing an optimal set of extraction taxes seems quite demanding. First, each user's consumption must be measured accurately. Second, the regulator would have to know each user's private net benefit functions *and* their expectations about future stock levels in order to calculate the correct fee rate for each user. Both are clearly unrealistic assumptions in a third world setting.

The aggregate extraction tax

Here we will assume that the regulator can only measure the ground water stock and recharge and from this derive the aggregate extraction. It is further assumed that the regulator is able to identify the set of users who extract groundwater. However, we assume that the regulator is *not* able to accurately measure individual users' extraction levels, or the net benefit functions of individual users. Furthermore, we assume that the regulator has no information about individual users' stock expectations.

As mentioned above, we will assume that the regulator can estimate the aggregate net benefit function, $B(.,.)$. Although this seems an unrealistic assumption, it turns out *not* to be so *if* the tax on aggregate extraction suggested below is actually implemented. If this is the case, the aggregate net benefit function can be estimated by trial and error experiments (see subsection below about estimating aggregate benefit). Under this assumption, the regulator can solve the following maximisation problem:

$$\underset{H_t}{Max} \int_{t=0}^{\infty} \left[B(H_t, x_t) \right] e^{-\rho t} dt \tag{26}$$

s.t.

$$\dot{x}_t = F_t - H_t, x_0 = a \text{ given} \tag{27}$$

Using the solution procedure and transversality constraints as above, the optimality condition can be calculated to be:

$$\frac{\partial B}{\partial H_t} e^{-\rho t} - \left(\int_t^{\infty} \left[\frac{\partial B}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \right) = 0 \qquad (28)$$

Thus, the regulator can identify the social shadow price of extraction $\left(\int_t^{\infty} \left[\frac{\partial B}{\partial x_\tau} \right] e^{-\rho\tau} d\tau \right)$ found in (16). Now let the regulator implement a current value fee:

$$f_t = \left(\int_t^{\infty} \left[\frac{\partial B}{\partial x_\tau} \right] e^{-\rho(\tau - t)} d\tau \right) \qquad (29)$$

The fee is based on aggregate extraction H_t (which he can measure) that must be paid by each user irrespective of his own extraction level. Thus, rather than measuring each individual user's extraction and calculating a tax payment based on this, all users pay the same tax calculated from the aggregate extraction measure $H_t = \sum_{i=1}^{n} h_{it}$ (i.e. all users pay the same fee on aggregate extraction). The regulator announces taxes (fees) and expected resulting groundwater stocks for all future periods found from (28), but also makes clear that the taxes (fees) will not be changed if stocks should deviate.

Hence, as we assume that the individual water user recognises that his water extraction influences aggregate extraction and thus his tax payment, the maximisation problem of user *i* may be formulated as:

$$\underset{h_{it}}{Max} \int_{t=0}^{\infty} \left[b_i(h_{it}, x_{it}^e) - f_{it} H_{it}^e \right] e^{-\rho t} dt \qquad (30)$$

s.t.

$$\dot{x}_{it}^{e} = g_i(F_t - H_{it}^{e}), x_0 = a \text{ given} \tag{31}$$

Using the standard solution procedure, transversality condition and assuming interior solution, the key optimality condition for the privately optimal solution corresponding to (20) becomes:

$$\left(\frac{\partial b_{it}}{\partial h_{it}} - f_{it}\,\frac{\partial H_{it}^{e}}{\partial h_{it}}\right)e^{-\rho t} + \left(\int_t^{\infty}\left[\frac{\partial b_i}{\partial x_\tau}\right]e^{-\rho\tau}d\tau\right)g_i\,\frac{\partial H_{it}^{e}}{\partial h_{it}} = 0 \text{ for } i = 1,...,n \tag{32}$$

Inserting the fee defined in (28) and rearranging terms, the optimality condition becomes:

$$\frac{\partial b_{it}}{\partial h_{it}}e^{-\rho t} - \left(\int_t^{\infty}\left[\frac{\partial B}{\partial x_\tau}\right]e^{-\rho(\tau)}d\tau\right)\frac{\partial H_{it}^{e}}{\partial h_{it}} + \left(\int_t^{\infty}\left[\frac{\partial b_i}{\partial x_\tau}\right]e^{-\rho\tau}d\tau\right)g_i\,\frac{\partial H_{it}^{e}}{\partial h_{it}} = 0 \text{ for } i = 1,...,n \tag{33}$$

Now comparing with the corresponding optimality condition for social optimum in (10), we see that if water users have myopic Nash perceptions ($g_i = 0$, $\frac{\partial H_{it}^{e}}{\partial h_{it}} = 1$), the suggested aggregate extraction tax implements social optimum (i.e. (33) reduces to (16)). If water users have correct Nash perceptions ($g_i = 1$, $\frac{\partial H_{it}^{e}}{\partial h_{it}} = 1$), the tax 'over corrects' since benefits reaped by user *i* are counted twice. In this case, social optimum is not implemented. However, if *n* is large the error is small. A large *n* implies that individual benefit is small compared to aggregate benefit. Thus, as long as *n* is large and users have Nash conjectures the tax will, irrespective of user perceptions about the effect of extraction on stocks, achieve a set of extraction paths that are 'close to' optimal (second-best optimal).

Now consider users that have *Non-Nash perceptions* ($g_i = 1$, $0 < \frac{\partial H_{it}^{e}}{\partial h_{it}} < 1$). On the one hand, the private shadow price of extraction is reduced, which makes users react more myopically at the outset. Thus, the 'small' approximation error that appeared with correct Nash perceptions is scaled down. However, since $\frac{\partial H_{it}^{e}}{\partial h_{it}} < 1$ the incentive effect of the aggregate extraction tax is also scaled down and will be smaller. Thus, since users take into account the fact that the reactions of other users reduce the stock effect of their initial extraction change; the efficiency effect of the tax is also reduced. This is potentially devastating for the regulatory effect of the tax. In the extreme case in which users believe that other users' reactions completely remove the initial effect, the tax will have little or no incentive effect.

Estimating the aggregate benefit function

Now consider the key assumption that the regulator can estimate the optimal allocation aggregate net benefit functions, $B(.,.)$. In case of myopic perceptions, the regulator can use a trial and error period with the aggregate consumption tax to generate data to estimate the aggregate net benefit function. Since the tax under myopic Nash perceptions ensures the optimal allocation of aggregate extraction, aggregating (24) over users gives $\frac{\partial B(H_t, x_t)}{\partial H_t} - f_t = 0$ for $t = 0,....,T$ in the trial and error period. All the aggregate variables are observed by the regulator making estimation of $B(.,.)$ possible. This is also approximately the case when users do perceive an effect of extraction on stocks, as long as the number of users is large and they have Nash conjectures.

For Non-Nash perceptions, this breaks down since the incentive effect of the tax is scaled down. Without knowledge of the scaling effect of Non-Nash perceptions, the regulator does not know the perceived value of the incentives generating variation in aggregate extraction and stock in the trial period.

6. Conclusion

In this paper, we have suggested a fee for regulating common resource water use based on aggregate extraction. All users pay the same tax calculated from an aggregate extraction measure. This makes implementation of the tax feasible, also for regulators who are unable to monitor individual water users' extraction – a situation that is common in developing countries. Further, use of the fee would make it possible for the regulator to estimate the aggregate benefit function and so make it possible for him to set the fee level optimally.

The fee results in an efficient allocation of water use if water users believe that their own extraction does not affect their own extraction costs (i.e. myopic perceptions). When water users recognise this, the fee still results in an approximately efficient allocation The critical assumption about water users' perception needed for the mechanism to ensure an approximate efficient allocation of water use is that they do not believe that their own water extraction affects the water extraction of other users (i.e. that they have Nash conjectures about how other water users react). If water users believe that other users react by mitigating the initial change in water extraction, then the incentive effect of aggregate tax is scaled down, which is potentially devastating for the regulatory effect of the tax. However, water is a necessity with a low elasticity of demand once demand has been reduced substantially. Further, the goal of reducing extraction is to reduce the importance of cost increasing stock effects. Thus, both these effects suggest that once regulation has been initiated, extraction will not be highly responsive to changes in ground water stock and so Nash perceptions or even myopic perceptions are easier to rationalise.

Another important consideration is fairness. The fact that an agent's tax payment is influenced by the extraction of other agents could be perceived as unfair . This 'problem' grows as the number of regulated agents grows and the mechanism is perhaps politically unfeasible unless the number of regulated agents is small. The reason why the problem grows with the number of agents is that the aggregate benefit grows. The fairness problem increases with the number of agents, but at the same time, efficiency increases with the number of agents if they have Nash perceptions. Thus, there is a trade-off between fairness and efficiency. Hence, a lack of complete fairness must be weighed against the additional costs under other forms of regulation and the costs under open-access. Clearly, costs under other forms of regulation, based on the measurement of individual extraction, is higher than the costs associated with the mechanism proposed in this paper. Further, it is also clear that if other regulatory incentives are in place when the mechanism is imposed (for example social control incentives), then the resulting allocation will not be efficient. Thus, when comparing the proposed mechanism to that of self governance, it should not perhaps be seen as an alternative, but rather as a fall back possibility in situations in which self governance is ineffective. When self-governance is effective it generates a Pareto improvement that is perceived as fair by water users without any reliance on regulatory infrastructure. The proposed mechanism does require a regulatory infrastructure that can identify water users, undertake the measurement of aggregate extraction and collect taxes. Thus, the type of situation for which one might think the suggested mechanism could be relevant is one in which social control mechanisms are *not* active among a relatively small group of regulated water users. As noted, social control mechanisms may be strong within a village. However, since social control mechanisms are typically weak across village boundaries when a common water resource is used by several villages, the proposed mechanism may be applicable at the village level. One could imagine the village council being made subject to the tax on a measure aggregating the water use of all villages which draw water from the same reservoir. The tax would not necessarily have to be paid in currency – but could be in the form of supply in kind (labour), or in the form of reduced government subsidies, supplies or access to government resources (land). Another possible application could be the regulation of a group of large farms using a common water resource among which social control mechanisms are not strong. A possible next step could be to investigate this type of mechanism experimentally in a third world setting resembling those discussed here.

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