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Demand management of groundwater with monsoon forecasting

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Abstract

This paper presents an operational approach to setting prices for groundwater in accordance with the interannual variability of monsoon rainfall and the dynamic cost of groundwater use to society. The pricing system is designed for the state of Tamil Nadu, India, where groundwater is largely unregulated and the electricity for pumping is heavily subsidized. Depletion of aquifers during the primary growing season causes environmental damage and drying of wells. The proposed price-setting system estimates the marginal social cost of groundwater use based on the current state of aquifer storage and the forecast of the coming monsoon. Prices are set prior to onset of the monsoon so farmers can plan crop rotations according to the expectation of seasonal rainfall as reflected in the pricing signal. During years that forecasts accurately characterize the probability distribution of monsoon outcomes the market signal encourages economically efficient use of the resource. When monsoons differ from the expected outcome farmers are cushioned by ancillary effects of the pricing system.

Keywords: Seasonal climate forecast applications; Decision-making; Groundwater management; Systems analysis; Pricing

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1. Introduction

The availability of water is highly variable in the state of Tamil Nadu, India. The majority of the rainfall occurs during the winter monsoon, falling more or less over the months of October, November and December. The amount of rain that falls during the winter monsoon exhibits a great deal of interannual variability. Mean rainfall of these months since 1871 is 45.4 cm with a standard deviation of 14.0 cm and extremes of 85.9 cm and 16.4 cm. Due to this variability and the low rainfall totals rainfed agriculture is a difficult prospect. While it is practiced by some, the majority augment the paltry rainfall with irrigation from tanks or groundwater. Farmers are charged for the use of surface water according to a system based on the variety of crops they grow.

Groundwater is accessed by electric pumps for which farmers receive free electricity. Not surprisingly, groundwater resources are overexploited and adverse impacts are accumulating, such as falling water tables, land subsidence, structural storage loss, reduced baseflow in streams and saltwater intrusion. In addition, losses and underdevelopment in the electrical power industry are blamed on the huge energy demand of agriculture to power farmers' pumps, for which the energy companies receive little or no reimbursement. Most worrisome is the prospect of the absence of groundwater resources that are so critical for helping crops survive in dry years. Due to the common property nature of groundwater, those who extract it do not feel the costs to society of overuse and so there is no signal to reduce their rates of extraction. Pricing groundwater according to the social cost of extraction can provide the signal, motivating conservative water use in dry years and full productivity in wet ones.

Groundwater extraction charges are common in many countries and some include environmental costs in the price (Rogers et al., 2002). Many studies have described economically optimal groundwater development (Burt, 1964; Brown and Deacon, 1972; Rogers and Smith, 1970; Gisser and Sanchez, 1980; Tsur, 2000; Tsur and Graham-Tomasi, 1991). The present study attempts to consolidate the economic lessons of previous findings and incorporate the variability of supply and demand and a broader definition of opportunity cost to promote sustainable groundwater use. This is achieved by pricing groundwater based on the expectation of the forthcoming monsoon.

Monsoon forecasting can provide the foreknowledge needed to set the groundwater price efficiently. Forecasts of the Indian monsoon have been sought since at least the famine of 1877, when H.R. Blanford, director general of the Indian Meteorological Service began the quest (Krishna Kumar et al., 1995). Krishna Kumar et al. (1995) provides a review of monsoon forecasting focusing on statistical efforts while Webster et al. (1998) review the challenges to modeling. Prospects for monsoon prediction are burnished by advances in predicting ENSO (El Nino-Southern Oscillation) with which Indian monsoon rainfall is correlated (Ropelewski and Halpert, 1987, 1996). The winter monsoon of Tamil Nadu has received much less research attention. Nonetheless, the winter monsoon rainfall is also correlated with ENSO and the coincidence of its timing with the typical ENSO peak may offer a temporal advantage for predictions made 6–9 months ahead, as they would not overlap the springtime dip in ENSO correlations known as the "predictability barrier" (Webster et al., 1998; Webster and Yang, 1992).

Despite growing skill in monsoon forecasting, use of the predictions is limited, as predictions perceived as failures remain prominent in the minds of potential users (Hartman et al., 2002; Glantz, 1982). Significant research has focused on the improving the use of forecasts by farmers (reviewed in Hammer et al., 2001). This is a useful endeavor. However, there are advantages of scale to promoting efforts that improve the use of forecasts at higher administrative or economic levels than the individual farmer. Arndt and Bacou (2000) provide a rare example of an economy wide study of drought forecast impacts on Mozambique. They found greater economic returns to forecast use by market sector participants in comparison to use by farmers alone, though their results are tentative due to the generality of the model. As the authors stated, it is likely easier to train thousands of the market sector agents than millions of farmers, who would also receive the forecast information in pricing signals (such as higher interest rates for loans when drought is forecast).

In a similar manner, water managers are a logical focus for the implementation of forecast information. The outcome of their decisions, such as setting water prices, reservoir storage levels, outflows and allocations, is highly dependent on daily weather and seasonal climate. Yet their use of seasonal climate forecasts is limited by, among other factors, lack of appropriate tools or mechanisms for implementing probabilistic forecasts (Bates, 2002). In this paper our objective is to propose a mechanism that transforms probabilistic categorical forecasts into a decision algorithm for water managers. The mechanism is designed to improve the economic efficiency of groundwater price setting with the use of probabilistic monsoon forecasts. A simple conceptual case study is presented to illustrate the method. Additionally, we hope to demonstrate an approach to forecast implementation, i.e. utilizing economic mechanisms, that has potential for general application. The development of the pricing model will be described in the following section. Section 3 will present the case study, set in Tamil Nadu, India and the results of that study are discussed in Section 4. Finally, concluding remarks are presented in Section 5.

This paper does not attempt to compare pricing mechanisms to quantity rationing, or quota, mechanisms. There are important arguments in favor of rationing water (Ray, 2002; De Fraiture and Perry, 2002). While the approach presented here utilizes prices to mitigate demand, quantities could have similarly been prescribed. If a market develops for farmers to trade water then the same price could be reached with either mechanism. However, the role of uncertainty and the slope of the water demand curve may favor price instruments over quantity instruments in terms of economic efficiency (Weitzman, 1974).

2. Methodology

2.1. Model development

Economic theory would contend that an efficient price is one that equals the marginal cost of producing the water. As the familiar story goes, water users, in this case farmers, adjust their water use based on the price that they pay for water as they attempt to maximize profits. A higher water price would raise the production costs for their crops. In order to maximize profits farmers reduce their water use, through a switch to crops that require less water, by planting fewer crops (farming less area) or through more efficient irrigation. Ray (2002) reports evidence that farmers do react in these ways. Several studies have concluded that farmers react to price changes primarily through cropping choices, while water applied remains relatively inelastic once the cropping choices are made (Sunding et al., 1997; Tsur and Dinar, 1997; Moore et al., 1994). Therefore it is important that water prices are known prior to deciding cropping plans.

In theory, society would benefit from higher water prices as any loss in benefits to individual farmers would be offset and surpassed by the benefit to society of the avoided costs of water production. These include the added pumping costs that farmers incur on each other by reducing the water table elevation. In practice, there will likely be substantial opposition to implementing groundwater pricing. An effort such as this must include compensation to farmers for their losses. Funds raised by tariffs should be used for this purpose, as well as funding relief in drought years (Dinar, 2000). In accordance with theory, evidence in the literature shows that raising water prices does reduce demand, though the prices must be raised above very low prices, which have no significant impact (Ray, 2002).

In the classic economic model, the price of a commodity such as groundwater would be determined by market transactions at the point that the marginal revenue derived from its use equaled the marginal cost. According to economic theory, this point maximizes social benefit, the sum of consumer and producer surplus. In the case of groundwater this model breaks down for three significant reasons, namely, because externalities cause the social cost of groundwater to exceed the private cost, because, for the most part, there are no markets for groundwater and, finally, due to the uncertainty of water supply. Groundwater is a common property resource and as such requires government intervention, or a committed community of irrigators, to prevent overuse (Bromley, 2000; World Bank, 1981). To this end, the government or water management authority can promote near optimal water use by setting groundwater prices at the point where estimated marginal benefit, or demand, equals estimated marginal cost.

The net benefit of such a policy will depend largely on the quality of these estimates. Few studies of optimal control of groundwater have proposed operational methods to use price to regulate groundwater. Schuck and Green (2003) describe an irrigation district in California that raises surface water prices in drought but leaves groundwater unpriced, leading to over-exploitation of groundwater that runs counter to their objectives. In the case of India, an adaptive water management strategy with climate-responsive prices is recommended due to the variability and size of the monsoon. In this analysis we will employ seasonal climate forecasting to estimate probable benefits of alternate tariff choices to select the tariff that maximizes benefits.

2.2. Estimating groundwater demand

The typical economic model of the farmer's decision problem can be presented as (based on Willis and Yeh, 1987):

$$\max \sum_{i=1}^{m} (r_i Y_i(q_i + s) - pq_i) \cdot T_i, \tag{1}$$

where r_i is the marginal revenue from crop i (Rs/kg), Y_i is the yield for crop i (kg/ha) as a function of applied water, q_i, (mm/ha) and rainfall, s (mm). The price of groundwater is p (Rs/m^3) and T_i is the area planted with crop i. Using this model the farmer's response to the price of water can be estimated in terms of crop and water allocation decisions. The price of groundwater is parametrically varied within the decision model to determine crop choice, water use and net income at each price (Willis and Yeh, 1987). We used this procedure to derive groundwater demand curves conditional on a specification of the marginal revenue, r_i, for each crop for farmers of the Palar River basin in Tamil Nadu, India. Values for crop revenue, average crop yield, non-water costs and area of agricultural land was obtained from Harshadeep (personal communication, 2002).

The model included decision variables for the land area planted to one of four crops, cotton, groundnut, pulses or ragi and decision variables for the quantity of groundwater applied. The objective of the crop modeling was not to reproduce the actual yield and revenue that would be produced in a given season. Rather, the modeling was an attempt to compare relative changes in revenue for changes in rainfall, applied water and crop choice. Crop growth was modeled with a simple equation developed by Hargreaves (1975) and Hargreaves and Samani (1984):

$$\Psi = 0.8\xi + 1.3\xi^2 - 1.1\xi^3,$$

where ξ is the fraction of full evapotranspiration; Ψ is the fraction of yield when evapotranspiration requirement is fully met.

This equation was developed for the prevailing conditions of California irrigated agriculture for a variety of crops and for effective rainfall ranging from 102–660 mm. These rainfall amounts almost fully encompass the historical record of rainfall in Tamil Nadu, and temperatures during winter are similar to those in California during summer. Full evaporation was estimated for each crop using the irrigation water demands listed in Harshadeep (personal communication, 2002). The baseline crop yield of which Ψ is a fraction is also taken from the World Bank data. The data represent average historical yields for irrigated agriculture in the Palar River basin of Tamil Nadu, India. The data are listed in Table 1. This model has not been validated for irrigated agriculture in Tamil Nadu, but it provides a basis for the comparative analysis used in this study. Physically-based, spatially distributed modeling is necessary to advance this analysis beyond the conceptual level.

The percent of land devoted to a single crop has been limited to sixty percent and crop decisions are assumed to be made to maximize revenue based on input and output prices. In Eq. (1) the crop yield depends on the sum of groundwater and rainfall,

Table 1
Yield and water requirements for crops in the Palar River basin, Tamil Nadu, India, from Harshadeep (personal communication, 2002)

Crop	Full evaporation (mm/season)	Yield (kg/ha)	Duration (days)
Cotton	700	800	160
Groundnut	566	1800	135
Pulses	400	650	70
Ragi	405	1600	90

The water requirements used are for October–November–December only (92 days). For crops with longer growing seasons average rainfall was assumed to occur for those months (e.g., January, February, March, etc.), however, relatively little rainfall falls in those months (mean <2 cm/month).

and therefore the demand for groundwater will be a function of rainfall. We produced three demand curves by estimating farmer response to above normal, normal and below normal winter monsoon rainfall. The rainfall categories were based on the historical record, with each category representing one third of observed outcomes (terciles). The median value of each tercile category was used in the decision model to generate the demand curves for each categorical outcome of the monsoon rainfall. The curves, shown in Fig. 1, are in agreement with expectation as the derived willingness to pay for groundwater increases as the rainfall decreases.

2.3. Estimating the cost of groundwater use

In practice assessing a cost to the pumping of groundwater is tricky business. Here we categorize costs in terms of how they may be calculated. The usual definition of the social cost of groundwater includes only the increased pumping costs induced by

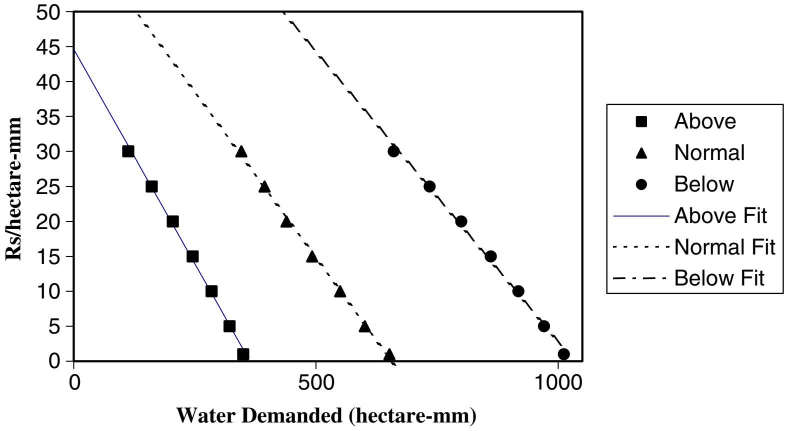

Fig. 1. Demand curves for below normal, normal and above normal monsoon. Data points were generated with an optimization model with crop type, area and water applied as decision variables and net income as the objective. The curves were generated with rainfall input of above normal, near normal and below normal. Ordinary least squares regression was used to fit the data (all $p < 0.001$).

a lowering of the water table (Burt, 1964; Brown and Deacon, 1972; Rogers and Smith, 1970; Gisser and Sanchez, 1980). In this analysis we will include not only extraction costs, but also opportunity costs and the cost of diminished non-use values. Extraction costs are the social cost of the power or labor used to run pumps. In India the private cost of extraction is very small or nothing, as electricity has been supplied freely to encourage groundwater use. In order to estimate the social cost of groundwater we must use the social cost of the power, because the price of power does not reflect its social cost.

The opportunity cost of groundwater use is due to the competing demands for this finite resource. Opportunity costs describe the situation where water can be used for a higher return elsewhere in comparison to the return for its current use. Previous studies quantify the opportunity cost as the increased cost of pumping due to a lowered groundwater table. If the consumption of water by one user prevents that water from being used in a higher value process (as reflected by a higher willingness to pay), the difference in value between those uses represents an opportunity cost as well (Rogers et al., 2002). In the case of groundwater, opportunity costs may arise in several ways. A common example is the difference in the returns that water earns in agriculture, which are very low compared to returns that would be earned if that water were used in industry or for domestic use. This analysis is concerned with the best use of water solely within the agricultural sector, without regard to economic interactions with domestic or industrial sectors. In general, water transfer from agriculture to domestic or industrial use is competitively priced in India, and so benefits of pricing reform in agriculture will likely translate to water use in other sectors. Within the agricultural sector, a farmer choosing to use water to grow a low value crop in the place of a high value crop with the same amount of water would represent an opportunity cost. In this analysis we assume that all farmers are endeavoring to maximize their profits and will choose to plant crops that represent the greatest expected net revenue. Therefore this opportunity cost would be minimized. All farmers are doing the best they can given their endowment of land, soil and water.

Another opportunity cost arises due to the interannual variability of the value of water. It can reasonably be assumed that water that is not used this season will be available for use during the next growing season. If water is abundant this season due to a good monsoon then groundwater is likely to be worth more in the following season, especially if there is deficient rainfall during that season. A good monsoon may be followed by a drought, in which case the value of water stored in the aquifer for use next year would exceed the value of water pumped and used in the present. Conversely, a drought may be followed by a year of abundant rainfall, and so the value of pumping water from the aquifer in the present exceeds the value of the water stored for the next year.

Finally, the cost of using groundwater must include the loss of its non-use values (NRC, 1997). These include protection against salt-water intrusion and land subsidence that a higher water table offers and the ecological services that groundwater provides through baseflow to streams and moisture to habitat. The non-use value of groundwater is difficult to quantify. The loss of protection against saltwater intrusion or subsidence might be estimated through the avoided costs of mitigation. The contingent value method could be used to estimate the value of ecological services. However, these methods are inexact and costly (NRC, 1997). In this study we will estimate the loss of non-use value as simply the increased pumping cost due to a lowered water table. While this will underestimate the true loss of non-use value, it is easily calculated and allows a conservative estimate of the social cost of groundwater use.

The total marginal social cost of groundwater use is then the sum of the extraction, opportunity and non-use costs

$$\mathrm{TMC} = D(x) + \mathrm{O}(s, x, q_t) + \mathrm{NU}(x, q_t), \tag{2}$$

where q_t is the total quantity of water extracted for all crops ($q_t = \sum q_{i},$), x is the elevation of the groundwater table, s is total monsoon rainfall and $D()$ is electricity or fuel cost of operating the pump. Single period models typically use a static approach in regard to state variables and disregard the effect of groundwater pumping on aquifer volume (see e.g., Tsur, 2000). Dynamic models attempt to include the discounted future value of groundwater in the objective function to decide the optimal extraction path (see Tsur and Graham-Tomasi, 1991). In this study we propose an adaptive model that accounts for the effect of this year's groundwater extraction on next year's groundwater level. In this way the model suggests a year to year, piece-wise optimal path by determining the optimal rate of water use given the probable outcome of the monsoon and the current state of the aquifer. It is worth noting that piece-wise optimal decisions do not ensure long-term optimality. For example, in our model, serially correlated monsoon outcomes, such as multi-year droughts, may cause solutions to differ from the optimal solution based on perfect knowledge of such an event.

The opportunity cost will be calculated as the discounted cost of replacing groundwater with an inexhaustible water source, such as desalination, multiplied by a factor that penalizes groundwater pumping that exceeds the expected recharge from rainfall

$$\mathrm{O}(s, x, q_t) = \left(\frac{\text{Replacement Cost}}{\rho}\right) \cdot \left(1 - \frac{x + s - q_t}{X}\right) \tag{3}$$

with X representing the target level of the aquifer, ρ the discount rate, s the recharge from rainfall as a depth and q_t representing the change in groundwater depth due to pumping. This term increases the cost of water when the groundwater table is projected to finish the season below the target level and will decrease the cost when the table will finish above the target level. This is similar to the approach employed by Azaiez (2002) who used a reward function to credit the amount of water remaining in the aquifer at the end of the planning period.

The non-use value will be estimated by the increased cost of pumping due to a lower water table

$$N(x, q_t) = \frac{1}{\rho} k \frac{\mathrm{d}C}{\mathrm{d}x}, \tag{4}$$

where $\mathrm{d}C/\mathrm{d}x$ represents the cost of pumping water an additional unit of head and k is a dimensional constant that relates extraction to the change in groundwater level. Because the opportunity cost depends on the unknown outcome of the monsoon, s, the total cost of groundwater use is a probabilistic quantity. The expected value of TMC is

$$E[\mathrm{TMC}] = D(x) + E[\mathrm{O}(s, x, q_t)] + \mathrm{NU}(x, q_t), \tag{5}$$

where $E[\,]$ represents the expectation operator. It can be estimated from historical frequencies of monsoon outcomes or the probabilities assigned by a monsoon forecast:

$$E[\mathrm{TMC}] = D(x) + \sum_i \mathrm{O}(s_i, x, q_t) \cdot P(s_i) + \mathrm{NU}(x, q_t). \tag{6}$$

2.4. Groundwater pricing model

With the marginal social cost of groundwater use established and demand curves derived from crop production modeling, the price of groundwater that encourages optimal use can be set. The point where expected marginal cost equals the expected demand represents the economically efficient point. However, the actual demand curve depends on the outcome of the monsoon and therefore will vary from year to year. Monsoon forecasts offer an opportunity to reduce the uncertainty associated with the location of the demand curve.

This application was designed for probabilistic, categorical forecasts of the monsoon. Probabilistic, categorical forecasts assign a probability to each category of monsoon outcome. The probabilities of each categorical outcome can be based on a monsoon forecast, generated statistically or with a dynamic model, or based on historical frequencies, often referred to as climatology. A statistical model that generates categorical probabilities for the Tamil Nadu winter monsoon based on principal components of Pacific Ocean sea surface temperatures and Indian Ocean surface level pressure has been developed for application to the groundwater pricing system presented here (Brown, unpublished dissertation, Harvard University, 2004).

Fig. 1 shows three demand curves for above normal, normal and below normal rainfall based on the historical record of the winter monsoon in Tamil Nadu. The marginal cost curve intersects with each demand curve, indicating an efficient social price for each of the three categorical monsoon outcomes. Of course, when an actual monsoon outcome falls within a particular category, the amount of rainfall will likely not equal the median of the category, which was used to generate the demand curves. Therefore the use of categorical demand curves generates a loss of economic efficiency based on how far a monsoon outcome within a specific category differs from the mean value of that category. However, the forecast information currently available is not sufficient to justify either a single valued forecast of the monsoon outcome, or more than three categories.

Nonetheless, the categorical forecasts can be used to increase the efficiency of groundwater pricing. Farmers make cropping decisions prior to the monsoon, so in order for the price response to influence cropping decisions and water demand, prices must be set in time for farmers to use them in decision making. As mentioned earlier, the largest effect on water demand is due to cropping choices. Otherwise, once cropping decisions are made farmers' demand is likely to be inelastic to price (Gibbons, 1986). Therefore, the selection is based on the price that maximizes the expected net benefit, based on the monsoon forecast. The net benefit of a price for water set before the monsoon can be modeled as a probabilistic quantity dependent on the probability of the monsoon outcome. To set the price, the net social benefit is calculated for the three candidate prices and the expected value is calculated based on the probability of each categorical monsoon outcome.

Let p_k $(k = 1, 2, 3)$ represent the three candidate prices for water that are calculated from the intersection of the demand curves (Fig. 1) with the expected cost curve. The expected net benefit of each pricing plan is estimated by calculating the net benefit of the pricing plans for each monsoon outcome and multiplying by the probability of that outcome according to the forecast. The pricing plan that maximizes the probability-weighted expected net benefits should be chosen (Johnson and Holt, 1997):

$$E[\mathrm{NB}(p_k)] \equiv \max_p E_{s|f}[\mathrm{NB}(p_k, s)|f_1] = \max_p(\mathrm{NB}(p, s) \times P(s|f_1)), \tag{7}$$

where NB is the net social benefit, p_k, $(k = 1, 2, 3)$ is the price of water, f_1 is the forecasted probability for the three $(j = 1, 2, 3)$ monsoon outcomes and there are m crop choices. The net social benefit is the agricultural income minus private production costs and the social costs of groundwater use, and is calculated for the three categorical monsoon outcomes:

$$\mathrm{NB}(p_k, s_j) = \sum_{i=1}^{m}(r_i Y_i(q_i + s_j) - p_k q_i) \cdot T_i - E[TC]. \tag{8}$$

The expected net benefit of the pricing plan based on climatology, that is, without a forecast, is estimated by multiplying the net benefit for each plan and each monsoon outcome by the probability of each outcome based on the historical record:

$$E_s[\mathrm{NB}(p^c, s)] = \sum_{k,j} \mathrm{NB}(p_k^c, s_j) \times P(s_j). \tag{9}$$

The benefit to society of using a forecast-based pricing system is estimated by comparing the expected net benefit of using the system to the expected net benefit of using a pricing plan based on climatology, p^c. The long-term benefit of this pricing system can be calculated empirically by simulating the outcome of the pricing system decision model with historical data over T years:

$$\text{Long-term NB} = \sum_{t=1}^{T}[\mathrm{NB}(p_t^*, s_t)] - [\mathrm{NB}(p^c, s_t)]. \tag{10}$$

This represents an estimate of the value of information provided by the forecast for this groundwater management application. We are currently preparing a simulation to estimate this value based on a statistical forecast of the winter monsoon in Tamil Nadu (Brown and Rogers, 2006).

Fig. 2 shows that when the monsoon rainfall is deficient the price for groundwater should be set high to account for the expected social and opportunity costs. This can be understood intuitively. With a forecast of above average precipitation the cost of groundwater use is expected to be low, reflecting the expected abundance of available water. Farmers reacting to the low price of water will select crops to take advantage of low cost water, perhaps investing effort in crops with greater water demand and greater market value, such as sugarcane and cotton. When the forecast is for a bad monsoon the cost will reflect the high value of groundwater in a drought. Farmers will react to expensive water with a reduction in demand and water conservation and consequently loss of non-use services will be decreased. Year to year, society will reap increased net benefits due to greater agricultural production in water-plentiful years, reduced groundwater pumping costs and associated environmental costs in most years (in comparison to the status quo of free water) and conservation of water for the years and uses for which it is most needed.

In practice, the candidate prices indicated by the analysis of social cost and expected demand curves may be unpalatable to farmers and lead to political opposition. Instead, candidate groundwater prices for each forecast scenario could be produced through stakeholder discussions. Water management authorities could determine prices that would engender efficient water use and be politically tenable. These prices are then compared with the efficient prices that are indicated by the intersection of the marginal benefit and cost curves. If the prices selected by the water managers are less than the prices derived from the social cost analysis, the water will effectively be sold at a discount in terms of its true social cost. The difference between the economic price and the selected price may be considered a subsidy to the groundwater users at the expense of the environment and the cost of future groundwater use

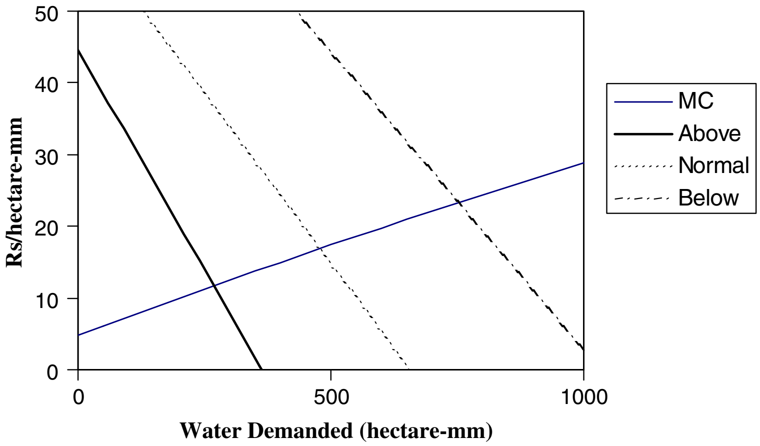

Fig. 2. The fitted demand curves as determined in Fig. 1 with the marginal social cost of groundwater use superimposed. The cost curve was calculated as described in the text.

(the sources of total marginal cost). Quantifying these subsidies and incorporating them into future stakeholder discussions should aid efforts to move prices in a socially beneficial direction, i.e. in the direction of decreasing subsidies.

A groundwater management strategy that effectively reduces demand will likely cause hardship on farmers accustomed to receiving groundwater for free. To compensate for this economic slowdown, funds generated from groundwater charges should be used to provide training in water conserving strategies or assistance for those unemployed as a result. Providing compensation for the negative impacts of pricing reform is an important part of engendering acceptance (Dinar, 2000).

3. Case study

A simple illustrative case is presented for the Palar River basin in Tamil Nadu, India. Agricultural income and fixed cost estimates were based on data collected by the World Bank for three taluks in Kanchipuram district (Harshadeep, personal communication, 2002); the typical total area of groundwater irrigated agriculture is 24,940 ha. All economic and crop production figures are for 2000. Evapotranspiration requirements for crops were obtained from FAO (2003). Although farmers there grow a variety of crops, for this case we will limit their choices to cotton, groundnuts, pulses and ragi. Cotton yields the highest returns but also demands the most water; ragi is drought resistant and requires much less water but is a less valuable crop; groundnuts and pulses lie between cotton and ragi in terms of water requirements and economic return. For the purposes of this case, we assume stakeholder discussions have produced agreed to prices of 20, 10 and 5 Rs/ha mm for a monsoon outcome of below normal, normal and above normal, respectively (1 dollar = 45 rupees). These values are less than those indicated by the economic analysis (see below). They were chosen to demonstrate the outcome for the expected case where the water management authority chooses values that are less than those indicated by the analysis; the specific values are arbitrary.

The social value of water for each of these cases is determined from the intersection of the marginal social cost and marginal benefit curves. From Fig. 2 the costs are approximately 24, 17 and 11 Rs/ha mm for below normal, normal and above normal monsoons, respectively. The social cost of groundwater used is subtracted from the total benefit to produce net social benefit. The marginal social cost curve of Fig. 2 is based on average pumping equipment and costs in the study area, $\mathrm{d}C/\mathrm{d}x = 0.37$ Rs/ha mm m, $k = 1$ m, an initial groundwater depth equal to the target depth of 10 m, and the electricity price for groundwater pumping is based on the average utility cost of supplying electricity to farmers in neighboring Andhra Pradesh (2.5 Rs/kW h). A conservative estimate by the authors of the unit cost of desalination (250 Rs/ha mm) was used as the replacement cost of groundwater. The discount rate, ρ, was set equal to unity to avoid judgement of present versus future value of water, which is not clear given the possibility of future water scarcity. Further, the calculation is over a single year period so the effect of discounting is small. The water tariff is decided using Eq. (6) and choosing the price that maximizes the net social benefit.

Farmers are assumed to be price takers and will choose the crop that maximizes profit based on the price of water. Their profits will depend on the monsoon outcome, for water requirements not met by the monsoon must be purchased at the water price. In a simple decision model for the farmers, we have assumed that their expectation of the coming monsoon is equal to the long-term average. Anecdotal evidence suggests that farmers are typically not influenced by monsoon forecasts when making cropping decisions. Economic (dis)incentives may be used to guide them to optimal cropping and water use decisions. The linear optimization model used to generate the demand curves is used to simulate the farmers' choice of crop plan under each water price scenario. We calculate the net income and water used for each plan under the three monsoon scenarios (above normal, normal, below normal) with Eq. (1). The subsidy is determined by calculating the social cost of groundwater extracted with Eq. (2) and subtracting the amount paid for the water. Fig. 3 depicts this graphically. If the groundwater tariff is 5 Rs/ha mm the water demanded is 322 ha mm for an above average monsoon and the social marginal cost is 13 Rs/ha mm. The subsidy is the social cost of 13 × 322 minus the amount paid (5 × 322) which equals 2576 Rs.

The decision of the water authority is to price the water at 20, 10 or 5 Rs/ha mm in order to maximize expected net social benefits based on the monsoon forecast. Table 2 shows the calculation of expected net benefit for forecasted monsoon probabilities of 70% above normal, 20% normal, 10% below normal. For this forecast a water price of 5 Rs/ha mm should be chosen because it yields the highest expected net social benefit. Table 3 shows the same calculations for forecasted probabilities of 10%, 20% and 70%, respectively. In this case the best price for groundwater is 20 Rs/ha mm.

The consequences of mispriced water due to a low probability monsoon outcome can be interpreted from the data in Table 2. For example, with the water priced at

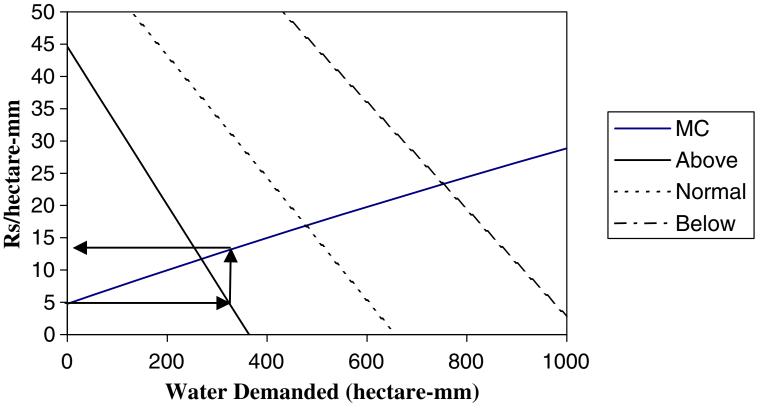

Fig. 3. Schematic of the determination of the social value of groundwater at the quantity used. In this scenario, the price of groundwater has been set at 5 Rs/ha mm. For an above normal monsoon the amount of groundwater used is determined by the corresponding demand curve, in this case 322 ha mm. When that amount of water is used, the marginal social cost of groundwater is 13 Rs/ha mm.

Table 2
Expected net social benefit of each water price given forecasted monsoon probabilities of 70% above normal, 20% near normal, and 10% below normal

Water pricing	Monsoon	Water value	Net income	Subsidy	Net benefit	Forecasted probabilities	Expected benefit
20	Above	10	10,132	−2050	7329	70	6736
	Normal	16	8251	−1756	6654	20	
	Below	24	5792	3200	2753	10	
10	Above	12	10,889	570	10,329	70	8220
	Normal	19	9969	4950	5450	20	
	Below	26	8739	14,688	−5538	10	
5	Above	13	14,371	2576	12,064	70	8235
	Normal	20	12,157	9015	4245	20	
	Below	28	10,342	22,333	−10,593	10	

For each monsoon outcome category, the net benefit is calculated based on the social value of water and net income. The expectation of net income is determined with the forecasted probabilities of each monsoon outcome category. See text for description of calculations.

Table 3
Expected net social benefit of each water price given forecasted monsoon probabilities of 10% above normal, 20% near normal and 70% below normal

Water pricing	Monsoon	Water value	Net income	Subsidy	Total net benefit	Forecast	Expected benefit
20	Above	10	9379	−2050	7329	10	5528
	Normal	14	8410	−1008	7402	20	
	Below	17	5953	−1218	4735	70	
10	Above	12	11,547	−795	10,977	10	1998
	Normal	16	10,400	3114	7286	20	
	Below	23	9150	9945	−795	70	
5	Above	14	14,640	2880	11,760	10	−486
	Normal	17	13,260	6660	6600	20	
	Below	25	11,740	16,000	−4260	70	

5 Rs/ha mm, if the monsoon outcome is below normal, the agricultural profit will be 10,342 Rs/ha, the social cost will be 22,333 Rs/ha and the net social benefit is −10,593 Rs/ha. In this scenario the farmer does not suffer great losses because the deficient rainfall is mitigated by cheap groundwater. The social cost is high in this case due to the overuse of water, but it is proposed that the resiliency of society exceeds that of the individual farmer and infrequent shocks are less catastrophic than for a farmer who could be forced into debt. The consequences of overpricing water when the monsoon is above average can also be seen. From Table 2, when the water is priced at 20 Rs/ha mm and the monsoon is above average, the net income is 10,132 Rs/ha. If the water had been priced correctly, at 5 Rs/ha mm, the net benefit would have been 14,371. The mispricing results in lost welfare of 4239 Rs/ha. In the long-run a society would suffer from regular losses of potential benefits such as this, but if infrequent the damage should not be significant. The farmers have still earned

a profit. Still, misrepresentative forecasts have negative consequences. The effect of forecast uncertainty will be presented in a future paper.

4. Discussion

Shifting the forecasting decision from crop planning to water management may reduce the risk of miscommunication. The development of mechanisms for implementation of probabilistic forecast information by water management authorities may be more feasible than developing similar tools for individual farms (assisting farmers' use of forecasts is an area of active research, e.g., see Roncoli et al., 2002; Hansen, 2002). An economic mechanism, such as price setting, then communicates the expectation of the future monsoon to water users in much the same way that a federal interest rate communicates the expectation of a nation's future economy, or a stock price communicates expectation of a company's future earnings. The water management authority that sets the price still bears the risk of water being undervalued or overvalued, with the losses being incurred by society. However, with an effective forecast the net benefit to society should be positive in the long-run. In consideration of the costs to society of the current overexploitation of groundwater, the short-term losses to society caused by the policy are slight and justified by the long-run efficiency gains. Farmers gain the benefit of the forecast use while the uncertainty of water supply is mitigated by the efficient pricing system.

While this groundwater pricing system should decrease the social cost of groundwater use, one must check the distributive effects of the system on general welfare. Farmers who are now receiving free groundwater will be negatively impacted by the new water tariffs. The poorest farmers, those who are landless and those who do not have the capital to get access to groundwater, currently receive no benefits from this common property. In fact, their crops suffer at the market by competition from crops that have been irrigated by groundwater (Rogers et al., 1998). Therefore the current situation constitutes an inequitable distribution of groundwater benefits to those who can afford to access it (World Bank, 1981). While it may be unrealistic to expect a groundwater pricing policy to alleviate income inequities (Bromley, 2000; World Bank, 1981), pricing groundwater should not increase inequity and may very well improve the equitable distribution of groundwater benefits.

Another important concern is for the welfare of farmers when the monsoon outcome is the opposite of the forecast. There are two worst-case scenarios. In the first scenario, the forecast is for above average rainfall and the outcome is below average rainfall. Water has been priced cheaply reflecting its expected abundance. Farmers may have planted higher value crops with greater water requirements. The lack of rain threatens a complete crop failure. However, because the groundwater is priced cheaply, the farmers are likely to be able to irrigate crops affordably despite needing excess water. Their risk is mitigated by the availability of low cost water. The long-term temporal opportunity cost of the water is low as it is unlikely to be needed more in the future than it is now. The environmental cost, however, is high as groundwater pumping reduces the elevation of the water table, reducing baseflow to streams and risking consolidation of the aquifer structure. This scenario represents the worst-case forecast misfire. All is not lost; farmers' risk of financial ruin due to a low probability event is mitigated by the pricing scheme. The environmental cost could be large but the environment suffers this fate in every drought year under the current system. The proposed system should make such occurrences unlikely. This extreme forecast miss would be an important criterion with which to screen forecasts. A forecast that has the quality of rarely predicting excess rainfall when drought occurs would be especially useful for this pricing method.

In the second scenario, the forecast is for below average rainfall and the outcome is above average. This is a case of opportunity lost. The price of water is high in anticipation of scarce supplies; farmers react by planting less ambitiously. There is an efficiency loss to society because the water charge is too high in relation to cost of groundwater use and more should be used. The positive results are significant. Good rainfall means the farmers will have water for the crops and will need to rely less on groundwater, which reduces their production costs. Rainwater harvesting is encouraged by the abundance of rainwater and high cost of groundwater. Water tables are replenished and the volume stored remains available for next year's or dry season crops. This scenario is not as dire as the previous scenario, but still should be avoided to maximize the productivity of water in the long-run.

The important result from the two worst-case scenarios is that in each case there is a "silver lining" for the farmer that mitigates the chance of catastrophic loss. In the first case the farmer has inexpensive groundwater to sustain the crops and in the second case there is abundant rainfall that reduces the cost of production of the crops. The losses are incurred by society in terms of lost opportunity and by the environment in the form of damage from depletion of aquifers. There may be advantages to focusing on forecast implementation on systems with resiliency, such as a water management plan, that can withstand short-term efficiency losses to gain long-term efficiency. In the same manner, short-term environmental impacts are off set by the long-term sustainability of the aquifer and environmental health.

The evaluation of the uncertainty associated with a forecast is a critical factor in assessing the value of the information provided by the forecast in an application such as described here. The uncertainty of a forecast can be evaluated in terms of the variance of the probabilities assigned to a tercile category. This can be compared to the uncertainty of the climatology in terms of its variance from the true terciles, which are unknown because the complete history of rainfall is unknown. Alternately, the benefit of a single price optimized for climatology and its variance may be compared to the benefit of a forecast-based price. These topics are currently being investigated by the authors.

5. Conclusion

Without community or government intervention, groundwater use in agriculture may lead to social costs that outweigh the private benefits derived from its use (Bromley, 2000; Provencher, 1995; World Bank, 1981). With the private benefit of groundwater depletion far exceeding the private cost when electricity is subsidized, farmers have incentive to ignore the social cost of falling water tables. In addition, the water requirements of crops planted may be greater than can be supplied by the aquifers in dry years and may be less than could have been supported in wet years. We propose a groundwater pricing system based on monsoon forecasts to reduce the losses that society bears due to groundwater depletion and lack of foreknowledge of the monsoon. Higher prices are charged when the forecast is for a deficient monsoon, encouraging conservative cropping patterns and water conservation. Lower prices in years of wet forecasts encourage aggressive cropping patterns.

In addition to the efficiency benefits groundwater pricing reform brings, the system also provides a mechanism for implementation of climate forecasts by water managers. It is proposed that the use of prices to communicate expectations of future monsoons may be an efficient and readily understandable mechanism for disseminating forecast information. With skilled forecasts, economic efficiency and environmental health should benefit in the long-term, as groundwater depletion is financially discouraged and water is allocated to its most productive uses. This pricing reform will have its greatest negative effects on farmers who currently rely on groundwater. The poorest farmers are usually not able to access groundwater and so their situation should not be adversely affected. However, revenue generated from groundwater charges must be returned to the community to compensate for lost income, especially in drought years.

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