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Effect of Forecast-Based Pricing on Irrigated Agriculture: A Simulation

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Abstract: Seasonal climate prediction offers potentially useful information for water managers. However, implementing forecast information is challenging due to the probabilistic nature of forecasts and limited demonstrations of usefulness. In this study, an adaptive groundwater pricing model utilizing operational seasonal climate forecasts was evaluated for groundwater management. The price for groundwater in the upcoming season was selected according to an algorithm that incorporates the current groundwater elevation and a prediction of seasonal rainfall. A simulation based on 37 years of rainfall data and operational monsoon forecasts for Tamil Nadu, India, was conducted to assess the effect of forecast-based pricing on societal benefits, groundwater elevation, and farmer income. Results indicate the adaptive pricing model is far more effective at maintaining groundwater elevations and maximizing societal benefits than a static groundwater price. Current groundwater elevation was a more effective input to the pricing algorithm than the forecast of seasonal rainfall when evaluated separately. A comparison of forecast use by water managers to select prices and use by farmers to choose crop patterns found similar societal benefits for each approach. Controlling demand for groundwater through pricing will cause hardship for current groundwater users who currently access groundwater without tariffs. Water managers should consider using tariff revenue to provide drought relief and transitional assistance.

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Introduction

Theorists and practitioners have long considered how best to manage groundwater. The common property nature of groundwater, where there is little restriction to those who would extract an ultimately finite resource, begs an analysis of shared management, and the results of many studies are well documented. Optimal control analyses of groundwater management have shown that in general the rate of groundwater withdrawal under a common property (unregulated) regime exceed optimal withdrawal rates (Burt 1964; Bredehoeft and Young 1970; Brown and Deacon 1972; Tsur 1990). The greater than optimal groundwater withdrawal rate is a result of individuals maximizing their private net benefits of groundwater without regard to the aggregate effect of lowered groundwater tables on their stream of future net benefits. Optimal in this sense refers to the withdrawal rate that maximizes benefits to the water users. In most of these cases, regulation provided only small increases in benefits that were probably not worth the economic and political expense of implementing a groundwater management system (Gisser and Sanchez 1980).

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However, there are some cases where the overdraft of groundwater has necessitated the involvement of water management authorities. Interestingly, in these cases where regional management has proved necessary, it appears common that managers employ command and control strategies to achieve water extraction objectives instead of optimal control (Reichard 1995; Ahn 2000). For example, in South Florida the regional groundwater management authority can enact reductions in groundwater extraction when the region experiences certain drought conditions. Under optimal control it is implicitly assumed that water is extracted up to the point that marginal benefits of water use equal the marginal costs, and this is the economically efficient quantity. By setting groundwater extraction objectives without regard to the marginal costs and benefits of extraction, water managers may be pursuing strategies that are no more efficient than the common property situation.

However, achieving optimal control may ultimately be thwarted by the stochastic nature of rainfall. The rainfall that occurs during the growing season determines, to a large extent, the optimal extraction rate. Accounting for stochastic rainfall introduces inefficiencies that reduce the returns to optimal control. Seasonal rainfall predictions have potential for reducing the uncertainty inherent in water management, which could yield increased efficiency. Several studies have investigated the value of seasonal precipitation forecasts for surface water management (Hamlet et al. 2002; Hamlet and Lettenmaier 1999; Pagano et al. 2001). Analyses of groundwater management often employ stochastic or deterministic values for precipitation and groundwater recharge (Knapp and Olson 1995; Tsur and Graham-Tomasi 1991; Provencher and Burt 1993). Forecasts of these variables are rarely, if ever, utilized in typical studies of groundwater management. Ahn (2000) provides a rare example of a forecast of groundwater levels used for the management of groundwater re-

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sources. In that study, a statistical time series model is used to forecast groundwater elevations one month ahead, allowing the regional water management authority to issue water use restrictions if the forecasted elevations are below objectives. This method is termed a "feedforward control" policy.

In this study, feedforward control will be utilized to achieve an operational optimal control strategy. The method differs from that of Ahn (2000) by recommending pricing methods to influence groundwater extraction in place of water use reduction directives. In this way, benefits are maximized by setting expected marginal costs equal to expected marginal benefits. As a result, reductions in groundwater use are achieved in the least costly manner.

This study differs from previous optimal groundwater control studies by accounting for the societal value of groundwater, enlarging the typical definition of social costs of groundwater use. The result is an operational strategy for adaptively managing groundwater through the setting of tariffs based on the expected demand as predicted with seasonal rainfall forecasts. In particular, we envision incorporating the tariffs as part of electricity charges that will be introduced for pump operation. The tariffs would not be applied to small-quantity water users, such as those using manually operated pumps and hand-dug wells. Setting prices to communicate forecast information has not been explored in the literature but may be an effective alternative to communicating probabilistic forecasts directly to water users. The simulation study evaluates the performance of the groundwater management model using observed rainfall and operational forecasts, as well as perfect forecasts. In addition, the effect of the farmers' expectation of seasonal rainfall on the efficiency of the management model is investigated.

Method

Groundwater management models use estimated benefit and cost curves as functions of extracted groundwater to identify the amount of groundwater extraction that maximizes net benefits (Provencher 1995). According to economic theory this occurs at the point where marginal benefits equal marginal costs, given first-order conditions. This study will also follow this approach for identifying the optimal quantity of groundwater extraction with an important extension. First, the groundwater control will be implemented through pricing, with the price corresponding to the optimal quantity, which could be determined in the usual way. Instead, here the marginal benefit curve (inverse demand curve) for the season ahead is estimated with a seasonal climate forecast of precipitation, representing an extension to the basic model. Previous studies have either assumed constant surface water flows and precipitation or generated them stochastically. In this study, a probabilistic forecast of precipitation based on sea surface temperatures and sea level pressure is used to generate an expected groundwater demand curve. The marginal cost curve of groundwater use is estimated based on the current storage level of the aquifer and the cost of replacing water use that exceeds recharge. A detailed explanation of this groundwater pricing model is presented in Brown and Rogers (2005).

Demand Curve

The demand function for groundwater use can be derived by estimating the benefit received for a quantity of groundwater. Given a farmer's production function, the quantity of groundwater that maximizes the net benefit at a specified groundwater price can be

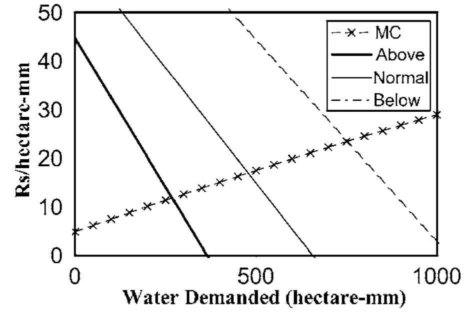

Fig. 1. Three demand curves calculated by maximizing farmer net benefit for a given seasonal rainfall outcome and parametrically varied water price. The marginal social cost of groundwater use is calculated with Eq. (2).

calculated. By parametrically varying the price, a series of extraction quantities and price pairs is generated, producing a curve. Assuming that farmers do indeed attempt to maximize their benefits, the curve represents an approximation of their demand function for groundwater. The area under the curve up to the amount of water used equals approximately the total benefit they receive for the water used.

For this study the farmer's net benefit derived from water use was represented as

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

The farmer faces the decisions of how much land area T_i to allocate to each crop i based on r_i, the marginal net revenue from crop i (revenue less the cost of inputs); Y_i, the yield for crop i as a function of rainfall, s; and applied water, q_i, which costs p. We assume fix costs are constant between crops. With this model the farmer can respond to changes in the price of groundwater with changes in crop selection, area planted, and the amount of groundwater to extract and apply to the crops. The demand curves were generated by parametrically varying the price and optimizing water use and crop area choice. The resulting curves (see for example, Fig. 1) were then approximated with linear fits (Brown and Rogers 2005). In this way the model represents farmer response to price changes in terms of crop choice and water application, though it does not include the effect of risk aversion on decision making (Ray 2002). Other studies have shown some benefit from including a risk term in such an objective function (Arriaza and Gomez-Limon 2003), though sensitivity analysis (not presented here) did not reveal a significant impact due to benefit curve shape.

Cost Curve

Estimating the social cost of groundwater extraction becomes a case of deciding what to include. In the simplest case, a rational farmer considers the cost he pays for extracting the groundwater. This might be considered the private cost function. A social cost function would include the costs that society incurs as a result of groundwater extraction. It remains a classical water resources example of common property to show that if farmers consider the additional cost of pumping they incur as a result of the overall lowering of the groundwater table, they would all extract less water and their benefits would be greater than when they disregard the effect on the groundwater table. Going further, the dis-

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counted value of returns from the use of the groundwater in the future can be included as an opportunity cost (Provencher 1995). While there is a clear theoretical case for considering the loss of future benefits from groundwater that is used in the present, a means for estimating this cost is less clear. Finally, as recommended by the Natural Resources Council (1997), the cost of groundwater use should include the loss of its "in situ use" values, such as prevention of groundwater intrusion or land subsidence, and reduced baseflow to surface waters. Quantifying these values remains problematic (NRC 1997).

In previous work, an approach to develop an operational method for estimating the social cost of groundwater by considering its replacement value was proposed (Brown and Rogers 2005). It is based on the premise that the value of groundwater use in the present should exceed the cost of replacing that water in the future. Otherwise the use of groundwater is not economically justified (Provencher 1995). Replacing water used in the present with future water requires more groundwater resources or an alternative source, such as desalinated ocean water. In regions with plentiful water resources, the cost of replacement would equal the cost of developing those supplies. However, in southern India, there are few undeveloped water resources and so desalination is a likely long-term alternative. For this reason, the unit cost of desalination will be used in the calculation of the cost of groundwater use.

In the determination of the replacement cost, we include only the extraction that exceeds recharge. This value was then scaled according to the distance of the groundwater elevation from a target elevation that is decided by water managers. As the water table falls farther from the target elevation, the cost of groundwater will increase providing negative feedback to further groundwater extraction. With these considerations, the equation for the marginal social cost of groundwater use consists of the cost of pumping the groundwater from its current level, the increased cost of pumping incurred by all in the future by the lowering of the groundwater table due to current extraction, and the cost of replacing the nonuse (or *in situ*) value of groundwater, yielding

$$MSC = C(x) + \frac{1}{\rho}k\frac{dC}{dx} + \left(\frac{\text{Replacement Cost}}{\rho}\right)\left(1 - \frac{x+s-q_t}{X}\right) \tag{2}$$

where $C(x)$, represents the cost of pumping a unit of water from a groundwater elevation of x. The second term represents the increase in pumping cost due to a decrease in groundwater elevation (dC/dx) multiplied by a scaling factor and discounted for a single year time step at discount rate ρ.

The third term in Eq. (2) may require further explanation. It is based on the concept of the value function that is used in many analyses to represent the opportunity cost of current groundwater consumption (Provencher 1995; Provencher and Burt 1993). The value function represents the return to groundwater use over an infinite planning horizon under an optimal policy of groundwater withdrawals from some initial state [Provencher and Burt 1993, Eq. (3)]. We propose the use of the third term in Eq. (2) to quantify the theoretical term for the value function used in the cited references. In doing so we argue that the value of water in the future is best represented by the future cost of supplying it. The *replacement cost* in this case will be represented by the unit cost of desalination, as described above. It is reduced by an appropriate discount rate and then multiplied by a scaling factor relating the current groundwater elevation $(x+s-q)$ to a target elevation (X), where s is recharged in the period of interest, and q_t is the total amount of groundwater extracted measured as a depth.

The net benefit to society is the sum of the farmers' profits from Eq. (1) less the social cost of groundwater use, calculated from Eq. (2). The net benefit is maximized when the marginal benefit of groundwater use is equal to the marginal cost. Fig. 1 depicts marginal benefit curves for three seasonal rainfall totals and the social cost curve based on the data used in this study. Solving for the intersection of the curves produces the socially optimal quantity of groundwater extraction for a given seasonal rainfall total. The value of the demand curve at the optimal quantity represents the price that farmers should be willing to pay. Water managers can engender optimal water use by charging this price for groundwater.

Seasonal Rainfall Forecasts

Farmers' demand for water is also dependent on their expectation of rainfall and the amount of rainfall they actually receive. Their expectation of rainfall affects their crop selection, which consequently affects the benefit gained from each unit of water applied. The amount of rain they receive replaces the need for groundwater, obviating demand. As a result, the farmers' demand curve for groundwater can be quite variable and the certainty with which the selection of the optimal price was described above is, in fact, only as certain as the rainfall.

Recent advances in short-term climate forecasting can reduce the uncertainty associated with certain climate events, such as seasonal rainfall (Goddard et al. 2001). A forecast of the total rainfall for the season ahead could provide a water manager a better estimate of what farmers' demand curves will be. This could improve the economic efficiency of attempts to optimally price groundwater. By establishing the price of groundwater prior to farmers planting, water managers will communicate the expected value of water with the economic signal of the price. Otherwise, once farmers' crop decisions are made they are likely to be inelastic to price (Gibbons 1986).

In general, water managers have not made use of seasonal climate forecasts despite the applicability of the predictions to their variables of interest. A series of interviews with water managers in the American Southwest found that uncertainty about forecast accuracy precluded forecast use (Hartman et al. 2002). A workshop covering water managers and forecast developers at the International Research Institute for Climate Prediction (IRI) revealed common obstacles to the use of forecasts by water managers. Water managers expressed a need for implementation tools and policies, and of demonstrated benefits, to encourage and facilitate the utilization of forecast information (Bates 2002).

These studies point to a gap between the probabilistic information provided by climate experts and the information needs of the water professionals. Water resource researchers can help bridge this gap by designing and evaluating tools that interpret forecast information and reduce the uncertainty distribution of the decisions facing water managers. One example is the adjustment of rule curve constraints on reservoir operation using streamflow forecasts based on El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) to increase revenue from hydroelectric generation on the Columbia River (Hamlet et al. 2002). The groundwater elevation forecast model described by Ahn (2000) is another example. In this paper we strive to further this effort by presenting a model incorporating forecasts and current groundwater elevation with which water managers may in-

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crease the economic and social efficiency of their water management decisions.

Adaptive Groundwater Management

This groundwater management model constitutes adaptive management in two ways. First, the forecast of seasonal rainfall is used to generate the demand curve that represents the farmers' benefit from groundwater use. This is termed "feedforward control" (Bennett 1979). With skillful forecasts this method provides better estimates of farmers' demand than would an estimate based on the climatological average. Second, the current and future elevation of the groundwater table is part of the calculation of the social cost of groundwater use (feedback). When the elevation of the groundwater table differs from the target elevation, the social cost changes accordingly, providing economic stimulus to either greater or reduced groundwater extraction. The sum result is an operational management model that fosters economically efficient use of groundwater resources, conditioned by the target elevation.

In the Ahn (2000) study, control of groundwater is practiced through the enforcement of pumping restrictions when forecasted groundwater elevations are below the water management authority's objectives. While this approach may maintain targeted groundwater elevations, it may also come at high economic cost. Consider the case of an orchard owner who requires a specific quantity of water to keep fruit trees alive. If groundwater extraction restrictions prevent the orchard owner from accessing the required amount of water, not only may this year's crop be lost but the entire orchard risks failure due to the death of the trees.

By advocating for price controls of groundwater, we are promoting the management of groundwater in the most economically efficient manner. Those with the greatest need for water will be willing to pay more and their consumption is averaged out by those who are not willing to pay as much, since the average demand curve reflects these individual demand curves. When groundwater levels are forecasted to fall below target levels, water managers would raise prices [this would occur automatically using Eqs. (1) and (2)], which would achieve the desired reduction in groundwater consumption from those who required the water the least (as determined by their willingness to pay). Thus the orchard owner could purchase the water needed to sustain the fruit trees while other farmers with more drought-tolerant crops would reduce groundwater consumption when prices exceed the economic benefit they would gain.

There is a fundamental question to be asked regarding the rationale of imposing a financial burden on poor farmers in order to slow groundwater depletion. There are many regions of the world where groundwater resources are underutilized. Use of these resources could provide farmers an improved livelihood that would justify any discrepancies between the value of the resource and the value of their output. Subsidized access to groundwater has significantly improved the lives of farmers throughout Asia (Shar et al. 2001).

At some point, however, there are likely to be negative financial consequences from providing subsidized access to groundwater. Parts of India have experienced declining water levels, reduced flows, saline water intrusion of coastal aquifers, and land subsidence (Singh and Singh 2002). Furthermore, when water tables decline below the level of hand-dug wells, groundwater access is limited to those with the capital required to deepen wells. Interviews conducted with farmers in the Coimbatore district of Tamil Nadu, where groundwater overuse is perhaps the most severe in India, found that they often sell land in order to finance well deepening. A longitudinal study of farmers conducted by Palanisami and Suresh Kumar (2002) conducted between 1990 and 2000 suggested a consolidation of land in the hands of large farmers (>10 ha), whose farms showed an increase in size, and a decrease in the size of small and marginal farms (<5 ha). During the same period, gross area cropped by small and marginal farmers had decreased while large farmers increased their gross area. Gross crop area is an indication of water access as well as land holdings.

Another question that arises is the appropriateness of charging farmers a tariff that is a function of a replacement value for water used. Why not allow or even encourage groundwater exploitation to encourage economic development? The argument made in this paper is based on the sustainability and distribution of that economic development. We do not argue that groundwater mining is never justified. On the contrary, the success of tube well irrigation throughout much of Asia demonstrates the benefit of groundwater exploitation (Shar et al. 2001). Rather, because groundwater reserves are finite, we argue it should be used in ways that are most likely to make sustainable agriculture possible—that is, endeavors that can cover the cost of supplying water when groundwater is fully depleted. Therefore, if groundwater withdrawal exceeds recharge, it is possible that the profits derived from groundwater use may finance technological improvements that effectively replace the mined water (e.g., by improving water use efficiency or creating a new water supply).

In some regions, subsidized groundwater has contributed to worsening the economic plight of the poorest farmers (Palanisami and Suresh Kumar 2002). In general, private well ownership in Asia reflects inequalities in land ownership and wealth (Shar et al. 2001). Implementing groundwater tariffs is, perhaps, counterintuitively, an approach to protect the access of poor farmers to groundwater. For this reason we argue that it is not only economically rational, because water price is a function of its value, but also fundamentally fair. In his seminal work, Rawls (1971) argues that in a fair society inequality in the distribution of resources are only justified if it improves the welfare of the worst off. Tisdell and Harrison (1992) used a Rawlsian approach to address equitable distribution of water entitlements. A policy of unregulated pumping of groundwater, often with subsidized electricity, fails this principle of justice, since the inequitable distribution of the resource is favoring relatively well-off farmers. We argue the pricing policy presented here is fair in the Rawlsian sense in that it may prevent groundwater tables from falling to levels that are beyond the reach of the poorest farmers, for example, below the level of hand-dug wells. Therefore, it may be used to benefit the worst off. It also reduces the market advantage of those with access to groundwater, who use a public resource at a subsidized rate, over those without access, whose profits are negatively impacted by competition from farmers using groundwater (Rogers et al. 2002).

Achieving balance between groundwater use in the present and preserving groundwater for the future depends on local conditions, both hydrogeological and socioeconomic. The pricing mechanism presented here is envisioned as a useful tool for striking that balance. In this vein, the target groundwater elevation is a parameter that is to be set by local planners in accordance with their assessment of the urgency of groundwater regulation. For example, planners might choose to target maintenance of current groundwater elevations, or to maintain groundwater levels above a minimum required to prevent salt water intrusion at the coastal interface. If groundwater is plentiful they may set a lower target

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elevation to encourage its use. This variable is purposefully left in the hands of local planners as a means of capitalizing on local participation and priority setting.

Application

The simulation study is set in the Palar River basin located in the state of Tamil Nadu in southern peninsular India. The Palar basin is located directly southwest of the city of Chennai and has a population of 5.2 million people. Agricultural land makes up 63% of the total land area of 18,300 km^2. Farming is mostly small scale, with 80% of farms holding less than 1 ha of land. The vast majority of water withdrawals, 88%, go to agriculture. There are about 250,000 wells and 50% of the administrative blocks are considered "overexploited," meaning extractions exceed annual recharge, with another 41% "critical/semicritical," where extractions reach 90–100% of annual recharge. The upper level aquifer is fairly shallow, with depth to bedrock ranging from 6 to 15 m (unpublished data, World Bank). The basin faces serious water resources challenges and this realization has led to the establishment of the Palar River Basin Management and Development Board with a goal of improving the management of water and land resources. In addition, the government of Tamil Nadu is convening a review of all water tariffs. These developments present an opportune time to establish efficient, equitable, and sustainable water management practices.

The area considered for this study was the Kancheepuram district of the Palar River basin. Crop production data, crop prices, crop water requirements, and land use data were provided by the World Bank. The simulation model was developed for the 43,940 ha of farmland not served by surface water irrigation systems. The demand curve for groundwater was generated as described above. A wide variety of crops are grown in the area but for the purposes of the model farmers' crop choices were restricted to cotton, ragi, pulses, and groundnut. Farmers' crop choices were modeled by optimizing the selection of decision variables (area and water allocation to each crop) to maximize the farmers' net benefit function [Eq. (1)].

Crop planning and production were modeled for the rafi season (October to December). This is the season of the winter monsoon in Tamil Nadu, which produces almost half of the annual rainfall total in most areas. The average rainfall during this three-month period is 45.4 cm. The influence of ENSO on the seasonal rainfall totals implies an atmospheric signal that may be predicted. A statistical model was developed relying on Pacific Ocean sea surface temperatures (SSTs) and Indian Ocean sea level pressure (SLP) that assigns probabilities to three categories of rainfall up to three months prior to the onset of the monsoon (Brown 2004). The model was used to produce categorical probabilistic forecasts for Tamil Nadu rainfall from 1963 to 1999. These forecasts were used in the water pricing model presented here.

A schematic of the simulation model is shown in Fig. 2. Groundwater demand curves were generated in the manner described above with rainfall equal to the median of three categories, each representing one-third of the historical record: above normal, normal, and below normal. This creates a demand curve that corresponds to each category used in the rainfall forecast. An initial cost curve was created using a groundwater elevation equal to the target elevation, chosen as 9.7 m above bedrock, reflecting the average in the area. The water manager decision problem then consisted of choosing between the three candidate prices for

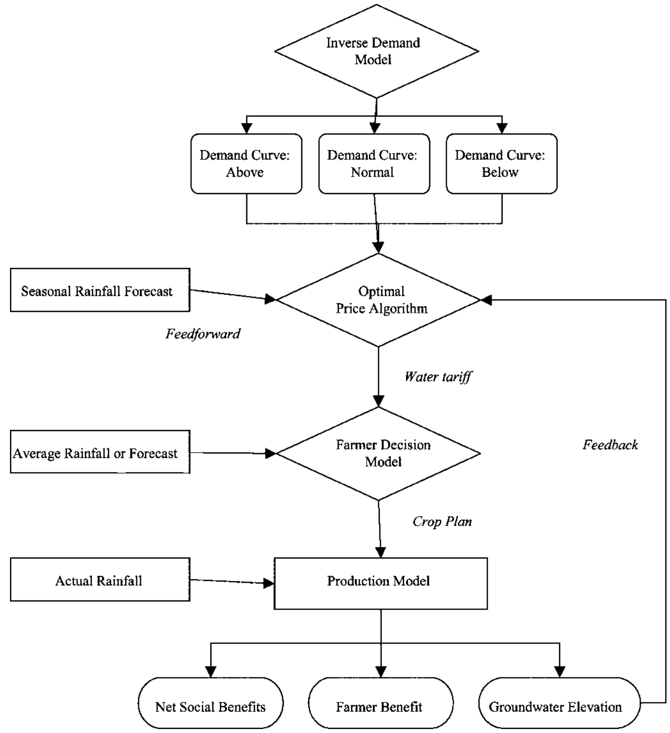

Fig. 2. Schematic of simulation model

groundwater, each representing the point where the marginal cost curve intersects the three marginal benefit (demand) curves. The decision model chooses the price that maximizes the expected net social benefit given the probability of each rainfall category. The expected net social benefit for each price is the sum of the net social benefit for each rainfall category multiplied by the probability of that category. The forecast of the upcoming seasonal rainfall assigns the probability to each category of rainfall used in the calculation of the expected net social benefit.

This optimal price for groundwater is then used in the farmers' decision model. Farmers' crop choices were modeled by optimizing the selection of decision variables (area and water allocation to each crop) to maximize the farmers' net benefit [Eq. (1)]. The farmers' expectation of rainfall can be varied to ascertain the effect of the farmers' knowledge of forecast information. In the cases presented here, the farmers' rainfall expectation was either set to equal the historical mean or the forecast. This decision model produces a cropping pattern for the upcoming season.

The cropping pattern and observed rainfall for the season are input to the production model, which calculates the crop production, groundwater usage, net income, net social benefit, and the resultant groundwater elevation. In the single-cell aquifer model, the state equation for groundwater elevation is $x_{t+1}=x_t+s_t-\Delta V/S\cdot A$, where ΔV=volume of groundwater extracted through pumping; S=storativity; and A=horizontal area of the aquifer. The groundwater elevation is used to calculate the new marginal social cost curve and the process is repeated for the 37 years of the simulation.

The values of the parameters used for Eqs. (1) and (2) in the simulation model were based on locally collected data and best estimates. The social cost of pump operation, $C(x)$, is based on electricity rates of \$0.71/kW·h, although currently farmers are not charged for electricity in Tamil Nadu, and the rate of increased cost with depth is \$0.008/ha·mm·m (unpublished data, Water Technology Centre, Tamil Nadu Agricultural University).

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Table 1. Average Values Based on a 37-Year Simulation for Each of the Groundwater Pricing Models

Model	Price ($/ha·mm)	NSB ($/ha)	NSB increase (%)	Farmers' NB ($/ha)	Water use (mm/ha)	GW change (m)
Fully adaptive w/perfect forecasts	0.58	177	113.3	163	204	−0.59
Fully adaptive	0.62	171	112.9	158	207	−0.73
Feedback (no forecast)	0.62	169	112.7	158	208	−0.72
Feedforward (no groundwater)	0.30	−1,217	8.40	206	506	−11.41
Static	0.28	−1,329	—	212	518	−11.80

Note: The percent increase is the increase in net social benefits of each model in comparison to the static pricing model. Groundwater (GW) change is the final level of groundwater elevation relative to zero.

The replacement cost of water was estimated as $5/ha·mm, based on a target for economical desalinated water of $0.5/m^3. The objective groundwater elevation was assumed to equal the initial groundwater elevation of 9.7 m measured relative to the bedrock layer. Recharge to the aquifer was assumed to equal the portion of rainfall not consumed by crops as evapotranspiration and therefore represents a conservative estimate of potential groundwater depletion. A sensitivity analysis was then conducted on the percentage of rainfall contributing to recharge. The discount factor, ρ, was set equal to 1, justified by the use of a single-year model (considering only next year's use of groundwater) and the premise that as water might become more valuable in the future, a negative discount rate might be as defensible as a positive one.

There are several simplifying assumptions employed that limit the usefulness of the specific values generated by the model; however, general results are still informative. Groundwater movement is not modeled in a physical way. This might exaggerate the benefits achieved by the optimal pricing scheme. Wells are assumed to be placed optimally so drawdown is uniformly distributed; as such the aquifer is modeled as a single cell (Brown and Deacon 1972; Gisser and Sanchez 1980; Provencher and Burt 1993). Effective rainfall, the amount of rainfall assumed to be available to crops, was calculated according to the following relation (Brouwer and Heibloem 1986)

$$P_e = 0.8P - 25 \quad P > 75 \text{ cm/month} \tag{3a}$$

$$P_e = 0.6P - 10 \quad P < 75 \text{ cm/month} \tag{3b}$$

Runoff is not calculated; rainfall or irrigation water that does not contribute to plant growth is assumed to contribute to groundwater recharge. In Tamil Nadu, rivers typically flow for only 15 days per year. The portion of applied water that recharges groundwater is a parameter that was varied as part of a sensitivity analysis, revealing, as expected, that the difference between pricing schemes decreases as recharge increases. Finally, the crop production model neglects the effects of fertilizer and the temporal distribution of rainfall on crop growth.

The simulation model was used in multiple runs to analyze different aspects of the groundwater management model. The topics of interest were the effect of the complete model, which we call fully adaptive, versus a management model that only considered the rainfall forecast (feedforward), a model that only considered groundwater elevation (feedback), and a model that based prices on historical averages (static). In addition, the farmers' crop planning was varied between the case of expecting the historical mean rainfall (climatology), and expecting the weighted average of the probabilistic categorical forecast (forecast follow). For all cases, operational and "perfect" forecasts were used, where perfect forecasts assign a probability of 1 to the observed category and 0 to each of the other categories.

Results

In order to evaluate the various groundwater management models described above, a performance measure is needed. Tsur (2000) proposes efficiency and income distribution as two potential yardsticks. Limited by the scope of the simulation model, we will evaluate performance primarily in terms of efficiency (i.e., the net social benefit), while keeping an eye on farmer income and groundwater elevation. While the simulation model does not attempt to capture the full spectrum of income generating activity a farmer might employ, nor the dynamics of groundwater flow, a large drop in either is a warning sign for the management model.

Net Social Benefits

Average net societal benefits (NSBs) for the 37-year simulation period are listed in Table 1. The results show that adaptive groundwater pricing produces greater societal benefits as measured in this study. Greater than 100% increases were calculated for each adaptive management model in comparison to the static price. Only the model that did not include groundwater feedback had a small increase (8%). Similar trends are reflected in the graph of NSB (Fig. 3). The adaptive pricing model produces relatively stable values that center on the average value of $170/ha. The static price causes steadily decreasing net social benefits over the 37 year simulation, with an average of $−1,329/ha. The NSBs are negative because the returns from groundwater use are less than the social cost, as calculated by this model. Society is worse off in the long run because they have exchanged the value of the groundwater for agricultural returns that are worth less.

The models produce trends in groundwater trajectory that reflect the NSB results (Fig. 4). In general, each of the models that include a "feedback" component based on the current groundwater elevation produce a stable groundwater trajectory with a drawdown of approximately 1 m throughout the 37-year period. In contrast, the pricing models that do not include groundwater elevation trace a steadily decreasing groundwater trajectory with a drawdown of almost 15 m after 37 years. This could readily create conditions of dry wells and aquifer consolidation in this area where aquifer thickness is on the order of 10–20 m. These are symptoms that in fact do occur in the Palar River basin.

We do not attempt to define sustainable groundwater use nor evaluate groundwater use in terms of a "safe yield." As Dingman (1994) notes, safe yield is affected by more factors than simply the rate of recharge. Further, there may be cases where groundwater should be extracted when recharge is negligible, perhaps in a desert where no alternative sources of water exist. Extraction decisions should include social and economic consequences (NRC 1997). We attempt to do so by pricing groundwater in a way that ensures the social gain from its use outweighs the cost of replacing the water that is used.

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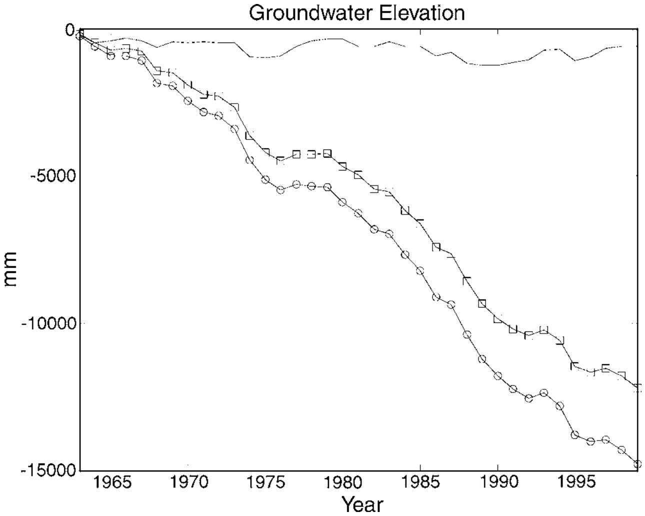

Fig. 3. Groundwater elevation (in mm) of three pricing models relative to 0 over the 37-year simulation. The trajectories shown are for the fully adaptive model (solid line), the feedforward model (line with squares), and the static model (line with circles). The fully adaptive groundwater pricing model maintains a groundwater elevation just below the initial (and target) elevation while the static model produces a steadily decreasing groundwater elevation. The feedforward model yields a groundwater elevation slightly above the static model.

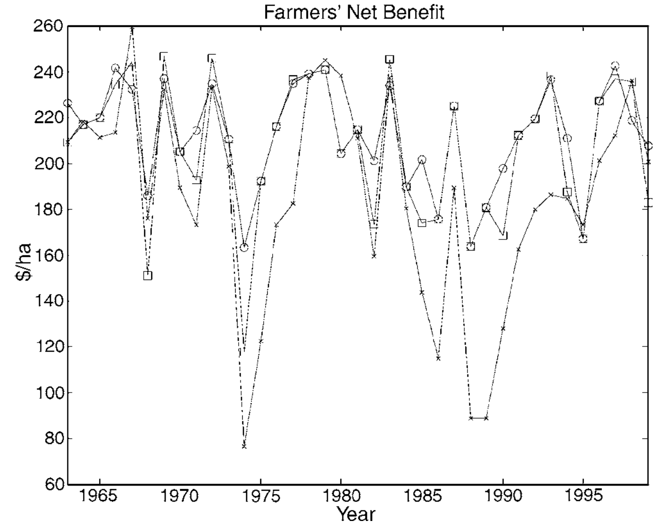

Fig. 5. Farmers' net benefit measured in $/ha for three pricing models for the 37-year simulation period. The trajectories shown are for the fully adaptive model (solid line), the feedforward model (line with squares), and the static model (line with circles). The fully adaptive pricing model yields slightly decreased farmer benefits.

Farmers' Income

The average values of farmers' net benefits in Table 1 reveal the higher income returns that make groundwater depletion financially attractive, at least in the short term. The adaptive management models decrease farmer income on average by about $50/ha. The models that price groundwater in response to the social cost of water use create a negative effect on farmer agricultural income. Fig. 5 demonstrates that the fully adaptive model also magnifies the variability of their agricultural income. This model does not reflect any nonfarm income and wage earning that farmers may engage in. Nor does it reflect the hardship and agricultural consequences that might occur if groundwater elevations were drawn down to the low levels that would likely be required to achieve the income this figure shows. In the Coimbatore district of Tamil Nadu, where groundwater depletion is advanced, nonfarm income represents a large portion of farmers' total income as irrigated area decreases as a result of depleted groundwater (Palanisami and Suresh Kumar 2002). Nonetheless, pricing groundwater at the social cost will cause hardship to farmers in drought years especially (as Fig. 5 shows) and could only be enacted if alternative employment was available and the revenue generated from water tariffs was committed to relief services.

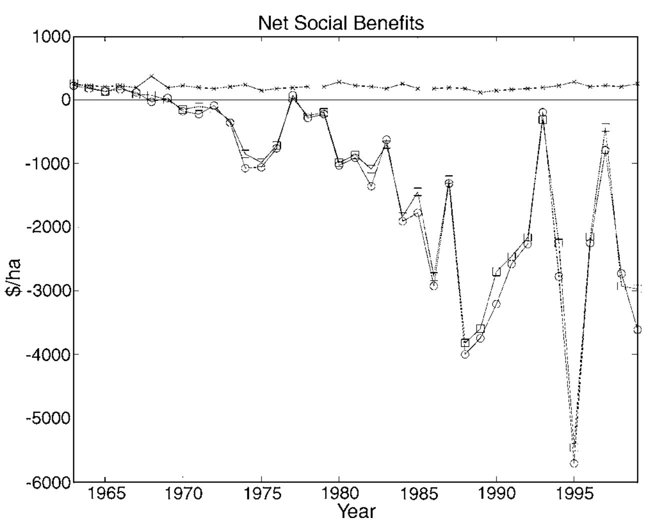

Fig. 4. NSB in $/ha of three pricing models for the 37-year simulation. The trajectories shown are for the fully adaptive model (solid line with x's), the feedforward model (line with squares), and the static model (line with circles). The fully adaptive pricing model results in continuously positive NSB averaging about $170/ha, while the feedforward and static models yield steadily decreasing NSB.

Previous studies of the optimal management of groundwater have typically found small societal returns in comparison to common property management (Knapp and Olson 1995; Kim et al. 1989) or no societal advantage to optimal management (Gisser and Sanchez 1980; Gisser 1983). However, few studies have attempted to include any value of groundwater beyond the volumetric addition to surface water supplies. Notable exceptions are the assignment of a buffer value by Tsur (1990) and Tsur and Graham-Tomasi (1991) and the assignment of a "reward value" for groundwater left in the aquifer by Azaiez (2002). The assessments of buffer value found that the buffer value of groundwater (the value of groundwater in a context of uncertain surface water supplies minus the value with certain surface water) could exceed the value of the volumetric increase in water supply provided by the groundwater. This is due to the ability of groundwater to smooth the variability in surface water supplies. By considering external costs of groundwater extraction in addition to the increased cost of pumping due to lower groundwater elevations, our results imply greater return to operational, optimal groundwater management than is typically revealed.

Adaptive Model versus Static Model

Several comparisons between the simulation results of the different pricing models were made to analyze different aspects of the

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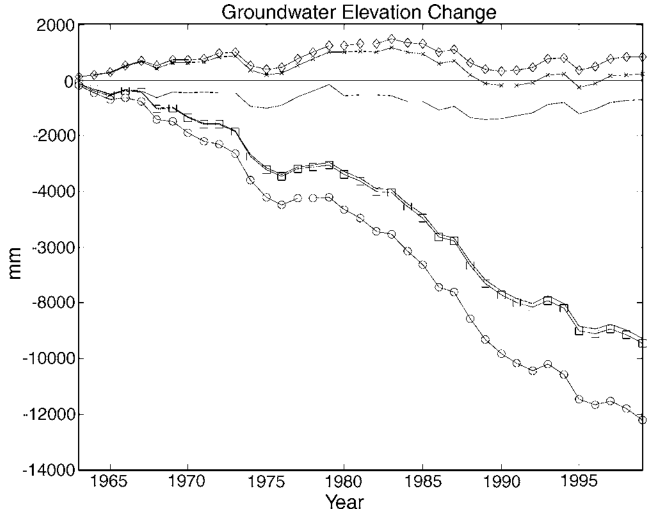

Fig. 6. Comparison of selected static prices with the fully adaptive pricing model. The trajectories are groundwater elevation (in mm) over the 37-year simulation for the optimal price based on climatology (static model price of \$0.28/ha; line with circles), \$0.44/ha (line with squares), \$0.46/ha (solid line just above line with squares), \$0.56/ha (line with x's), \$0.62/ha (average price of fully adaptive model; line with diamonds), and the fully adaptive pricing model (solid line). Static groundwater prices below 21 produce rapidly declining groundwater elevation while prices greater than 21 produce an apparent underutilization of groundwater.

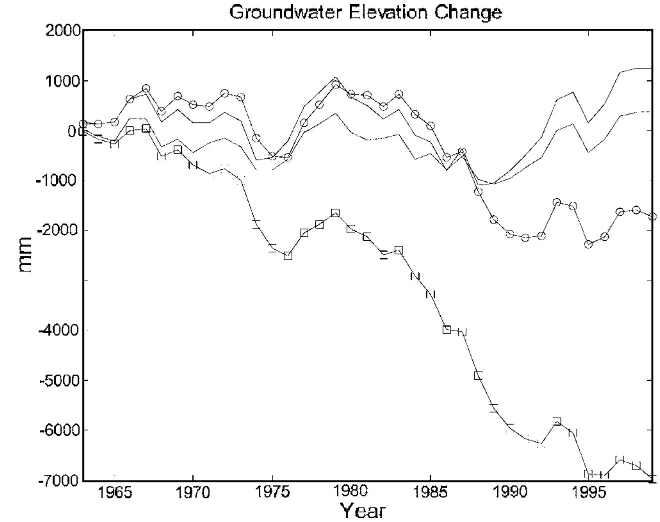

Fig. 7. Effect of recharge on groundwater elevation. Groundwater elevation over the 37-year simulation for a recharge rate of 100% of rainfall (black line=fully adaptive model; line with circles=static model) and a recharge rate of 70% of rainfall (blue line=fully adaptive model; line with squares=static model). Higher recharge rates decrease the gap between groundwater elevations produced by the adaptive pricing and static pricing models to some extent.

fully adaptive model. The first comparison of results attempts to answer the question as to whether an adaptive management model outperforms a static model that prices groundwater using historical averages. Based on the average net social benefit of each, the fully adaptive model clearly performs better, with a 112% increase over the static model (Table 1). When perfect forecasts were employed, the return was improved by 113% over the static case, a surprisingly low return for forecast improvement. The impact of the fully adaptive model on farmer income, however, is large and negative, as farmers are required to pay more for irrigation water. The decrease in farmer income may be overstated, as noted above, since the amount of groundwater extraction required to achieve that income might very well reduce groundwater table elevation to the point of drying wells, as the groundwater trajectories shown in Fig. 4 depict. These results bolster the need for adaptive pricing of groundwater if management is to be achieved through pricing. As shown here, a single price, even if calculated to maximize efficiency, will not achieve it over the long term.

A range of prices were evaluated in the static model. The results, as Fig. 6 shows, lend further credence to the need for an adaptive pricing model. Static prices of less than \$0.46/ha·mm result in downward trajectories not much different than the trajectory for a price of \$0.28/ha·mm (the optimal charge based on the historical rainfall average). More interestingly, prices of \$0.47/ha·mm and above lead to underutilization of groundwater, which is indicated by groundwater levels that exceed the target groundwater elevation (0.00 meters in Fig. 6). Without adaptive pricing, a static price would likely lead either to groundwater depletion in the long term or underuse that could potentially cause waterlogging.

The role of groundwater recharge from rainfall was assessed by varying the percentage of rainfall that contributes to recharge from 20 to 100%. Fig. 7 shows the results on NSB. In the fully adaptive pricing model the recharge parameter caused little change in NSB. Resource use is efficient regardless of the recharge rate, and that is reflected in NSB. However, for the static model increasing recharge rates cause increased NSB. At the highest percentages of recharge, the NSB of the static model approaches the NSB of adaptive pricing. Greater recharge offsets agricultural extractions and there is less need for optimal management. However, it is unlikely that recharge will approach 80–100% of rainfall.

Forecast Effects

The next comparison of results seeks to identify the comparative gains of the components of the adaptive management model. In the case of the feedforward model, which chooses the best price based on forecast but does not adjust the cost curve for the groundwater elevation, the results are 8% better than the static case, 16% better with perfect forecasts (Table 1). With the feedback model, which selects the groundwater price using demand curve derived for average rainfall (no forecast used) and a cost curve adjusted for the groundwater elevation, the results are much higher and comparable to the fully adaptive model. NSB was improved by 113% above the static price case. It appears that the adjustment of the cost curve in accordance with the groundwater elevation is responsible for most of the gains in NSB achieved by the fully adaptive model.

Forecast User Effects

The final comparison addresses the benefits of forecast use with respect to the user group. Much of the current emphasis in improving the utility of seasonal climate forecasts has focused on farmers' decision making and their understanding of probabilistic forecasts (Hammer et al. 2001; Hammer et al. 2000; Katz and Murphy 1997; Roncoli et al. 2002). This is a useful endeavor,

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Table 2. Average Values Based on 37-Year Simulation for Each of the Forecast Use Scenarios

Forecast use	NSB ($/ha)	Increase (%)	Farmers' NB ($/ha)
Farmers only	171	112.9	162
Farmers only-perfect forecasts	174	113.1	167
Farmers and water managers	155	111.7	142
Farmers and water managers-perfect	166	112.5	154
Static	−1,329	—	212

Note: The percent increase is the increase in net social benefit (NSB) of each model in comparison to the static pricing model. Results indicate that farmers' use of forecast yield benefits that are comparable to water managers' use (fully adaptive models).

especially for the benefit of the forecasters who strive to improve the utility of their products. There are fewer reports of cases where tools have been devised to help water managers make use of probabilistic forecasts, as is attempted here. There may be benefit to focusing on this effort, since it may be less difficult to train a smaller number of water managers to use forecasts than a much larger number of (often less-educated) farmers (Arndt and Bacou 2000). Here we attempted to model the effects of only water managers using forecasts, only farmers using them and both.

For the fully adaptive model, the farmers' expectation of rainfall used to generate cropping plans was set equal to the historical average for the three-month winter monsoon. This represented only water managers having forecasts. To simulate farmers using forecasts, their rainfall expectation was set equal to the weighted average of the probabilistic categorical forecast. For perfect forecasts this results in an expectation equal to the median of the correct forecast category. In general the results show that there is not much difference in whether water managers use the forecast or farmers do, as NSB, farmers' benefit, and groundwater elevation are very simlar (Table 2). The best results in terms of net social benefits, as well as income and final groundwater level, are achieved with perfect forecasts used solely by water managers or farmers. Interestingly, these results are slightly better than when both farmers and water managers use the forecasts, both for perfect and operational forecasts. This might be caused by a decrease in diversification that results from the alignment of planning expectations of the farmers and water managers. For example, the reaction to low prices and expectation of high rainfall could produce an extremely optimistic crop plan that is less than optimal in all but the exact expected outcome. Even in the case of perfect forecasts, an outcome that is in the correct category can be distant from the median category value, which was used for planning purposes.

While these results indicate little difference between the use of forecasts by water managers or farmers, one must also consider the likelihood of perfect communication of forecast information that was applied here. There are many examples of miscommunication and misinterpretation of forecasts, especially in the case of poor rural farmers (Hammer et al. 2001). However, the adaptive management model presented here does not require any interpretation of probabilistic forecasts. Instead the forecast is simply an input to the decision model, as are other factors such as groundwater elevation. While water managers may not implement prices generated by this model, it could be a useful input to the decision process that is executed for the purpose of pricing groundwater. The further development of such implementation tools may be very useful in water resources management and in agriculture.

Conclusion

An adaptive management model for groundwater resources has been presented. The model utilizes seasonal forecasts of precipitation and the current elevation of the groundwater table and its distance from the target groundwater elevation in order to select the groundwater price that maximizes the expected net social benefit. A simulation was conducted to assess the performance of the adaptive model in comparison to a price based on historical averages using 37 years of rainfall data and forecasts. The results indicate that the adaptive management model provides substantial value in terms of social benefit.

These results are contrary to many of the original studies of optimal control of groundwater management, which in general did not find that it yielded great benefit. These studies do not attempt to estimate a social value of water to include its nonuse and replacement value. That groundwater does have value in excess of its simple addition to surface water volume was demonstrated in Tsur (1990) and Tsur and Graham-Tomasi (1991) in the form of "buffer value," and in Provencher and Burt (1993) as a "risk externality." That the nonuse value of groundwater should be considered in economic analyses was asserted by the NRC (1997). Here we attempted to include the nonuse value in pricing decisions, which was mostly responsible for the large returns to optimal control.

Further benefit can be assigned to the use of seasonal climate forecasts in adaptive pricing. The simulation revealed an improvement of 8–16% in NSBs, depending on forecast skill, over the static price. While the benefits were modest in this scenario, adaptive pricing based on forecasts demonstrates a method for water managers to tune demand management in response to expected future climate conditions.

The benefit of the management model on farmer income is less clear. The results show a decrease in average farm income in comparison to the static model value. However, the model does not account for off-farm income that farmers might undertake in years of expensive water, nor the costs of well deepening or the drying of wells that might occur with static pricing of groundwater. This presents two useful extensions of the model evaluation. First, a physically based groundwater model that would allow a realistic representation of groundwater elevation changes could constrain the income of farmers in the static pricing simulation. Second, a socioeconomic model would be useful to assess the income distributive effects and off-farm income generation. Studies in other regions of Tamil Nadu indicate that falling groundwater tables consolidate the access to groundwater into the hands of the few with the resources to invest in greater well depth and pump capacity (Palanisami and Suresh Kumar 2002). The effect of this groundwater management model on the distribution of income and access to resources should be investigated prior to any consideration of implementation. Since the costs to farmers of implementing the social price of groundwater might be prohibitive, a possible alternative use of the pricing model is to estimate the economic impact of continued groundwater exploitation. This figure could then be used in cost-benefit analysis of alternative groundwater recovery activities.

The balance between the competing objectives of fostering sustainability for the future and encouraging immediate economic development is dependent on local conditions, such as the state of groundwater resources and the plight of local agriculturalists. For this reason we propose that local planners set the target groundwater elevation used in the tariff calculation. Setting the target level below the current groundwater level subsidizes groundwater

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use, favoring economic output in the present. This is appropriate, for example, in least-developed areas where groundwater potential has not been tapped. Elsewhere, falling groundwater tables require a choice of target elevation that mitigates the accompanying socioeconomic and environmental impacts. Otherwise, choosing a target elevation that is below the level of the hand-dug wells of the poorest farmers (or choosing not to regulate groundwater at all) will have serious economic consequences for those worst off.

In fact, an ancillary benefit of the pricing scheme is that it makes explicit the target elevation of groundwater pricing. It might be argued that a lack of groundwater tariffs and subsidization of energy costs is an implicit choice of target elevation far below the current depth, wherever it may be, as evidenced by rapidly falling groundwater tables. That is, the target elevation of current policy in overexploited areas is far below the reach of the poor. We argue that pricing groundwater in a fashion that is economically efficient and appropriate to local conditions is fair in that it will benefit the worst off—those who are denied groundwater use due to the overuse by others.

Finally, this paper presents a tool for water managers that incorporates the growing ability of climate scientists to predict seasonal climate variables. A review of the literature reveals that more effort has focused on the ability of farmers to interpret and use forecasts than on water managers. While the results here do not indicate great gains from forecast use by water managers, it does provide an example of designing management schemes with the objectives of water managers in mind. The International Research Institute for Climate and Society produced a report that summarizes the concerns and needs that many water managers have with regard to seasonal climate forecasting (Bates 2002). It provides excellent guidance for those who might undertake this task.

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