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Feasibility of adopting smart water meters in aquifer management: An integrated hydro-economic analysis

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ABSTRACT

The feasibility of groundwater monitoring was investigated by a case study on adopting smart water meters to measure groundwater extraction at individual farms and a centralized online information management system to measure collective aquifer water extraction. Benefits of optimal groundwater management was estimated using hydro-economic models that simulate, for a 70-year period, private and social optimality, taking into account the effects of seawater intrusion on groundwater salinity. A Bayesian inference system was used as an interface between a dynamic programming model and MODFLOW groundwater simulation model. The case study's cost data were scaled-up to the aquifer level and compared to the incremental benefits between private and socially optimal water extraction. The results showed that the Net Present Value of measuring and monitoring groundwater extraction using smart water meters as $790 million ($1332/ha/year) with an Internal Rate of Return of 93%. The sustainable use of the aquifer results to a reduction of the cropped area by 10%, a reduction of the groundwater extraction by 20%, a change in the crop mix, and 42% of the least-efficient farms exiting farming. The exiting farmers could convert farm lands to other land uses such as residential, urban, industrial land use, with adequate facilitation provided by the government. The impact of change of groundwater management strategy on the arid ecology with reduction in tree cover is noted.

1. Introduction

Globally, 43% of groundwater is used by agriculture, accounting for 38% of irrigated land (Siebert et al., 2010). Farmers' over-extraction of groundwater has caused a drop in the water table, land subsidence, and extended salinization in coastal aquifers, which has resulted in irreversible economic losses among farming communities and a threat to food security (Foster, 2012). Theoretically, open access to the groundwater resource is considered to be a cause of over-extraction due to the divergence between private and social optimum groundwater extraction related to spatial and temporal externalities (Strand, 2010). In contrast, empirical research has shown that the benefit of groundwater management as the difference between the outcomes of private and socially optimal groundwater extraction is insignificant (Bredehoeft and Young, 1970; Gisser and Sanchez, 1980), discouraging policy and strategy efforts from managing groundwater. Subsequently many empirical studies have been conducted that represent different hydro-economic-social conditions and analytical approaches, which were overlooked by Gisser and Sanchez (1980). Through a comprehensive review of the above-mentioned research, Koundhouri (2004) found that most of these studies also confirm that the benefits from groundwater management are low, ranging from 0.01% (Gisser and Sanchez, 1980) to 28.98% (Worthington et al., 1985). When the impact of the aquifer's near depletion is considered, an exceptional estimate of a 409% benefit results (Koundhouri, 2000, quoted in Koundhouri, 2004). Koundhouri (2004) noted that most studies have addressed the quantitative aspect of groundwater extraction, and very few studies (Zeitouni and Dinar, 1997; Dinar and Xepapadeas, 1998) have addressed the groundwater quality component. Some studies (Larson et al., 1996; Vickner et al., 1998) have considered groundwater's pollution by exogenous agents such as fertilizer and other agrochemicals. Very few studies (Zeitouni and

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Dinar, 1997; Dinar and Xepapadeas, 1998) have examined the impact of salinity, which is an endogenous aspect of groundwater pollution, and its implications for groundwater management. By considering the externalities that arise from both quantitative and qualitative aspects of groundwater extraction, the benefits from groundwater management strategies could be expected to increase (Roseta-Palma, 2002). Koundhouri (2004) noted “the absence of economic instruments designed for quality quantity management,” particularly in arid and semi-arid regions where quality quantity management problems are dominantly prevalent. The recent debate has focused on the institutional aspects of groundwater management and the state’s role in its regulations, coordination and monitoring (Madani, 2010; Madani and Dinar, 2012; Madani and Dinar, 2013).

Ninety-four percent of Oman’s groundwater is used in the agricultural sector. The total demand for agricultural water has increased by 3.3% per year during the 2000–2011 period. The over-extraction of groundwater has increased from 285 Million Cubic Meters (MCM) in 1990 to 316 MCM in 2011, with alarming levels of seawater intrusion in the coastal areas (MRMWR, 2013). Since 2000 (MRMWR, 2000), water regulations in Oman, require government institutions to regulate optimum exploitation of groundwater by determining the quantity of water to be extracted by each permitted well and by compelling well owners to install water meters. So far, this law has not been enforced because water meters have not been installed on the wells. The failure to implement the regulations is fundamentally caused by the high cost of conventional mechanical water meters (Zekri, 2009), as well as the absence of studies related to the optimal allocation of groundwater rights and quotas. Regardless of the strategy that is used, it must be possible to measure the groundwater extraction of individual farmers in order to manage groundwater.

For many years, researchers have proposed monitoring groundwater pumping by using electricity pricing or electricity quota (Chandrakanth and Romm, 1990; Turral, 1994, Mohanty and Ebrahim, 1995; Kemper et al., 2004; Kumar, 2005; Strand, 2010; Scott, 2011; Kumar, 2013; Scott, 2013). This is because once a well is installed, the major cost in groundwater extraction is the energy required to lift water, and because energy is metered, it can be monitored easily. However, the relationship between water pumping and electricity consumption is not linear. Furthermore, the efficiency of electricity that is used for pumping varies drastically from one pump to another, making the measurement of electricity use an imprecise way to monitor groundwater. Thus far, no successful cases have been reported to indicate that electricity has been used properly for groundwater monitoring. Because electricity for groundwater pumping is plagued by problems, we propose the use of smart water meters to measure the individual farmers’ groundwater extraction directly.

This study quantifies with the use of hydro-economic models and a case study, the benefits and costs of managing groundwater of an aquifer that is vulnerable to salinization, where smart groundwater meters have been installed at farms on a pilot scale, with information on the farms’ groundwater extraction monitored centrally online. This paper is organized as follows. Section 2 provides a brief description of the study area. Section 3 describes the analytical methodology. Sections 4 and 5 present the results and conclusions, respectively.

2. Study area

The study area covers 7281 farms overlying an aquifer located in Al-suwayq, which is in the Batinah region of Oman. The total agricultural area covers 14,198 ha, while the cropped area covers only 8,476 ha. The farm sizes range from 0.13 to 37.25 ha, with an average of 1.95 ha. The most common crops are date palm, mango, lime, banana, maize, barley, sorghum, Alfalfa, Rhodes Grass, onion, tomato, pepper, potato, watermelon, melon, cabbage and lettuce. The agricultural profit is closely dependent on farming methods, crop types, and soil and water salinity. Farms are generally operated by expatriate labor, and most farm owners do not depend on farm income alone. In the Batinah area, water quality is deteriorating due to excessive extraction of groundwater and seawater intrusion (MRMWR, 2013). Consequently, a large number of farms have been abandoned, and many other farms have also been affected negatively by water salinity (Zekri, 2008, 2009). Kalbus et al. (2014) reported that the land area in Al-Suwayq which is affected by high to very high salinity levels, increased from 15.8% in 1974 to 25.1% in 2014.

3. Materials and methods

This study formulated and used an integrated hydro-economic dynamic optimization model to generate scenarios of groundwater extraction and seawater intrusion under the circumstances of private and social optimal groundwater extraction. The difference between private and social optimal groundwater extraction is the benefit of optimal groundwater management. The study also simulated the continuation of current agriculture and water extraction practices of Business As Usual (BAU). Based on the private optimal, extraction of groundwater is formulated as an Agent Based Model (ABM), where profit is maximized by individual farmers at the farm level by reallocating existing farm resources and given technology, and decision making related to water extraction is based on individual farm efficiency, without considering the intertemporal and spatial (other farms) negative externalities of groundwater extraction. Extraction of groundwater on the social optimal is formulated as a Central Planner Model (CPM), which represents an ideal scenario where the total profit of all farms is maximized by a single agent who takes into consideration the intertemporal and spatial (other farms) negative externalities of groundwater extraction. The ABM and CPM models were developed using a simulation-optimization approach, where a hydrogeological simulation model is coupled with an economic dynamic optimization model. In the optimization models, the main decision variables are the groundwater extraction rates and location, seawater intrusion, and spatial distribution of salinity, crop yields, crop profitability and crop mix during the planning horizon. Salinity is the interaction variable, which couples the economic optimization model with the hydrogeological simulation model. By comparing the results of the ABM with the results of CPM, the incremental benefits between private and socially optimal extraction of groundwater can be determined over a long period of time as the benefit of optimal management of groundwater. The socially optimal water extraction is achieved by establishing smart water meters in farms and the central monitoring of the farms’ water use. Costs of establishing smart water meters in farms and central monitoring of farms’ water use are estimated based on a pilot study. The BAU scenario simulates groundwater extraction and changes in the salinity levels of groundwater, considering the present farming practices and the crop mix adopted by farmers (described in Section 2), while over time, the crop yields and profits change according to changes in the salinity of groundwater. The comparison of the results of the BAU with ABM, gives an estimate of the incremental benefits that could be derived by reallocating all resources that are used in farming to achieve private optimality of profit maximization, under ideal conditions.

3.1. Hydrogeological model

MODFLOW, the hydrogeological simulation model that was used in this study, is a finite-difference based model for solving the