Agricultural Water Management 181 (2017) 85–93

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

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

Slim Zekri[a,*], Kaveh Madani[b], Mohammad Reza Bazargan-Lari[c], Hemesiri Kotagama[a], Edda Kalbus[d,1]

[a] Department of Natural Resource Economics, Sultan Qaboos University, Muscat, Oman
[b] Centre for Environmental Policy, Imperial College London, London SW7 1NA, UK
[c] Department of Civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran
[d] Department of Applied Geosciences, German University of Technology in Oman, P.O. Box 1816, Athaibah PC130, Muscat, Oman

ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form
20 November 2016
Accepted 21 November 2016
Available online 8 December 2016

Keywords:
Farming
Seawater intrusion
Hydro-economic modeling
Optimal extraction
Groundwater management

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

* Corresponding author.
E-mail addresses: slim@squ.edu.om (S. Zekri), k.madani@imperial.ac.uk (K. Madani), bazargan@iauet.ac.ir (M.R. Bazargan-Lari), hemkot@squ.edu.om (H. Kotagama).
[1] Present address: Research and Evaluation Unit, Auckland Council, Auckland, New Zealand.

http://dx.doi.org/10.1016/j.agwat.2016.11.022
0378-3774/

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 three-dimensional form of groundwater flow-governing equations (Harbaugh et al., 2000; Harbaugh, 2005). SEAWAT is a MODFLOW-based public domain code that has the capability of simulating the density-dependent transport of groundwater in a transition zone between freshwater and saltwater (Guo and Langevin, 2002). Both MODFLOW and SEAWAT have been used extensively as classical groundwater modeling tools in various studies (Bazargan-Lari et al., 2009; Bashi-Azghadi et al., 2010; Kalbus et al., 2014; Antonellini et al., 2015; Lathashri and Mahesha, 2015; Mehdizadeh et al., 2015; Van Pham and Lee, 2015; Zekri et al., 2015).

3.2. Economic model on private optimal

The ABM developed in this study rests on the assumption that farmers are short-term profit maximizers. Currently, farmers do not monitor groundwater salinity, and they have no clear information on the link between groundwater salinity at the farm level and the over-extraction of groundwater and seawater intrusion. In addition, they do not have precise information on the effect of salinity on crop yields. However, they do personally witness the effect of salinity on their crop yields after salinity increases, causing them to adjust after a shock has taken place by changing their crop mix. They adapt to the increased level of salinity each time they experience its effect on their crop yields. They make this adjustment by decreasing the area of the salt-sensitive crops and increasing the area of crops that are less sensitive to salinity. Prices of inputs and outputs are considered constant over the optimization period; thus, only crop yield changes affect profitability. The drawdown of the water table is not considered to be a limiting factor in the model because energy prices are heavily subsidized and the farmers' financial burden that results from the declining groundwater level related to energy charges is insignificant. Our surveys in the study area confirmed that farmers are primarily concerned about the salinity levels; they have no complaints about deepening the water table.

The objective of each agent is to maximize his own annual profit. Therefore, optimizing the annual gross marginal profit of farms (Eq. (1)) is the objective function of ABM. Each farm's crop area of 17 crops (mentioned above in Section 2) establishes the decision variables of the optimization model (Eq. (1)–(6)). The relationship between salinity and yield is described by Eq. (2) (Ayers and Westcot, 1985; Stedutoet al., 2012). The corresponding annual water extraction is calculated using Eq. (3). It is assumed that the current extraction level at each farm is the maximum attainable level of extraction that could be practically maintained, and it is equal to each farm's current extraction (Eq. (4)). Because both traditional and modern farming systems are commonly used in the study area, the different farming systems are also taken into account in the optimization model. CPLEX software (Brooke et al., 1996) is used to solve the optimization model. A field survey of 40 randomly selected farms was undertaken to estimate the gross profit per crop according to irrigation systems and with different salinity levels. The gross profits were estimated to be revenues minus variable costs.

$$\text{Maximize}: \quad AP_i^y = \left(\sum_j UP_{i,j}^y.PR_{i,j}^y\right) - \left(\sum_j UC_{i,j}^y.A_{i,j}^y\right) \tag{1}$$

Subject to:

$$PR_{i,j}^y = A_{i,j}^y.Y_j^o\left(1 - b_j\left(S_i^y - a_j\right)\right) \tag{2}$$

$$TW_i^y = \sum_j \sum_f A_{i,j,f}^y \times WD_{j,f} \tag{3}$$

$$TW_i^y \le APL_i \tag{4}$$

$$TW^y = \sum_i \sum_j \sum_f A_{i,j,f}^y \times WD_{j,f} \tag{5}$$

$$\sum_j \sum_f A_{i,j,f}^y \le \sum_j \sum_f A_{i,j,f}^0 \tag{6}$$

where:

AP_i^y Annual gross margin profit of farm i in year y ($)
$UP_{i,j}^y$ Unit farm-gate price of crop j at farm i in year y ($/ton)
$PR_{i,j}^y$ Production of crop j in farm i in year y (ton)
$UC_{i,j}^y$ Unit variable cost of farming crop j in farm i in year y ($/ha)
$A_{i,j,f}^y$ Area under cultivation of crop j in farm i in year y and farming system f (ha)
Y_j^o Initial yield of crop j (ton/ha)
S_i^y Groundwater salinity at farm i in year y (mg/L)
a_j Salinity threshold for crop j (mg/L)
b_j Slope of crop yield response function of crop j
TW^y Total regional water extraction in year y (m^3)
WD_j Water demand of crop j (m^3/ha)
APL_i Annual extraction limit of farm i (m^3)
TW_i^y Total water extraction at farm i in year y (m^3)
f Farming system (traditional/modern)
$A_{i,j,f}^0$ Initial area under cultivation of crop j in farm i and irrigation system h (ha)

Once each agent independently develops his farming and water withdrawal plan for a given year, the overall effects of the agents' decisions on the groundwater status and their resulting profit are simulated using the simulation model that includes the MODFLOW-SEAWAT component. Fig. 1 outlines the modeling process of the ABM scenario.

3.3. Economic model on social optimal

As mentioned above, the Central Planner Model (CPM) represents an ideal model to maximize profits from the use of groundwater at the aquifer level. In this case, all decisions are made by a central decision maker (central planner) who takes into account the interactions between extraction, seawater intrusion, salinity, and crop yields and maximizes the total present value of the profits for all farms over a long period (70 years) using a 2% discount rate to ensure sustainability of farming (Eq. (7)).

$$\text{Maximize}: \quad PV = \sum_y \frac{\sum_i \left(\left(\sum_j UP_{i,j}^y.PR_{i,j}^y\right) - \left(\sum_j UC_{i,j}^y.A_{i,j}^y\right)\right)}{(1+r)^{y-1}} \tag{7}$$

Where:

PV Present value of total gross profit ($)
r Discount factor

CPM is run under the same constraints that are used to define ABM (Eqs. (2)–(6)). The present value of the total gross profit is highly dependent on the water salinity levels because the salinity has a significant temporal and spatial variation that is closely related to the rate and location of groundwater extraction. Thus, to determine the optimal crop mix and the optimal extraction rate and location, it is vital to have a precise estimation of salinity and its variation over time and space. The most challenging modeling task and the primary innovation of this study was to provide this estimation to reliably measure the interactions between salinity, yield and optimal groundwater withdrawal.

The developed method to estimate salinity can be considered to be an innovative mix of the Reinforcement Learning method

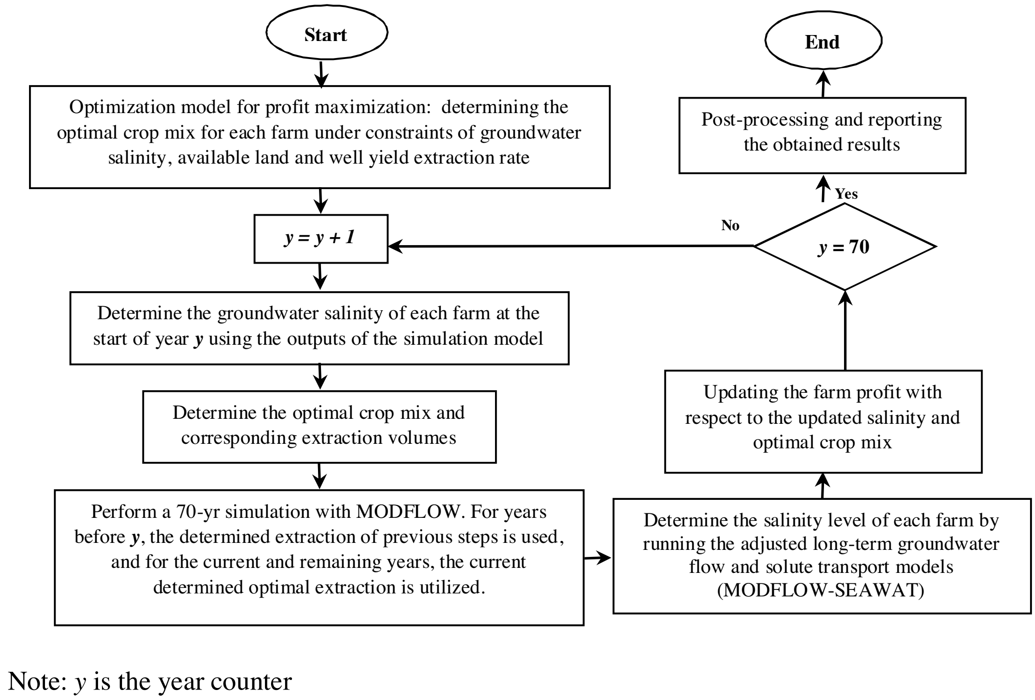

Fig. 1. Agent-based optimization model.

(Madani and Hooshyar, 2014) and the Bayesian Inference (BI) System-based model. This method puts an optimization agent in charge of optimization while the agent is tasked with a reliable estimation of salinity changes without knowing the exact mathematical details used in the MODFLOW-SEAWAT model. Using an adaptive linear regression function (Eq. (8)), the optimization agent attempts to estimate the salinity changes.

$$\Delta S_i^y = \beta_i \sum_i Q_i^y - \beta_i{}^* \times NR \tag{8}$$

Where:

ΔS_i^y is the change in the salinity of farm i in year y

NR is the aquifer's natural recharge per year

β_i and β_i^* are the coefficients of the approximation function, which are updated using the BI method as explained below.

The first term of Eq. (8) ensure that the salinity variation in a specific point depends on the extraction rate in all other points of the aquifer. The second term represents the changes in salinity due to a natural recharge of the aquifer. Therefore, in the case of zero extraction, the first term is zero, and salinity decreases due to a natural recharge.

The agent is tasked with choosing appropriate values for the linear regression function parameters by learning from its past success and failure in estimating salinity changes, which is done by using numerous iterations of the BI functions. In each iteration the agent optimizes the net present value of the gross profit while estimating the salinity changes using the most recent parameter values. Once the values for different variables (groundwater extraction in each farm, crop mix, etc.) are determined, the hydro-economic simulation model is run to calculate the actual values of different variables including salinity changes. Using the new information, the parameter values are updated based on Eqs. (9) and (10).

$$\beta_i^{iter+1} = \frac{iter \times \beta_i^{iter} + \hat{\beta}_i}{iter + 1} \tag{9}$$

$$\hat{\beta}_i = \frac{\Delta\bar{S}_i^y + \beta_i{}^* \times NR}{\sum_i Q_i^y} \tag{10}$$

where:

$\Delta\bar{S}_i^y$ is the average of ΔS_i^y

$iter$ is the iteration number

$\hat{\beta}$ is the realized value of β, which is calculated using the hydro-economic MODFLOW-SEAWAT simulation model.

The updating process is repeated until, using Eq. (8), the estimated (expected) salinity changes are within a reasonably small range from the actual salinity changes, and the required accuracy is met. The R^2 is used as a statistical measure to evaluate the accuracy of the optimization agent's performance. Fig. 2 illustrate the iterative process through which the central agent optimizes its long-term groundwater management plan.

3.4. Pilot study on water metering

Intelligent Energy & Water Meters (IEWMs) that are currently available enable the measurement of groundwater extraction. This facilitates the regulation of the permissible amount of the farmers' groundwater extraction and communicates the farmers' water use to a centralized database, allowing comprehensive groundwater management. IEWMs use the characteristics of online reading, which not only reduces the cost of meter reading but also allows a thorough control and detection of cheating on the measurement of groundwater extraction. The water extraction volume can be controlled by designating a water quota to the smart card associated with a particular well. In the case of water quota depletion, the smart groundwater meters also include an auxiliary relay that can optionally send an interruption signal to the electro-pump (Moazedi et al., 2011). Forty farms were randomly selected from the study area and were equipped with IEWMs to collect groundwater extraction data. For one year, the online daily meter readings were used to calibrate the hydro-geological model (Kalbus et al., 2014). The cost of installing IEWMs, telecommunication costs and

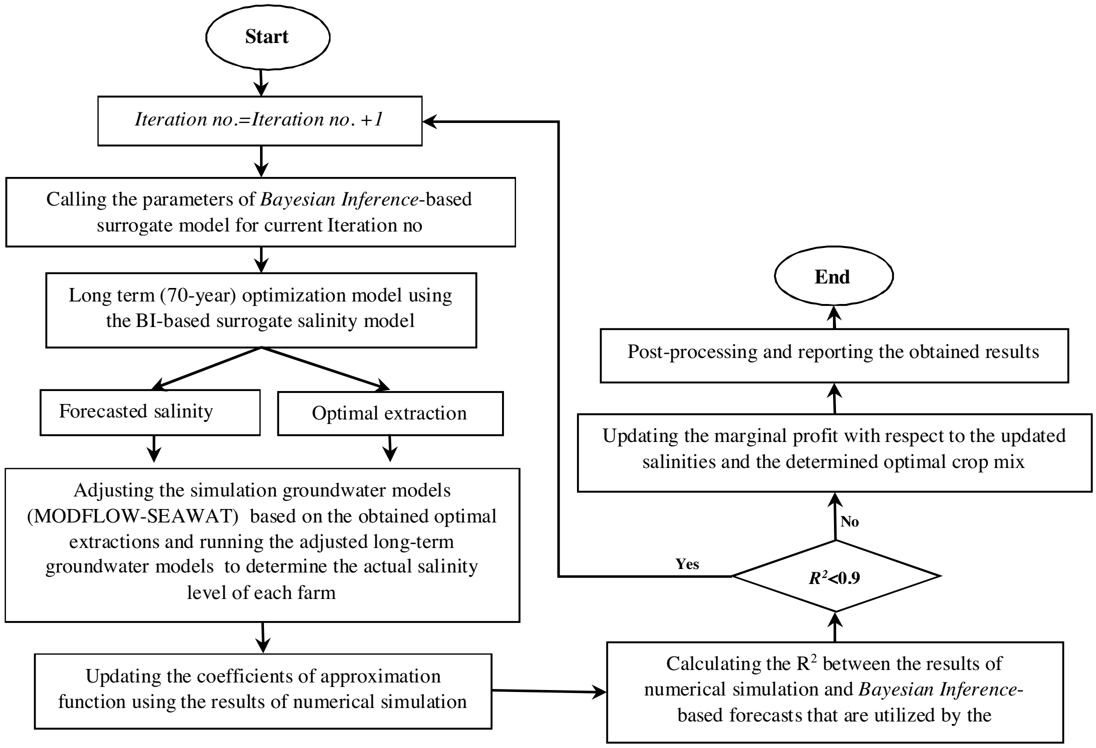

Fig. 2. Central planner model.

centralized data management costs of the pilot project were appropriately scaled-up to estimate the costs to adopt the same tools for the aquifer area. The total cost for the aquifer area was estimated to be $10.5 million for a life span of 40 years, plus an annual operating cost of $140,000 for the telecommunication and data management needs.

4. Results and discussion

4.1. Economic feasibility

Fig. 3 shows the annual profit of farms in the aquifer area for the ABM and CPM scenarios. The ABM profit decreases from $109.9 million per year to $74.5 million, with an average annual loss rate of 0.56%. On the contrary, the CPM profit gradually increases with an average rate of 0.18%. The gradual increase in CPM profit reflects the effects on crop yields of improvements made to groundwater salinity, which are due to the aquifer's resiliency when groundwater extraction is managed properly. The cost for an IEWM to measure and monitor the groundwater extraction is estimated to be $34/ha/year, while the potential benefit is estimated to be $1332/ha/year. Using a 2% discount rate, the Net Present Value (NPV) of the groundwater extraction management is estimated to be $790.6 million and the Internal Rate of Return (IRR) is 93%. In this case, the NPV and IRR show that the potential benefit from optimal groundwater management is high enough despite only considering the aquifer's agricultural uses. In fact, the losses to potable groundwater users, values lost due to the irreversibility of aquifer use, and the values of other environmental goods and services have not been included in this analysis. Thus, the low costs of technological advances in groundwater measurement and monitoring encourages policy and strategy efforts for improved management

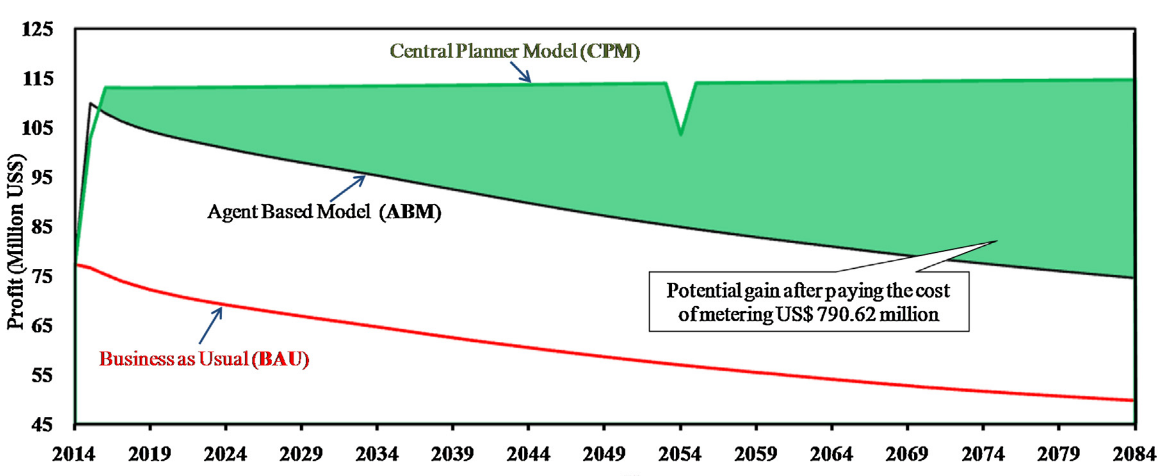

Fig. 3. Annual profit over time based on different groundwater management options.

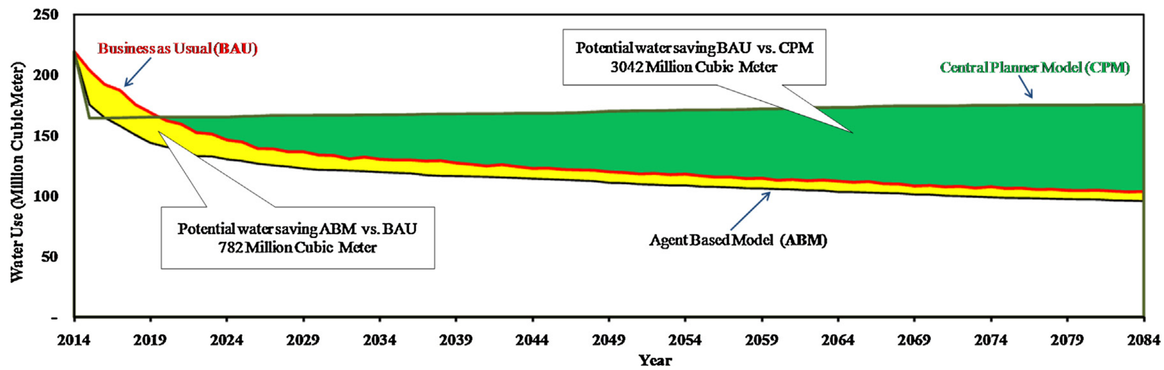

Fig. 4. Potential water savings between Business as Usual (BAU), Agent Based Model (ABM) and Central Planner Model (CPM).

of groundwater. However, further aspects such as the aversion to the possible irreversible loss of water resources, the impact on social equity that results from the changes to management and policy and the impacts on vegetation in arid habitats, must be considered and are discussed below.

Both CPM and ABM are based on the assumption of idealized farmer behavior, which considers farmers to be profit maximizers who operate at the highest level of efficiency at the group (aquifer) level and individual (farm) level, respectively. Nevertheless, comparison of the ABM results with the BAU scenario (Fig. 3) shows that the current level of inefficiency in operations (e.g., groundwater withdrawal, resource use other than water and choice of crop mix) is relatively high. Thus, even profit maximization at the individual level with optimal allocation of all resources and choice of crops can result in reduced groundwater extraction and improved profits but will not be sustainable.

4.2. Irreversibility

With the exception of a few studies (Tsur and Zemel, 1995; Koundhouri, 2000), most prior studies related to hydro-economic modeling of groundwater extraction fail to recognize the important value of the ecological and economic impacts of the irreversible loss of groundwater. Fig. 4 shows that groundwater extraction will fall by 20%, from 219 MCM/year to 175 MCM/year, and will remain constant in the case of CPM. Furthermore, the distribution of groundwater extraction among farmers has changed entirely, as wells located in the beach front area should be closed. On the contrary, for the ABM scenario, groundwater extraction will decline continuously due to salinity increases, which reach only 95 MCM by 2084. As shown in Fig. 5 after 70 years, only 36.0% of the water would be non-saline (fresh) with ABM, while 62.4% of the water would be non-saline (fresh) with CPM. The water quality will be retained by CPM, which prevents an irreversible loss of the aquifer services. By including the values of preventing the irreversible loss of aquifer services, the benefits of adopting CPM increase.

4.3. Equity

Due to the lixiviation fraction, farms with high salinity require more water for the same crops; and due to the crops' sensitivity to salt, farms produce lower yield per m^3 of water in comparison with farms with access to fresh water. Thus, the CPM suggests exiting or closing farms that are located in areas with high to very high salinity levels. Only farms with access to fresh and low salinity water should continue farming. As shown in Fig. 6, the cropped area for CPM abruptly decreases from its current extent of 8476 ha, to approximately 7344 ha in year 1 and subsequently increases at a slow rate, while the BAU cropped area persistently decreases at a higher rate, reaching 4561 ha by the end of the planning horizon. Consequently, the loss in cropped area will reach 5015 ha under ABM. This represents a 40.8% loss of the current cropped area during the planning period.

This finding will have social implications because many farmers will be forced to quit farming due to the shutdown of 3075 farms (42%) in the first year. In addition to shutting down farms, CPM controls and modifies the allocation of water to farms, thus limiting the profitability of some farms by preventing their high

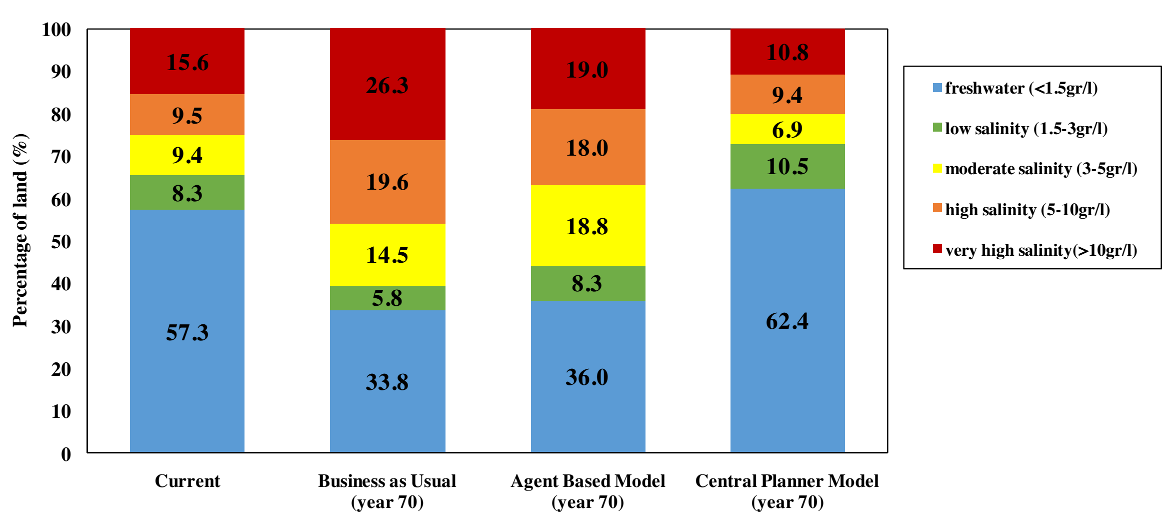

Fig. 5. Comparison of quality of water under different scenarios.

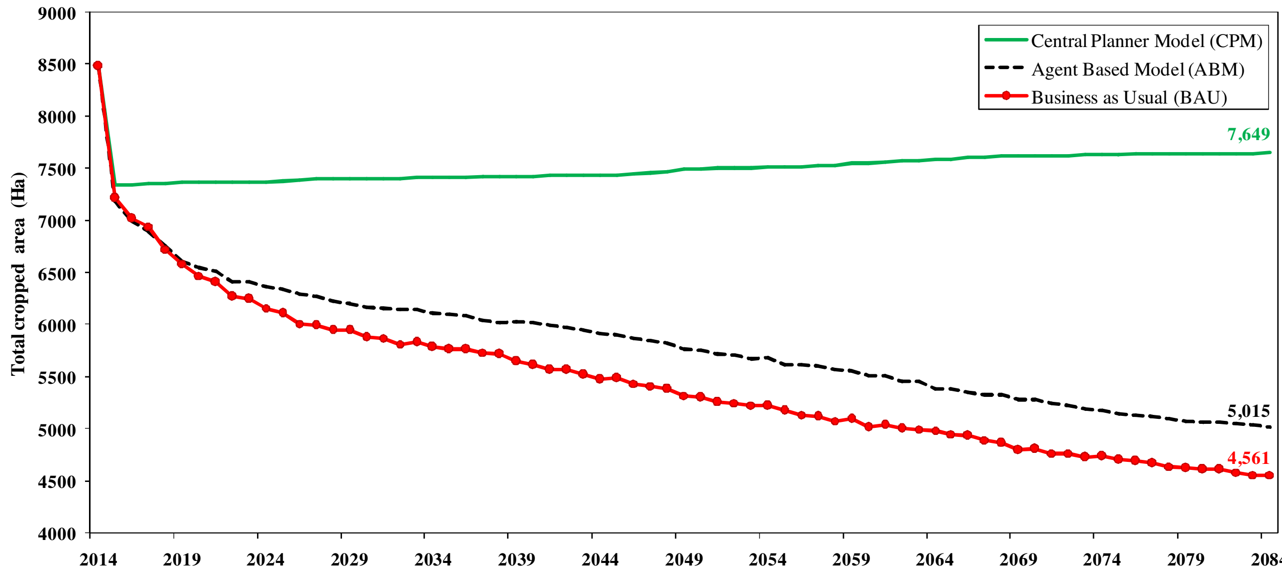

Fig. 6. Total annual cultivated area over time.

rates of groundwater extraction. Such farmers are likely to oppose a management strategy that adopts CPM, unless a compensation mechanism is instituted. The number of farmers that will benefit or lose in CPM versus ABM is an important factor for decision makers when implementing groundwater management strategies.

Approximately 3650 farms will benefit from a CPM management strategy, while approximately 725 farms will potentially lose. In addition to the number of farms that will gain and lose, it is equally important to measure how much these farmers will gain or lose. Presently, the two groups of farms' potential values of gains and losses are $796.86 million and $0.74 million, respectively. In general, CPM provides far more benefits to the farmers' community in the long term. This result clearly shows that any action that aims to implement the CPM results should be accompanied by a mechanism to compensate those farmers who will quit farming and support those who will be disadvantaged by the CPM management strategy. Because it will be difficult to convince the gaining famers to compensate the losing ones, other compensation instruments should be put in place. For instance, as there is demand for it, the government can use market instruments that enable agricultural land to be converted for urban uses. This will encourage farmers who are located in the beach front area, which is more affected by salinity, to quit the farming business, give up their right to pump groundwater, and sell their land at attractive prices (SCTP, 2014). This strategy is feasible because most owners are part-time farmers and do not depend only on farm income for their living. On the other hand, the worse-off farms can be supported through the provision of subsidies that aim to improve the irrigation efficiency or the provision of an extension service to improve management practices and crop mixes.

4.4. Changes in vegetation

The total cultivated area in ABM is persistently decreasing at an average rate of 0.52%. Under BAU, the average rate of the cultivated area's decrease is 0.67%. This represents a 46% loss of the current cropped area during the planning period. Vegetable crops are the dominant crop choice for the CPM, covering approximately 60% of the total crop area. Fig. 7 shows the changes to the crop area over the planning period caused by the cultivation of trees and vegetables under different scenarios. Under CPM, trees are reduced in the first year primarily because of their high water demand, and they are substituted with profitable vegetables that use 2–3 times less water. The tree area is stabilized during the planning horizon, and CPM saves more trees compared to BAU and ABM. The drastic reduction in the tree area may have a significant impact on the micro-habitat of small home garden farms, as it provides ornamental, landscaping and shade values, and also may have an impact on the macro-habitat of agrobiodiversity. The reduction of the date palm area also may be socio-culturally unacceptable in arid regions, where, apart from its direct economic use as a food crop, the date palm has been a socio-cultural icon.

5. Discussion and conclusion

A dynamic programming coupled with a groundwater simulation model MODFLOW was applied to a coastal aquifer in Northern Oman. A Bayesian Inference system was used as an interface between the dynamic programming model and the groundwater simulation model. Two dynamic optimization models were developed for a period of 70 years, representing two generations. The first one is an Agent Based Model (ABM) that aims to optimize the behavior of farmers towards private optimality in groundwater extraction under open-access, where individual farmers tend to ignore spatial and inter-temporal externality in water extraction decisions. The second model is a Central Planner Model (CPM), which is an idealization of the aquifer management towards social optimality, taking into account the aquifer's spatial and inter-temporal externalities in the quantity and quality (salinity) of groundwater extraction. A third model, Business As Usual (BAU), simulates the impact of water extraction and farming decisions on present behavior.

The results show that, towards the end of 70 years, BAU will lead to a deterioration of groundwater quality and a 46% loss of cropped land. If farmers accept a CPM approach to manage the aquifer for groundwater extraction, the Net Present Value (NPV) of the potential net benefit is $790.62 million. The potential net benefit is estimated as the discounted difference between potential benefits of farm productivity improvement and the costs of adopting smart water meters at farms for groundwater measurement and a system of central monitoring of groundwater extraction. The Internal Rate of Return (IRR) for the same was estimated as 93%. Furthermore, with CPM, the cropped area could stabilize in 70 years at a level of 7650 ha, compared to 4560 ha with BAU.

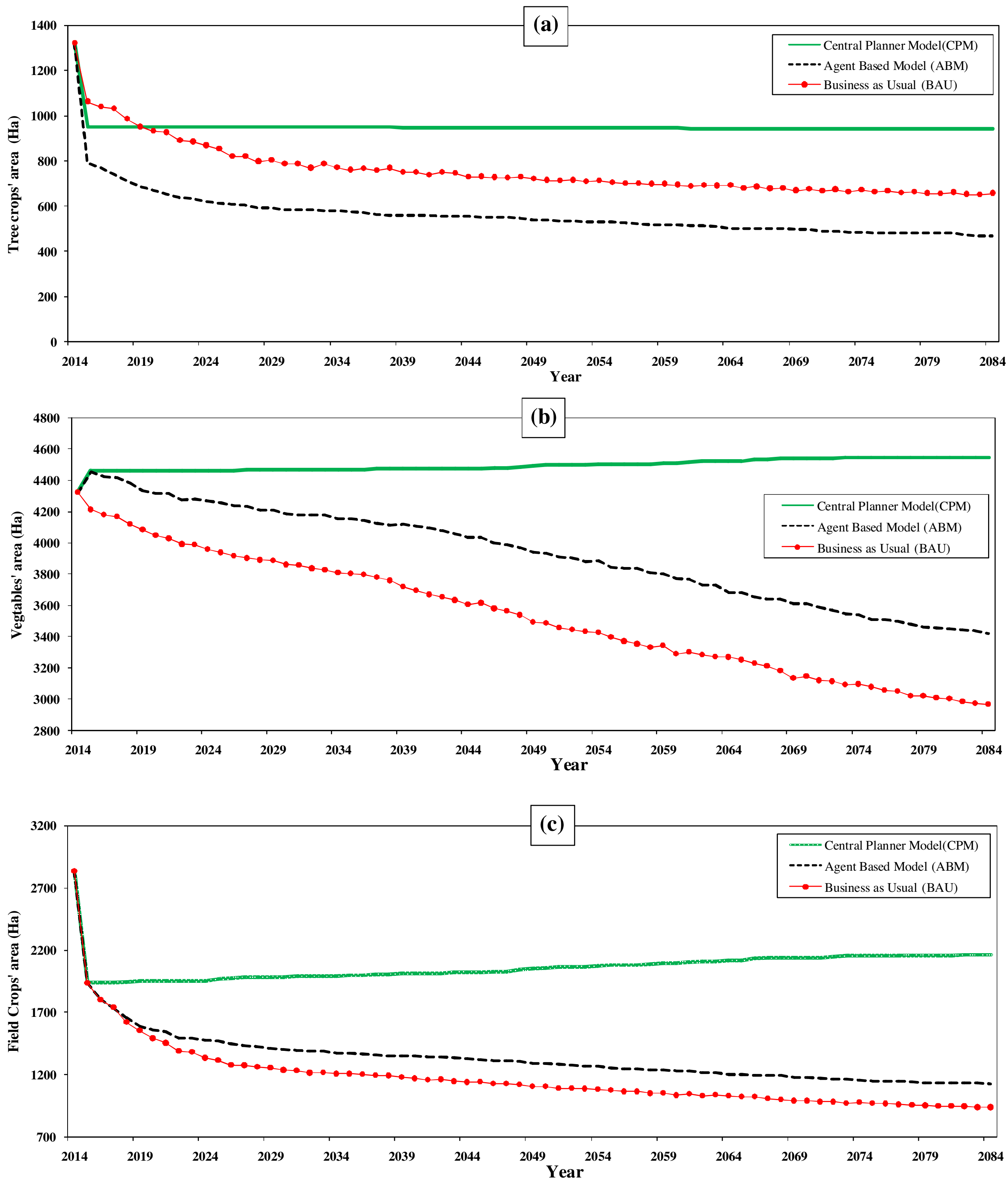

Fig. 7. Annual change in the areas under cultivation of (a) trees, (b) vegetables, and (c) field crops, over the planning horizon.

The results also show that the CPM solution will force 3075 farmers (42%) to exit farming. These farms are located in the beach front area and are heavily affected by salinity. Among the remaining farmers, approximately 725 (10%) will see their benefits decrease slightly, and approximately 3600 farms will highly benefit from the CPM approach, as the present value of their benefits will reach $796.83 million. These results call for a solution for the farmers who will quit farming or lose benefits because of the CPM effects on groundwater extraction. Because there is a high demand for urban land in beach front areas, the government can ease the conversion of agricultural land into urban land to compensate farmers who must quit the business because of a halt to groundwater extraction. This solution is politically feasible because most agricultural activities depend on contractual expatriate farmers.

Finally, the present agricultural area must be reduced drastically to sustain the farming activity and farmers profits in the future. A change to the crop mix is essentially required to avoid excessive extraction from the aquifer and increase the profit, which would encourage farmers to adopt the metering option. A compensation mechanism is also required to compensate those who will be worse off if they remain in business or support them by improving their efficiency. Further research work is needed to find out the optimal institutional setting to enable convergence of private and social optimality.

Acknowledgements

The authors are thankful to the Research Council of Oman for the financial support provided under the Open Research Grant RC/AGR/ECON/12/01. The authors would also like to thank the Ministry of Agriculture and Fisheries, as well as the Batinah Farmers' Association and their members for allowing the installation of the smart meters in their farms. We are grateful to RSA Electronics for the financial and logistical support provided during the three years of the project. We highly appreciate also the helpful comments of two reviewers.

References

Antonellini, M., Allen, D.M., Mollema, P.N., Capo, D., Greggio, N., 2015. Groundwater freshening following coastal progradation and land reclamation of the Po Plain, Italy. Hydrol. J. 23 (5), 1009–1026.
Ayers, R., Westcot, D., 1985. Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29 Rev. 1. Food and Agricultural Organization, Rome.
Bashi-Azghadi, S.N., Kerachian, R., Bazargan-Lari, M.R., Solouki, K., 2010. Characterizing an unknown pollution source in groundwater resources systems using PSVM and PNN. Expert Syst. Appl. 37 (10), 7154–7161.
Bazargan-Lari, M., Kerachian, R., Mansoori, A., 2009. A conflict-resolution model for the conjunctive use of surface and groundwater resources that considers water-quality issues: a case study. Environ. Manage. 43 (3), 470–482.
Bredehoeft, J.D., Young, R.A., 1970. The temporal allocation of ground water – a simulation approach. Water Resour. Res. 6, 3–21.
Brooke, A., Kendrick, D., Meeraus, A., 1996. GAMS/Cplex 4.0 User Notes. GAMS Development Corporation, Washington-USA.
Chandrakanth, M., Romm, J., 1990. Groundwater depletion in India-institutional management regimes. Nat. Resour. J. 30 (3), 485–501.
Dinar, A., Xepapadeas, A., 1998. Regulating water quantity and quality in irrigated agriculture. J. Environ. Manage.
Foster, S., 2012. Groundwater Resources and Irrigated Agriculture: Making a Beneficial Relation More Sustainable. International Water Management Institute.
Gisser, M., Sanchez, D.A., 1980. Competition versus optimal control in groundwater pumping. Water Resour. Res. 31, 638–642.
Guo, W., Langevin, C.D., 2002. User's guide to SEAWAT; a computer program for simulation of three-dimensional variable-density ground-water flow.
Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW- the US Geological Survey Modular Ground-Water Model: User Guide to Modularization Concepts and the Ground-Water Flow Process. US Geological Survey, Reston, VA, USA, pp. 2000.
Harbaugh, A.W., 2005. MODFLOW- the US Geological Survey Modular Ground-Water Model: The Ground-Water Flow Process. US Department of the Interior, US Geological Survey, Reston, VA, USA, pp. 2005.
Kalbus, E., Zekri, S., Karimi, A., 2014. Can smart irrigation technologies reverse saltwater intrusion in an arid area coastal aquifer? In: Meeting of the German Association for Hydrogeology, Bayreuth, Germany.
Kemper, K., Foster, S., Tuinhof, H.G.M.N.A., 2004. Economic Instruments for Groundwater Management. The World Bank, Washington D.C, Brifieng Notes Series, 2002–2006(7).
Koundhouri, P., 2000. Three Approaches to Measuring Natural Resource Scarcity: Theory and Application to Groundwater. PhD Thesis. Department of Economics, Faculty of Economics and Politics, University of Cambridge.
Koundhouri, Phoebe, 2004 Current issues in the economics of groundwater management, Munich Personal RePEc Archive, Paper no. 38425, http://mpra.ub.univ-muenchen.de/38425/.
Kumar, M.D., 2005. Impact of electricity prices and volumetric water allocation on energy and groundwater demand management: analysis from Western India. Energy Policy 33 (1), 39–51.
Kumar, D.M., 2013. Raising agricultural productivity, reducing groundwater use and mitigating carbon emissions: role of energy pricing in farm sector. Indian J. Agric. Econ. 68 (3).
Larson, D., Helfand, G., House, B., 1996. Second-best tax policies to reduce nonpointsource pollution. Am. J. Agric. Econ. 78, 1108–1117.
Lathashri, U.A., Mahesha, A., 2015. Simulation of saltwater intrusion in a coastal aquifer in karnataka, India. Aquat. Procedia 4, 700–705.
MRMWR, 2000. Water Wealth Protection Law Promulgated by Royal Decree 29/2000. Ministry of Regional Municipalities, Environment and Water Resources, Sultanate of Oman.
MRMWR, 2013. Water Balance Computation for the Sultanate of Oman. Final Report. Ministry of Regional Municipalities and Water Resources (MRMWR), Oman.
Madani, K., Dinar, A., 2012. Non-cooperative institutions for sustainable common pool resource management: application to groundwater. Ecol. Econ. 74, 34–45.
Madani, K., Dinar, A., 2013. Exogenous regulatory institutions for sustainable common pool resource management: application to groundwater. Water Resour. Econ., 57.
Madani, K., Hooshyar, M., 2014. A game theory?reinforcement learning (GT–RL) method to develop optimal operation policies for multi-operator reservoir systems. J. Hydrol. 519, 732–742 (Part A).
Madani, K., 2010. Game theory and water resources. J. Hydrol. 381 (3–4), 225–238.
Mehdizadeh, S.S., Vafaie, F., Abolghasemi, H., 2015. Assessment of sharp-interface approach for saltwater intrusion prediction in an unconfined coastal aquifer exposed to extraction. Environ. Earth Sci. 73 (12), 8345–8355.
Moazedi, A., Taravat, H., Jahromi, K., Rashedi, A., Rahimian, S., 2011. Energy-water meter: a novel solution for groundwater monitoring and management. In: World Environmental and Water Resources Congress 2011, American Society of Civil Engineers, pp. 962–969.
Mohanty, S., Ebrahim, A., 1995. Energy pricing and groundwater use. Nat. Resour. Forum 19 (4), 321–330.
Roseta-Palma, C., 2002. Groundwater management and endogenous water quality. J. Environ. Econ. Manage. 44, 93–105.
SCTP, 2014. Al Batinah Master Plan. Supreme Committee of Town Planning, Sultanate of Oman.
Scott, C.A., 2011. The water-energy-climate nexus: resources and policy outlook for aquifers in Mexico. Water Resour. Res. 47 (6) (n/a-n/a).
Scott, C.A., 2013. Electricity for groundwater use: constraints and opportunities for adaptive response to climate change. Environ. Res. Lett. 8 (3), 035005.
Siebert, S., Burke, J., Faures, K., Hoogeveen, J., Döll, P., Portmann, F.T., 2010. Groundwater use for irrigation–a global inventory. Hydrol. Earth Syst. Sci. 14 (10), 1863–1880.
Steduto, P., Hsiao, T.C., Raes, D., Fereres, E., 2012. Crop Yield Response to Water. Food and Agriculture Organization of the United Nations Rome.
Strand, Jon, 2010. The full economic cost of groundwater extraction, Policy Research Working Paper 5494, The World Bank, Development Research Goup, Enviroment and Energyu Team, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1721332.
Van Pham, H., Lee, S.I., 2015. Assessment of seawater intrusion potential from sea-level rise and groundwater extraction in a coastal aquifer. Desalin. Water Treat. 53 (9), 2324–2338.
Vickner, S., Hoag, D., Frasier, W.M., Ascough, J., 1998. A dynamic economic analysis of nitrate leaching in corn production under nonuniform irrigation conditions. Am. J. Agric. Econ. 80, 397–408.
Worthington, V.E., Burt, O.R., Brustkern, R.L., 1985. Optimal management of a confined aquifer system. J. Environ. Econ. Manage. 12, 229–245.
Zekri, S., Triki, C., Al-Maktoumi, A., Bazargan-Lari, M., 2015. An optimization-simulation approach for groundwater abstraction under recharge uncertainty. Water Resour. Manage. 29 (10), 3681–3695.
Zekri, S., 2008. Using economic incentives and regulations to reduce seawater intrusion in the Batinah coastal area of Oman. Agric. Water Manage. 95 (3), 243–252.
Zekri, S., 2009. Controlling groundwater extraction online. J. Environ. Manage. 90 (11), 3581–3588.