Policy measures for reducing aquifer depletion in a context of climate change: the case of the coastal area of Cap-Bon (Tunisia)

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Abstract

Groundwater resources are critically important for irrigated agriculture in Tunisia. However, excessive irrigation extractions where groundwater is slowly renewed are causing a widespread depletion of the aquifer systems, with the impacts of climate change expected to further exacerbate this problem. These circumstances call for the development of methodologies and analyses that can support the design of sustainable groundwater management policies. This paper presents a hydro-economic mathematical programming model that is used to evaluate the effects of different policy measures for reducing aquifer depletion in the Cap-Bon region of Tunisia. Three policies have been evaluated: a quota defining the maximum quantity of groundwater extractions, environmental taxation, and supply expansion with subsidized desalinated seawater. Overall, results highlight the economic and social tradeoffs among these different policy choices and the challenges facing the implementation of sustainable groundwater management in Tunisia. More specifically, results show the advantages of using subsidized desalinated seawater compared to the other two policy alternatives in terms of the value of agricultural production, farmers' profits, and employment, despite of its sizeable budgetary burden.

Keywords: *Climate change, Groundwater depletion, Mathematical programming, Water policy measures, Tunisia.*

1. Introduction

Irrigated agriculture plays an important role in securing global food production, and sustaining locally rural livelihoods and ecosystems. It is estimated that 17% of agricultural lands are irrigated, yet they account for 40% of the global food production (Abdullah, 2006). At the same time, irrigation is the main user of water resources worldwide, and especially in arid and semi-arid regions (Shiklomanov, 2000). On the other hand, groundwater represents the world's largest freshwater resource and is critically important for irrigated agriculture (Koundouri, 2004). However, depletion is widespread in large groundwater systems in both semi-arid and humid regions of the world (Konikow, 2011). Excessive extraction for irrigation where groundwater is slowly renewed is the main cause of the depletion, and

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climate change has the potential to exacerbate the problem in some regions (Wada *et al*. 2012).

Tunisia is one of the countries in the world least well-endowed with water resources. These resources are scarce and their quality is degraded. Therefore, Tunisia has become a water stressed country in terms of per capita renewable water resources, with only 400 m^3 per capita, which is well below the global average of 1000 m^3 per capita (WB, 2014). Water problems in Tunisia are linked to the country's shrinking water supply, and to the exceedingly high and growing water demand, mainly in the agricultural sector (that already uses 85% of total water withdrawals) (ITES, 2014). With most available surface waters already polluted, groundwater resources are now being heavily overexploited. The challenges posed by non-sustainable groundwater use are most notable in Tunisia, with extractions significantly exceeding the natural recharge. For instance, the total number of aquifers in Tunisia is about 273, of which 71 are overexploited at an average rate of 146% (i.e. 46% higher than their natural recharging rate), with total groundwater depletion amounting to about 650 Mm^3 per year (ITES, 2014; TICET, 2009).

Several policy measures have been progressively introduced and implemented to address groundwater depletion in Tunisia during recent decades (Frija *et al*., 2015). This includes the requirement for an authorization for the pumping of groundwater resources; the classification of some overused aquifers as "exclusion areas", where the exploitation of groundwater has to be strictly authorized by government administrations; and the classification of other more critical aquifers as "prohibited areas", where all types of new wells are strictly prohibited and any infraction is punished by law. Despite these efforts, groundwater policies in Tunisia are considered to be insufficient (Faysse *et al*., 2011). For instance, the use of economic instruments to deal with groundwater depletion remains limited, with the main economic instrument used is related to the National Program for Water Savings, which offers farmers subsidies for investing in irrigation-saving technologies (Bachta and Elloumi, 2005).

The majority of studies conducted in Tunisia about groundwater management policies are thus far descriptive (Faysse *et al*., 2011, Frija *et al*., 2015, Ghazouani and Mekki 2016; Elloumi 2016), despite the valuable recommendations provided to address groundwater depletion. Mahdi and Sghaier (2017) used the theory of information asymmetry to investigate the incentive regulation for public irrigation water services managed by irrigation agencies in the south of Tunisia, which could be considered as the only study tried to introduce quantitative approach into groundwater management. Our paper aims to provide a quantitative comparative analysis of the effectiveness of different policy measures (water use quota, environmental tax, and supply expansion with subsidized desalinated seawater) to control groundwater extractions under current and future climate conditions in Tunisia, using a hydro-economic mathematical programming model. To the best of our knowledge, there are no studies in the literature that used a hydro-economic modeling approach to evaluate groundwater policies in a context of climate change in Tunisia.

Our analysis focuses on an intensive irrigated area in Northeastern Tunisia, the Cap-Bon region. This region is one of the most productive agricultural areas in Tunisia, produces most of country's exported crops, and provides considerable employment opportunities. Intensive irrigation activities in this region have caused a substantial increase of groundwater extractions, and consequently the depletion of groundwater resources along with the degradation of their quality. The sustainability of groundwater-based irrigation in the Cap-Bon region has become a real challenge for decision makers (Frija *et al*., 2015, Elloumi, 2016).

The remainder of the paper is organized as follows. First, a literature review on the available policy measures to control groundwater extractions is conducted in Section 2. Section 3 describes the study area and data sources, followed by the explanation of the modeling framework and scenarios of groundwater management in Section 4. Section 5 discusses the results. Finally, Section 6 concludes with the summary and policy implications.

2. Literature review: policy measures to control groundwater extractions

This section reviews a number of studies in the literature that investigated the use of policy measures to regulate groundwater extractions and reduce aquifer depletion. A large bundle of policy measures are proposed in the literature for managing groundwater resources (Koundouri, 2004). The most commonly used measures are based on restricting water pumping by establishing quotas that define a maximum quantity of water extraction or a minimum water table level. The advantage of water quotas is that they allow equity issues to be taken into consideration and promote transparent reallocation of water (Johansson *et al*., 2002; Blanco-Gutiérrez *et al*., 2010). However, some studies in the literature indicate that water quotas are less efficient compared to other measures, too inflexible to adapt to changing climate and market conditions, and associated with high implementation costs (Zekri, 2008; Molle, 2009; Esteban and Dinar, 2013). An alternative to water quotas is the buyback of pumping permits by the public authorities. This measure has the advantage of permanently reducing extractions and does not harm farmers' income, as they are compensated, but it has both a high public budgetary cost and significant impacts on the rural economy (Carmona *et al*., 2011).

Public policies that provide different type of subsidies to reduce groundwater extractions, such as subsidies for investments in improved irrigation technology or the use of alternative water sources, are often viewed as effective and politically-feasible control measures. Perry and Hellegers (2012) show that, contrary to widespread expectations, subsidized improved irrigation technology in Yemen triggered the expansion of irrigated areas and the shift towards more profitable and water-intensive crops, which increased groundwater extractions. Similar results on the effects of subsidized improved irrigation technology on groundwater extractions are found in the United States (Pfeiffer and Lin, 2014). Martínez-Granados and Calatrava (2014) analyze the opportunity to reduce aquifer depletion in Southeast Spain with the use of desalinated seawater and find that desalinated water may not be effective to reduce groundwater extractions if farmers have to bear the full desalination cost and no subsidy is provided. Zekri *et al*. (2014) evaluate the cost-effectiveness of managed aquifer recharge using treated wastewater in Oman, which seems to be an appealing measure from an economic perspective if groundwater is used for drinking purposes, but not for irrigation because of the high cost of wastewater treatment.

Tax instruments that penalize the use of groundwater or the decrease in the water table level are also policy measures commonly analyzed in the literature for their water-saving potential and their reputation as appropriate cost-recovery mechanisms (Sorensen and Herbertsson, 1998). In most countries around the world, farmers using groundwater usually pay for the investment and operating costs of water pumping but they do not pay any additional fee (Berbel *et al*., 2007). Thus, the financial costs of groundwater pumping are fully recovered, but resource and environmental costs are usually not included, causing the depletion of aquifers (Garrido and Calatrava, 2010). From a theoretical point of view, a tax instrument is an effective policy measure to control the level of groundwater extractions (Esteban and Dinar, 2013). However, many empirical applications conclude that irrigation water demand is very inelastic in the short term, at least for low water prices or reduced water availability (Wheeler *et al*., 2008), and that the taxation of groundwater extractions can have a significant impact not only on farmers, but also on the whole agricultural sector and the rural economy (Scardigno *et al*., 2014).

The last two decades witnessed the upsurge of new water management measures based on the involvement of stakeholders, including market-based instruments and voluntary agreements. Market-based instruments, such as water tradable permits, in which users are assigned a quantity of water (permits) and they have the option to sell them to or to buy from other users (private market rules) are efficient mechanisms because the market establishes the optimal prices and quantities (Easter *et al*., 1999). However, one challenge facing the implementation of such measures is the necessity of having well-functioning water institutions to manage the rights and setup the rules (Skurray and Pannell, 2012). On the other hand, the voluntary agreements which users undertake by themselves to reduce the extractions and protect the resource are efficient instruments, but usually require the creation of incentives for farmers to collaborate and monitoring costs to prevent cheating (Madani and Dinar, 2012; Esteban and Albiac, 2012).

3. Study area and data sources

The Cap-Bon region is located in Northeastern Tunisia (Figure 1). Its climate is semiarid with an average annual precipitation of 420 mm (INM, 2005). Water used in the region originates from four sources: surface water in local dams, groundwater, treated wastewater, and surface water transfer coming from the Medjerda River in Northern Tunisia. Only surface water and groundwater resources are used for irrigation. However, the reduction of surface water allocation to irrigated agriculture in order to meet the growing demand of competing uses is increasing irrigation pressures on groundwater resources.

At present, irrigation in the Cap-Bon region extends over 26,000 ha, which represents 2.6% of the total agricultural area in Tunisia. It contributes with about 35% to the country's agricultural production (ITES, 2014). Irrigation in the Cap-Bon region uses about 74 Mm^3 of water, of which 54 Mm^3 are groundwater resources from the East Coast aquifer, 8.5 Mm^3 are surface water resources from local dams, and 11.5 Mm^3 are surface water resources coming from the Medjerda water transfer project (DGGREE, 2012).

For the purpose of the present paper, our analysis focuses on the coastal irrigated area (highlighted in red with dashed lines in Figure 1), which covers 15% (or 3,930 ha) of the total irrigated area in the Cap-Bon region, which well represents the cropping pattern and farming practices in the whole region. Data used in this study has been collected from several primary and secondary data sources. A survey was conducted during 2011 and 2012 with 150 farmers spread across the study area. The data set in table 1 includes revenues and costs of crops, crop area, labor use, yields, water use, and crop prices. The data set also includes information on

Figure 1 - Map of the Cap-Bon region.

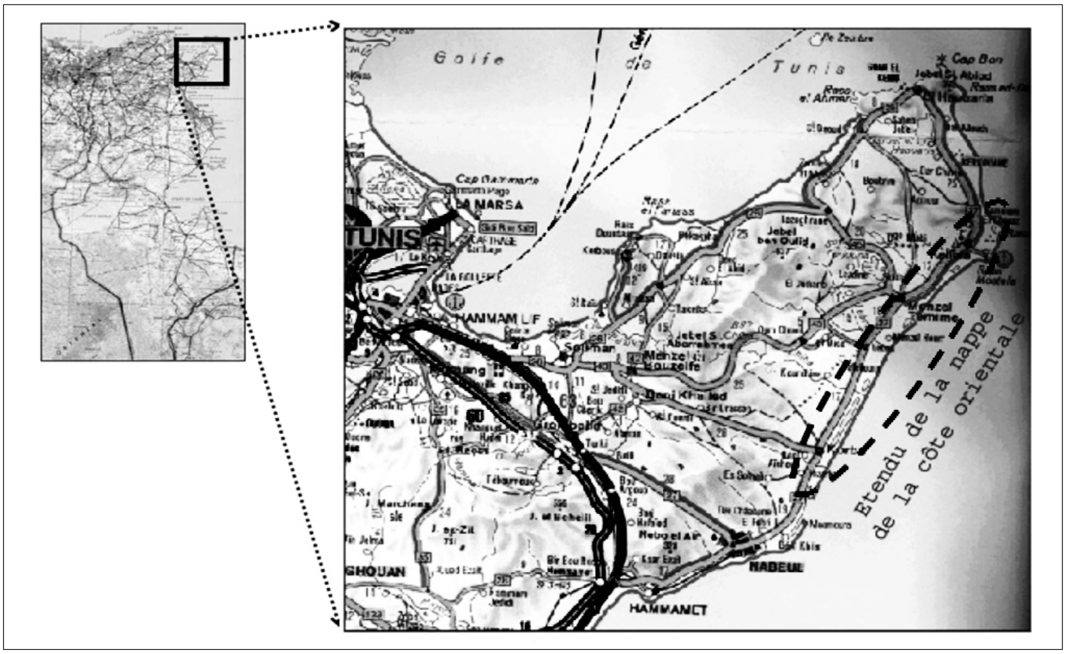


Table 1 - Crop area, water use and economic data in the study area.

Crops	*Land in production (ha)*	*Water use (m^3/ha)*	*Labor use (day/ha)*	*Yield (T/ha)*	*Crop Price (dt/T)*	*Revenue (dt/ha)*	*Cost of production (dt/ha)*	*Gross margin (dt/ha)*
Tomato	865	4,500	109	80	127	10,160	5,079	4,766
Pepper	395	6,745	80	13	500	6,500	4,253	1,775
Strawberry	564	7,841	57	30	1,750	52,500	28,551	23,401
Other summer vegetables (OVS)	56	4,000	52	30	400	12,000	8,330	3,390
Cabbage	88	3,802	103	70	250	17,500	5,022	12,212
Other winter vegetables (OVW)	1,166	3,500	58	45,000	0.3	13,500	3,350	9,905
Grenade	144	2,500	23	11	650	7,150	1,297	5,678
Grapes	22	6,000	76	11	1,350	14,850	1,622	12,808
Citrus	72	8,892	27	40	500	20,000	7,254	12,124
Other fruit trees (OFT)	101	4,500	121	20	650	13,000	4,285	8,400
Fodder	457	3,000	21	350	8	2,800	1,361	1,229
Total	3,930							

Source: Benalaya et al. (2015). Note: One Tunisian Dinar (dt) is equivalent to 0.54 US Dollars in 2014.

the water prices in the study area, which amount to 0.07 dt/m^3 for surface water diversion and 0.3 dt/m^3 for groundwater pumping. These data are obtained from a series of surveys within the framework of the project "Virtual water and food security in Tunisia, 2012-2015" (Benalaya *et al*., 2015).

The selected irrigated area uses water from two sources: surface water that amounts to 11.2 Mm^3 per year (60% of total water use) originating from both the Medjerda water transfer project and local dams, and groundwater extractions from the East Coast aquifer amounting to 7.4 Mm^3 per year (40% of total water use). Groundwater extractions are well above the natural recharge of the aquifer, estimated to be around 0.24 Mm^3 per year. The intensive pumping for irrigated agriculture in this area has caused considerable water table level drawdown (about 5 m below the sea level), and seawater intrusion (with salinity concentration of water between 5 and 8 g/l) (Chebil *et al*., 2014).

4. Methodology and scenarios

4.1. *Modeling framework*

The analysis of the policy measures to reduce aquifer depletion is conducted using a hydro-economic mathematical programming model. This model follows a similar approach used by Kahil *et al*. (2015a, 2015b and 2016a), which integrates hydrologic, agronomic and economic components into a unified modeling framework for a comprehensive policy analysis. This type of models simulates land and water allocation among crops and computes several economic indicators (value of agricultural production, production costs, farmers' profits, public expenditures and collections, cultivated area, and agricultural employment). The objective of our model is to maximize farmers' profits in the study area, subject to various technical and resource constraints. A Leontief production function technology is assumed with fixed input and output prices, where farmers are price takers.

The mathematical formulation of the model is as follows:

$$Max\ \pi = [(\sum_i (P_i \cdot Y_i - Prodcosts_i) \cdot X_i) - P_{sw} \cdot SW - P_{gw} \cdot GW] \quad (1)$$

subject to

$$\sum_i X_i \leq Landavail \quad (2)$$

$$\sum_i W_i \cdot X_i \leq Wateravail \quad (3)$$

$$\sum_i L_i \cdot X_i \leq Laboravail \quad (4)$$

$$X_i \geq 0 \quad (5)$$

where equation (1) is the objective function of farmers' profits from irrigation activities, which is defined by the difference between crop revenues and production costs (including water and non-water costs). This objective function is maximized subject to land use constraint (equation 2), water availability constraint (equation 3), and labor constraint (equation 4). Equation (5) is the non-negativity constraint. The parameters of the model are: P_i = price of crop i; Y_i = yield of crop i; P_{sw} = price of surface water diversion; P_{gw} = cost of groundwater pumping; and $Prodcosts_i$ = production costs other than water costs of crop i. *Landavail* is land available for crop cultivation, *Wateravail* is the amount of surface and ground waters available for irrigation, and *Laboravail* is labor availability in the region. The variables of the model are: X_i = area of each crop i; SW = surface water diversion; and GW = groundwater extractions. The solution of the model provides information on the optimal cropping pattern and associated inputs use including water and labor use, as well as the economic benefits and costs associated with the agricultural production.

The use of mathematical programming models to analyze agricultural production at regional level faces the problem of aggregation and overspecialization because farms in a region are different in terms of resources endowment, technologies, and management skills. Ideally, a regional model should include a component for every individual farm, but this is unfeasible because of the complexity of such a model. Many approaches have been developed to solve this problem and to calibrate regional models to observed conditions such as the representative farm approach (Day, 1963), the convex combination approach (Önal and McCarl, 1991), and the positive mathematical programming (PMP) approach (Howitt, 1995).

Our model is calibrated to observed crop area using the PMP approach. The application of this approach as a mean for calibration has significantly increased during the last two decades. The main advantages of PMP compared to other approaches are the exact representation of the base conditions, lower data requirements, and a smooth response of the model to continuous changes in exogenous parameters when the model is used for analysis of policy changes. In this study, we follow the standard PMP approach to calibrate our model to observed crop area, which involves a two-step procedure for implementation (Fragoso and Marques, 2015). In the first step, the model described in equations (1) to (5) is bounded by observed crop area by introducing a set of calibration constraints. In the second step, dual values associated with the calibration constraints are used to calculate calibration parameters, which represent the marginal cost coefficients of a convex cost function, and are incorporated into the objective function (1), such that once the calibration constraints are removed, the modified model reproduces exactly the observed crop area.

4.2. *Policy and climate scenarios*

The hydro-economic model is used to assess the effects of three policy measures under two climate scenarios. The three policy measures are the following:

Policy 1: This measure aims to eliminate aquifer overexploitation, by establishing a quota that limits the maximum quantity of groundwater extractions for irrigation purposes to the natural recharge of the aquifer.

Policy 2: This measure introduces an environmental tax on groundwater extractions in order to reduce extractions up to the natural recharge of the aquifer, following the "polluter pays" principle and reflecting the full cost of water supply as well as the scarcity value of the resource. This measure is similar to the water pricing policy advocated by the European Water Framework Directive.

Policy 3: This measure expands the water supply for irrigated agriculture. The measure seeks to substitute non-renewable groundwater resources with subsidized desalinated seawater. Tunisia has the advantage of having a relatively long coastline which gives it easy access to this resource. Therefore, one potential solution to address the growing water scarcity in Tunisia is to invest in desalination plants.

The considered climate scenarios are the following:

Scenario 1 or *current climate conditions*: This scenario represents the current climate conditions in the study area.

Scenario 2 or *future climate change conditions*: This scenario reduces surface water availability by 10% and groundwater recharge by 30% by 2030. This scenario is in line with the IPCC climate projections for the Mediterranean region (IPCC 2014).

5. Results and discussion

5.1. *Scenario 1: Current climate condition*

Table 2 and Figure 2 show the outcomes of the different policy measures under current climate conditions. In the baseline scenario (i.e. observed situation), farmers' profits amount to 32.5 Million Tunisian Dinars (Mdt). The value of agricultural production is 64.3 Mdt. The production costs other than water costs are 29 Mdt and water costs are 3 Mdt. Irrigated area is 3,930 ha. Total water use is about 18 Mm^3 of which 11 Mm^3 are surface water and 7 Mm^3 are groundwater resources (Table 2).

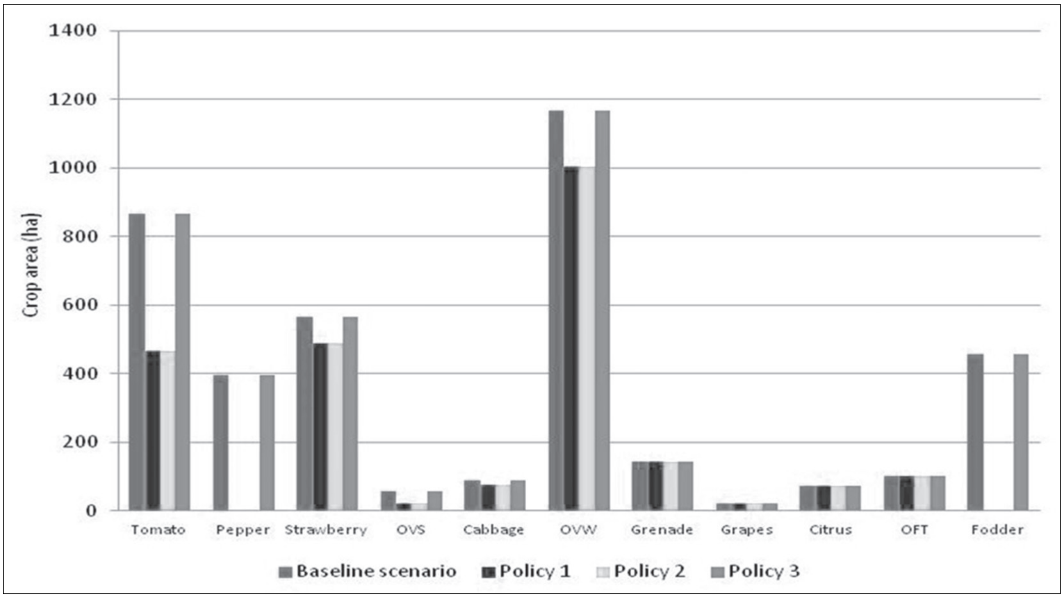
Results of *Policy 1*, that eliminates aquifer overexploitation and limits irrigation groundwater extractions to the natural recharge of the aquifer, indicate a reduction of irrigated area by 39%, with water-intensive and low-value crops (e.g. pepper and fodder) removed from the production plan, and water is more efficiently used, allocating it to high-value crops (e.g. strawberry and grapes) (Figure 2). Water use is reduced by 38%. Production costs and water costs are reduced by 30 and 70%, respectively. The value of agricultural production falls down by 22% from 64 Mdt in the baseline scenario to 50 Mdt under *policy 1*. Farmers' profits decrease by only 5%. Labor demand is reduced by 38%.

Results of *Policy 2* that introduces an environmental tax on groundwater extractions indicate that the optimal environmental tax that reduces extractions up to the natural recharge of the aquifer is equal to 0.77 dt/m^3. This policy produces almost the same outcomes of *Policy 1* in terms of crop area, water use, value of agricultural production, and labor demand. However, there is a

Table 2 - Results of the policy measures under current climate conditions.

	Baseline scenario	*Policy 1*	*Policy 2*	*Policy 3*
Crop area (ha)	3,930	2,393	2,393	3,930
Total water use (Mm^3)	18.6	11.4	11.4	18.6
SW use (Mm^3)	11.2	11.2	11.2	11.2
GW use (Mm^3)	7.4	0.24	0.24	0.24
Desalinated water use (Mm^3)	0.0	0.0	0.0	7.2
Value of Agricultural production (Mdt)	64.3	49.6	49.6	64.3
Production costs (Mdt)	28.8	17.8	17.8	28.8
Water costs (Mdt)	3.0	0.9	1.0	3.0
Farmers' profits (Mdt)	32.5	30.9	30.7	32.5
Public collection (Mdt)	0.8	0.8	1.0	-5.2
Labor use (days)	266,383	164,874	164,874	266,383

Figure 2 - Land use decision for each policy measure under current climate condition (ha).



slight decrease of farmers' profits and increase of water costs. In addition, public collection of water fees rise by 24% compared to both the baseline scenario and *Policy 1*.

Results of *Policy 3* that expands the supply of water with subsidized desalinated seawater indicate that for a full elimination of groundwater depletion in the area, the government should provide a subsidy of 0.83 dt/m^3 (75% of the cost of seawater desalination equal to 1.15 dt/m^3). Desalinated seawater use amounts to 7.2 Mm^3. The outcomes of *Policy 3* are similar to those of the baseline scenario in terms of crop area, total water use, value of agricultural production, production costs, water costs, famers' profits, and labor demand. However, public collection is considerably reduced because of the huge costs of desalination. Under *Policy 3*, the government spends 5.2 Mdt.

5.2. *Scenario 2: Future climate condition*

Results of the different policy measures for this climate scenario are shown in Table 3 and Figure 3. Results of *Policy 1* that eliminates aquifer overexploitation and limits irrigation groundwater extractions to the natural recharge of the aquifer show a reduction of crop area by 43%, with pepper and fodder removed from the production plan (Figure 3). Water use decreases by 41%. Production costs and famers' profits are reduced by 46 and 8%, respectively. The value of agricultural production falls down by 28% from 63 Mdt in the baseline scenario to 45 Mdt under *policy 1*. Labor demand is reduced by 44%.

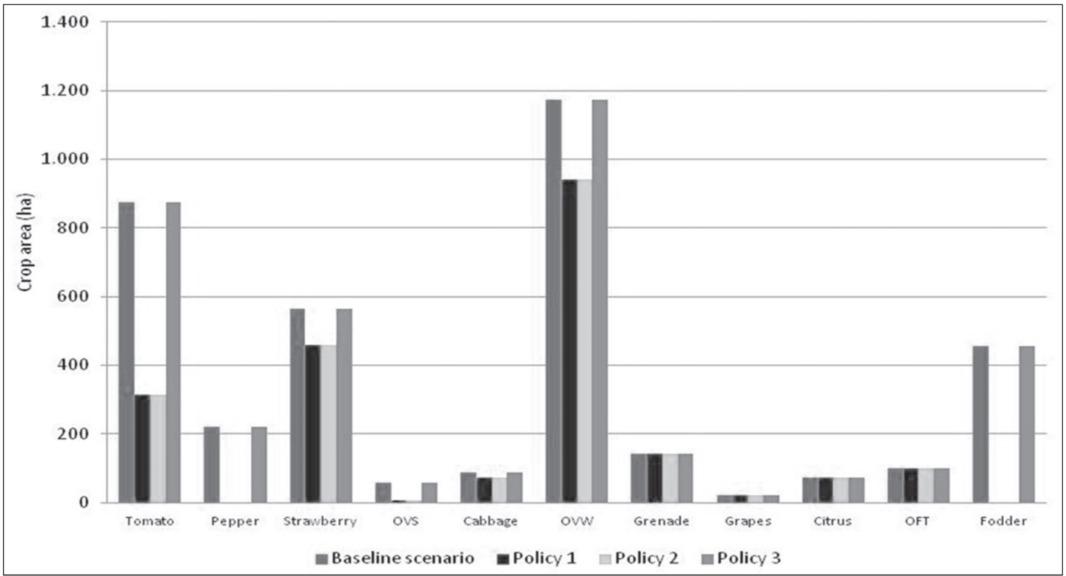
Results of *Policy 2* that introduces an environmental tax on groundwater extractions, indicate that the optimal environmental tax that reduces extractions up to the natural recharge of the aquifer is equal to 1.04 dt/m^3, 35% higher than under the current climate condition (or scenario 1). This policy produces almost the same outcomes of *Policy 1* in terms of crop area, water use, value of agricultural production, and labor demand. However, there is a slight decrease of farmers' profits and increase of water costs. In addition, the public collection of water fees rises by 26% compared to baseline scenario and *Policy 1*.

Results of *Policy 3* that expands the supply of water with subsidized desalinated seawater indicate that for a full elimination of groundwater depletion in the area, the government should provide a subsidy of 0.83 dt/m^3 (the same

Table 3 - Results of the policy measures under future climate condition.

	Baseline scenario	*Policy 1*	*Policy 2*	*Policy 3*
Crop area (ha)	3,772	2,134	2,134	3,772
Total water use (Mm^3)	17.5	10.2	10.2	17.5
SW use (Mm^3)	10.0	10.0	10.0	10.0
GW use (Mm^3)	7.4	0.17	0.17	0.17
Desalinated water use (Mm^3)	0.0	0.0	0.0	7.3
Value of Agricultural production (Mdt)	63.4	45.5	45.5	63.4
Production costs (Mdt)	28.2	15.2	15.2	28.2
Water costs (Mdt)	2.9	0.8	0.9	2.9
Farmers' profits (Mdt)	32.2	29.6	29.4	32.2
Public collection (Mdt)	0.7	0.7	0.9	-5.3
Labor use (days)	253,836	142,078	142,078	253,836

Figure 3 - Land use decision for each policy measure under future climate condition (ha).



amount as under the current climate condition). Desalinated water use amounts to 7.2 Mm^3. The outcomes of *Policy 3* are similar to those of the baseline scenario in terms of crop area, total water use, value of agricultural production, production costs, water costs, farmers' profits, and labor demand. However, public collection is considerably reduced because of the huge costs of desalination. Under *Policy 3*, the government spends 5.3 Mdt.

6. Conclusions and policy implications

Groundwater depletion is a major environmental issue in Tunisia. Intensive groundwater-based irrigation activities have increased significantly the pressures on aquifers leading to considerable groundwater table level drawdown, and water and soil quality degradation. Climate change impacts are expected to reduce water availability and increase the frequency and intensity of extreme events in Tunisia. Under these circumstances, water authorities in Tunisia are considering policies to reduce groundwater depletion without damaging the welfare of irrigation activities under climate change conditions. The choice of these policies requires an evaluation of their economic, environmental and social effects. This paper aims to contribute to the ongoing policy discussion about the potential policy interventions to reduce groundwater depletion in Tunisia. The paper presents the development of a hydro-economic mathematical programming model and evaluates the effects of various policy measures to reduce groundwater depletion under current and future climate conditions. The selected policy measure alternatives are a quota limiting groundwater extractions, an environmental tax on groundwater extractions, and the substitution of overexploited groundwater for desalinated seawater resources.

Results of this study indicate that establishing a quota limiting groundwater extractions, in absence of alternative substituting resources, will have large negative impacts on agricultural production under both climate scenarios, by reducing irrigated area and the value of agricultural production. In addition, employment is significantly reduced under this policy measure. These results confirm previous findings in the literature indicating that water quota, which is the mainstream policy instrument to control groundwater extractions in Tunisia, might not be very effective to address groundwater management issues and would likely be met by opposition from farmers and rural community leading to policy failure (Giannoccaro *et al*., 2010). An environmental tax on groundwater extractions yields similar outcomes to those of the water use quota. Its only advantage is that it generates tax revenues, but its implementation would be unfeasible from a political point of view (Kahil *et al*., 2016b). In contrast, the substitution of overexploited groundwater for desalinated seawater resources protects the agricultural production, farmers' profits, and employment, although the costs for the government are disproportionate compared to the other two policy alternatives. This policy measure could further gain ground in the future given the projected decreases in the costs of seawater desalination and the expected climate change impacts on conventional water resources (Ghaffour *et al*., 2013; Martínez-Granados and Calatrava, 2014).

The comparison between the policy and climate scenarios presented in this study shows the economic and social tradeoffs among the different policy choices and the challenges that could face the implementation of sustainable groundwater management in Tunisia. The complete restriction of non-renewable groundwater pumping is a challenging and potentially conflictive measure that would likely have a large political cost. Policymakers need to take into account that the success of any water policy intervention largely depends on the cooperation of the affected users that, in this case, would be more prone to accepting the option of substituting overexploited groundwater for subsidized desalinated seawater. Experiences in other regions around the world suggest that it is unlikely that groundwater pumping could be reduced without providing incentives for farmers, such as compensations and subsidies (Madani and Dinar, 2012; Esteban and Albiac, 2012).

As a final remark, the hydro-economic model developed in this study could be improved in future work by including the dynamic aspects of groundwater resources, water quality issues, and environmental damages to groundwater-dependent ecosystems. Additional policy measures could be also evaluated including improved irrigation efficiency, reuse of recycled wastewater for irrigation, artificial aquifer recharge, and groundwater trade.

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