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Exploring regional irrigation water demand using typologies of farms and production units: an example from Tunisia.

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Abstract

Most methods used to predict irrigation water consumption at a regional scale are based on biophysical models and cropping patterns. Their aim is to provide accurate estimations of "water demand" that are useful for water resource management. However, in the case of free access to the water resource, for example pumping from a water table, it is only possible to prevent overexploitation by "managing" the demand for water, which thus needs to focus on farmers' choices and behavior. In this paper, we propose a framework to represent agricultural activities using typologies of farms and production units aggregated at a regional scale. The framework can be used to estimate consumption of irrigation water and of other inputs, as well as the production of outputs. The framework can also be used to evaluate the effects of technical, economic or institutional changes on farm income, and to predict the consequences of changes for farmers' choices at regional scale. We used this method in Central Tunisia to estimate irrigation water demand in 1999. We then simulated the changes that would occur if drip irrigation were adopted. The results of the simulation showed some savings in water and in labor, and, with fertigation, an increase in yields. Using drip irrigation would consequently enable farmers to extend the area of drip-irrigated land. We then simulated the widespread adoption of drip irrigation and the resulting extension of irrigated areas: the results showed no savings in water at the regional scale. These hypotheses were confirmed in 2005 using new typologies to estimate the new demand for irrigation water. We also simulated the effects of economic changes on farm incomes. A major increase in the cost of water affected a minority of farms, which consumed only 17% of total irrigation water, whereas a slight decrease in watermelon and melon prices affected a majority of farms, which consumed 78% of total irrigation water. Water demand management tools therefore need to focus on the effects of technical, economic, or institutional changes and on farmers' choices.

Keywords: regional water demand, farmers' choices, farming system, modeling.

1 – Introduction

Accurate prediction of agricultural water consumption is required for better management of water resources. Most predictions are based on biophysical components and estimates of crop water requirements. The accuracy of the estimates depends on knowledge of soil properties, climatic variability, and irrigated cropping patterns. Satellite imagery combined with crop models is currently widely used to estimate irrigation water requirements at a regional scale (Heinemann *et al.,* 2002). Including farmers' practices and choices can improve the accuracy of such estimates (Maton *et al.,* 2005). Farmers choose their own cropping patterns and crop management practices. Crop rotation can be taken into account, for example by using past cropping patterns and crop transition probabilities (Benoît *et al.*, 2001; Leenhardt *et al.*, 2005). Bergez *et al.* (2005) proposed a regional framework using a crop model combined with irrigation rules observed by farmers. In this approach, the prediction of irrigation water consumption is based on the implicit assumption that the future is a repetition of the past. This assumption is justified for biophysical processes when formulating hypotheses on future climatic variability (Victoria *et al.*, 2005), but not for economic processes that influence farmers' choices and that - like prices - can change very quickly (Cantin *et al.*, 2005). For example, in Europe, how might cropping patterns and irrigation rules change as a result of changes in the common agricultural set-aside policy or changes in the current high prices of agricultural products? This type of question can be answered using economic optimization based on mathematical programming or econometric models (Scheierling et al., 2005; Bartolini et al., 2007). Agricultural water demand is thus the consequence of optimal cropping patterns and irrigation practices for a given market with given output prices and input costs, including water (Gomez-Limon and Riesgo, 2004).

After years of water management based only on supply, it is increasingly necessary to manage the demand for water (Brooks, 2006) to prevent over-exploitation of free-access water resources, such as groundwater (Foster *et al.*, 2000). Tarjuelo *et al.* (2005) suggested developing a multidisciplinary approach and innovating water management to account for the economic, social and environmental viability of irrigated agriculture. For the World Bank, water demand management includes a set of different actions that can modify the parameters that affect water demand (Berkoff, 1994). Water demand management is concerned with technological, institutional, economic and behavioral mechanisms (Froukh, 2007). It is thus important to focus analysis at the level of individual farms, where the choices of crops and techniques are made.

To analyze irrigation water demand at the regional level, we propose a representation of agricultural activities based on typologies of farms and cropping systems. This representation combines the technical and economic functioning of farming systems and enables us to test the effects of changes in farm incomes, and to simulate farmers' reactions to these changes. The aim is not so much to obtain an accurate estimate of water consumption as accurate knowledge of the farming system, and thus anticipate changes in water demand. We illustrate our method by estimating water consumption in a plain in central Tunisia, where farmers irrigate with groundwater drawn from an aquifer with a constantly decreasing piezometric level. First, we describe the results of a survey conducted in 1999 before the Tunisian government began promoting drip irrigation. Second, we simulate possible consequences of the widespread adoption of drip irrigation in the region. We then describe a second assessment made in 2005 to check our previous hypotheses. Finally, we test economic incentives that could slow down the consumption of agricultural water.

2 – Methods

2-1 Model of regional water demand by aggregation of farmers' choices

The usual way to model regional water demand is to aggregate water consumption at the plot scale. Consumption depends on the climate, the soil properties, and the crop. Choices concerning crops, irrigation techniques, and management are made by farmers. Many models represent water demand at the plot scale only using crop water requirements, and GIS for regional scale aggregation (Herrero and Casterad, 1999, Mateos *et al.,* 2002). Some models also try to take farmers' practices into account (Weatherhead and Knox, 2000; Leenhardt *et al.*, 2004) when estimating the daily irrigation demand based on crop distribution at the regional scale, and on water management at the plot scale. While this approach enables accurate assessment of irrigation water consumption when plots are directly aggregated at the regional scale, it fails to take into account the farm scale at which farmers choose crop patterns and crop management strategies based on economic – not only monetary – criteria. As a result, it is not easy to predict the changes in the demand for irrigation water that result from farmers' reactions to economic or institutional changes.

We thus propose a regional representation that focuses on the farmers' choices and practices at the farm scale. This enables us to estimate both annual consumption of agricultural inputs (particularly water), and the production of outputs at the farm scale, and subsequently at the regional scale, by aggregating farm consumption and production. Following Wichelns (2003), we place agricultural water use in the context of the functioning of the farm as a whole. This representation is based on a typology of farming systems that corresponds to a combination of animal and plant production (irrigated or not), and a typology of production units for crops - i.e. cropping systems - and for livestock (Le Grusse, 2001). Next, we consider a region as an aggregation of farm types, with weighting corresponding to the number of farms of each type. A farm is considered as an aggregation of production unit types, with weighting corresponding to the size of each production unit type. A production unit consumes inputs (water, work, fertilizer, etc.) and produces outputs (grain, straw, etc.) at given unit quantities. Inputs and outputs have costs, which enable calculation of net income for each production unit and farm type, and for the entire region.

This type of regional model is widely used for economic optimization (Audsley, 1993, Rounsevell *et al.,* 2003). Here we use it to aggregate the consequences of consumption and production for farmers' choices, particularly with respect to cropping patterns and cultivation techniques, at the regional scale. These simulations enable us to assess the economic consequences of price changes (i.e. an increase in the cost of water or a decrease in the sales price of watermelons, for example) for each type of farm. Because the consequences are usually heterogeneous among cropping systems, the farmers' responses may also differ (Landais, 1998; Andersen *et al*. 2007).

2.2 Building farm and production unit typologies

Typologies are a way of representing the diversity of farming systems and production units in a given region (Jollivet, 1965, Cristofini, 1986; Capillon, 1993; Dobremez and Bousset, 1995; Landais, 1998). As described by Maton *et al.* (2005), two types of methods can be used to build a typology: (i) the "positivist method" based on statistical analysis of farm surveys (Mignolet *et al.*, 2001), and (ii) the "constructivist method" where types are built from "expert knowledge" and then validated by surveys (Perrot and Landais, 1993).

We propose using the "positivist method" to build a farm classification based on structural data and statistical methods (Lebart *et al.*, 1995). In practice, this classification needs to be validated by the stakeholders involved, for example agricultural advisors or members of agricultural institutions. Next, a survey is conducted of a sample of farms in each class enabling the production unit typology to be built using the "constructivist method". The production unit typology is then validated by the farm survey and by the stakeholders. Subsequently, the farm typology can be built using the "positivist method" by combining the production units in the farm sample. This farm typology is then extended to the whole population using the farm classification.

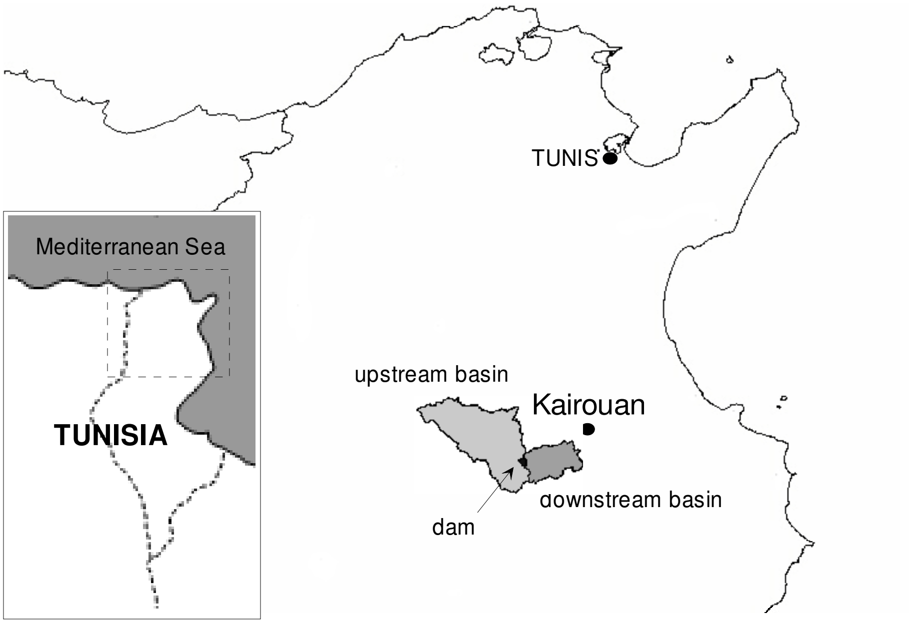
The first step is an exhaustive inventory of the farms with their structural characteristics (size and production orientation). These data usually already exist in the statistics departments of public institutions. If not, the information must be gathered in surveys conducted by people who know all the farmers in their territory, for example mayors or agricultural extension officers. The inventory is then used to build the farm classification and to calculate the number of farms in each class.

2-3 Application to the Kairouan plain

The Merguellil Wadi basin in central Tunisia (from 35°44'N, 9°25'E, to 35°33N, 10°04'E) was chosen by Tunisian authorities to design integrated water management models. The study was entrusted to Tunisian and French researchers and was conducted in collaboration with the

"*Commissariat Régional du Développement Agricole*" (CRDA) of Kairouan, the regional institution for agricultural and rural development.

Figure 1: Map showing the location of the Merguellil Wadi basin



Water management in this basin is characteristic of semi-arid regions with an upstream sub-basin that collects the water resource, a storage catchment (the El Haouareb dam), and a downstream sub-basin with irrigated agriculture (Fig. 1). Irrigation is made possible by pumping from the Kairouan water table, which covers an area of more than 3,000 km^2. This renewable resource is mainly supplied by the Zeroud, Merguellil and Nebana watersheds, which have been closed by dams since the 1980s. The main user of the Kairouan water table is agriculture, which consumes 80% of the total amount extracted each year. Annual consumption exceeds the annual supply from the water table resulting in a piezometric decrease of between 0.5 m and 1 m per year (Nazoumou and Besbes, 2000; Leduc *et al.* 2004).

Our study zone covers about 300 km^2 located below the El Haouareb dam (35°34'N, 9°45'E). The area is delimited in the north and south by low hills, and in the east by the town of Kairouan (35°40'N, 10°06'E). Most farmers in the Kairouan plain extract water for irrigation directly from private wells, while a few are involved in public irrigation schemes, called "*Périmètres Irrigués Publics*" (PPI") based on collective water distribution networks linked with boreholes. In practice however, farmers usually own several plots (some of which are irrigated), and some might be in a "PPI", while others depend on private wells.

Demand for agricultural water in the Kairouan plain was originally surveyed in 1999-2000 (Feuillette, 2001; Feuillette *et al*., 2003; Kadi *et al.*, 2005). That study was based on an exhaustive inventory and typology of farms in the Kairouan plain, and results suggested water demand would change with the expansion of drip irrigation. In the present study, we used the 1999 data set with our representation framework to evaluate demand for irrigation water before the development of drip irrigation, and to simulate the changes suggested. Then in 2005, we conducted a new study of agricultural water demand based on farm and crop management typologies to check the original hypothesis, and to test the effects of economic changes.

Most European countries (including France) have inventories of the farms in each department. In Tunisia, this type of data rarely exists and an inventory of farms in the study area consequently had to be compiled by the researchers. Feuillette (2001) built the inventory with the help of "*Omdas,*" i.e. people who represent public authorities (for example the mayor) in each "*imada*", which corresponds to a municipality. Each *Omda* meets everyone who lives in the municipality (particularly farmers), when they prepare official papers. Each *Omda* compiled a list of farmers in his municipality, with the size of the farm, the number of sheep, and the type of production, the latter being classified in one of five production categories (i.e. olive groves, cereals, animal rearing, vegetable cropping, fruit orchards). Each category was scored with respect to its importance for the farm (0 for "none", 1 for "a few", and 2 for "many"). The first farm inventory was conducted in 1999 for the entire study area, which comprises seven *imadas.* The second inventory was conducted in 2005 using the same methodology.

In 1999 and 2005, we performed multiple correspondence analysis (Tenenhaus and Young, 1985), followed by hierarchical classification using Ward aggregation criteria (Lebart *et al.*, 1995), using the five scores as variables and the farms as population. The resulting classification was discussed with the CRDA in Kairouan. Next, a survey was made of a sample of farms in each class. The size of the sample depended on the total number of farms in the class (the samples ranged from 5% to 15% of a class), but also on the importance of the class as a function of its need for irrigation water (low ratio for dry cropping, high ratio for irrigated cropping). The surveys we made on this farm sample (crop pattern and crop management, size of flock) enabled us to build a farm typology for 1999 and 2005.

In 1999, the typology of the production units built with the CRDA concerned only irrigated crops and was based on the yield, irrigation water consumption, and gross margin of each crop. In 2005, the production unit typology concerned both rainfed and irrigated crops, and included land preparation, use of fertilizers and pesticides, harvesting, and labor. In addition, production unit income was calculated using the average prices of inputs and outputs in the region. Incomes, costs and prices are given in Tunisian Dinars (TND; 1 TND = 0.57 Euro). The characteristics of each production unit, particularly consumption of irrigation water and crop yield, are given for three types of weather: a dry, rainy and "normal" year. The characteristics of the three types of years were checked against local crop parameters and climatic data using the CROPWAT model (Allen *et al.*, 1998). Aggregated consumption and production were compared to economic studies on agricultural crops (Albouchi, 2006) and hydrologic studies of the lowering of the Kairouan water table (Leduc *et al.*, 2004).

3 – Results

3-1 Demand for agricultural water and production in the Kairouan plain in 1999

In 1999, we counted 2,106 farms on the Kairouan plain, representing a cultivated area of about 17,000 ha. We identified eight types of farms (Table 1). About 26% of the farmers who cultivated 13% of the land had no irrigated crops, but instead cultivated rainfed cereals and olive trees. Some farmers owned a large flock of sheep. These farms were mainly located on hillsides within the limits of the plain. In contrast, 59% of farmers irrigated their entire farm. In this category, most farmers cultivated irrigated vegetables and young fruit orchards in association with olive groves, while some farmers irrigated only annual crops. About 15% of farmers, (representing about 20% of the total area) cultivated both rainfed and irrigated crops.

Olive groves and annual crops were mostly irrigated using furrows, while cereals were irrigated with sprinklers in public irrigation schemes ("PPI"). The emergence of drip irrigation mainly concerned summer vegetable crops, young fruit orchards and olive groves. The production typology of Feuillette (2001) indicated for each crop (or crop category) the irrigation water supply, yield and gross margin per hectare, including the cost of mechanization, fertilizers and pest control for three types of weather: dry, normal and wet (Table 2). Data describing the consumption of irrigation water resulted from surveys made with the CRDA on different types of farms with access to public (like in "PPI") or private water. Irrigation water requirements for crops were estimated by Lardilleux (2000) using CROPWAT, regional parameters, and climatic data.

Table 1: Number of farms (% total) and characteristics of each of the eight farm types in 1999 (I a: strictly rainfed crops ; I b: animal rearing and rainfed crops; II: mainly rainfed crops with irrigated cereals and vegetables; III a: mainly irrigated vegetables and cereals with rainfed crops; III b: mainly irrigated vegetables with rainfed crops; IV: irrigated olive groves and vegetables; V: irrigated olive groves, fruit orchards and vegetables; VI: irrigated vegetables and cereals). Average farm area (ha), number of sheep per hectare, cropping pattern (% of total area) with strictly rainfed crops (cereals with olive and almond trees) separated from other crops that can be irrigated (vegetables, cereals, olive groves and fruit orchards).

	Farm type							
	I a	I b	II	III a	III b	IV	V	VI
number (% total of farms)	11	15	7	2	6	33	11	15
farm area (ha)	3.56	5.09	7.59	7.73	8.28	6.51	7.46	4.21
sheep (no . ha-1)	0.3	2.4	0.5	3.8	0.3	0.4	0.9	1.1
cereal and olive plantation* (% farm area)	100	100	52	34	33	5	0	0
cereals** (% farm area)			22	21	4	16	14	24
total vegetable cropping** (% farm area)			25	67	91	30	21	73
summer vegetable cropping** (% farm area)			11	35	53	16	14	24
olive groves** (% farm area)				7	5	53	30	3
fruit orchards** (% farm area)				4			35	

(* strictly rainfed crops ; ** crops that can be irrigated)

Sum of crops can be more than 100% because trees can be cultivated with annual crops, and several different crops (particularly vegetables) can be grown in the same field in the same year (in rotation).

Table 2: Yields, irrigation water supplies (from our surveys) and requirements (estimated with CROPWAT), labor requirements, and incomes for the main irrigated crops in 1999: irrigated wheat, olive groves (100 trees per ha), watermelons (harvested in summer), tomatoes (harvested in summer), and beans (grown in winter). Values are those of a "normal" annual weather with deviations for dry or wet annual weathers.

	yield (t)	irrigation water supply (m^3)	*irrigation crop water requirement (m^3)*	labour (days)	income (TND)
Wheat (sprinkler irrigation)	3.0 (±0.5)	2,500 (±1,000)	*2,100 (±1,500)*	20 (±5)	300 (±50)
Olive groves (100 trees per ha)	2.2 (±0.8)	2,000 (±1,000)	*2,500 (±1,250)*	20 (±5)	1000 (±500)
Watermelons (harvested in summer)	25.0 (±5.0)	7,000 (±1,500)	*6,250 (±1,200)*	135 (±10)	1600 (±750)
Tomatoes (harvested in summer)	30.0 (±7.0)	7,500 (±1,500)	*6,500 (±1,200)*	200 (±10)	1400 (±800)
Beans (winter vegetable cropping)	3.5 (±0.5)	2,500 (±1,000)	*3,000 (±2,500)*	130 (±5)	1200 (±500)

As shown in table 2, irrigation water supplies monitored at field level appeared to satisfy estimated crop water requirements or were slightly less than requirements. But the efficiency of irrigation in the field is commonly about 0.85 for sprinkler irrigation and 0.6 for surface or furrow irrigation (Rogers *et al.*, 1997). One can thus assume that irrigation water available for the crop was 15% to 40% less than the water consumption monitored, and that the supply of irrigation water thus did not satisfy crop requirements. As a result, actual yields reached only about half the potential yields for the region (Lardilleux, 2000; Champion, 2003). The effect of weather on yield and water supply resulted in variability of gross margins. But the high gross margins for vegetable crops (e.g. watermelons and tomatoes) are more affected by product prices, which can vary considerable depending on the market (Champion, 2003; Albouchi, 2006). The gross margins for irrigated cereals are much lower than those for other irrigated crops, particularly summer vegetables.

However, cereals are a necessary component of cropping patterns, as the straw is used to feed the flocks of sheep. In addition, cereal fields can be rented for pasture after harvest, and vegetables cannot be grown in the same plot more than once every four or five years due to phytosanitary risks. However farmers can rent plots to grow vegetables (Albouchi, 2006).

Based on these typologies and on the number of farms in each farm category (Table 3), the cropping patterns, agricultural consumption and production were aggregated at the scale of the entire plain for 1999. The supply of irrigation water for the study area was estimated to be between 25 and 45 million m^3 depending on the weather in the year concerned. Summer vegetable cropping (which covered about 3,000 ha), half of which was combined with olive or fruit trees, represented about half of total water consumption. Irrigated cereals (also about 3,000 ha), consumed an average of 17% of the total supply of irrigation water, but with considerable variation due to weather.

Due to water losses of between 20% and 30% caused by surface transport and the outdated distribution network, the total water extracted for agriculture was about 45 million m^3 per year. This extraction rate corresponds to the annual decrease of 0.5 m in the level of the water table observed during the 1990s (Leduc *et al.*, 2004).

Table 3: Cropping pattern at the scale of the Kairouan plain and average volume of irrigation water consumed by each crop with deviations for wet or dry years.

	area (ha)	irrigation water supply (10^6 m^3)
Rainfed crops and fallow	6,422	
Cereals	2,996	6.0 (±3.0)
Olive groves (alone)	908	1.8 (±0.9)
(with annual irrigated crop)	1,907	1.9 (±0.9)
Fruit orchards (alone)	469	2.8 (±0.7)
(with annual irrigated crop)	152	0.6 (±0.1)
Watermelons and melons	1,872	13.1 (±2.8)
Tomatoes and hot peppers	743	5.6 (±1.1)
Other summer vegetables	278	1.7 (±0.3)
Bean and winter vegetables	811	2.0 (±0.8)
Total irrigated crops	8,077	35.5 (±10.6)

3-2 Hypotheses on changes in water demand and cropping patterns

To prevent overexploitation of water tables without disturbing agricultural development in rural regions, Tunisian authorities introduced incentives for the purchase of equipment needed for drip irrigation (irrigation pipes, basin and pumps). These incentives depended on the size of the farm and covered up to 60% of investment costs for small farmers, but only 20% for large farmers. In 1999, drip irrigation was used only on a few crops, particularly vegetables and young olive groves and fruit orchards. We used our representation of agricultural activities to estimate the consequences of the extension of drip irrigation to vegetables and fruit orchards.

At the scale of the field, the change in irrigation technique enabled savings in irrigation water. Based on surveys made by the CRDA in drip-irrigated fields, we estimated that the supply of irrigation water could be reduced by 30% to 40% in vegetable cropping and fruit orchards. At the scale of the entire plain, this reduction was estimated at about 9.5 million m^3 in a year with “normal” weather. The extension of drip irrigation would also improve the efficiency of water transport from the well to the plots by using pipes instead of earthen ditches.

Table 4: Characteristics of the 18 farm types in 2005. Number of farms, average size, cultivated and irrigated areas, number of sheep per hectare, rainfed and irrigated crops (% of total cultivated area) of each farm type.

	Farm type																	
	I a	I b	II a	II b	III a	III b	IV	V a	V b	V c	VI a	VI b	VI c	VII a	VII b	VIII a	VIII b	VIII c
Number of farms (% total)	7.6	7.2	3.6	2.2	5.6	4.3	6.7	9.8	3.7	0.2	16.4	9.5	0.4	14.1	5.1	1.6	1.7	0.3
Average total area (ha)	4.1	7.5	9.7	13.5	3.6	11	10.1	3.5	13.4	61.7	4.1	13.4	33.3	3.8	13.6	5.2	15.5	66.3
Cultivated area (% total area)	80	100	90	70	100	70	90	90	90	60	100	100	80	100	90	100	80	90
Irrigated area (% cultivated area)	0	33	0	35	0	0	80	100	91	100	92	80	75	100	100	100	100	100
Sheep (number / total area)	1.7	2.0	2.5	2.0	4.5	2.6	1.2	0.4	0.4	0.0	2.6	1.1	0.9	1.3	0.5	0.3	0.2	0.0
Rainfed crops (% cultivated area)																		
Olive groves	69	45	10	5		17	5					4						
Olive groves-almond orchards	13		27		50	34	5					1						
Cereals with olive trees	5		5		50	41	5											
Cereals	13	20	58	60		8	5		9		8	15	25					
Irrigated crops (% cultivated area)																		
Olive groves		5		15					14		8	7		40	65		15	16
Olive groves-almond orchards																		8
Cereals with olive trees							30											
Vegetables with olive trees		20		6			21				7	4		30	7	16	15	
Fruit orchards with olive trees												5				33	30	
Cereals				2			8		8		40	33	40		8	3		
Summer vegetables		5		10			12	90	65	100	22	17	20	10	5	3	10	33
Beans and winter vegetables				1			5	10	4		15	9	7	15	4	4		
Fruit orchards													3		8	35	30	43

Moreover, drip irrigation enables fertigation, which can increase vegetable yields. As a result, gross margins for summer watermelons and tomatoes were 50% higher in drip-irrigated fields than in surface irrigated fields, with less manual labor needed for irrigation. We thus hypothesized that farmers would use this increase in income to buy new drip irrigation equipment and to extend vegetable cropping using the water saved from private wells. The irrigation water thus saved (about 9.5 million m^3) would allow the land used for summer vegetable cropping to be to be extended by about 1,500 ha. This extension could be at the expense of non-irrigated land, in association with olive groves for example, or of irrigated cereals, which result in low income. We thus hypothesized that the extension of drip irrigation would not result in a decrease in overall demand for agricultural water, except for savings due to the increased efficiency of water transport. Moreover, Feuillette (2001) supposed that farmers would use their extra income to build new wells, resulting in an increase in water pumped for irrigation. The study we conducted in 2005 provided the opportunity to test these hypotheses.

3-3 Agricultural water demand, consumption and production in 2005

In 2005, using a similar methodology to that used in 1999, 2,230 farmers who cultivated 17,081 ha were subdivided into seven categories in the first classification round. A sample of 150 farms was chosen at random in each category i.e. a ratio of between 2% and 10% depending on the irrigation activity and on the size of the category (low ratio in large categories with rainfed farms, high ratio in categories with farms specialized in irrigated crops). This sample allowed us to distinguish eight groups of farmers (Table 4) who cultivated from 0% to 100% of irrigated crops. The first three groups represented about 30% of the farmers (28% of the total area) who cultivated mainly rainfed crops (cereals with olive groves and almond orchards); some farmers (less than 10%) grew irrigated vegetables and olive groves on 33% to 35% of their cultivated land. An intermediate farm type grouped 7% of farmers (about 9% of the total area) who mainly grew irrigated crops on 80% of their cultivated land, along with irrigated cereals and vegetables intercropped with olive trees. Next, we distinguished four groups of farmers who specialized in irrigation. The first group comprised 14% of farmers (13% of the total area) who specialized in summer vegetable cropping. The second group comprised 26% of farmers (27% of the total area) who mainly cultivated irrigated cereals and vegetables. The third group comprised 19% of farmers (16% of the total area) who mainly cultivated irrigated olive trees. The last group comprised less than 4% of farmers (7% of the total area) who specialized in irrigated crops with summer vegetables, and fruit orchards associated with olive groves. These eight groups were subdivided into 18 farm types according to average farm size and specific cropping patterns (Table 4).

Production unit typology was based on the main crops. We distinguished 24 types of pure (i.e. only one crop in the plot) production units: four rainfed crop production unit types (olive groves, olive groves and almond orchards, wheat, and barley); two irrigated cereal types classified according to their level of irrigation; one type comprising irrigated olive trees; 13 vegetable cropping types classified according to the harvest date and the degree of intensification; one winter vegetable cropping (mainly beans); and three fruit orchards. Intercropping cereals, vegetables or fruit orchards represented two thirds of the pure production units in association with rainfed or irrigated "intercropped olive trees". The characteristics of the main production units are listed in Table 5. Almost all the irrigated vegetable crops and fruit orchards were drip irrigated; irrigation (surface or sprinkler) of cereals was either systematic or additional; olive groves were mainly furrow irrigated. The distinction between summer vegetable production units was based on the harvest period which influenced the intensification of crop management, i.e. the use of hybrid plants and plastic tunnels. Sales prices of summer vegetables varied considerably within a given production season: early watermelons and melons, or out-of-season tomatoes and hot peppers fetched higher prices than in-season products but required specific production techniques like hybrid plants, plastic tunnels and mulching. As a result, summer vegetable cropping could produce high incomes but was very risky because of the variability of prices, whereas traditional crops (cereals, beans and olives) produced lower incomes but also crop residues that could be exploited by flocks of sheep.

Table 5 : Costs, products, sale prices (minima and maxima) and incomes (minima and maxima) for the main production units (rainfed wheat and olive groves, and irrigated wheat, olive groves, watermelons, hot peppers and apple trees), with irrigation water supplies (minima and maxima) and labor requirements, yields, and externalities that can be used by sheep flocks, in 2005.

		Rainfed crops		Irrigated crops					
		Wheat	Olive trees	Wheat	Olive trees	Beans	Watermelons	Hot peppers	Apple trees
Production cost (TND)	min	200	200	340	750	1,200	2,500	2,500	1,500
	max			540	850	1,400	6,000	4,000	2,000
Irrigation water supply (m^3)	min			1,500	1,800	2,200	3,500	3,000	6,000
	max			3,000	2,500	2,700	5,500	4,500	7,000
Labor (days)		10	25	20	60	125	125	190	190
Yield (t)	min	0	0,6	2	1,7	10	20	10	4
	max	1	1,2	4	2,5	14	50	25	8
Price (TND/t)	min	250	700	250	700	200	50	200	500
	max	300	900	300	900	250	300	500	600
Gross product (TND)	min	0	500	500	1,300	2,200	2,000	3,000	3,000
	max	250	900	1,000	2,000	2,800	15,000	6,500	4,500
Other products		Straw thatch	Wood sheets	Straw thatch	Wood sheets	Crop residus			
Income (TND)	min	-200	300	150	500	1,000	- 1,000	500	1,500
	max	50	700	500	1,200	1,500	9,000	2,500	2,500

Table 6: Total area of rainfed and irrigated crops, water supply and labor requirement, production and income for the whole plain of Kairouan.

	Fallows (ha)	1,452
Rainfed crops	Olive groves and almond orchards (ha)	2,161
	Intercropping with olive trees (ha)	660
	Cereals (ha)	2,266
	Total area rainfed crops (ha)	4,647
Irrigated crops	Olive groves and almond orchards (ha)	2,195
	Intercropping with olive trees (ha)	2,479
	Cereals (ha)	2,232
	Melons-watermelons (ha)	2,445
	Tomatoes-hot peppers (ha)	1,587
	Beans-winter vegetables (ha)	933
	Fruit orchards (ha)	670
	Total irrigated area (ha)	10,888
Consumption	Total irrigation water (10^6 m^3)	36.8
	For vegetable cropping (10^6 m^3)	20.7
	For cereals (10^6 m^3)	5.2
	For orchards (10^6 m^3)	11.0
	Labor (10^3 days)	927.6
Production	Olives (10^3 t)	8.95
	Wheat (10^3 t)	6.75
	Watermelons (10^3 t)	44.69
	Melons (10^3 t)	28.50
	Tomatoes (10^3 t)	37.52
	Hot peppers (10^3 t)	16.56
	Total income (10^6 TND)	18.01

Based on these typologies, we aggregated the cropping area of the farms, their consumption of water and other inputs (especially labor), and their production at the scale of the whole plain (Table

6). The area of land and total production for each crop were validated with CRDA data. Total irrigation water demand was estimated at 37 million m^3, which corresponded to 46 million m^3 of extracted water for an improved transport efficiency of 0.8. This improved efficiency was due to the use of pipes to transport water from wells to drip-irrigated fields used for vegetable cropping, fruit orchards, and new olive plantations. Our estimate of water consumption corresponds to the piezometric decrease observed in the water table (Leduc *et al.*, 2004). Regarding economics, agricultural activities in the Kairouan plain produced an average of 18 million TND per year, consuming more than 900,000 days of labor. Using other methods of evaluation, Albouchi (2006) obtained the same results for cultivated areas, and for agricultural production and consumption, particularly of irrigation water. Vegetable cropping covered about 5,000 ha, part of which was in association with olive groves, and consumed 56% of the total irrigation water.

Compared to 1999, vegetable cropping covered an additional 1,500 ha. This extension was at the expense of irrigated cereals and rainfed crops. Rainfed olive groves were used to expand intercropping with vegetable crops.

3-4 How to reduce consumption of irrigation water and the lowering of the water table

We used the regional model of agricultural activities to test the effects of economic changes in farm income that led to changes in the use of irrigation water.

Water tariffs are often used to reduce water consumption (Montginoul, 1997). However, in this particular case it would be not easy because most water is extracted from private wells. Nevertheless, the CRDA considered the use of a “water tariff” through the widespread introduction of electric pumps and the pricing of electricity consumption. We tested this “water tariff” in the model using an overall increase of 50% in the cost of irrigation water. The resulting decrease in income at the regional scale was only 6.7%, while the decrease in farm income varied with the type of farm (Table 7). The decrease in farm income was more than 10% for three farm types that represent about 13% of farms and that consume 17% of total irrigation water used. The proportion of the cost of water out of the total production cost varied considerably depending on the crop: for example, it represented 22% of total production cost for irrigated wheat, 19% for “in-season” watermelons, but only 3% for early melons. The rise in the cost of water may therefore first affect irrigated cereals, which are yet encouraged by the Tunisian authorities, or in-season vegetable crops, which are cultivated primarily by small farmers.

Sales prices of watermelons and melons vary considerably depending on the date of harvest. Early products (beginning of June) generally sell for six times the prices received for in-season products (July). These prices can also vary from year to year depending on market conditions, which vary considerably with the quantities available. In our model, an overall decrease (for early and in-season products) of 20% in watermelon and melon prices led to a 16.6% decrease in regional income (Table 7). The decrease in income at the farm level was more than 15% (1½ times more than for water costs) for 10 irrigated farm types representing 70% of farms and consuming 78% of the total irrigation water used. This decrease in income exceeded 20% in 32% of farms that consumed 32% of total irrigation water.

Our simulation results suggest that changes in the market prices of products might be more effective in influencing farmers’ behavior than changes in the cost of irrigation water. Moreover, according to Montginoul (19997), the effect of economic measures on farmers is not uniform: the impact of changes varies with the type of farm and the same percentage drop in farm income would be perceived differently by small-scale or large-scale farmers.

Table 7: Effects of a 50% increase in water cost and of a 20% decrease in watermelon and melon prices on the incomes of each type of irrigated farm and an the total income of the region.

	I b	II b	IV	V a	V b	V c	VI a	VI b	VI c	VII a	VII b	VIII a	VIII b	VIII c	Region
Income (1,000 TND)	6.5	5.1	10.2	4.5	20.0	80.6	5.3	14.9	20.9	6.2	14.8	6.3	18.7	118.7	18,014
Number of farms (% total)	7.2	2.2	6.7	9.8	3.7	0.2	16.4	9.5	0.4	14.1	5.1	1.6	1.7	0.3	
Irrigation water supply (% total)	4.2	1.3	8.9	8.4	9.6	2.5	10.4	18.0	1.4	9.3	12.3	2.2	6.2	5.2	
% decrease in income due to 50% increase in water cost	5.4	6.6	6.5	11.0	7.5	9.2	4.9	5.7	7.2	5.7	9.2	12.9	11.7	8.8	6.7
% decrease in income due to 20% decrease in watermelon and melon prices	18.7	20.9	15.4	29.4	24.8	26.9	23.9	17.5	14.4	17.3	4.6	5.0	0.0	19.3	16.6

4- Discussion – Conclusion

Our method of representing agricultural activities at the regional scale enabled us to represent cropping areas and irrigation water demand for the whole plain of Kairouan in 1999 and 2005. Our main aim was not to obtain an accurate estimate of irrigation water volume and its distribution in a given year, but to evaluate the cascade of consequences for regional irrigation water demand resulting from technical, economic or institutional changes.

To slow down the demand for agricultural water, like other Mediterranean countries, Tunisian authorities introduced incentives for drip irrigation that enable water to be saved at the field scale. But the adoption of drip irrigation would generate changes in cropping patterns at the farm scale with an expansion of summer vegetable crops. As a result, simulations predicted an extension of irrigated area and of summer irrigated crops, and thus no savings in water at the regional scale, and continued overexploitation of the water table. However, this “negative” result was associated with an increase in the regional income without an increase in the volume of water extracted. The “positive” result was thus that water productivity was improved.

To prevent a further drop in the water table, new incentives are needed to encourage farmers to save irrigation water by changing their cropping pattern or irrigation practices. Our simulations showed that a drop in sales prices of summer vegetables would have a greater effect than an increase in the cost of water. But it would be difficult for the government to change market prices. This model could help to evaluate economic means to encourage farmers to reduce their water consumption by changing their cropping pattern or irrigation practices. For example, the cost of water could vary as a function of water consumption per hectare, or a water-related tax could be introduced on the sale of products that require high water consumption, etc. Our simple model would allow their effect on incomes to be computed at regional and farm scales: which farms would be the most affected and the proportion of irrigation water consumption they represent in the region as a whole. We assume that the greater the drop in farmers' incomes, the stronger and more rapid their reaction would be. But it would be then necessary to conduct others surveys of each farm type to identify the farmers’ reactions. The individual reactions could be then introduced in the model and aggregated for the entire region.

Our representation framework does not enable integration of interactions between farms (exchanges of labor or fields for example) or between production units (fodder output from grass and feed input for flocks for example). These interactions have to be "managed" outside the model. On one hand, the lack of such interactions means the model can be simple. On the other hand, changes in farm activities engender changes in these interactions that are difficult to envisage *ex ante*.

Farmers do not behave passively when faced with technical, economic or institutional changes. To analyze the consequences of the extension of drip irrigation, Feuillette (2001) interviewed farmers to account for their behavior. In the present study, we simulated the consequences of the generalization of this behavior. It would be possible to use a regional economic optimization model to identify the optimal agricultural activities for each type of farm in response to new economic or technical changes (Bartolini *et al.*, 2007). Another way would be to run the model in collaboration with the farmers who represent the different farm types, and to simulate the consequences of their behavior (Le Grusse *et al.*, 2007). In this case, the regional model would be a support tool in a collective simulation game (Piveteau, 1996; Gaudé, 2003, Le Bars *et al.*, 2003) enabling stakeholders to imagine and test individual and collective behavior in response to technical, economic or institutional changes. The simplicity of the model would be an asset for its use by stakeholders (Axelrod, 1997; Conte, 1997).

References

Albouchi L., 2006. Gestion de l'eau en Tunisie : d'une politique de mobilisation à une politique de réallocation de la ressource selon sa valorisation économique. Thesis, Montpellier I University.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. FAO 56: Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO of UN, Rome, Italy.

Andersen, E., Elbersen, B., Godeschalk, F., Verhoog, D., 2007. Farm management indicators and farm typologies as a basis for assessments in a changing policy environment. Journal of Environmental Management, 82 (3): 353-362.

Audsley,E.,1993.Labour,machineryandcroppingplanning.In: Annevelink, E., Oving, R.K., Vos, H.W.(Eds.), Farm planning. Labour and labour conditions. Computers in agricultural management, Proceedings of the XXV CIOSTACIGR V Congress, Wageningen, Netherlands, pp. 83–88.

Axelrod R., 1997. Advancing the Art of Simulation in the Social Sciences. In Hegselmann R. and Terna P. (Eds.), "Simulating Social Phenomena", Springler, Berlin: pp. 21-40.

Bartolini F., Bazzani G.M., Gallerani V., Raggi M., Viaggi D., 2007. The impact of water and agriculture policy scenarios on irrigated farming systems in Italy: An analysis based on farm level multi-attribute linear programming models**.** Agricultural Systems, 93 (1-3): 90-114.

Benoît M., Le Ber F., Mari, J.F., 2001. Recherche des successions de cultures et de leurs évolutions: analyse des données Ter-Uti en Lorraine. Agreste vision - La statistique agricole, 31: 23-30.

Bergez J.E., Leenhardt D., Maton L., Garcia F., Salles D., Amigues JP., 2005. Comment modéliser les pratiques des agriculteurs pour estimer la demande régionale en eau d'irrigation ? Communication pour le Symposium international "Territoires et enjeux du développement régional" ; Lyon, 9-11 mars 2005.

Berkoff, J., 1994. A strategy for Managing Water in the Middle East and North Africa. The World Bank, Washington, D.C.

Brooks D.B., 2006. An operational definition of water demand management, International Journal of Water Resources Development, 22 (4): 521-528.

Cantin, B., Shrubsole, D., Aït-Ouyahia, M., 2005. Using Economic Instruments for Water Demand Management: Introduction. Canadian Water Resources Association, 30: 1-10.

Capillon, A., 1993. Typologie des exploitations agricoles, contribution à l'étude régionale des problèmes techniques. Doctoral thesis, INAP-G, Paris.

Champion J, 2003. Typologie des systèmes de culture et gestion de l'eau dans un bassin versant: application à la culture de la pastèque dans la plaine de Kairouan (Tunisie Centrale) Mémoire d'ingénieur ESA Purpan, IRD Tunis.

Conte R., 1997. The necessity of intelligent agents in social simulation. In Ballot G. and Weisbuch G. (Eds.), "Applications of Simulation to Social Sciences", Hermès, Paris (France): pp. 19-38.

Cristofini, B., 1986. La petite région vue à travers le tissu de ses exploitations: un outil pour l'aménagement et le developpement rural. INRA Etudes et Recherches sur les Systèmes Agraires et le Développement, 6, 48 pp.

Dobremez L., Bousset, 1995. Rendre Compte de la Diversité des Exploitations Agricoles - Une démarche d'analyse par exploitation conjointe de sources statistiques, comptables et technico-économiques. Cemagref Editions (Ed.), Coll. « Etudes, Gestion des Territoires », 318pp.

Feuillette, S., 2001. Vers une gestion de la demande sur une nappe en accès libre: exploration des interactions resource usages par les systèmes multi-agents. Application à la nappe de Kairouan, Tunisie centrale. Thesis, Montpellier II University, Montpellier.

Feuillette, S., Bousquet, F., Le Goulven, P., 2003. SINUSE : a multi-agent model to negotiate water demand management on e free access water table. Environmental Modelling and Software, 18: 413-427.

Foster, S., Chilton, J., Moench, M., Cardy, F., Schiffler, M., 2000. Groundwater in rural development: facing the challenges of supply and resource sustainability. World Bank Technical Paper n°463.

Froukh L.J., 2007. Water demand management of the west bank. Third regional workshop on water and sustainable development in the Mediterranean, CIHEAM-IAMZ, Zaragosa (Spain), march 19-21 2007.

Gaudé P., 2003. Système Multi-Agents et Jeux: Domaines d'application et bénéfices mutuels. Observatoire Français des Techniques Avancées, Paris.

Gomez-Limon J.A, Riesgo L., 2004. Irrigation water pricing : differential impacts on irrigated farms. Agricultural economics 31 (1): 47-66.

Heinemann, A.B., Hoogenboom G., de Faria R.T., 2002. Determination of spatial water requirements at county and regional levels using crop models and GIS: An example for the State of Parana, Brazil. Agricultural Water Management, 52 (3): 177-196.

Herrero, J., Casterad, M.A., 1999. Using satellite and other data to estimate the annual water demand of an irrigation district. Environmental Monitoring and Assessment, 55: 305-317.

Jollivet, M., 1965. Une méthode typologique pour l'étude des sociétés rurales. Revue Francaise de Sociologie, 4: 33-54.

Kadi A., Feuillette S., Le Goulven P., Le Grusse P., 2005. Modèles d'exploration des dynamiques entre ressources et usages de l'eau pour une gestion intégrée des nappes souterraines. Application à la nappe de Kairouan en Tunisie. - In Le Goulven P., Bouarfa S., Kuper M. (Ed.), « Gestion intégrée de l'eau au sein d'un bassin versant », CIRAD Montpellier (CD Rom, ISBN : 2-87614-591-X), 12 p.

Landais, E., 1998. Modelling farm diversity: new approaches to typology building in France Agricultural Systems, 58 (4): 505-527.

Lardilleux, S., 2000. Fonctionnement de périmètres irrigués à différents stades d'évolution en Tunisie centrale. Analyse des irrigations par modélisation du bilan hydrique. Mémoire d'ingénieur ENGEES, IRD Tunis.

Le Bars M., P. Le Grusse, M. Allaya, J.M. Attonaty, R. Mahjoubi, 2003. NECC : un jeu de simulation pour l'aide à la décision collective. Application à une région méditerranéenne virtuelle. In « La modernisation de l'agriculture irriguée dans les pays du Maghreb », Wademed seminar, Rabat (Morocco), April 19-21 2004.

Lebart, L., Morineau, A., Piron, M., 1995. Statistique exploratoire multidimensionnelle. Chapter 2, section 2. DUNOD, Paris, pp 155-175.

Leduc C., Calvez R., Beji R., Nazoumou Y., Lacombe G., Aouadi C., 2004. Evolution de la ressource en eau dans la vallée du Merguellil (Tunisie centrale). In « La modernisation de l'agriculture irriguée dans les pays du Maghreb », Wademed seminar, Rabat (Morocco), April 19-21 2004.

Leenhardt, D., Trouvat, J.L., Gonzales G., Pérarnaud, V., Prats, S., Bergez, J.E., 2004. Estimating irrigation demand for water management on a regional scale. I. ADEAUMIS, a simulation platform based on bio-decisional modelling and spatial information. Agricultural Water Management, 68: 207-232.

Leenhardt D., Cernesson F., Mary J. F., Mesmin D., 2005. Anticiper l'assolement pour mieux gérer les ressources en eau : comment valoriser les données d'occupation du sol ? Ingénieries, 42: 13-22.

Le Grusse P., 2001. Du local au global les dynamiques agro-alimentaires territoriales face au marché mondial. Quels instruments d'aide à la décision pour l'élaboration de Stratégies Territoriales ? CIHEAM, Options méditerranéennes Série B Etudes et recherche, 32: 239-258.

Le Grusse P., Belouhchette H., Le Bars M., Carmona G., Attonaty J.M., 2006. Participative modelling to help collective decision - making in water allocation and nitrogen pollution. Application to the case of the Aveyron-Lère Basin. International Journal of Agricultural Resources, Governance and Ecology, 5 (2-3): 247-271.

Mateos L., Lopez-Cortijo I., Sagardoy J., 2002. SIMIS: the FAO decision support system for irrigation scheme management. Agricultural Water Management, 56: 193–206.

Maton, L., Leenhardt, D., Goulard, M., Bergez, J.E., 2005. Assessing the irrigation strategies over a wide geographical area from structural data about farming systems. Agricultural Systems, 86 (3): 293-311.

Mignolet C., Benoît M., Bornerand C., 2001. Différenciation du bassin de la Seine selon les dynamiques des systèmes de production agricoles depuis les années 70. Agricultures, 10 (6): 377-387.

Montginoul M., 1997. Une approche économique de la gestion de l'eau d'irrigation: des instruments, de l'information et des acteurs. Thesis, « Economie du développement agricole agro-alimentaire et rural », University of Montpellier I, Montpellier.

Nazoumou, Y., Besbes, M., 2000. Modélisation des lâchers de barrage et recharge de la nappe de Kairouan (Tunisie). In : IRD (Ed.), « Hydrologie de régions Méditerranéennes », November 19th-20th 2000, Montpellier.

Perrot, C., Landais, E., 1993. Exploitations agricoles: pourquoi poursuivre la recherche sur les méthodes typologiques? CIRAD, Les Cahiers de la Recherche-Developpement, 33 : 13-23.

Piveteau V., 1996. Prospective et territoire : apports d'une réflexion sur le jeu, Cemagref-Editions, Antony (France), 298 pp.

Rogers D.H., Lamm F.R., Alam M., Trooien T.P., Clark G.A., Barnes P.L., Mankin K., 1997. Efficiencies and water losses of irrigation systems. Irrigation Management Series, Cooperative Extension Service, Kansas State University, Manhattan, 6 p.

Rounsevell M.D.A., Annetts J.E., Audsley E., Mayr T., Reginster I., 2003.,Modelling the spatial distribution of agricultural land use at the regional scale. Agriculture, Ecosystems and Environment, 95 (2): 465-479.

Scheierling M., Loomis J.B, Young A., 2006. Irrigation water demand: A meta-analysis of price elasticities. Water resources research, 42, W01411, doi:10.1029/2005WR004009.

Tarjuelo, J.M., Martin de Santo Olalla F., Pereira L.S., 2005. Preface. Agricultural Water Management, 77 (1-3): 1-3.

Tenenhaus, M., and Young, F.W., 1985. An analysis and synthesis of multiple correspondence analysis, optimal scaling, dual scaling, homogeneity analysis and other methods for quantifying categorical multivariate data. Psychometrika, 50: 91-119.

Victoria, F.B., Viegas Filho J.S., Pereira L.S., Teixeira, J.L., Lanna A.E., 2005. "Multi-scale modeling for water resources planning and management in rural basins." Agricultural Water Management, 77 (1-3): 4-20.

Weatherhead, E. K., Knox, J. W., 2000. Predicting and mapping the future demand for irrigation water in England and Wales. Agricultural Water Management, 43 (2): 203-218.

Wichelns, D., 2003. Enhancing water policy discussions by including analysis of non-water inputs and farm-level constraints. Agricultural Water Management, 62 (2): 93-103.