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Abstract — Accurate estimation of water demand at the irrigation scheme scale is a key requirement for water management, which is made difficult by the large diversity of crops and production systems. The main objective of this study was to estimate irrigation water demand at the farm scale, taking different types of knowledge into account: (i) database study, where water demand is supposed to be the supply (L0); (ii) actual cropping pattern (L1),; (iii) actual irrigation techniques and cropping pattern (L2); and (iv) actual irrigation practices, actual irrigation techniques, and cropping pattern (L3). Farm typology makes easy this estimation as it takes into account various farm characteristics. Firstly, a farm typology was established based on 115 farms surveyed in the irrigation scheme of Borj Toumi Toungar (Tunisia), selected for the study. Secondly, climatic crop water irrigation requirements were estimated using the agro-meteorological water balance model Pilote. Typology results were used to estimate water demand at the scale of family farms taking into account different levels of knowledge Six classes of farming areas were identified based on irrigation subsystems, cropping pattern (fruit tree area, cropping vegetable area and field crop area), intensification crop level and cropped surface. Results showed that supply could not entirely cover the climatic water demand. However, it could nearly meet actual water demand at the farm scale. According to the water demand estimation at different levels, results showed that there were few changes in water demand at farm scale when moving from L1 to L2. At the opposite, actual water demand (L3) represented about half the climatic water demand (L2). Calculations based on farm classes highlighted the importance of actual farm practices. Within the same class, the difference between water demand estimation at different levels of knowledge was remarkable. Network rehabilitation is thus necessary to enable farmers to increase water delivered to crops and limit water stress**;** the collective network was conceived to deliver a flow of 0.34 l/s/ha in this sector. Given changes in farming and varietal choices, this flow proved insufficient to face the climatic water demand.

Introduction

World population is steadily growing, making the task of increasing food production a great challenge. According to the Food and Agriculture Organisation of the United Nations (FAO), most of the increase will have to come from intensified irrigated agriculture. Reasonable management of water is therefore of primary importance, especially in a situation of increasing water scarcity (ICID – CIID, 1996), and accurate estimation of water demand by agriculture is a key need for water management (Leenhardt *et al.,* 2004). Tunisia is an arid to semiarid country with limited water resources. Mobilizing new water resources is practically impossible and its costs increase as climate conditions worsen. This situation as well as population growth and improved living conditions should be taken into account to develop water demand management. Estimating water demand at the territory scale is essential since agriculture is the main water consumer. An appropriate estimation of water demand is also interesting to improve the delivery scheduling and to manage upstream controlled irrigation systems (Teixeira *et al.,* 1995). However, to reflect the actual water demand, the estimation has to include farmers' practices (Weatherhead and Knox, 2002). As little is known in general of farmers' practices more applied research focusing particularly on the on-farm level is needed (Tollefson, 1995). Crop models are very useful for water management (Bergez *et al.,* 2002), especially for planning water resources and determining irrigation requirements (Mailhol, 1992; Hernemann *et al.,* 2002). One limitation of these models is that they do not use farmers' practices. Considering each farm as unique in relation with farm practices is neither convenient nor realistic, so groups of similar farms have to be identified to determine typical or representative situations. We propose here to build estimates of the irrigation water demand using different levels of knowledge on farmers' practices. This knowledge is based on a farm typology and irrigation practices surveys. The different estimates are then compared to determine the part played by farmers' practices.

Materials and methods Case study

The irrigation scheme of this study was created in 1966; it comprises 785 ha in North Tunisia and borders Medjerda River (9.45° lat. N, 36.45°long. W). The climate is Mediterranean in the higher semiarid bracket. Annual rainfall is about 450 mm with intra- and inter-annual irregularity, and potential evapotranspiration (Penman formula) is about 1120 mm. The irrigation scheme is subdivided into two sectors: a sector with water gravity delivering (G) to an area of 425 ha, and another operated under pressure (P) delivering to an area of 360 ha. In the project document of the scheme it was planned to grow several crops in each sector. Irrigated vegetables and fruit trees combined with rainfed field crops were envisaged for sector G, and irrigated vegetables, combined with rainfed field crops for sector P. Water service delivery of the irrigation scheme was performed by a pumping station built on Medjerda River upstream of Laroussia dam.

Farm typology

An exhaustive survey of the farms was carried out in 2005 to describe farmers' practices. It was divided into three main sections: the first section focused on the cropping pattern establishing the area of each crop, irrigated or not, and intercropping area, the second on irrigation systems, and the third on irrigation practices. A typology was implemented based on the positivist method (Mignolet C. *et al.,* 2002) to characterize variables of the studied farms. The choice of farms and variables for the typology was not neutral: after examining the data, farms of relatively disproportionate sizes were omitted. Eight of the following variables were kept for the typology:

– G(%), S(%), D(%) were the percentages of areas irrigated by surface[gravity?], sprinkler, and drip irrigation systems, respectively
– UAA, useful agricultural area
– Atr/UAA, Aveg/UAA were fractions of fruit tree and vegetable irrigated areas, respectively, compared to the useful agricultural area
– Afc/Sas was a fraction of the field crop irrigated area compared to the cropped area (Ca)
– Ifr, intensification farming rate.

Water demand evaluation method

The crop water requirement evaluation method used the Pilote model (Mailhol *et al.,* 1997, Maihol *et al.,* 2004). This model estimates soil water balance and crop yield assuming that water is the sole limiting factor. Compared to other crop models, Pilote requires a low number of parameters, and can be easily calibrated (Mailhol *et al.,* 2004). It uses daily climatic data such as solar radiation, average air temperature, rain, and evapotranspiration calculated with Penman equation (Allen *et al.,* 1998). Soil parameters used were volumetric water content at field capacity (H_{fc}), as well as volumetric water content at wilting point (H_{wp}). For climatic estimation of crop water irrigation requirements, data concerning irrigation starting, ending rules and other parameters of initialization and irrigation scheduling were summarized in Table I.

Table I. Parameters governing soil water balance and irrigation practice.

Crop	Crop parameters			Irrigation parameters		
	Z_{max}(m)	RAW/AW	$K_{c\ max}$	Threshold ratio (%)	Istart	Istop
Tomato	1	0.55	1.2	50	06/03	20/07
Melon	0.5	0.55	1.05	50	01/05	30/08
Pepper	0.5	0.55	1.05	50	05/04	30/08
Wheat	1	0.55	1.2	75	16/11	20/05
Sorghum	1.2	0.55	1.2	65	10/05	25/08
Olive	1.5	0.55	0.7	75	01/07	15/09
Peach	1.2	0.55	0.9	60	01/02	31/10

Z_{max} Maximum root depth;
AW Maximum available water reservoir;
RAW Readily available water reservoir;
$K_{c\ max}$ Maximum crop coefficient ;
Threshold(%) Threshold ratio to set on irrigation;
Istart Date of irrigation starting;
Istop Date of irrigation stopping.

Simulations on meteorological daily data over a 22-year period (1983 – 2005) allowed to estimate crop water requirements and to propose an irrigation scheduling program for the whole crop development cycle, according to Table I data. We chose to keep simulations for which the actual evapotranspiration was slightly lower than the maximum evapotranspiration because farmers usually did not irrigate at the MET rate (MET = maximum evapotranspiration). Climatic water demand (theoretical) was estimated based on the month with a peak, i.e. July; simulated net water requirements during July for each year and each crop were submitted to a frequential analysis to determine median net requirements for July. A probability level of 50% represents median net requirements (Teixeira *et al.,* 1995). Gross water requirements, which are supposed to be the irrigation water demand, can be estimated by using medium net crop water requirements and efficiency coefficients of each irrigation system. Irrigation efficiencies are commonly 0.6 for furrow irrigation, 0.8 for sprinkler irrigation, and more than 0.9 for drip irrigation (Rogers *et al.,* 1997). In the irrigation scheme, irrigation efficiencies were 0.6, 0.7 and 0.8 for surface, sprinkler and drip irrigation, respectively. Irrigation scheduling was based on the crop with the highest water requirements; for example, if tomatoes were intercropped with olive-trees, tomatoes were irrigated. Irrigation water demand during July in different family farm types, according to typology, was estimated at different levels of knowledge: (i) based on the data of the basic project study, (ii) considering the actual cropping pattern, (iii) considering the actual cropping pattern and actual irrigation techniques, (iv) considering both previous levels and irrigation farmers' practices. Typology results were used to estimate water demand at three levels: L1, L2 and L3. The determination of water demand of the standard farm in each class allowed to estimate water demand of all family farms using the number of farms in each class

Level 0 (L_0): basic project study

The irrigation network was conceived on the basis of a standard cropping pattern, where water demand was supposed to be supplied by a flow of 0.6 l/s/ha in the under pressure sector to irrigate cropping vegetables and of 0.43 l/s/ha in the gravity irrigation sector to irrigate cropping vegetables and fruit trees. Supply was determined based on the farm surface area in each sector and was supposed to meet water demand.

Level 1 (L_1): actual cropping pattern

The actual cropping pattern was determined by aerial photographs taken at different dates. In this case, it was possible to know the surface area for each crop of the irrigation scheme but it was usually impossible to identify the irrigation system used in each field. Such a water demand will account for actual cropping pattern chosen by farmers, which considerably differs from planned cropping patterns.

Level 2 (L_2): actual cropping pattern and irrigation systems

Using a survey carried out on farms determining cropping patterns and actual irrigation systems enables the theoretical or climatic irrigation water demand estimation. Irrigation system efficiencies were used to calculate water demand to match water irrigation needs.

Level 3 (L_3): irrigation practices

Even in level 2, the irrigation water demand was theoretical. This was the reason why farm irrigation practices were introduced at this level to estimate the actual water demand. Enquiries regarding farmers' practices revealed that they all adopted the same technological approach. For example all the farmers used the gravity surface technique to irrigate one hectare of olive trees over three days at a rate of 8 h/day and with a flow of 10 l/s. As they irrigated twice during July, water demand could be determined.

Results and discussion Data preliminary analysis

Despite the distinctions between both sectors in terms of water distribution mode, the three techniques of irrigation were present in each sector. Farmers used surface, sprinkler and drip irrigation systems in both sectors (Fig 4) and sometimes even on the same farm. A high number of fields with drip irrigation were observed throughout the irrigation scheme, irrigation was also applied to field crops that were intended to be rainfed. A large area of vegetable cropping and field crops in association with olive plantation was also observed.

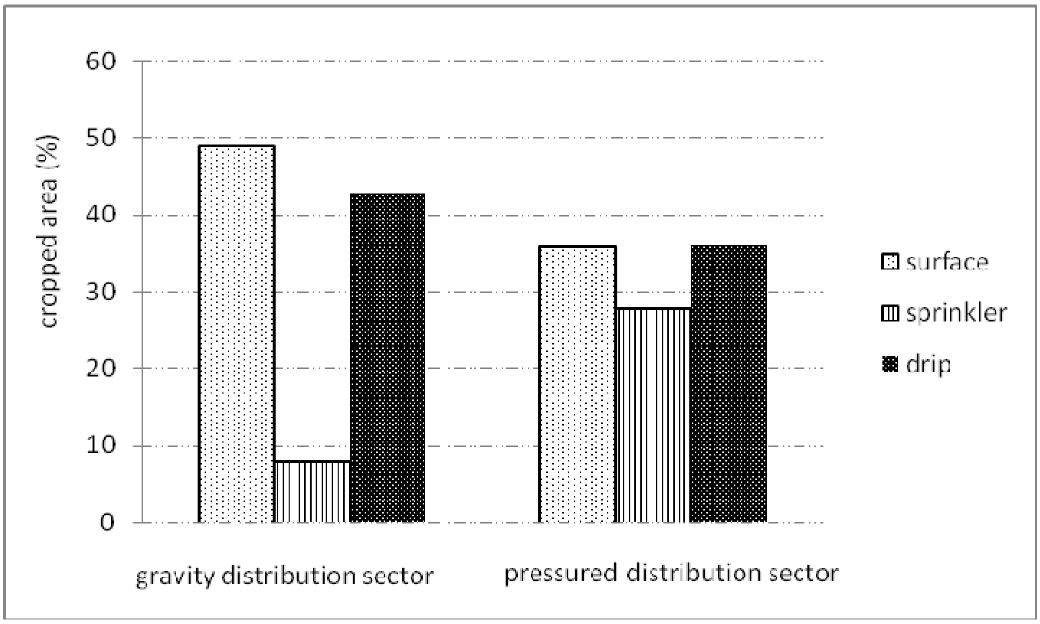

Figure 4. Distribution of irrigation techniques in the sectors.

Farm classification

The hierarchical classification distinguished six farm groups. Homogenous groups were those for which we could more or less make the same recommendations (Byerlee *et al.,* 1980). In class 1 farm tended to have field crops irrigated by sprinkling. In classes 2 and 5 they were similar in that they grew fruit trees using the gravity delivery system. But farms in class 2 differed from those in class 5 in that they had introduced drip irrigation and were more intensive. Class 3 were farms with a high cropping intensification rate (1.82). In class 4 were farms that had the most frequent use of drip irrigation; this technique was adopted in 73% of the cropped area. Characteristics of the average farm of each class, resulting from the typology, are presented in Table II.

Table II. Characteristics of the average farm of each irrigated farm class.

Class	UAA(ha)	Ca(ha)	ifr	G(%)	S(%)	D(%)	Atr/UAA	Aveg/UAA	Afc/Ca
1	7.36	7.82	1.07	24	55	21	0.28	0.17	0.62
2	6.50	9.46	1.47	73	0	27	0.70	0.34	0.52
3	7.01	12.82	1.82	47	28	25	0.50	0.61	0.15
4	6.93	7.96	1.16	21	5	74	0.44	0.54	0.19
5	6.19	6.20	1.00	93	0.00	7	0.71	0.05	0.22

Updating crop water requirements

Simulation results with Pilote made it possible to estimate net water irrigation requirements during July of each year. From the frequential analysis on these requirements, median requirements for each crop were obtained and summarized in Table III.

Table III. Median crop water requirements during July.

Crop	Net requirements (mm)
Tomato	190
Melon	170
Pepper	180
Olive	180
Peach tree	140
Sorghum	120

These results were needed to estimate water demand at farm scale and at different levels of knowledge.

Evaluation of water demand

Ex ante evaluation of irrigation water demand (L0)

Irrigation water demand envisaged by the initial project document at this level was supposed to be the supply. The network was designed to provide a flow of 0.43 l/s/ha and 0.6 l/s/ha in the sector using gravity and the sector under pressure, respectively, and functioned round the clock in July, supplying 189,802 and 530,323 m^3 of water, respectively.

Table IV. Water supply during July with round the clock functioning.

Sector	Area (ha)	Dfc(l/s.ha)	Supply(m^3)
Gravity irrigation	164.8	0.43	189,802
Under pressure	330	0.6	530,323
Total			720,125

Then water demand at family farm scale according to the basic study was supposed to be 720,125 $m^{3.}$

Evaluation of irrigation water demand using only the cropping pattern chosen by farmers (L1)

At this level we assumed that we knew the actual farm cropping pattern, so we can use the results of typology and refer only to the actual cropping patterns as indicated in the following table.

Table V. Characteristics of the average farm of each class referring to the cropping pattern.

				Aveg			Afc		
class	UAA(ha)	Ca	Atr	fallow	int	tot	fallow	int	tot
1	7.36	7.8	2.1	1	0.1	1.1	3.9	0.5	4.4
2	6.5	9.5	4.5	1.2	0.9	2.1	1.4	1.1	2.5
3	7	13	3.5	2.2	2	4.2	3.0	1.9	5
4	6.9	8	2.9	2.5	1.2	3.7	1.0	0.2	1.2
5	6.1	6.2	4.4	0.3	0	0.3	1	0.3	1.3

int: crops in association with trees.

All farms of classes 1, 3 and 4 belonged to sector P. The majority of farms in classes 2 and 5 belonged to sector G except some which were located in the under pressure sector. For this reason, irrigation water demand calculations of the average farm of classes 2 and 5 were made depending whether (i) the average farm was in the sector using gravity (G), or (ii) in the under pressure sector (SP). Knowing the number of farms for each class in each sector, it was possible to calculate the irrigation water demand for all farms. Water demand was considered to be the gross requirement.

Table VI. Irrigation water demand per class during July (L1).

Class	Sector	manpower	Gross requirement/medium farm	total/class
1	SP	15	7,698	115,470
2	SP	3	12,068	36,203
2	G	11	14,079	154,870
3	SP	14	12,446	174,245
4	SP	13	13,746	178,701
5	G	16	12,864	205,827
5	SP	4	11,026	44,106
Total				909,421

Taking into account only the actual cropping pattern, the irrigation water demand at the family farm scale was 909,421 m^3, i.e. about 189,296 m^3 more than the supply.

Evaluation of irrigation water demand using the cropping pattern chosen by farmers and actual irrigation systems (L2)

Farmers had integrated their own practices to reach their objectives, which relate to economic purpose, labour cost and hydraulic context. At this level, results of the typology, which referred to the practised cropping pattern associated to the irrigation techniques, were used. So, in addition to data in Table IV, information concerning irrigation techniques from table VI was used. The emergence of drip irrigation was apparent all across the irrigation scheme and up to 73% of the area in class 4 was drip irrigated. Even though farms in class 2 were mainly in sector G, 27% of the area was irrigated by drip systems. Farmers used individual pumps to set their water systems under pressure. At the opposite, a considerable area in sector P was irrigated with surface techniques. For example, in class 3, 47% of the area was irrigated with this technique.

Table VII. Characteristics of the average farm of each class referring to irrigation techniques.

Class	G (%)	S (%)	D (%)
1	24	54	22
2	73	0	27
3	47	28	25
4	22	5	73
5	93	0	7

Table VIII. Irrigation water demand (m^3) of all farms during July (L2).

Class	Number of farms	Gross requirement/medium farm	Class total
1	15	7,999	119,979
2	14	12,429	174,006
3	14	12,806	179,290
4	13	12,967	168,570
5	20	12,636	252,721
Total			894,566

Taking into account actual cropping pattern and irrigation systems, the irrigation water demand at the family farm scale was 894,566 m^3.

Evaluation of irrigation water demand using the cropping pattern chosen by farmers, actual irrigation systems and actual farm irrigation practices (L3)

Water demand at the family farm scale taking into account cropping pattern, real irrigation systems, and practices was 554,673 m^3 (Table VIII), i.e. a much lower volume than that calculated at previous levels.

Table IX. Irrigation water demand at irrigation scheme level during July (L3.).

Class	manpower	Gross water requirement/medium farm	total/class
1	15	5,449	81,735
2	14	8,017	112,238
3	14	6,908	96,712
4	13	8,236	107,068
5	20	7,846	156,920
Total			554,673

Discussion

In sector G, climatic water demand was only 56% of the supply (table IX). Considering that the collective network was designed to deliver a flow of 0.34 l/s/ha, and that farming and crop choices changed, the flow was insufficient to meet the climatic water demand. However, water supply matched at 89% the estimated actual water demand. Taking into account farmers' irrigation practices, the remaining water demand could be provided by private wells. In the under pressure sectors, water supply covered about 95% of climatic water demand. In fact at Level L3), water demand was only 64% of the supply.

Comparison of water demand at levels L1 and L2 (Table X) showed that there were no major changes in water demand at the family farm scale because of the compensation obtained from irrigation system conversion: In sector G, part of the area converted to under pressure systems. The conversion improved irrigation efficiency but generated extra costs in materials and energy. In sector P, 30% of the area converted to surface irrigation systems. With regard to farmers' irrigation practices (L3), the used volumes accounted for only approximately 60% of climatic water demand (L2).

Table X. Comparison of water supply with water irrigation demand depending on the knowledge level and sector.

	Supply/Demand (%)		
Sector	L1	L2	L3
SP	97	95	156
G	53	56	89
total	79	80	130

Table XI. Comparison between water demand estimations at different levels of knowledge.

Sector	Demand (L2)/Demand (L1) (%)	Demand (L3)/Demand (L2) (%)
SP	101	61
G	94	63

Analysis at farm class level showed the following: In sector P, efficiency markedly improved in class 4 where 73% of the area switched from sprinkler to drip irrigation systems (table XII). Water supply within this class decreased by 6% from L1 to L2. Conversely, efficiency regressed in classes 1 and 3 where 24 and 47%, respectively, of under pressure systems switched to surface irrigation. In sector G, efficiency remarkably increased in class 2, where 27% of surface irrigation systems switched to localized irrigation; water supply in this class decreased by 9% from L1 to L2.

Table XII. Water demand comparison at different levels of knowledge in each class.

Class	sector	Demand(L2)/Demand(L1) (%)	Demand(L3)/Demand(L2) (%)	G%	A%	L%
1	SP	104	68	24	54	22
2	majority G	91	65	73	0	27
3	SP	103	54	47	28	25
4	SP	94	64	22	5	73
5	majority G	101	62	93	0	7

Class 3 was characterized by a significant farming intensification rate (1.82), but intensification could not be linked to irrigation because farmers of this class applied the lowest amount of irrigation: actual water demand represented only 54% of climatic water demand.

Summary and conclusion

This study presented water demand estimation using different types of knowledge for an irrigation scheme, in the low valley of Medjerda, in the north of Tunisia. A survey was carried out in 2005 to characterize farms in the irrigation scheme. The scheme was divided into two sectors: a sector with water supplied by gravity (for surface irrigation systems), and an under pressure sector (for sprinkling systems) designed to deliver a flow of 0.34 l/s/ha and 0.6 l/s/ha, respectively.

Survey data analysis showed that there was a switch in each sector from under pressure irrigation to surface irrigation and private pumping systems. A typology highlighted the presence of six farm classes (a non irrigated one excepted).

Irrigation water demand was estimated using different levels of knowledge: the actual cropping pattern only, level 1 (L1); the actual cropping pattern and irrigation techniques, level 2 (L2); the actual cropping pattern, irrigation techniques, and irrigation practices, level 3 (L3).

Results showed that:
– in sector P, the network supply managed to cover about 95% of climatic water demand but actual water demand was only 64% of the supply;
– in sector G, supply could only cover 56% of climatic water demand. However the actual water demand was covered.

Irrigation system conversion did not generate major changes when moving from L1 to L2:
– in sector P, efficiency improved when sprinkler systems were converted to drip systems, but regressed when sprinkler systems were converted to surface irrigation;
– in sector G, efficiency improved as a result of a farm class converting as much as 27% of surface irrigation to dripping systems.

At the farm scale, it was not necessary to consider the techniques used by the farmers to estimate water demand:
– in the under pressure sector, the difference in estimates between L1 and L2 was only 1%. This was due to compensation results when converting to other irrigation techniques. In some areas, efficiency improved and in others it declined;
– in the sector using gravity, the difference in estimates between L1 and L2 was 6% as efficiency improved

when surface irrigation was switched to under pressure systems. Also, in each sector, actual water demand (L3) was about 60% of climatic water demand.

Evaluation at farmers' class level appeared useful to highlight the importance of techniques and practices used by farmers. This was actually verified for a farm class in sector G. The difference between estimates at L1 and L2 was 9%. Similarly, in another farm class in the under pressure sector, water demand estimation at level L2 was lower by 6%. Network rehabilitation is thus necessary to reduce crop stress.

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