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Considering groundwater use to improve the assessment of groundwater pumping for irrigation in North Africa

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Abstract

Groundwater resources in semi-arid areas and especially in the Mediterranean face a growing demand for irrigated agriculture and, to a lesser extent, for domestic uses. Consequently, groundwater reserves are affected and water-table drops are widely observed. This leads to strong constraints on groundwater access for farmers, while managers worry about the future evolution of the water resources. A common problem for building proper groundwater management plans is the difficulty in assessing individual groundwater withdrawals at regional scale. Predicting future trends of these groundwater withdrawals is even more challenging. The basic question is how to assess the water budget variables and their evolution when they are deeply linked to human activities, themselves driven by countless factors (access to natural resources, public policies, market, etc.). This study provides some possible answers by focusing on the assessment of groundwater withdrawals for irrigated agriculture at three sites in North Africa (Morocco, Tunisia and Algeria). Efforts were made to understand the different features that influence irrigation practices, and an adaptive user-oriented methodology was used to monitor groundwater withdrawals. For each site, different key factors affecting the regional groundwater abstraction and its past evolution were identified by involving farmers' knowledge. Factors such as farmer access to land and groundwater or development of public infrastructures (electrical distribution network) are crucial to decode the results of well inventories and assess the regional groundwater abstraction and its future trend. This leads one to look with caution at the number of wells cited in the literature, which could be oversimplified.

Keywords: irrigation; agriculture; groundwater management; North Africa

1. Introduction

It is increasingly recognized that irrigated agriculture in North Africa is more and more supported by the use of groundwater, despite the historical implementation of large-scale public surface irrigation schemes. According to Kuper et al. (2016), groundwater supplies more than 500,000 farms in Algeria, Morocco and Tunisia and pumping wells irrigate continuously growing areas now estimated at more than 1.75 million ha. Such an economic development strategy largely relies on groundwater resources that have been prone to severe depletion since the start of their intensive exploitation nearly 40 years ago. The future of this groundwater economy is thus now questioned whilst the total groundwater reserve is generally poorly known. Before the massive groundwater development, the centralized decision-making systems did not have to pay much attention to assessing groundwater abstraction. But having a blurred picture of the situation is now making control and regulation difficult. Groundwater abstraction is highly dominated by private initiative, so pumping wells are isolated (outside classical irrigation schemes) and installing monitoring equipment such as water meters is usually badly received by farmers, especially when the experiment lasts a long time. The density of the wells is usually high (several per km²) and they are scattered in the landscape with a very active turnover between abandoned, deepened and new drilled wells due to water table decline. Estimating groundwater abstraction from small individual farms is then challenging and this is the reason why withdrawals of small individual farms are usually indirectly estimated. For instance, Ruud et al. (2004) estimated groundwater abstraction as the closing term of the water budget and Martínez and Martínez (2010) used the water table fluctuation method (Healy and Cook, 2002). Hunink et al., (2015) used remote sensing to estimate vegetation water demand linked to groundwater pumping. Liu et al. (2015) estimated groundwater pumping by combining signal analysis and modelling of the water table fluctuation. Some other authors combined remote sensing to compute crops' water demand and water balance approaches, like Zhu et al. (2009) on the Hai basin in China. Ahmad et al. (2005) did the same in Pakistan using the concept of 'net groundwater use'. In addition to using indirect approaches, these studies focus only on 'groundwater accounting' (consumptive use only) and not on 'groundwater use' (meant as consumptive use, groundwater access, decision making etc.). Yet it is especially behind the groundwater use that lies most of the information about groundwater abstraction mechanism and future trend. Groundwater pumping is not only a discharge value but it is also the result of complex decision making processes. As argued by De Stefano (2015), the 'core problems related to groundwater lie in agricultural uses [and] economic, political and social reasons prevail on legal obligations set by national and supranational authorities'. Current methods to determine regional groundwater withdrawals underestimate the interactions of complex, anthropized aquifer systems, ignore the user, and do not provide keys for potential management options. They usually provide a steady picture of an evolving situation. This is especially problematic for the rapidly evolving groundwater economy in the Mediterranean, as it amounts to making decisions on situations that no longer apply. This makes it impossible to consider the dynamics that drive groundwater use and to provide appropriate scenarios for the future.

This paper aims to point out the need for understanding the dynamics of groundwater use when estimating the regional groundwater abstraction for irrigation of individual farms. It also aims to draw

attention to the consequences of these dynamics on the prediction of the development of the withdrawals. The analysis was undertaken using a user-oriented methodology (taking users as the starting point of the analysis and involving them in the study) on three small regions in North Africa as a way to take stock of both the current situation and the decision making processes. The final objective is to contribute to recent debates on groundwater governance, assuming that 'Improvements in groundwater management require strategies to change human behavior' (Mitchell et al. 2012).

2. Presentation of the study sites

2.1. Three similar Mediterranean sites in North Africa

The study sites in North Africa were the Saïss plain in Morocco, the Kairouan plain in central Tunisia and the Ziban region near Biskra in Algeria (Figure 1). The climate is typically Mediterranean with erratic and low annual precipitation (from 500 mm/year in the Saïss and 300 mm/year in Kairouan to 100 mm/year in the Ziban) during autumn, winter and spring and with very high potential evapotranspiration during the hot summer (1500-2000 mm/year). The drainage network is highly intermittent with no perennial surface water. Groundwater reserves are abundant with large shallow to deep reservoirs that are intensively exploited. In the Kairouan plain, the Plio-Quaternary aquifer is thick (up to 700 m), with a shallow unconfined to semi-confined water table (20-60 m below ground level). In the Saïss, the shallow Plio-Quaternary aquifer is poorly productive and pumping wells draw water from 200 to 300 m in the deep Liassic confined aquifer. In the Ziban, the two main confined aquifers of the Continental Terminal are exploited. The fissured Eocene limestone and the Mio-Pliocene sand aquifer are tapped up to 600 m deep (Aidaoui, 1994). Exploited aquifers of the three sites have presented a general drop of the piezometric heads over the last 40 years, from 30 m in the Kairouan plain (Jerbi et al., 2014) to 90 m in the Saïss (ABHS, 2011) and in the Ziban (ANAT, 2003).

At the three sites, the intensification of agriculture since the 1970-1980s has relied on groundwater supply except for some small surface irrigation schemes connected to dams. The main irrigated crops are high value horticultural crops, cereals, orchards and palm groves and the intensification has induced a transition from subsistence to market farming. Public actors try to respond to the economic development challenge. The agricultural administration aims to develop crop production and yield, whilst the water administration advocates water savings and water resource sustainability. Private actors, for their part, are trying to improve their livelihood or simply making money in various ways, which are beyond the purpose of this paper.

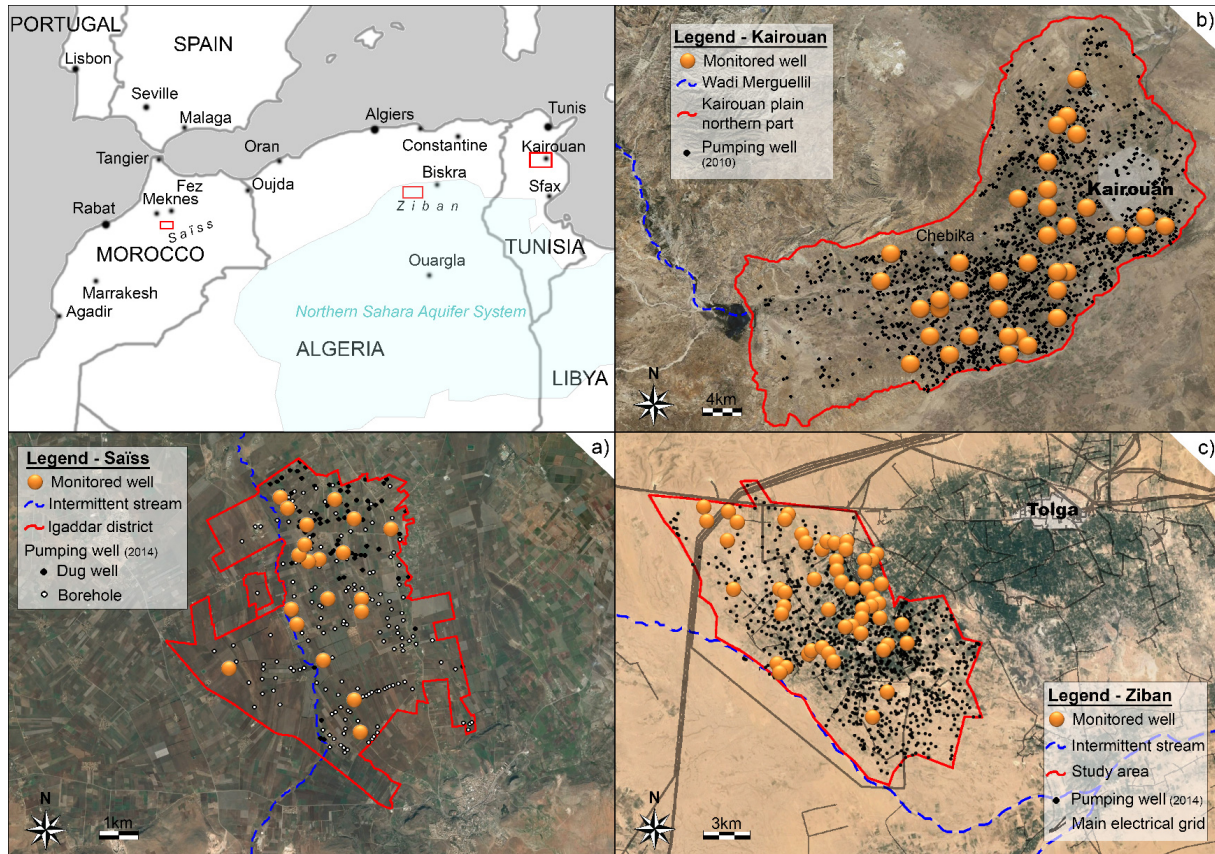


Figure 1: maps of the three study sites: a) the Saïss plain; b) the Kairouan plain; c) the Ziban region (image 2016 ©CNES/ASTRIUM)

2.2. Three contrasted modes of access to groundwater

The three case studies present substantial differences regarding modes of groundwater management and State involvement. In the Saïss and Kairouan plains, agricultural areas are mainly bounded by the horizontal limits of the aquifers, with little potential for expansion. In contrast, the agricultural territory in the Ziban is small compared with the very large cross-border fossil aquifers shared by Algeria, Tunisia and Libya (Northern Sahara Aquifer System). In the Saïss, the expansion of groundwater irrigation depends on the conversion of large areas of rainfed agriculture to irrigated agriculture. On the groundwater front, the main constraints are linked to the limited financial capacities of the owners to invest in wells. But new investors from Moroccan cities are progressively purchasing these lands and make new deep boreholes. All these wells are private and individually managed.

In the Kairouan plain, the area is almost completely occupied by farms which combine irrigated and non-irrigated agriculture. The tendency is to intensify agriculture, not necessarily with additional wells, but by the deepening of existing wells to increase their capacity. The Tunisian State has invested in public and collective wells in some areas whereas others are private and individually managed.

In the Ziban, very large nomadic pastoral areas are now rapidly converted to irrigated agriculture with no apparent restriction on groundwater access. In these extensions, the main cultivated crops are horticultural crops under greenhouses and date palm groves. The expansion is accompanied by the

development of public infrastructure such as roads (for transport of agricultural products) and electricity networks (for deep groundwater pumping). The access to groundwater is mainly private, with a few public wells.

3. Methodology

3.1. A user-oriented approach

The methodology was designed to be adaptive and to involve the users. Several ways of measuring the pumping rates for irrigation were sought, and described hereafter, in order to cater for different local situations and different constraints. The users were explicitly integrated in the approach as they were fully aware of, and contributing to the assessment process. The knowledge was shared in both directions (see Ameer et al., 2017a). Farmers provided information about the configuration of the irrigation systems, about their agricultural practices and strategies, constraints etc. and they obtained information about the water resource from the study (drop rates of the water table, thickness of the saturated zone, depth to the water table, flow rates etc.).

Beyond the measurable pumped volumes lies the whole decision making process and motivational aspects that explain these groundwater withdrawals. The proposed methodology relies on a shared knowledge process and reveals groundwater uses through the understanding of users' behavior. Surveys were carried out among the different actors related to groundwater pumping (farmers, administration, drillers etc.). Questionnaires with open and closed questions and open discussions were conducted with farmers all along the monitoring process. Questions to farmers pertained for instance to the configuration of the irrigation system (related to the total dynamic head), the cropping pattern and cropping calendar and discussions were more about their personal history in the area, their concern about the water resource, etc. Statistics (well inventory, land use etc.) and geographical information were exchanged with the local administrations (agricultural and water services). Information was gathered from electricity suppliers about power network characteristics, pricing and invoices, development policies and future extension plans. Regulation authorities provided the prevailing water policies and the past and future policy of incentives for irrigation development and groundwater pumping.

3.2. Monitoring the pumping wells

Monitoring of individual pumping wells at a large scale is a highly sensitive issue. Instruments are usually not accepted because farmers do not want to risk any disturbance on their irrigation system and feel suspicious to see their practices closely monitored. It is considered as an intrusion. Further, expensive monitoring equipment can be quickly damaged without producing any data. The monitoring equipment must be transparent for the farmer and the purpose of the monitoring must be well understood to be accepted.

The approach was partly inspired from the monitoring method developed and fully described in Massuel et al. (2009). Small self-sufficient (self-powered and programmable) data loggers record the temperature of a transducer fixed with duct tape on the outlet pipe coming from the well. The pumping duration is then determined by identifying the periods within temperature time-series where the temperature of the

pipe is balanced with groundwater temperature. The method is cost effective and well accepted by the farmers because it is unobtrusive and non-invasive for the irrigation equipment. The data logger has to be regularly downloaded which enables continuous interaction with farmers to exchange on their irrigation and cropping practices. The pumped volume V_{pump} is then determined using the mean flow rate \bar{Q} of the irrigation system over a period i of stable flow rate and n identified pumping periods of duration t as follows:

$$V_{\text{pump}} = \sum_{(i,n)} \bar{Q}_i \times t_n \quad (1)$$

Depending on the monitoring constraints (time, location, cost etc.), the mean discharge can be assessed with different methods but involves various levels of confidence (ultrasonic flowmeter, water meter, bucket method, calculation of pressure loss etc.). For instance, ultrasonic metering is well suited to measure the mean flow rate without disturbing the irrigation system or the irrigation practices of the farmer. The instant or averaged flow rates (over 1h) are measured under pressure flow and thus close to the usual rates. But the equipment is rather costly. The bucket method represents a good alternative; it is cheap and can be done by farmers, but engenders more uncertainty. Filling up a 200 L bucket provides a very good estimate of the pumping discharge for flood-furrow irrigation systems.

Obviously, the best assessments can be expected when the flow rate is stable in time, but it is regularly affected by water table fluctuations, voltage fluctuations, change in irrigation system configuration etc. The measurement frequency has to be adapted to the flow rate fluctuation. Steady conditions mean a lower frequency of measurement. The change in irrigation system configuration can be easily reported by the farmer as they are involved in the process.

When the power source is electricity, collecting electricity bills or monitoring the electricity meter can be a good way to estimate groundwater withdrawals. The relationship between power consumption and discharge has to be calibrated or, failing that, to be calculated knowing the hydraulic characteristics of the pump.

As presented above, the approach was developed to enable multiple options to adapt and find the best compromise in the field. In other words, the specific context of each site determined the measurement method implemented. The monitoring of the pumping volume was completed by gathering meta-information (related to the exploitation) in order i) to sample representative farms and ii) to document the groundwater uses. The sampling methods were based on a descriptive statistical analysis of the data from large inventories and adapted to each context.

4. Results: behind groundwater withdrawals, the groundwater use

This section explains how the groundwater abstraction assessment method was adapted to suit the local characteristics of each site. Results about the regional abstraction assessments are presented and put in perspective of relevant groundwater use related features, gathered from the exchange with actors or observed in the field.

4.1. The Saïss plain

4.1.1. Groundwater pumping emergence

The experiment showed that the 4,200 ha of the rural district of Iqaddar in the Saïss plain represent a juxtaposition of different farming systems. Groundwater exploitation for agriculture rapidly took momentum in the 1980s and the groundwater irrigated areas increased rapidly due to successive droughts and the availability of affordable new pumping technologies. The access to groundwater was first undertaken by small farms through shallow dug wells (10 to 50 m) using small diesel motors to capture groundwater in the phreatic aquifer (i.e. Plio-Quaternary). But the poor hydrodynamic properties of the aquifer rapidly led to severe drawdown and dug wells could only be operated for a few hours a day. In the late 1990s, farmers equipped deep boreholes (150 to 280 m) with submersible pumps with vertical axis, driven by subsidized energy supply (gas) fostering the use of modified powerful old car engines. A much larger groundwater resource confined in the Liassic aquifer was then accessible and boreholes could be operated 24 hours a day with no critical drawdown.

4.1.2. Groundwater abstraction assessment

A total of 377 farms and 430 pumping wells were identified in the Iqaddar district based on regular field survey. A classification was performed considering the access to groundwater, the access to land and the farming systems to enable the selection of 18 representative farms within 5 groups regarding the pumping and irrigation practices (Ameer et al, 2017b). The temperature monitoring method was applied (see section *Monitoring the pumping wells*) using the *Thermochron iButtons* (Maxim Integrated Products Inc.) over the 2013-2014 irrigation season. Whilst the method was very effective to monitor the duration of pumping, difficulties arose in determining the flow rate of the pumping equipment. The flow rate in the Saïss can be modulated by the farmer (engine throttle) depending on the part of the farm to be irrigated. Fluctuations can also be related to the energy supply with unstable installations unable to deliver a steady supply (both for gas bottles or electricity). The flow rate was measured using an ultrasonic flowmeter (Minisonic P). The method was adapted by increasing the flow measurement frequency combined with the regular field observations (every 10 to 15 days) about the irrigation practices (i.e. irrigated type of crop, irrigated plot, etc.). It was validated with 3 pumping wells equipped with a water meter. The measured flow rate for each well was compared to the reference flow (water meter readings divided by the total duration of pumping). The relative mean discrepancy between the two flow rates was found to be acceptable (2.6%). The results of the monitoring of the 18 dug wells and boreholes are plotted on Figure 2.

The broad picture shows boreholes considerably more exploited than dug wells. This is the logical consequence of deep boreholes tapping the highly productive Liassic confined aquifer. Some can exceed 30 L/s, but in the sample, the mean annual flow rate was around 7 L/s (from 3 to 12 L/s) yielding a total of 40,000 m³/year on average for a mean pumping duration of 1,600 hours/year. The mean annual flow rate of the dug wells was nearly 5 L/s (from 3 to 7 L/s), surprisingly only 30% lower than boreholes. Actually, the low yield of the phreatic aquifer forces the farmers to use the wells as reservoirs. The aquifer is drained in the well-shaft that fills up during the night and the storage is drawn during the day. The

installations are also prone to high breakdown rates. The main difference is thus the lower mean annual pumping duration limited to 1,000 hours, and the irrigation never exceeded 7 hours/day. As a result, the mean annual groundwater abstraction from a dug well was estimated to be twice as low as boreholes, i.e. 17,000 m³.

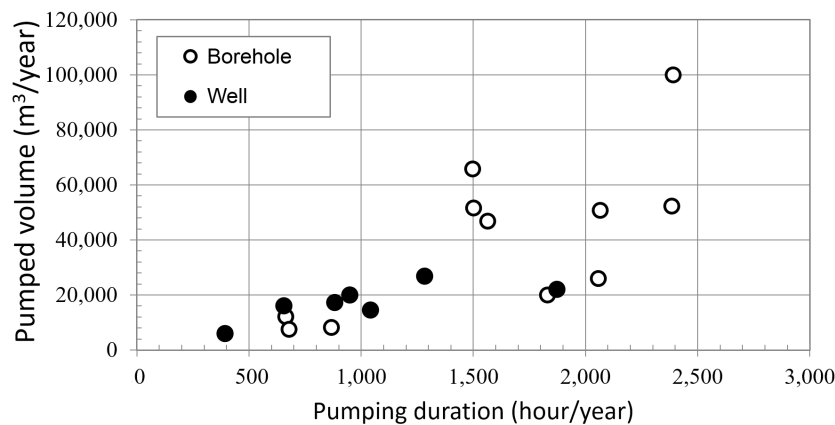


Figure 2: relationship between the annual pumping duration and the annual pumped volume of the dug wells and boreholes

In the study area, among the 430 pumping wells (dug wells and boreholes) identified, only 240 were actually in use during the period 2013-2014 (55%). A significant number of the shallow wells were dry (48%), while some others were not used due to the financial difficulties of small farmers producing for a saturated market with volatile prices. Considering the total number of 75 dug wells and 165 boreholes in use over the Iqaddar district, the total groundwater abstraction assessment in 2014 would be 7.9 hm³.

It was noticed that dug wells were usually used for irrigating relatively small plots (1-2 ha) and associated to a diversified farming system with short cycle irrigated crops (mainly onions or potatoes). The groundwater level drop of the phreatic aquifer intensifies the water access failure for the well owners. The borehole now stands for water access security and farmers who can afford it prefer this equipment.

4.1.3. About the farm holders

Going further into the analysis reveals a more complicated situation. Nearly half of the sampled boreholes actually show similar annual pumping duration and volumes than dug wells (Figure 2). A large variability exists in the relationship between groundwater withdrawals by boreholes and the surface to be irrigated because adjustments rely on the agricultural intensification mechanism. The boreholes that pumped less than 20,000 m³/year belong to small-scale farmers, unable to practice intensive pumping due to their critical financial situation. The pumping cost per hectare can be doubled compared to a dug well: it usually represents about 30% of the production cost for onions or potatoes, but the water access is secured. Conversely, the largest pumped volumes were mainly observed on farms endowed with better financial capacity. The farmers were essentially lessees, investing in intensive irrigated agriculture (onion, potato), on more than 5 ha. During the peak season they can afford pumping more than 20 hours/day. The farming system is far more intensive (2-3 crops per year) with yields twice as high. On the other hand, 2 dug wells produced a mean annual volume higher than 20,000 m³. One is a very deep dug well (62 m)

and used by a lessee. The other is used by 3 members of the same family, but with distinct farm holdings and having set up a water turn. The large storage capacity of the well enables a longer pumping duration of over 1,900 hours/year (14 hour/day during the peak irrigation period) at a low flow rate (3 L/s).

The type of farm holder operating the borehole is strongly discriminant with regard to the final pumped volumes. In the Saïss, the quest for accessing a more abundant groundwater resource in the confined aquifer concerns essentially actors recently settled on a farm holding in the region who engage in more entrepreneurial farming and are subsidized. The recent Green Morocco plan provides subsidies for fruit plantations and drip irrigation, while agriculture remains exempt from paying taxes. It contributes to maintain the lively crossed dynamics of the groundwater access and land markets. One of the direct consequences was the fast increase in the irrigated areas associated to a rapid proliferation of pumping wells. The intensification of the groundwater draft contributed to the water table drop and the yield of shallow wells was reduced. The River Basin Agency, in charge of the water resource management, frequently mentions the decline in groundwater levels in the Saïss and the overexploitation of groundwater resources. In parallel, the product of the groundwater-based intensive agriculture started to flood the national markets. The risk of losing money on agricultural production is now increasingly high (Lejars and Courilleau, 2015). A high turnover between agricultural holders can thus be expected in the region for the near future.

New investors arrive and rely heavily on groundwater to irrigate fruit trees, while some other actors, such as lessees, are temporary actors. Among historical holders, some can no longer remain in the groundwater economy and are excluded. For example, the groundwater withdrawal for assignees decreased by 26% between 2005 and 2014 (from 1.9 to 1.4 hm³), and will likely fall further in the coming years, with the continuous decline of groundwater levels and the overproduction of the onion market (Ameer et al, 2017b). Conversely, the recently installed lessees (essentially after 2005) already pumped in 2014 twice as much than the assignees (3.2 hm³/year), with a mean annual growth rate of 32% since 2005. Considering the development dynamics of the types of farm holders in addition to the types of pumping wells would lead to a predicted pumped volume of 13.1 hm³ by 2020. The estimation made considering only the development dynamic of the number of pumping wells by type would be 9.2 hm³ (-30%). The discrepancy is significant and illustrates the need to understand both the users as well as the uses of groundwater. Actually the growth rate of the number of pumping wells is slowing down; 9 new wells were in use each year over the period 1995-2009, only 4 over the period 2009-2014. But the type of well and the well operators are changing. There were 126 dug wells – with much lower discharges – in use in 2005 for 58 boreholes. In 2014 the number of dug wells was no more than 75 for 165 boreholes. Those pumping wells are increasingly operated by investors and lessees (+12% and +19% respectively since 2009) which transforms the relationship between the number of wells and groundwater abstraction.

4.2. The Kairouan plain

4.2.1. The development of private irrigation from groundwater supply

Before the French protectorate (1881), traditional wells (dug wells) of the Kairouan plain were supplying water for the livestock and domestic uses of nomadic herders. Topographical reconnaissance work

undertaken by the French army in 1898 mapped 212 wells (DTC, 1957). Later on, colonial farms started to exploit more intensively the springs, flood water and traditional wells to irrigate large farms. After the independence of 1957, the Tunisian government advertised its choice to 'intensively' but 'rationally' mobilize water resources notably to ensure food security and to secure rural livelihood and stabilize rural outmigration. Centralized institutions were created and national strategies were implemented like collective irrigation schemes supplied by groundwater through deep public boreholes (Le Goulven et al., 2009). The incentives (subsidies from the government, development projects) to develop individual water access and irrigation launched in the 1980s the era of private exploitation of groundwater for individual farms. From that moment on, the State started to lose control on groundwater exploitation (Riaux et al., 2016). Water authorities were torn between the laissez-faire policy to unlock the economic potential of agriculture and the need to ensure sustainable groundwater use. In the Kairouan plain, illicit drilling and pumping rapidly developed, while water authorities tried to maintain situational awareness by conducting regional inventory of the pumping wells and maintaining a regional network to monitor water table levels. Prospective scenarios for water resource planning strategies were essentially based on the evolution of the number of wells and groundwater levels.

4.2.2. Groundwater abstraction assessment

The last inventory in 2010 (Geohydro, unpublished report, 2010) identified approximately the location of 2,066 private pumping wells (dug wells and boreholes) for a total irrigated area of 12,000 ha (1 well for 6 hectares irrigated on average) within the 700 km² of the northern part of the Kairouan plain (see limits and spatial distribution on Figure 1). The inventory also provided some characteristics of the pumping equipment (pump capacity, energy type, total depth of the well, depth to the water table, instantaneous flow rate), the total irrigated area and the water salinity (water conductivity). To assess the reliability of such a large data set, crossed analysis of the data were carried out and enabled to eliminate major inconsistencies (e.g. depth to the water table > total depth of the well). Then a field campaign was conducted in 2012 to check random samples (78) out of the final data set of 928 private wells with fully filled information. The analysis revealed that the latter was relatively consistent with the newly collected data. The total depth could not be verified. Around 10% of the existing wells were found to be missing in the inventory with high differences between areas.

Based on this, a hierarchical ascendant classification (HAC) was performed considering the 6 descriptive variables available of the 928 wells (the total depth was rejected). The classification distinguished 3 groups of respectively 299, 562 and 67 wells (Table 1). The first group was dominated by diesel pumps, medium-sized irrigated area and low flow rate. The second group was represented by electric pumps of medium capacity, medium-sized irrigated area and rather low flow rate. The third group was more representative of large irrigated areas supplied by rather high capacity electric pumps with high flow rate (probably submersible pumps in boreholes). The depth to the water table and the water quality (salinity) did not clearly contribute to discriminate the groups. The three types of irrigation systems emerge in the classification actually described by the variables *pump capacity*, *energy type* and *instantaneous flow rate*. Groups 1 and 2 represent a majority of traditional and deepened wells whilst group 3 is representative of the deep boreholes (in accordance with the 78 wells checked in the field).

Group (tot. no.)	Energy type	Pump capacity [hp]	Inst. flow rate [L/s]	Total irrigated area [ha]	Depth to water table [m]	Water electrical conductivity [mS/cm]
1 (299)	Diesel	12	3.8	7	30	3.4
2 (562)	Electric	7	4.1	7	33	3.5
3 (67)	Electric	9	7.8	16	34	3.7

Table 1: Values of the descriptive variables of the barycenters of the 3 groups identified in the AHC

For the sake of representation, pumping wells to be monitored were selected considering characteristics of the groups and field constraints (ease of access, consent of the farmer etc.). A total of 38 wells were selected over the study area: 3, 23 and 12 from groups 1, 2 and 3, respectively (Figure 1). The temperature monitoring method was applied. The mean discharge was regularly measured (at least every 3 months) with an ultrasonic flowmeter (Fuji Electric Portaflow X). The monitoring time lasted 2 years (from August 2013 to August 2015; wet and dry years, respectively). It has proved difficult to maintain the full observation set over such a period simply because the agricultural activity is very dynamic in the Kairouan plain. Over only a 2-year period, some owners changed and the new ones refused to be monitored, some wells were abandoned, some others were drilled etc.

Finally 22 wells could be monitored over the full period and 6 lasted only the first year. The others (10) lasted only a few months. The measured mean annual pumping time was 4,300 h/year corresponding to a calculated mean annual volume of groundwater abstracted of 71,000 m³/year. Assuming that the number of missing wells in the inventory (10%) compensate the number of wells inventoried but not in use, the mean regional groundwater drafts should be around 150 hm³ in 2010 (2,066 wells). As a comparison, the groundwater withdrawals for irrigation from public boreholes was estimated between 85 and 125 hm³ (135 boreholes with a mean flow rate between 20 to 30 L/s running 24 hours a day, 7 days a week; public boreholes are equipped with water meters). The groundwater exploitation for drinking water supply was 9 hm³ in 2010 (Saida, 2015). The total groundwater withdrawals in the Kairouan plain can thus be estimated ranging from 245 to 285 hm³ in 2010.

4.2.3. On the pumping-well evolutionary path

The limited memory capacity of the loggers required a data download on a regular basis (<3 months). Continuous visiting and discussion helped in keeping a close link with the farmer and to be aware of any change in cropping pattern and cropping calendar, irrigation practices, irrigated areas or pumping equipment. From the numerous exchanges, the dynamics and the evolution of the pumping wells became apparent. Over the only 2-year period of observation, nearly all the wells faced at least technical changes that impacted the pumped volumes, but there is also a regular evolutionary path. Before the start of the groundwater drop, pumping wells were shallow or even artesian (<10-15 m deep). Then farmers had to run behind the dropping water table and deepened their traditional wells. The Tunisian Water Code (1975; article 9) fixed a drilling limit of 50 m below ground level. For a deeper pumping well, an authorization had to be granted. Because drilling had to go deeper for getting decent flow rate, the farmers who could not get the authorization (the large majority) worked around the limitation by illegally drilling boreholes

at the bottom of traditional wells (the so called "deepened wells"). This technique enables a stealthy continuous deepening up to 70-80 m (usually 4 m every 2 years) making it impossible to gauge the depth once the pumping system has been set up. However, the flow rate is usually limited ($<4\text{-}5\text{ L/s}$), even with a submersible electric pump, but the investment is progressive and moderate. After the revolution in 2011 and the disorganization of the central authority, the threat of punishment progressively diminished, and deep boreholes (90-120 m) started to replace the deepened wells. Drilling a borehole is more expensive (four-fold the cost of a deepened well), but secures the access to the dropping groundwater for a longer period and at much larger flow rates (6 to 35 L/s). Farmers report drawdowns in their boreholes with cones of depression noticeable in the surrounding pumping wells at distances beyond 100 m. So drilling deeper is also a way to get rid of the influence of the close neighborhood on the water table.

This means that the deep boreholes are likely to dominate the private water access in the near future with probably a massive abandonment of traditional and deepened wells. In other words, group 3 will expend to the detriment of groups 1 and 2 which will change significantly the relationship between the number of wells and withdrawn volumes. The race to groundwater access - the technical evolution of the wells and irrigation systems - therefore plays a significant role on determining present and future groundwater abstraction.

In addition, the results also pointed out various constraints more related to the socio-political context. For instance, the inheritance process has led to a continuous division of the land and conflicts between heirs are frequent. It was not unusual to see the well of the family plot abandoned because nobody wants to invest for maintenance or deepening as long as the attribution of the land is pending, which can span over several years. Then instead of sharing the family well, new wells were drilled for each divided piece of land. The heirs can practice more intensive irrigation to get the same return with a smaller area, or deal with lower incomes. By comparison, 50% of the wells were irrigating areas from 1 to 6 ha according to the inventory in 2010.

It was also rather frequent to find wells drilled exclusively to secure the land ownership (3%). Land ownership titles are very rare and owners do not necessarily live in their plot. Those wells remained generally unused. A well can also be drilled as a sign of wealth and social prestige or can be a gift to the family from a son working overseas and might never be used for irrigation.

This represents only a small piece of the wide variety of features related to the groundwater use in the Kairouan plain, but enough to question the assessment of groundwater abstraction in relation with the number of pumping wells and put into perspective its possible future evolution.

The evolutionary path in water access and its determinants actually appears in the analysis of the number of pumping wells itself. The evolution of the number of private wells from the 2010 inventory follows a steep growth often qualified as exponential (Figure 3a). A quick look at the graph (Figure 3a) shows that years finishing by 0 or 5 correspond to a peak of drilling (e.g. 1990, 1995, 2000 etc.). This simply means that the given dates are approximate and actual dates of creation span probably few years before or after. Discussions with farmers confirmed the latter and also indicated that the drilling date provided in

the inventory could correspond either to a drilling date or to a deepening date. As previously stated (see section *The development of private irrigation from groundwater supply*), 212 ancient wells were inventoried in 1898. They all share close locations with referenced wells in the inventory and some of them (10) were strictly identified in the field, still in use but repeatedly deepened. The presented exponential growth may thus be overstated as the pumping wells appear artificially younger in the inventory than they actually are. A reconstitution proposed in Figure 3b shows what the actual temporal distribution might look like in considering the above meta-information.

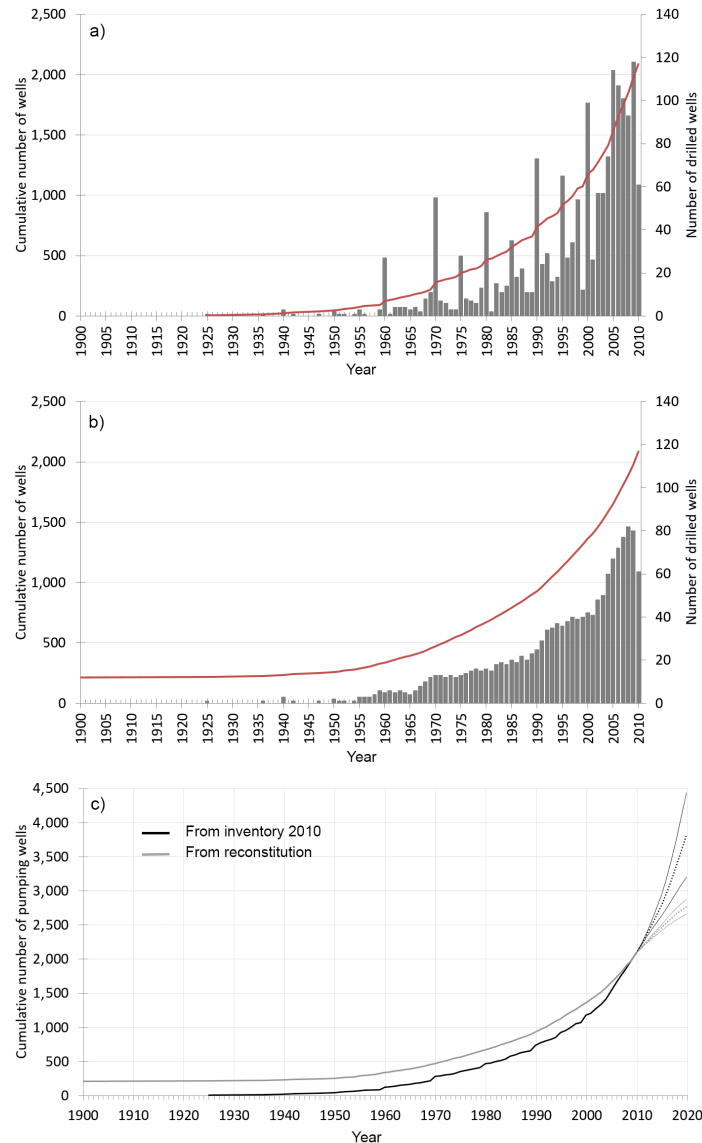


Figure 3: a) drilling date (grey bars) and cumulative number of private pumping wells (red curve) from the inventory 2010 in the northern part of the Kairouan plain; b) proposed reconstitution of the temporal distribution of the drilling dates and cumulative number of private pumping wells; c) comparison of the possible future trends of the number of pumping wells

Extrapolation of both trends for building management strategies produces very different outcomes (Figure 3c). For instance by 2020, the predicted total number of pumping wells would be $3,800 \pm 600$ and

2,800±100 according to the inventory and to the reconstitution, respectively. It is tempting to associate the future trend of the groundwater abstraction to the evolution trend of the number of wells. But the relationship is not so obvious. A stagnation of the newly drilled wells is expected due to the plot size reduction and to the shift from deepened wells to deep boreholes, but more investigations on the dynamic of the process would be needed to predict the period when the curve of newly drilled boreholes is the most likely to downtrend.

4.3 *The Ziban*

4.3.1. *The advent of irrigated agriculture in the desert*

The district of El Ghrouss in the West Ziban is a prosperous region whose prosperity comes from the presence of a series of large artesian springs that gave rise to oases (Cote, 1991). During the French colonization, boreholes were drilled to mobilize this abundant groundwater resource. After independence (1962), the Algerian State pursued drilling to stimulate agricultural development. Artesianism ceased in the mid-1970s. At the same time, drilling techniques became accessible by farmers who started to massively get access to groundwater individually, in particular in the new extensions outside of the traditional palm groves. Finally, the development of the electricity network enabled efficient groundwater draft from deep boreholes. Now, the sandy aquifer is tapped up to 600 m by large diameter boreholes (12", 30 cm) equipped with electric submersible pump. The electrical network in Algeria is well developed and widespread in agricultural fields. A field survey in 2015 identified 1,320 boreholes in the district of El Ghrouss, with merely 200 authorized by the hydraulic authorities. The inventory was considered as exhaustive since the total area was covered and the boreholes were easy to distinguish in the landscape. Only 5% (65) of the wells were waiting to be connected to the electricity network (usually 1-year delay). Date palm groves covered the largest area with almost 4,800 ha identified in 2012, then came the plastic greenhouse tunnels for market gardening with 470 ha (11,714 greenhouses were identified in the district) and a few rangelands were saved for livestock.

4.3.2. *Groundwater abstraction assessment*

The groundwater withdrawal assessment was made on the basis of the inventory of the 1,255 electrified boreholes. A representative sample of 29 boreholes were monitored (evenly distributed locations, all types of crops and farms) over the period 2014-2015. The pumping rates of the irrigation systems were regularly measured with an ultrasonic flowmeter (Digisonic Ultraflux). The flow rate of any borehole was found to be very stable at the season level, but during the peak irrigation season (March-August), the pumping systems were heavily loaded. An overall decrease of the flow rates was observed (-10%), probably due to the unsatisfied greater energy demand and to the created local groundwater drawdown. For the observation period, the measured mean flow rates were 7.6 L/s and 6.8 L/s for off- and peak-season respectively, but differed significantly between boreholes with a large variation range of ±40%.

It was possible to obtain access to the electricity meter readings and also to collect all electricity bills and create a database with the name of the borehole owner, the electricity current price and the quarterly energy consumption. The method to evaluate the groundwater abstraction was thus adapted to take advantage of this opportunity. The pumping duration was determined from the energy consumption

(total and rate). Over a short period of time (usually 1h) and under normal irrigation conditions, the energy consumption was monitored (individual electricity meter readings) and the average power use of the irrigation system was then inferred as follows:

$$P_n = \frac{E_{\text{meter}}}{t} \quad (2)$$

with P_n the power of the pumping system in kW for the borehole n under normal working condition, E_{meter} the energy consumption in kWh and t the monitoring time (i.e. the duration of pumping) in h. The estimated pumped volume was then given by the simplified Eqn (1):

$$V_{\text{pump}} = \bar{Q} \times t \quad (3)$$

with, V_{pump} the total pumped volume in m^3 , \bar{Q} the mean flow rate over the monitoring time in m^3/h , t the duration of pumping in h.

The calculated mean pumping duration was 5,500 h/year (i.e. equivalent to 230 full days of irrigation per year). It increased from 2,500 h during winter to 3,000 h during summer. Pumps were running more than 75% of the time over March to May. The estimated mean pumped volumes per borehole was around 135,000 m^3/year with a very strong variability between boreholes (from 100,000 to 300,000 m^3/year). With this method, in the El Ghrouss district, the annual groundwater abstraction of the 1255 boreholes connected to the electricity network would be estimated at 170 hm^3/year .

4.3.3. A methodical pumping well expansion

Actually, the field inquiries revealed a particular evolution of the farms related to the organization of the territory. The expansion mechanism of new cultivated lands leads to the creation of three distinct zones according to the dominant cultivated crop. The first one corresponds to palm trees and is developed around the old oases (i.e. the oldest cultivated lands). The second concerns the mixed zone with palm trees and horticultural crops (plastic greenhouses). The third one refers to the new lands where the horticultural crops are largely dominant. They actually correspond to different stages of land development. The typical evolution path starts from the third to the first one (Amichi et al., 2015). Consequently, the new drilled boreholes are first used to irrigate exclusively greenhouses, then mixed greenhouses and young palm trees and finally exclusively mature palm trees. This influences greatly the groundwater abstraction and explains a part of the large difference among the 29 boreholes. One of the reasons can be found in the expansion process of the electricity network (pioneering front). To stimulate the land development, the Algerian State invested in new boreholes in the desert, provided to farmers for collective use. When these boreholes are seen to be functioning, this is a signal for farmers who can invest in turn in private boreholes knowing that there is water and that the area will soon be electrified. This pioneering front is the scene of a strong increase in the number of boreholes that ceased when date palm tree groves are in place.

This typical land use evolution process may have a direct impact on the regional groundwater pumping assessment because the water needs are specific to each stage. In this context, it means that it is nearly impossible to assess the groundwater abstraction using only the number of boreholes.

It can thus be expected that the future groundwater withdrawals will be closely linked to the dynamic of agricultural development of the extension zones. This can be illustrated by the analysis of the electricity connections. Based on the electricity meter reference number, it can be shown that the increase of the number of boreholes is strictly located in the extension zones. Figure 4 shows the evolution of the number of connections to the electrical network for the years 2010, 2012 and 2014 in the district of El Ghrouss. The total number increased from 874 in 2010 to 1320 in 2014. Only a portion of the reference numbers did not change (554) and Fig 4 shows a rapid increase of the others. Actually, investigations showed that the unchanged reference numbers correspond to the mature palm groves where no new connections were recorded (i.e. no new borehole). The changing reference numbers correspond to the extension zone, illustrating the dynamic of drilling with emergence and loss of electricity meters, a dynamic closely tied up with the development of the electrical network in the district.

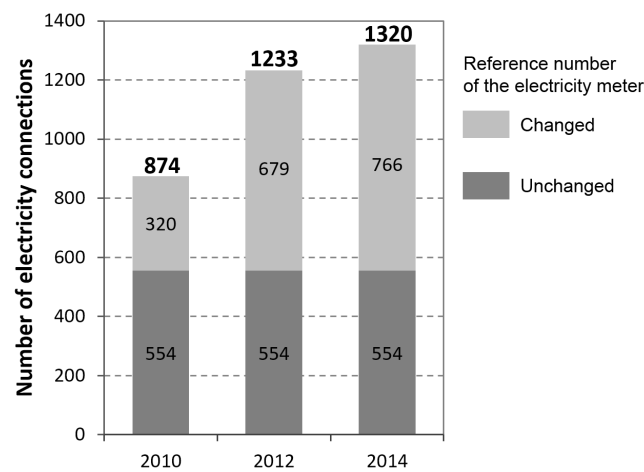


Figure 4: evolution of the number of electricity connections in the El Ghrouss district

5. Discussion

In the Kairouan plain, results suggested that the regional groundwater withdrawals assessment was prone to the constant changes farmers make on their equipment and in their farming systems. These salient features related to the groundwater use need to be accounted for, but the question is in what proportion. This can actually be evaluated on the narrow sample of 928 wells of the classification, since the 3 groups are representative of the technical type of the wells and irrigation systems. The mean monthly pumped volume for each group can be calculated (Table 2). This multiplied by the number of wells belonging to each group gives the total volume estimation.

Group (tot. no.)	Mean annual pumping time [h]	Mean annual GWA [m ³]
1 (299)	3,400	38,500
2 (562)	4,800	65,500
3 (67)	4,200	84,700

Table 2: Pumping time measurement and groundwater abstraction (GWA) calculation for each group of the classification

The resulting annual volume is 54 hm³/year. The discrepancy is significant compared to the total annual groundwater draft of 66 hm³/year (-20%) as calculated in section *Groundwater abstraction assessment* (928 x 71,000 m³/year). Assuming the considered descriptive variables of the 928 wells follow the same statistical distribution as the total 2,066 wells of the inventory, the regional groundwater withdrawals assessment would then be 120 hm³/year, 30 hm³ less than the first assessment of 150 hm³/year (i.e. almost 3-fold the annual pumping for drinking water supply).

In the Saïss plain, the regional groundwater withdrawals assessment is dependent on the diversity of uses and users involved in the groundwater-based agriculture. The regular field surveys have shown 5 types of farm holders with significantly different logics materialized in different irrigation practices: the agricultural companies, the lessees, the investors, the assignees and the small landowners. The companies rent large tracts of State land with a long-term perspective. They practice tree farming with moderate intensification. The lessees are newcomers, renting the plot for a short period of time. They try to make the most of the land by practicing very intensive agriculture before moving to another place. Investors buy lands from assignees (agrarian reform) and landowners to develop fruit orchards. They have a strong financial strength and get subsidies to modernize the farm (drip irrigation, tractor). The assignees and small landowners apply a logic of diversification and mix between irrigated and rainfed agriculture.

The mean groundwater withdrawals were calculated for each of the 5 types on the set of 18 farms. Despite the small sample set size, strong differences arise in terms of groundwater use between farm types. For instance, a borehole exploited by a lessee extracts 66,000 m³/year on average, while it extracts only 28,000 m³/year if exploited by an assignee. Making the distinction between operators of all the pumping wells in use would upgrade the groundwater abstraction assessment in the district to 9.7 hm³ in 2014 (see Table 3). This is 23% more than the assessment of 7.9 hm³ when making only the distinction between the two identified pumping devices. It can also be noticed in Table 3 that there is a poor relationship between irrigated area, land use (e.g. both the companies and the investors grow fruit trees, but not the same way) and pumped volumes.

Farmer type	Irrigated area		Groundwater access			GWA	
	ha	%	Wells in use	Boreholes in use	%	hm ³	%
Companies	1212	56	1	18	8	2.8	29
Lessees	329	15	12	44	23	3.2	33
Assignees	233	11	48	24	30	1.4	14
Investors	379	17	14	72	36	2.1	22
Landowners	29	1	0	7	3	0.2	2

Table 3 : Estimated groundwater abstraction (GWA) in 2014 for the different types of farmers identified.

In the Ziban, the logic of investment for land development drives the use of the pumping wells. The 3 zones identified correspond to specific groundwater uses. It was determined that the greenhouses use

sensibly the same amount of water, with 630 m³/year (i.e. 15,700 m³/ha) on average. The newly planted palm trees could use 11,000 m³/ha and mature trees up to 19,000 m³/ha. The 470 ha of greenhouses contribute to the pumping of 7.5 hm³/year while the 4,800 ha of palm trees would use between 55 and 90 hm³/year. The pioneering front zone was not assessed because it evolves too rapidly to get a representative picture over a complete year. This gives another picture of the groundwater withdrawals estimation (at least 40% lower than the regional estimation based on the pumping duration). But whilst the latter needs information to explain the strong variability of flow rates and pumping durations, this method also lacks of information about the distribution of mature and new trees.

Actually, a third independent approach can be applied in this area. The relationship between energy consumption and pumped volume can be calibrated for each of the 29 boreholes as follows:

$$V_{\text{pump}} = C \times E_{\text{meter}} \quad (4)$$

In Eqn (4), V_{pump} is the total pumped volume in m³, C is a calibrated parameter in m³/kWh and E_{meter} is the energy consumption in kWh from the quarterly electricity bill. The calibration gives $C = 1.57$ m³/kWh with a relatively good determination coefficient of 0.73. This means that with the total energy consumption invoiced in the district of 96,183,412 kWh in 2015, the total groundwater withdrawn by electric pumps would be 150 hm³.

These evaluations clearly show the necessity to include in the regional groundwater accounting methodologies the various aspects of the groundwater use. Here, at least three outstanding features can be listed: i) the type of farm holder, ii) the production systems (cropping intensities, degree of intensification) and iii) the trajectories/dynamics of the different types of agriculture. It also points out the necessity to cross validate such assessment with other regional independent approaches.

6. Conclusion

Assessing groundwater abstraction from private users in North Africa remains challenging because a large part of the groundwater exploitation is done through thousands of uncontrolled scattered private farms with specific irrigation practices. Direct measurement methods were implemented and gave consistent results at the scale of the pumping system (dug well or borehole). Resolutely user-oriented (integrating the user explicitly in the approach) and adaptive (to get the most out of the available knowledge), the approaches enabled to interpret the pumping well inventories in terms of regional withdrawals and dynamic of their past evolution. Critical factors affecting the regional groundwater abstraction for irrigated agriculture were identified on three comparable sites, such as the type of farm holder, the production systems and the trajectories/dynamics of the different types of agriculture. With similar climatic and environmental context, the three sites were prone to massive development of agriculture and to pumping wells proliferation and groundwater depletion. The identified factors affecting the regional were nonetheless very different. Taking them into account produced differences in the regional groundwater abstraction assessment of several tens of percent. In the Kairouan plain, the type of wells and its evolutionary path stood out (technical and social), while in the Saïss plain the role of the

type of farm holder and the type of wells were highlighted. The Ziban showed the crucial role of the dynamics of the extension zones also constrained by the infrastructure development.

These factors have a strong influence on the pumping systems, both on their exploitation and their future development. The evaluation of regional groundwater abstraction is only possible via a good understanding of farmers' practices and logics - and leads one to look with caution at the number of wells cited in the literature, which could be oversimplified. This is the reason why a user-oriented approach was taken in this study. It is even more crucial in a context of high agricultural development accentuated by various contractual arrangements around access to water resources, the use of boreholes and the absence of control means.

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