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Understanding Farmers' Adaptation to Water Scarcity: A Case Study from the Western Nile Delta, Egypt

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International Water Management Institute

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Front cover photograph shows individual pumps in action, with the rule that only one should be operating at the same time (*photo:* Wafa Ghazouani).

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Contents

Summary

This research study analyzes how farmers adapt to water scarcity in the command area of a secondary canal in the Nile Delta of Egypt (al-Bayda Canal). The results of the study show that farmers use several methods to adapt to water scarcity: changing cropping patterns, crafting collective irrigation rules, reusing agricultural drainage water, practicing deficit and night irrigation, and over-irrigating whenever water is available. The analysis then focuses on the changes in cropping patterns, seeking to demonstrate how crop choice is shaped and constrained by a set of factors, including water availability and economic profitability. Interestingly, the lowest water-intensive, but most cost-effective in terms of return per cubic meter, crop (watermelon) was mainly cultivated in the locations with the best water supply, while water-intensive crops, such as *luffah* (sponge gourd plant) or grapes, were mostly cultivated in the unfavorable lower reaches of the canal.

Understanding how farmers adapt to water scarcity reveals that there are other factors besides water scarcity and profit maximization that affect the responses of farmers. These additional factors include food security of the family, agronomic risk management, social capital and history of farmers, and most unexpectedly the collective dimension of crop choice. This illustrates the variegated rationales and constraints as well as the collective dimensions of individual crop choice, and cautions against the oversimplified view of profit maximization as the basis of farming system dynamics.

Understanding Farmers' Adaptation to Water Scarcity: A Case Study from the Western Nile Delta, Egypt

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Introduction

It has often been highlighted that irrigated agriculture receives the lion's share of water diversions, and that there is a need to improve resource-use efficiency (Kijne et al. 2003; Rijsberman 2006; FAO 2012). New investments in the improvement and management of irrigation infrastructure (e.g., rehabilitation of irrigation schemes, technical modernization, community development, capacity building and institutional reforms) are seen as being necessary for increasing water and soil productivity of irrigated cropping systems in the context of water scarcity coupled with the intense competition for water among different sectors (Rosegrant and Cline 2003; Rijsberman 2006; Khan and Hanjra 2008; FAO 2012). However, the management of irrigation systems under conditions of shortages and uncertainty in water supplies is a critical challenge to the productivity of irrigated agriculture. Water-use efficiency at the field level is often said to be low (Hamdy et al. 2003; Rajput and Patel 2005; El-Agha et al. 2011), and farmers are blamed for this inefficiency (Howell 2001; Bouman et al. 2007; FAO 2012). However, this view is often both incorrect and unfair (Perry 2007; Molle et al. 2010), as farmers operating under conditions of water scarcity are unlikely to waste water. The constrained environment in which farmers operate and make choices is frequently not well understood and documented.

Managing irrigation under conditions of water scarcity has been extensively documented. On the one hand, engineering approaches have provided a coarse view of how temporary and/or chronic shortages are distributed over the cropped command areas and over time. The changes in cropping patterns associated with growing uncertainty in irrigation supply have been addressed by a number of studies (e.g., Hussain et al. 2007; Gaur et al. 2008; Bekchanov et al. 2010; Venot et al. 2010; Carr 2013), which have developed a set of useful indicators from a water management perspective, but remained vague about the impact of water scarcity on farmers' practices and livelihoods. On the other hand, social and economic sciences have addressed the equity issues of top-down projects and policies (e.g., El-Shinnawi et al. 1980; Skold et al. 1984; Wichelns 1998; Wichelns 2000; Wichelns 2002; Hussain et al. 2003). For example, El-Shinnawi et al. (1980), Skold et al. (1984), Bhattarai et al. (2002), Brugere and Lingard (2003), Latif (2007), and Aruna Shantha and Ali (2013) identified an income gap between the upper and lower reaches of the canal, which is due to the large share of water used by farmers at the head end of the canal to the detriment of those at the tail end. The differences in water availability, inequity in water distribution, and the impacts of inadequate irrigation on yields and farmers' income have been well documented in Egypt and in many other arid and semiarid regions (e.g., El-Shinnawi et al. 1980; Skold et al. 1984; Brugere and Lingard 2003; Tyagi et al. 2005; Bekchanov et al. 2010; El-Agha et al. 2011). In other words, the past assessments have often viewed the individual responses of farmers to water scarcity through the lens of a single technical or economic factor.

A few analyses, however, have considered multiple factors that shape farmers' adaptation to imposed water scarcity and uncertainty in water supplies. For instance, Liwenga (2008) emphasized the importance of local knowledge and farmers' cumulative experiences, while Pereira et al. (2002) highlighted the importance of human capital, cultural skills and traditional know-how. This study seeks to understand how farmers respond to water shortages by considering water scarcity along with physical, environmental, agronomic, social, cultural and economic factors. This research study shows that the responses of farmers to cope with reduced water availability are driven by multiple factors and not only by water availability or average income alone, as usually perceived.

The focus of this study is on the multiplicity of factors that shaped farmers' adaptation in an environment of decreasing water availability and uncertainty in water supplies in the western part of the Nile Delta in Egypt. The report starts by describing the physical context and shows that there is a decrease in water availability along the al-Bayda branch (secondary) canal. It then continues to identify and analyze how farmers adapt to such decreases according to different locations, while an economic evaluation of the cropping patterns adopted is presented. Finally, we discuss the rationale for crop choice in more detail, which reveals its complexity. While the discussion is largely based on findings from the al-Bayda branch canal, it uses other studies on arid and semiarid areas to add relevant elements.

Materials and Methods

This case study is conducted in the al-Bayda branch canal, which is located at the tail end of the Mahmoudiya main canal in the northwestern part of the Nile Delta close to Alexandria (Figure 1). The study identifies farmers' responses to water scarcity as a result of the (i) priority given to drinking water supplies for Alexandria, which increasingly poses restrictions on water use for agriculture. Municipal water consumption represents 70% of the total water supply from the Mahmoudiya Canal, after the off-take of the Kafr el-Dawar regulator which is located before the off-take to al-Bayda Canal (WMRI 2010); and (ii) expansion of rice cultivation in the delta, which exceeded more than twice the area that is officially allowed (Arafat et al. 2010). Due to the continuous increase in demand, the capacity of the Mahmoudiya Canal is insufficient to provide water for both urban and agricultural uses during periods of peak demand in the summer.

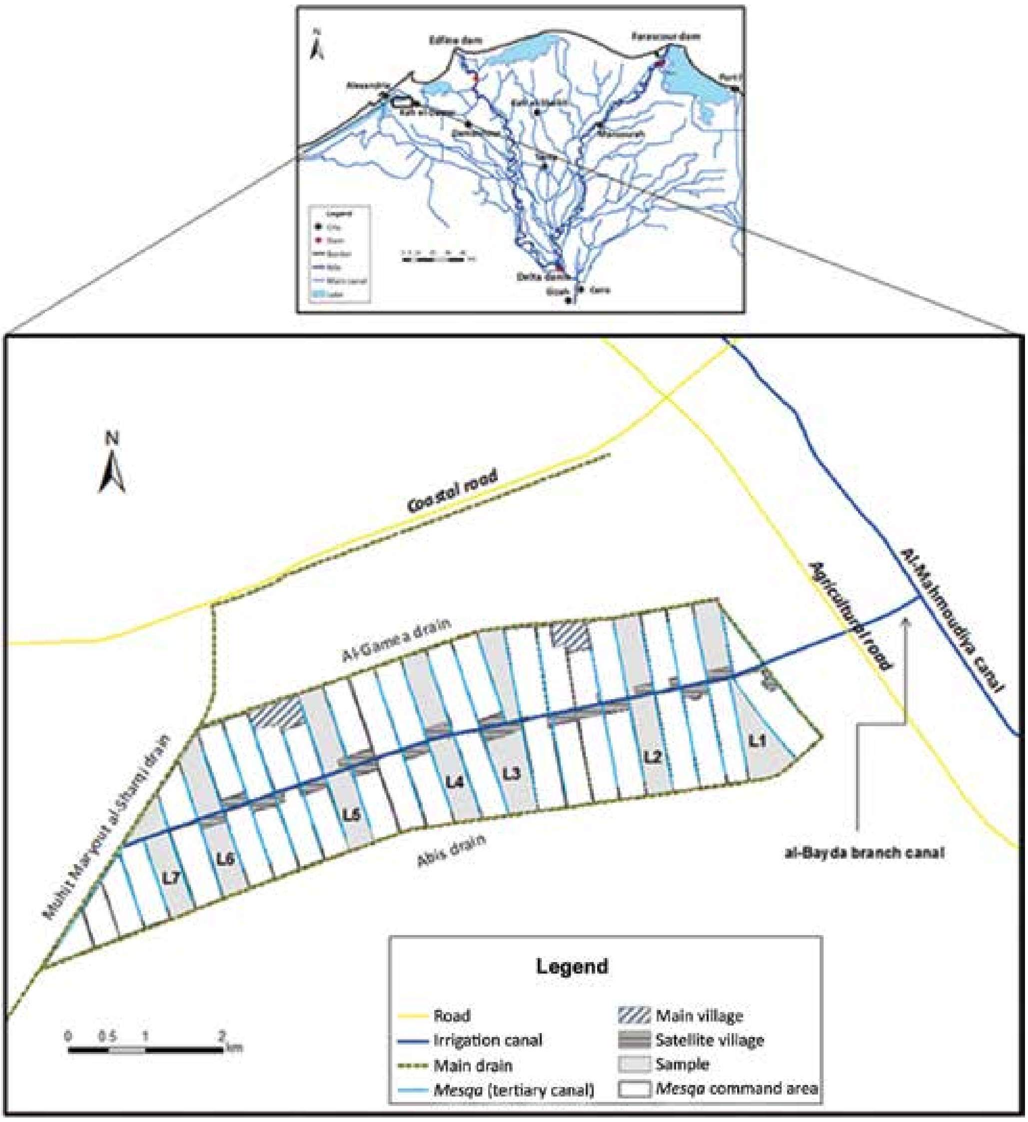
Case Study

The Mahmoudiya Canal (primary level) has a total length of 78 km and gets its water from the Rosetta branch of the Nile River. The average electrical conductivity (EC) of canal water is 0.59 dS/m (FAO 2005), which makes this water suitable for both drinking purposes and agricultural use. The Mahmoudiya Canal is operated on a continuous flow basis. Although there is sufficient water to meet the requirements during the winter season, there is barely enough water to meet the requirements of summer crops (WMRI 2009, 2010). In addition, rainfall near the coast is significant during the winter season, and is 200 mm/year, on average.

Water is distributed among 90 branch canals (secondary level) through sluice gates, where main inflows are controlled according to upstream and downstream water levels rather than actual discharge. The branch canal intakes are operated according to an '*on-day'* and *'off-day'* fixed rotational schedule. The gate operator (or *bahhar*) is responsible for opening and closing the gates, and adjusting the water level according to the schedule provided by the district engineer. At the tertiary level, open earthen tertiary canals (*mesqas*) provide water to individual pumps that feed quaternary field ditches known as *marwas* (ditches). The al-Bayda branch canal (Figure 1) serves a total command area of about 1,764 ha (or 4,201 *feddans*, where 1 *feddan* = 0.42 ha) of reclaimed land. Because of its relative tail-end position, the al-Bayda branch canal is disadvantaged and receives a relatively low amount of irrigation water supply per unit area (23.6 m^3/*feddan*/day) in the summer. In comparison, the Nekla branch canal, which is located at the head end of the main canal, receives more than double this amount of water (WMRI 2010).

The command area includes 52 *mesqas*, perpendicular to the al-Bayda Canal, and serves areas between 15 and 49 ha (with a mean of 34 ha), which are irrigated through 4 to 11 *marwas*. *Mesqas* receive irrigation water through gravity from the Al-Bayda branch canal via sliding gates, which were initially designed to be opened and closed according to a rotational schedule.

FIGURE 1. Map of the research site at the al-Bayda branch canal.



Marwas receive water from the *mesqas* through mobile and individual diesel pumps, owned by farmers, and is carried out according to a specific rotational schedule among farmers belonging to the same *marwa*. At the time of settlement in the early 1960s, young farmers received five *feddans* divided into three equal plots which were situated in different locations of the same *mesqa* (head, middle and tail end), in order to apply the obligatory agricultural rotation: rice/cotton/farmers' own choice. A majority of the young settlers came from the Governorate of ad-Daqahliyah in the eastern Nile Delta (Meet Ghamr and Beshla). Currently, the second and third generations of farmers own fragmented plots situated in different *marwas* of the same *mesqa*, and they use one to two pumps that need to be moved between their plots. The command area includes two main central administrative villages (Abis 3 and Abis 4), located on the secondary al-Gamea drain, and 18 satellite settler villages, located along the al-Bayda branch canal (see Figure 1).

As in the rest of the Nile Delta, the prevailing methods of irrigation at the plot level are basin irrigation for crops such as rice, wheat and *berseem* (Egyptian clover), and furrow irrigation (broad and narrow) for crops such as maize and vegetables as well as trees.

The drainage network is composed of both open drains and subsurface pipes. Each *marwa* has a parallel small field drain that transfers excess water to a tertiary drain (parallel to the *mesqa*), which itself discharges into the northern or southern secondary drains (parallel to the branch canal). The main collector, the Muhit Maryout al-Sharqi drain, then discharges drainage water to Lake Maryout (see Figure 1). The average EC of drainage water is 2.74 mS/cm (Elshorbagy 2000). There is no spill of canal water into drains. Operation and maintenance (O&M) of the main canal, branch canals, main drain collectors and secondary drains are the responsibility of the Ministry of Water Resources and Irrigation (MWRI), while farmers are responsible for the O&M of *mesqas*, *marwas*, and tertiary and field drains.

Cropping patterns include two crops per year, as in the rest of the Nile Delta, where rice and maize are the main summer (May - October) crops, and wheat and berseem are the main winter (November - May) crops. Summer vegetables (e.g., fine green beans, sweet potato, tomato, eggplant, pepper, cabbage, cucumber, watermelon [for seeds] and melon) can be found in addition to sponge gourd plants (*luffah*) and perennial crops, especially grapes. Maize can be planted in rows to produce sweetcorn (green or dry seeds) or broadcasted to serve as fodder crops in the summer. Rice nurseries are planted in May, and the seedlings are transplanted between the end of May and the mid-end of June. Rice harvesting usually takes place in October. Berseem is an important leguminous forage crop, since it has a nitrogen-fixing ability, with a fast winter growth rate and relatively long growing season (allowing from 5 to 10 successive cuts). Cattle, especially buffalo, cows, donkeys and more rarely sheep and goats, are always associated with farming activities.

The al-Bayda branch command area is part of the wet and salty lands that were reclaimed from the coastal lake as part of the Abis project, which was a land reclamation and community development project launched after the 1952 revolution and farmed since 1961 (Voll 1980). It consists of old alluvial plains with a very flat topography (FAO 2005), and heavy clay and mildly saline soils (Kotb et al. 2000). Groundwater is saline and found at shallow depths as the groundwater table fluctuates between 1 and 1.6 m below the surface in the Mahmoudiya command area. Towards the North, the freshwater layer overlaying saline water becomes thinner and more saline (FAO 2005).

Data Collection and Analysis

The case study is based on individual and semi-structured on-farm interviews focusing on farmers' crop choice and irrigation constraints associated with water scarcity, which is defined by FAO (2012) as a situation where "*demand for freshwater exceeds supply in a specified domain*." This provided a means of exploring perceptions and gaining a deeper insight into the different practices and strategies that farmers follow. Farmers were asked to describe the pattern of water distribution at several levels, irrigation and drainage constraints, the historical evolution of cropping systems, and their farm and livelihood strategies.

The fieldwork was conducted during the summer months of 2011 and 2012. Seven locations along the branch canal were selected and coded as L1 through to L7, from the head end to the tail end of the branch canal (see Figure 1). In each location, the *mesqas* situated on both the left and right banks of the al-Bayda branch canal were surveyed (14). In each *mesqa*, we selected three *marwas* located, respectively, at the head, middle and tail ends (42). In each *marwa,* one to two farmers were randomly selected for an on-farm interview, which resulted in a total of 60 interviews with farmers in the local Arabic dialect.

Through those farmer interviews, we collected information on the actual cropping pattern in the summer season of 2012 for all the 42 surveyed *marwas*, which represents 26% of the total surface area. An economic survey was also conducted with a restricted number of farmers (one to two farmers for each major crop), in order to (i) quantify the current costs, and gross and net margins under optimal conditions of irrigation (i.e., number of rounds of irrigation identified as being sufficient to reach potential yields); and (ii) perform an analysis of the water productivity of the main summer crops. The gross value of production was defined as the yield multiplied by (i) the local crop price (rice, maize, grapes, core melon); (ii) an average between the lowest price and the highest price during the season when the harvest is staggered (tomato); or (iii) an average price when there are different grades or categories of the same crop (*luffah*, cabbage, sweet potato). Costs include (i) inputs such as seeds, fertilizers, pesticides and diesel; and (ii) hired labor mainly for (trans) planting, weeding, irrigation and harvesting. Maize for forage, eggplant, pepper, okra, green beans and cucumber were not included in the economic survey due to their minimal contribution to household income.

Chi-square statistical tests were conducted to assess the probability of association or independence of two qualitative factors, which were applied here to test the spatial distribution of the adopted practices and strategies according to the proximity of an irrigation water resource. To show the spatial distribution of farmers' adaptation practices to varying water supply conditions, we analyzed the proportion of farmers, *marwas* or fields according to the proximity of an irrigation water resource.

Spatiotemporal Evolution of Water Availability

Farmers were unanimous in reporting that there were abundant water resources before the 1990s, which allowed a flexible irrigation system and consequently the ability to cultivate a large quantity of vegetables during the peak summer season, even at the tail end of the branch canal and *mesqas*. Water delivery was predictable, with a rotation of 4 days on and 4 days off in the al-Bayda Canal command area. It was initially reported that gravity irrigation could be practiced in some areas, but pumps were then progressively introduced to eventually cover the command area. The number of off-days was later increased to 6 days until 2000, and then to 8 days until 2005. Recently, the off-period was fixed by the MWRI at 10 days. In addition to increasing the off-period, the current on/off schedule was said to be increasingly unpredictable, especially during the peak summer season (June, July and August). Farmers usually expect a delay of 1 to 5 days and the off-period would frequently exceed 10 days.

Analysis of the current irrigation scheduling showed a dramatic decrease in water availability in the downstream reaches of the branch canal. Water reached the tail end *marwas* of the head location (L1) a few hours after the opening of the al-Bayda branch canal. During the peak summer season, water took a day to reach the tail end *marwas* in locations L2, L3 and L4. *Marwas* in the head end and middle end locations of L5, and those in the head end location of L6 received water 2 days later, whereas farmers belonging to the *marwas* in the tail end had just one day per turn to irrigate their crops. Freshwater seldom reached the extremity of the branch canal (L7) and was only used once in each of the three rotations, so farmers increasingly pumped water from the main drain. Drainage water reuse is a common strategy among farmers to increase supply to their fields.

The field survey also showed that most of the fields in the head end of the canal had more on-days than the four official days fixed by the MWRI. This means that even during the stated official off-period, the main gate feeding the branch canal could be 'un-officially' opened (farmers reported instances of bribing the *Bahhar*, who would allow the main sliding gate to be opened slightly). In addition, the control weir located at the head end of the branch canal allows for the storage of water in the upstream reaches, especially for the two *mesqas* represented by L1. Furthermore, due to the slope of the land towards the northern lateral drain, some *mesqas* benefited from stored water in the terminal reaches until the next rotation, even during the peak summer season.

All the farmers interviewed highlighted the current inequitable distribution of water across the head and tail end reaches of the branch canal. Inequity along the *mesqas* was also mentioned, but to a lesser extent. While farmers in the head end reaches spoke about luck and recognized being in a favorable situation, those in the tail end reaches referred to the injustice of water sharing arrangements. Land prices are also reported to vary as a function of the position of the branch canal (but also due to the asphalt main road along the branch canal).

Farmers reported three main options for adapting to a long period of water shortages: (i) seeking other sources of water such as drainage water; (ii) influencing the *Bahhar* to gain access to more water (bribing and in-kind 'gifts')[1]; and (iii) social mobilization, especially since farmers have become more aware of their rights after the revolution of January 2011 and feel less constrained to mobilize[2].

When asked about the reasons behind the gradual lengthening of the off-period and the current unpredictability of water supply, 35% of the farmers pointed to Alexandria, which is given priority to water supply from the Mahmoudiya main canal, particularly during the tourist summer period[3]. Some farmers (28%) blamed the continuous expansion of irrigated areas in the desert. Others (17% of the farmers) reported that the reason behind the current unpredictability of water supply was to push farmers to accept the planned improvement of the irrigation network (Integrated Irrigation Improvement and Management Project [IIIMP]), which was presented by the government as the best option for farmers to reduce water shortages.

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[1] Farmers reported that, in each village, the *Bahhar* appoints a person to collect the harvested crops, especially rice and wheat. Farmers do not hesitate to give the crops requested. They fear further unpredictability of water supply, and know that they cannot ask the *Bahhar* for a special water supply during the off-period.

[2] During the summer of 2011-2012, when the off-period exceeded 20 days, farmers blocked the agricultural road leading to Alexandria and then attempted to destroy the head-gate of the Bayda branch canal. In these demonstrations, farmers in the tail end reaches stressed their right to have water during the peak summer season, and were supported by their fellow farmers in the head end reaches. Almost all the farmers reported a high number of requests channeled to the cooperative and the district, or to higher political levels, which all remained unattended. Farmers stressed the lack of participation in decision making.

[3] A farmer reported a story that happened 10 years ago, when his relative (an engineer) was ordered to close all the gates feeding secondary irrigation canals along the Mahmoudiya Canal to bring water to Alexandria.

Coping with Water Scarcity: Adaptive Practices and Strategies

Farmers observe the increasing water shortage and its effects on yields. They reported many combined practices and strategies to mitigate the effects of water scarcity on yields and, consequently, on their incomes. In what follows, we explain the relationships between water scarcity (approximated here as the relative distance to a water source) and i) actual cropping pattern, ii) water sharing rules (in *marwas*), iii) reuse of drainage water, iv) night irrigation, v) number of individual diesel pumps owned by farmers, and vi) frequency of conflicts. The spatial distribution of any of these adopted practices is statistically related to the proximity to a water source when the p-value (p_v) is less than or equal to 0.05.

Cropping Patterns

The spatial distribution of irrigated summer crops reflects the distance to a water source, either the branch canal or the secondary drains. Figure 2 shows that rice was the slightly dominant crop at the head end and middle end of the al-Bayda Canal. Further, 76% of rice was concentrated on the *marwas* in the proximity of the secondary drains rather than near the branch canal, which shows the benefit of a perennial water source for rice cultivation. Field observations also showed that two to three *marwas* of each of the head and middle end *mesqas* were exclusively devoted to rice cultivation, according to a two- to three-year crop rotation. Rice occupies 33% of the cultivated area of L1, between 24% and 29% in L2, L3, L4 and L5, and is down to 6% in L6 and 8% in L7. In the tail end of the branch canal, rice cultivation only appears in the head *marwas* (near the al-Bayda Canal) and/or tail *marwas* (near the main drain), or not at all.

As explained later in this report, the cultivation of watermelon and melon is not correlated with conditions of water scarcity. Their cultivation is concentrated in the upper reaches of the branch canal (Figure 2), with L1 and L2 totalizing 65% of the fields against 9% for L6 and L7 together; similarly, while melon represented 18% of the plots in L1 and L2, it is almost absent in the tail end locations.

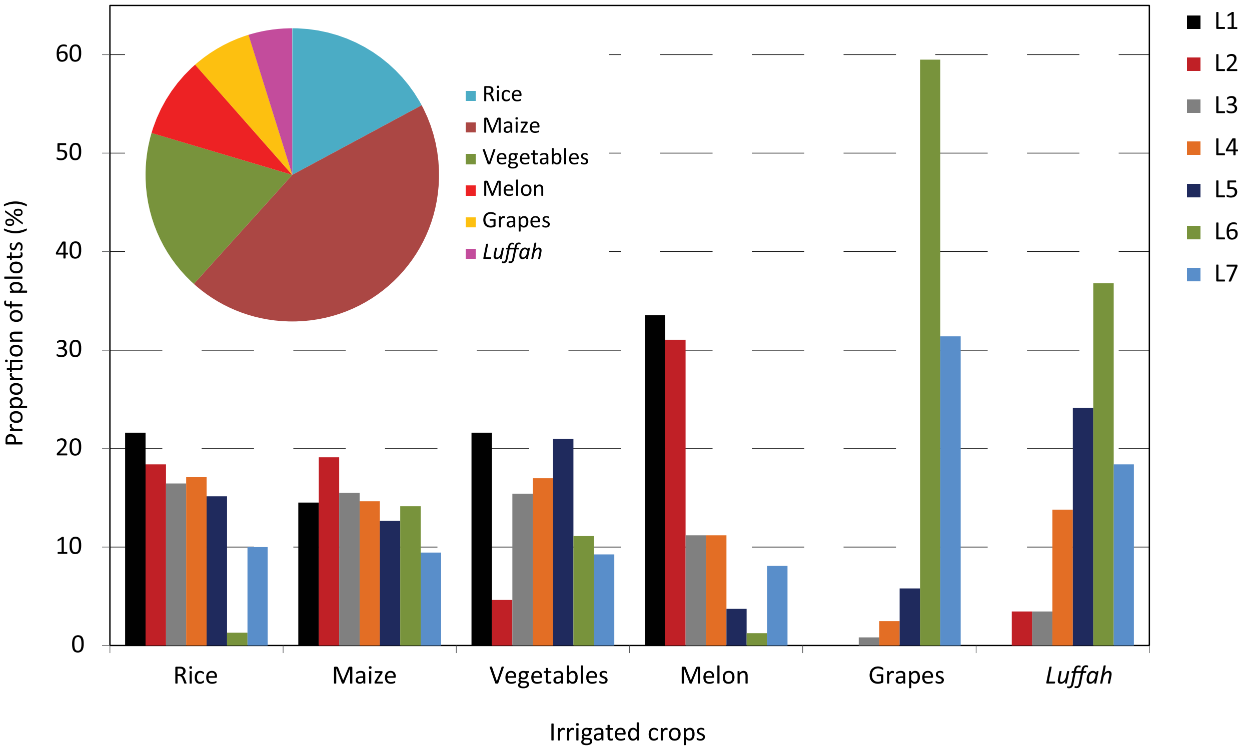
The cultivation of grapes is linked to water quality (salinity) rather than water availability, whereas the cultivation of *luffah* is more dependent on water availability. Grapes are mostly cultivated in the lower reaches of the al-Bayda branch canal. Indeed, locations L6 and L7 alone totalized 91% of the grape fields (which made up 28% and 19% of the total plots, respectively). *Luffah* is also dominant in tail end locations, with L6 and L7 concentrating 55% of *luffah* fields (which made up 12% and 8% of the plots, respectively). In addition, 90% of the grape fields were concentrated near the branch canal, while 64% of *luffah* fields are found close to the secondary drains.

Vegetable cultivation is driven or constrained by water availability more than by water quality (pollution). As a result, the water-demanding vegetables are concentrated at the head end of the branch canal (for instance, location L1 alone included 56% of tomatoes and 30% of pepper). On the contrary, eggplant, cabbage and potato are mostly found in middle locations, with L3, L4 and L5 totalizing up to 63%, 74% and 74%, respectively. In addition, the proximity of the secondary drains concentrated 67% of vegetables. Maize cultivation is equally distributed between the al-Bayda Canal and the secondary drains, indicating that it was not constrained by water availability or water quality.

Irrigation Rules

There is no rotation between the *mesqas* of the al-Bayda Canal. The sliding gates at each *mesqa* inlet are permanently open and farmers divert water from the al-Bayda Canal *whenever it is available*. No specific rule allowing an equitable distribution of water between *mesqas* in the head end and tail end can be found, and any particular

FIGURE 2. Distribution of the actual cropping pattern according to the position along the branch canal during the summer season in 2012 ($\chi^2 = 580.03$, df = 36, pv < 0.001, n = 1,809 plots).



mesqa is fed according to the level of water in the al-Bayda Canal. The same situation is observed *within* each *mesqa*, except that *only one pump* (or exceptionally, two, when water is abundant) can be operated at the head of a given *marwa* at any given time. An occasional additional rule applies to *mesqas* that supply rice, which puts a limit in terms of pumping duration.

More collective rules were identified at the *marwa* level, where farmers organized rotations between themselves. The Chi-square analysis shows the adoption of irrigation rules at the *marwa* level to be highly related to the position on the branch canal, with most rigorous rules observed at both the head and tail end reaches of the al-Bayda Canal. The rigidity of rules in the head end reaches of the canal is related to rice and vegetables, which require frequent rounds of irrigation, whereas the rules in the tail end reaches are related to increasing water shortages, as one goes downstream.

Results show that the dominant rule is 'first come first served' in 33% of the *marwas* surveyed. To avoid conflicts and instill some discipline, 19% of the *marwas* agreed to have 'order rules', whereby upstream fields are served first and in succession, with or without a sanction for upstream latecomers (i.e., if a farmer misses his turn then he has to wait until all the other fields are served). Alternatively, the turn from upstream to downstream is followed by a round that starts from the last field. Two more rigorous rules are justified by priorities linked with the value or the nature of the crop: vegetables are given priority in 26% of the *marwas*, and rice in 7%. Finally, an order rule (sometimes together with a fixed duration for each hectare) is agreed for the *marwas* (14.3%) that are exclusively under rice (Figure 3).

The three head locations (L1, L2 and L3) are characterized by the predominance of the rule 'priority to vegetables' in 61% of the 18 *marwas* surveyed. Once vegetables are irrigated, the 'first come first served' rule applied in 64% of the *marwas*. Rice is found in the entire cultivated area served by 14.3% of the *marwas* surveyed, and the irrigation duration of a *feddan* is agreed to be fixed at 2.25 to 3 hours in 67% of the cases. The tail end locations were characterized by the complete absence of the priority given to vegetables, the presence of order rules in 33.3% of the 24 *marwas* surveyed, while the irrigation of rice received priority in 12.5% of the *marwas* surveyed.

Reuse of Drainage Water

The frequency of drainage water reuse was expected to increase towards the downstream areas, as water availability decreased. However, the Chi-square analysis indicated that there was no significant difference in the frequency of drainage water reuse between the seven locations. Mainly, the frequency of reuse depended on both the actual needs and farmers' access to the secondary drains, while farmers did not have the option to consider the quality of the drainage water (mostly mixed with sewage water from 20 villages). In other words, the availability of drainage water mattered more than its quality in any location of the branch canal (although 4% of farmers stopped using drainage water because of its poor quality).

Data shows that during the off-days, 48% of the farmers interviewed did not use drainage water, 38% stressed its frequent reuse, 13% had the drains as their *only* water source and only 1% had stopped reuse because of "the bad quality of drainage water". The farmers who did not use drainage water were divided between those who did not want to use it (23%) and those who wished to use it but could not access it (25%) (Figure 4). The former did not need drainage water for the irrigation of maize, fruit trees and watermelon; a dominant proportion of this category of farmers was located in the head end reaches of the canal. The farmers who could not access drains – either because they are located far away or because neighbors did not grant them access - are scattered.

Farmers who were *only* using drainage water were, of course, generally located in the tail end of *marwas*, with direct access to secondary drains. Even those farmers in the tail of head-end *mesqas* opted for using drainage water to i) be *independent* from canal water supply, ii) avoid purchasing another pump, and iii) reduce labor and the burden of moving one pump from the *mesqa* to the secondary drain. For these farmers,

FIGURE 3. Nature of irrigation rules at the *marwa* level ($\chi^2 = 57.34$, df = 24, $p_v < 0.001$, n = 42 *marwas*).

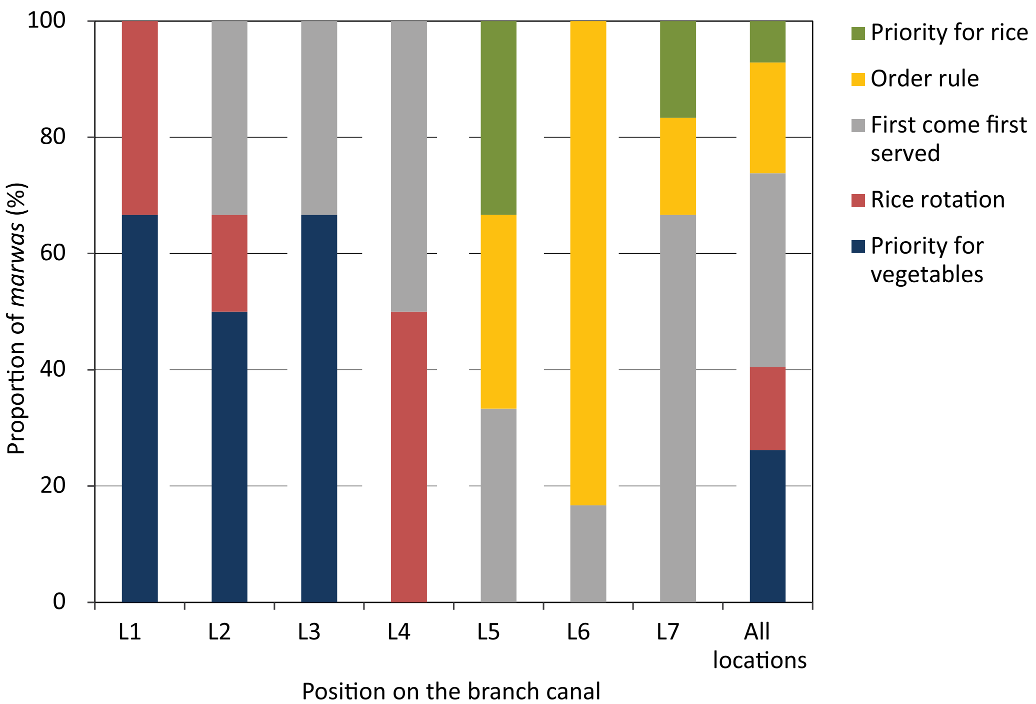
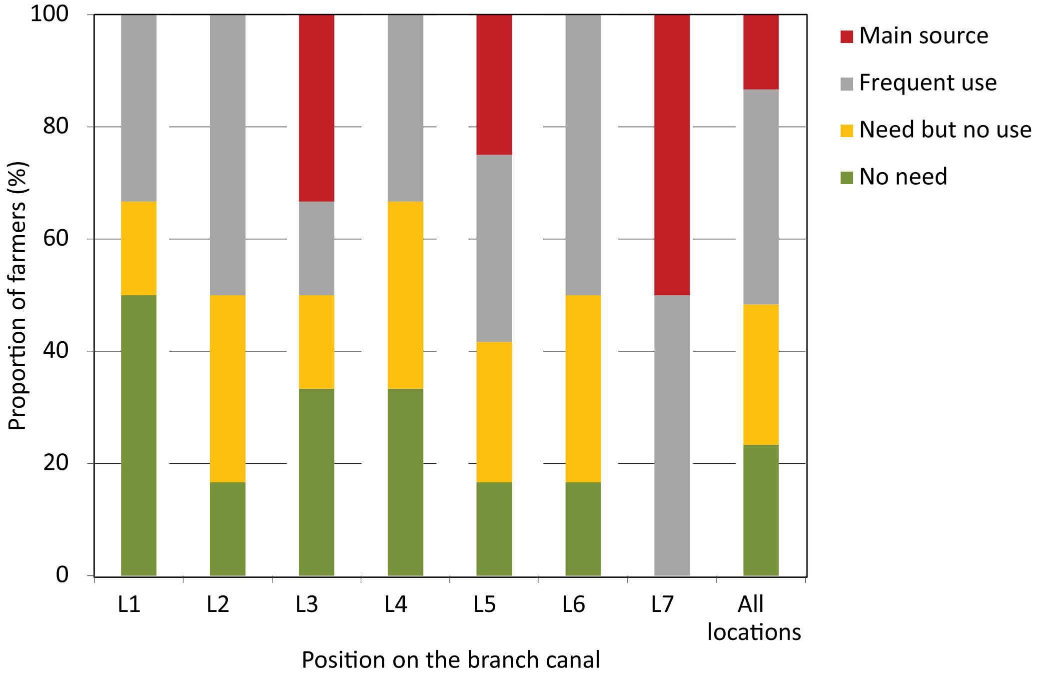


FIGURE 4. Degree of farmer's dependence on the reuse of drainage water according to the position along the branch canal (χ^2 = 25.97, df = 24, p_v = 0.355, n= 60 farmers).



the quality of drainage water was good due to the abundance of freshwater in the upstream fields. In contrast, farmers in tail end *mesqas* stressed that drainage water was their main source of water during the peak summer season, when only one-third of irrigation events are ensured by the al-Bayda branch canal. Farmers situated away from the secondary drains and located in tail end reaches of *mesqas* agreed to organize amongst themselves to pool several pumps and tap drainage water back to the *mesqa*.

The category of 'frequent reuse of drainage water' is high in tail end locations as well as in head end locations, but corresponds to different strategies. While farmers in head end locations (L1, L2 and L3) spoke about the need for a complementary water source mainly to irrigate rice when the duration of off-days exceeded 3 days (and 5 days for vegetables), those in tail end locations referred to the drains as the *main* available source of irrigation water during the peak summer season.

Farmers are aware of the consequences that the frequent reuse of drainage water would have on the soil as well as on people's health. All farmers described drainage water as a mixture of (saline) agricultural drainage water and wastewater, where the water quality decreases as one moves downstream. Most farmers referred to the health risks associated with the direct contact with this mixed drainage/wastewater. However, farmers in head end locations (especially in L1 and L2) state that the quality of the drainage water was good even for irrigating vegetables, which was due to the abundance of (still a little polluted) water coming from upstream fields. The majority of farmers further reported that the use of drainage water increases labor to move the diesel pump from the *mesqa* to the secondary or the main drain.

Increase in the Number of Night Irrigations

The limited supply of water resulted in the necessity to have additional irrigations at night. The assumption is that the frequency of night irrigation increases as water availability decreased in the downstream areas. However, results showed that farmers in both head and tail end locations practiced night irrigation. Busy farmers with alternative activities besides agriculture or farmers with sensitive plants such as *luffah* or vegetables prefer to irrigate at night, and to also enjoy a higher flow which allows continuous irrigation without the fear of the canal drying up. However, farmers in tail end locations were more dependent on night irrigation, because irrigation water is mainly available at night. For instance, whereas none of the farmers in location L1 were forced to irrigate at night, all farmers at the other extreme (L7) mainly depended on night irrigation (Figure 5).

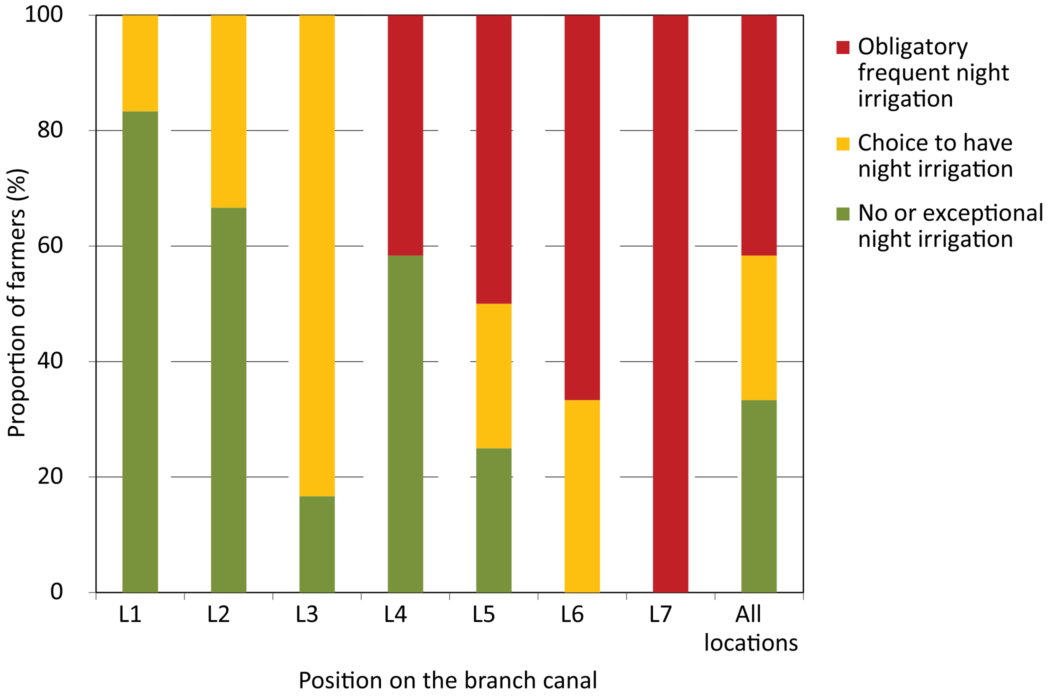
Increase in the Number of Diesel Pumps

The increased water shortage also drove farmers to owning more than one diesel pump, in order to be able to conduct synchronized independent irrigations of plots located in different *marwas* of the same *mesqa* (remember farmers were initially given three plots). Results confirmed the expectation that the proportion of farmers owning more than one pump would increase going towards downstream areas, as water availability decreased, with most of the 23% of farmers in the tail end reaches of the branch canal purchasing an additional pump. For instance, whereas only 16% of farmers in locations L1, L2 and L3 owned two pumps, this proportion was 33% in locations L5, L6 and L7. Of the farmers surveyed, only 8% did not use a pump for irrigation, because the high slope of the *mesqa* allowed gravity irrigation (in locations L1 and L5). Nevertheless, some of the farmers purchased one or two pumps to withdraw water from the secondary drain or from the *mesqa* during the off-days, since it served as a storage basin.

Conflicts among Farmers

All the farmers surveyed stressed the inequity of water distribution along both the al-Bayda branch canal and its *mesqas*, but none of them reported any conflict between *mesqas* or *marwas* of the same *mesqa*. They only reported conflicts to occur at the *marwa* level, where 31% of the 42 *marwas* surveyed experienced conflicts. Although most farmers implicitly referred to these conflicts,

FIGURE 5. Degree of farmers' dependence on night irrigation according to the location along the branch canal (χ^2 = 45.82, df = 12, p_v < 0.001, n = 60 farmers).



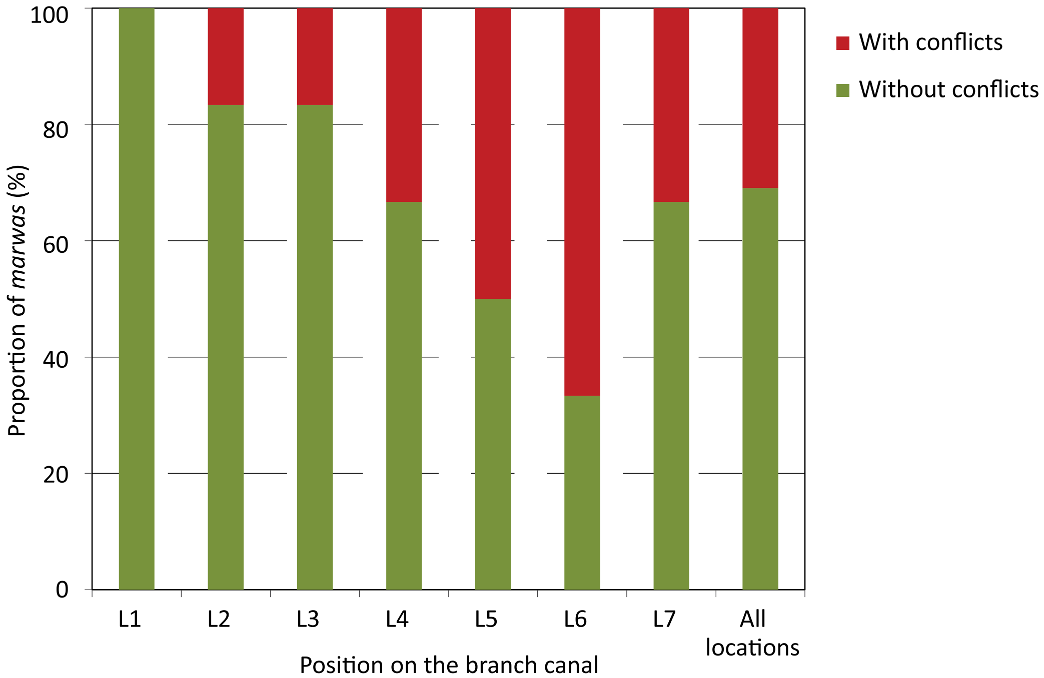
they comply with local norms, for example, as illustrated by local sayings ("*water does not pass the thirsty*" and "*water turns, it never remains with the same person"*) and the absence of a restriction on the number of *marwas* that are 'on' at the same time.

The frequency of conflicts at the *marwa* level was expected to increase when going towards downstream areas, as water availability decreased. Results confirmed these expectations, but to a lesser extent at the end of the branch canal. Figure 6 shows that the middle and tail end of the branch canal concentrated most of the *marwas* that were experiencing conflict, e.g., 50% and 67% in locations L5 and L6, respectively, compared to no reported *marwa* conflicts in location L1. Frequently, water did not reach the end of the branch canal (location L7) and farmers mainly depended on drainage water for irrigation. Thus, only 33% of the *marwas* located close to this branch canal are declared as being prone to conflicts. Farmers in the head end reaches of the al-Bayda canal related the low frequency of conflicts to the spread of vegetable fields under furrow irrigation, short irrigation durations, and also to the strict priority given to rice irrigation.

Although all the farmers of the lower reaches referred to the problem of water availability, they tried to de-emphasize the seriousness of the conflicts: "*why lose a relative, a friend or a neighbor because of a problem that is not under our control … a problem that all of us are subjected to"*[4].

The reasons behind conflicts are varied. Some conflicts are due to "*excessive pumping duration*", especially in the tail end reaches of the branch canal. Other conflicts occurred at the beginning of the on-period, especially for farmers cultivating vegetables in the middle of the al-Bayda canal. Some farmers declared that the most important reason behind irrigation rules, such as the fixed irrigation duration for each rice farmer or the priority for vegetables, is to avoid conflicts. Another kind of conflict is related to

FIGURE 6. Distribution of the frequency of conflicts along *marwas* according to the location along the branch canal ($\chi^2 = 13.07$, df = 6, $p_v = 0.042$, n= 42 *marwas*).



[4] In one case, a conflict went wrong and resulted in a murder.

access to the main drain, when farmers located alongside the drain refused to let upstream farmers access or lay some pipe through their land to access the drain. All these conflicts are generally mediated by elderly farmers and the conflicting parties usually accept their decision.

Cropping Patterns and Their Determinants

From Over-irrigation to Forced Deficit Irrigation

Farmers in both the head and tail ends of the branch canal are unable to provide sufficient freshwater to cover the water requirements during the long intervals between two successive irrigations (more than 10 days). However, head-end farmers may *over-irrigate* during the on-period as a means of storing water in the soil profile. Considering one irrigation turn and the same crop (in this case, rice) data showed that farmers irrigated from one to four times as long as water was available in the *mesqa*, particularly during the peak summer season. Some farmers reported that rice needs to be irrigated every day during the summer. In addition, a disparity between head and tail end reaches was observed. For instance, during the on-period, farmers in the head end locations (L1, L2, L3 and L4) irrigated their plots from 2.25 to 3 hours/*feddan* at least three to four times, while those in the middle and tail end locations (L4, L5 and L6) irrigated twice at most and farmers reported having to wait all day to complete an irrigation event due to the low inflow in the *mesqa* (which also compelled them to interrupt pumping water several times). In addition, during off-days, rice is irrigated at least twice from secondary or tertiary drains. In other words, as the highest water consumer, rice is irrigated at least 16 times between June and September, and the number of irrigation rounds could be more than twice this number for farmers in the upper reaches.

Other crops such as *luffah*, maize, trees and vegetables are less time (and water) consuming than rice (0.75 to 1.5 hours/*feddan*) since they are under furrow irrigation. However, *luffah* is also relatively water-consuming in terms of irrigation frequency, because it needs an irrigation per rotation from April to mid-November and then no irrigation until January (end of harvest) (16 to 18 irrigation rounds). With one to three irrigation applications per season, cantaloupe, watermelon for seeds and sweet potato are by far the lowest water consumers. Grapes need six to eight irrigation applications per year, with four applications (at most) in the summer season and no irrigation from November to January. Farmers irrigated tomato around six times and maize around five times.

Assessment of Costs and Benefits of the Cropping Patterns Adopted

The economic performance of the most commercialized crops, when grown under optimal conditions of irrigation in the al-Bayda Canal command area, are presented in figures 7, 8 and 9 in 2012 prices.

Results showed that, in line with farmers' accounts, *luffah* and watermelon (for seeds) have the highest returns. Indeed, the net revenue from *luffah* represented 1.5 times that of watermelon, 2.0 times that of tomato, 2.8 times that of grapes, 3.7 times that of rice, 4.8 times that of cabbage, 9.4 times that of green or dry maize and 10.8 times that of potato (Figure 7). However, *luffah* is also considered as the crop with the highest production costs (between 1.4 to 6.2 times that of other crops), bringing high production risks to farmers in the event of crop failure due to pests/diseases or low market prices. Indeed, growing *luffah* requires a sturdy wooden structure, because it is a climbing plant. The cost of such a structure is estimated at 73% of the total costs of the first production year (Figure 8). Consequently, after a 10-year amortization, the ratio of the net revenue of *luffah* to that of other crops varies between 2.3 to 17.1.

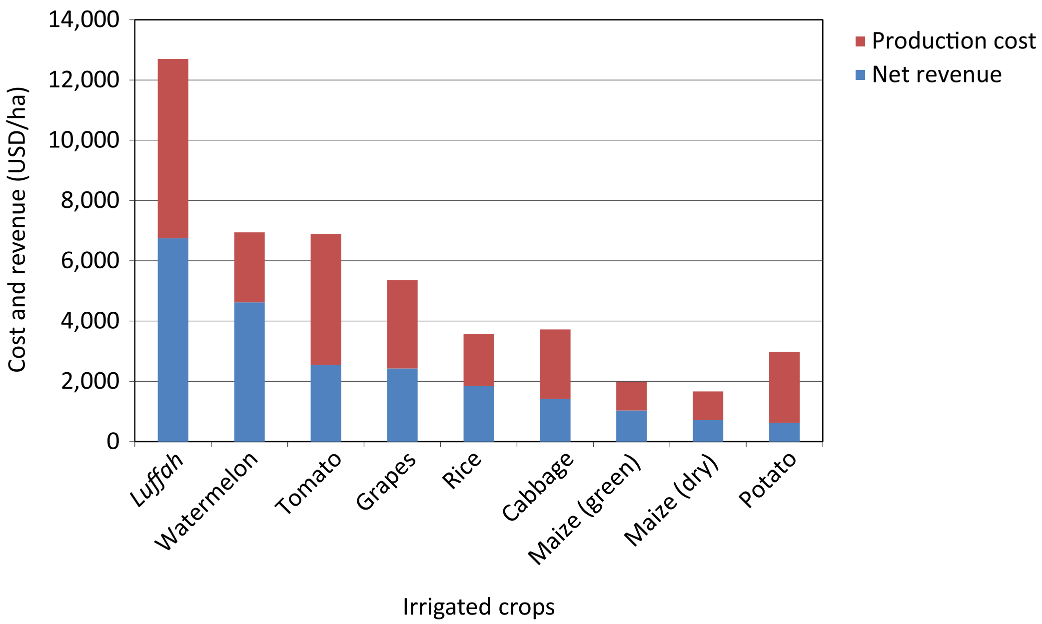
Watermelon ranked second in terms of net revenue, but with the highest ratio of net revenue to the production costs (2) compared with a ratio varying from 1.1 to 0.3 for the other crops. The second highest crop in terms of production costs after *luffah*, and third in terms of net revenue, is tomato. Tomato production costs are mainly related to harvesting (43%), fertilizers (26%) and pesticides (15%). However, its final revenue is still higher than the common crops, e.g., 1.4 times that of rice and 3.6 times that of maize.

Grapes is also considered as a high-cost crop[5] (1.7 times the production costs of rice or 3.1 times that of maize); and pruning, training, canopy management and weeding took the lion's share of production costs (49%). Sweet potato and cabbage are also high-cost crops, but cabbage has 2.3 times the net revenue of potato. The high production costs of potato are related to harvesting and washing the finished product (28%), and then to fertilizers (25%). For cabbage, pesticides are the main reason for the high production costs (30%) and then organic manure (15%).

Maize and rice are low-risk and low-profit crops that are, however, important for farmers' food security. Maize has the lowest production cost, but also the lowest net revenue; green maize (corn) has 1.4 times the net revenue of dry maize (grain). The highest cost was for fertilizers (31%) and then weeding (17%). Rice production costs and net revenue represented 1.8 and 2.6 times, respectively, that of maize (dry), with irrigation (33%), and transplanting and puddling (24%) comprising half of the costs.

Figure 9 shows the *water needs-profitability* relationship of the most commercialized crops in the al-Bayda branch canal: the lowest water consumer in terms of irrigation frequency

FIGURE 7. Distribution of net revenue, gross revenue and production costs.



[5] A farmer described the cultivation of grapes as a bank where one can deposit their money little by little and then take back the total amount at once.

(watermelon) has the highest water productivity (USD 2,312/ha/irrigation round) followed by tomato (USD 509/ha/irrigation round), *luffah* (USD 422/ha/ irrigation round) and grapes (USD 405/ha/irrigation round). However, the most water-intensive crop (rice) is ranked last (only USD 54/ha/irrigation round), just after the other most common crop: [dry] maize (USD 102/ha/irrigation round).

FIGURE 8. Distribution of production costs by crop.

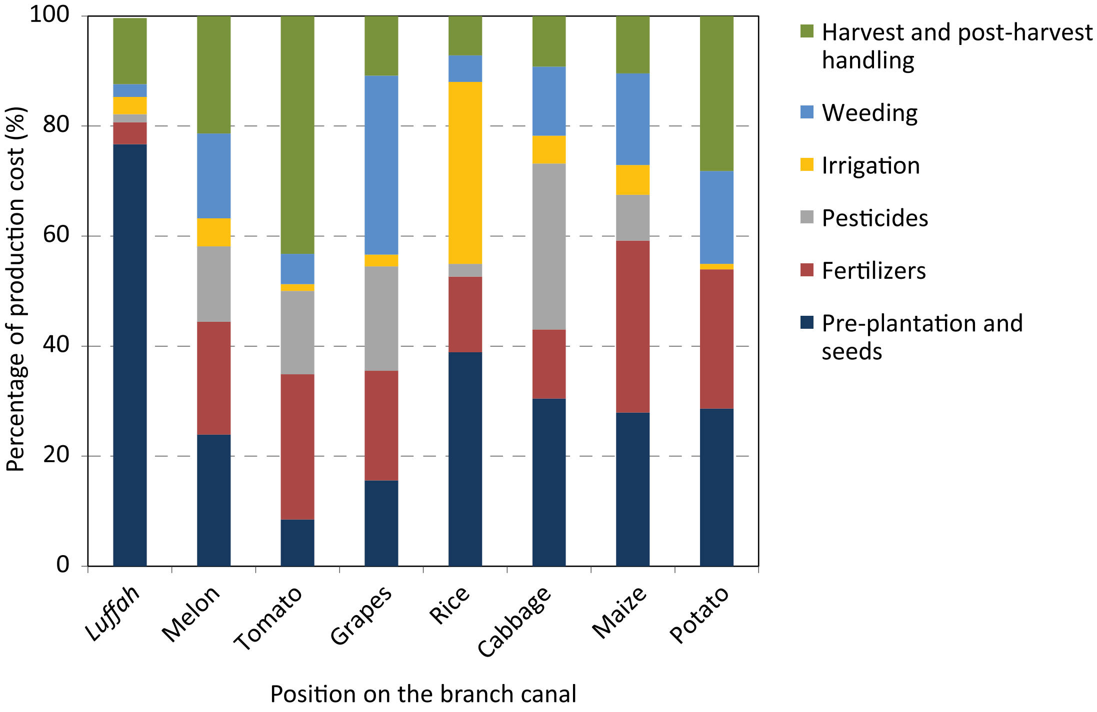
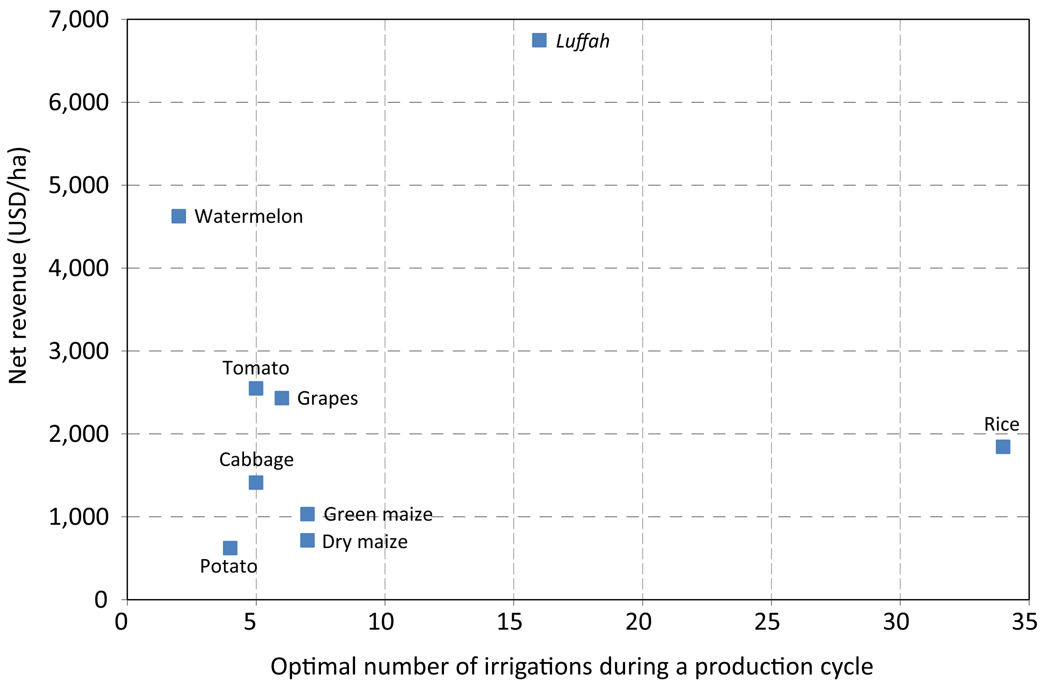


FIGURE 9. Cost-effectiveness in the use of water for the cultivation of commercialized crops.



Trends in the Spatiotemporal Distribution of Cropping Patterns and Yields

The cropping patterns of the farmers that originally settled in the area are different – to a varying degree - from the current cropping patterns of the second or third generations. These patterns evolved with time and space, and are not only related to water availability and farm profitability. An important factor that shaped cropping patterns in reclamation projects was the state policy of obligatory crop rotations. This national policy was implemented by agricultural cooperatives under the Ministry of Agriculture and Reclamation. After the mid-1980s, political and economic liberalization policies partially dismantled these obligatory crop rotations. Many other factors contributed to the evolution of land use and most of these are associated with trends that unfolded over the last 30 years. It is noteworthy that in spite of several individualizing trends, farmers also responded collectively in terms of their crop choice.

All the farmers in the head end locations (L1, L2 and L3) reported that they were still following the original crop rotation - cultivating rice and vegetables. In location L1, up to two-thirds of the cultivated area of the *mesqa* were still devoted to the cultivation of vegetables (mainly tomato and potato) and watermelon, while the remaining one-third was devoted to rice cultivation, according to the agreed crop rotation. The proximity to Alexandria via the agricultural road facilitated access to markets, while rice is said to be mandatory for both household consumption and soil leaching purposes. Farmers described watermelon as being highly profitable and "*not a tiring cultivation,*" since it needs one to three rounds of irrigation, one light weeding, and a low quantity of fertilizers and pesticides. However, they highlighted the strict necessity for the rotation of cultivating rice after watermelon to allow for better leaching, thus "*washing the soil.*" Surprisingly, watermelon was initially introduced by farmers who enjoyed the best water supply since 2007 in the location L1. This introduction can be explained by the specialization of cash crops in the area, and by the proximity to Alexandria via the agricultural road. However, the very low frequency of irrigation that is necessary for watermelon initially discouraged more traditional farmers in location L2 and beyond, who feared the degradation of the quality of their soil because of reduced leaching but gradually came to adopt it because of its high income and the ease of cultivation.

In contrast, farmers in downstream locations (L4, L5, L6 and L7) admitted facing more restrictions on crop choice. For instance, in location L5, 58% of the farmers reported that cultivating rice became very difficult and 50% reported giving up vegetable cultivation. Farmers in locations L5, L6 and L7, who shifted to the cultivations of trees, stressed that grapes are tolerant to water shortages (only four to six rounds of irrigation are needed during a production cycle).

The decision to shift from the common crop rotation based on rice to cash crops, such as grapes, took place in the early 1980s *before* the current water shortage. The widespread cultivation of grapes in the tail end of the branch canal is related to specific family know-how and also to farmer-to-farmer extension. Indeed, farmers in location L7 – where grapes were the dominant crop – reported that their parents were used to cultivating such trees in their village of origin (Beshla in Ad-Daqahliyah Governorate). After their settlement in the al-Bayda command area, they opted for grapes since the mid-1980s (after the dismantling of the obligatory crop rotation). Some farmers in location L6 acknowledged the know-how of farmers located in the tail end of the canal, who assisted them in grape cultivation. Interestingly, clustered grape plots were said to prevent fruit thefts and bird attacks, as farmers said "*trees protect trees.*"[6]

[6] Some farmers in upstream locations of the branch canal (locations L4 and L5) uprooted grapes because their plots were not protected by other surrounding fruit plots. Other farmers in the head and middle reaches of the canal (from locations L1 to L5), who either tried and then uprooted grape trees or talked about the experience of a relative or a neighbor, stated that tail end locations were the most suitable for grape cultivation because soils and the water table were deeper. This allowed for better leaching – "washing the soil" – and drainage conditions, which would not be found in the head end locations due to the shallow water table created by collective rice cultivation along with over-irrigation.

In addition, the decision to plant a perennial crop – and *sacrificing* one plot among the three original plots – was said to be easier with the first generation of farmers (who each had three plots of 1.33 *feddans*). Despite land fragmentation, the heirs of this first generation of farmers followed the practices of their parents on a smaller plot, because of the acquired skill and economic benefits of its cultivation; as a result, they also gave up raising cattle. *Luffah* developed in the same area as another cash crop. The proximity to Alexandria via the coastal road facilitated access to markets. A similar path dependency applies to vegetable cultivation in the upstream *mesqas*. Remarkably, the second and third generation of farmers find it harder to diversify to cash crops due to the importance of land for family food security (rice and wheat) and animal farming (berseem and fodder maize), especially when their plot is smaller (split at inheritance).

The collective cultivation of rice – and the resulting rise of the water table – is an additional factor behind the complete absence of grapes and the very limited spread of *luffah* in the head end locations. *Luffah* is reported to be both highly sensitive to diseases and vector-borne diseases (due to the intense shading of the contiguous canopy on the ground during at least half a year). It is also an exhausting plant for the soil, which limits its cultivation on the same field to a maximum of four consecutive years. Despite its well-known high return, capital investment needs and the risk of diseases limited the spread of *luffah* cultivation. The risk of disease and the high fluctuation of prices were reported to be the main limiting factors of tomato cultivation.

The end of cotton cultivation in all the areas is mainly related to insect proliferation, labor costs for harvesting, difficulty of marketing the product after the abolishment of the obligatory crop rotation, and cooperatives no longer being responsible for collecting the product.

The effect of the gradual lengthening of the off-period on yields is more difficult to assess. In the upper reaches of the branch canal, it did not change the cropping pattern, but 18% of the farmers in locations L1 and L2 admitted that increased water scarcity negatively affected yields. However, quantifying such an effect on rice was difficult for 36% of the farmers because of shifts from traditional to drought-tolerant crop varieties, mainly of shorter duration. The effect of water scarcity on yields is more explicit for farmers downstream of L2. For instance, farmers in location L3 reported a decrease of about 25% in rice and maize yields (which used to be 4 and 3.2 tonnes (t)/*feddan* for rice and maize, respectively), while farmers in locations L4, L5 and L6 admitted that there was an effect of water scarcity on yields, with a drop of 30 to 50% in rice yields (which used to reach 3.5 t/*feddan*)[7]. The majority of farmers in locations L6 and L7 reported that water shortages induced a decline in rice and maize yields (from 3 or 3.5 to 1 or 1.5 t/*feddan* of rice).

However, such reductions in yield were not only related to water scarcity; indeed, they were also related to decreasing soil fertility[8], increasing use of pesticides, increasing use of low-quality water (drainage water), aging trees (in the case of grapes), low quality of seeds and inputs (pesticides, fertilizers), fake products, etc. In addition, most farmers recognized that crop rotation practices, especially berseem and rice, benefitted the soils in relation to nutrition and recovery of essential elements, as well as for salt leaching.

When asked about which crop they would grow in the absence of any constraint on irrigation supply, almost all the farmers stated that they would cultivate the staple food rice and vegetables, and forage maize as fodder. Vegetables were produced mainly for family consumption and the remainder would be sold.

[7] A farmer reported that rice yield increased after land was divided between heirs, each one investing in more labor and fertilizers on their own fields.

[8] Before 1964, the Nile River flooded every year during the late summer. These floods brought water and sediment, which was rich in natural nutrients and minerals that enriched the fertile soils along the floodplain and the delta, annually.

Discussion

Urban expansion and increased rice cultivation have been the causes for water scarcity in the al-Bayda command area. This growing water scarcity was epitomized by the gradual lengthening of the off-period during the past 15 years, from 4 to 10 days. Furthermore, the current on/off schedule is not predictable, especially during the peak summer season (June, July and August). The current spatial distribution of water showed an inequity along the branch canal; while some farmers in the head end reaches had water in their *mesqas* for at least 4 days in each turn, most of the farmers in the tail end reaches would only have one day.

Farmers' crop choice and irrigation practices responded to this context of decreasing water availability coupled with the uncertainty of water supply:

- Adaptation of farming systems: (i) while we could not identify any effect of the gradual increase in the off-period on farmers in the upstream areas (who continued to cultivate rice and vegetables), most of those in the downstream areas found it difficult to cultivate rice and vegetables and showed more explicit declines in yields; and (ii) farmers adapted their cropping pattern in case of the proximity to an irrigation water source: water-consuming crops in terms of quantity and/or frequency of irrigation (rice and vegetables) were concentrated in the head end reaches and/or next to the secondary drains, whereas less water-consuming crops (grapes) were mostly located in the tail end reaches of the branch canal.
- Cash crop diversification: This is more common in the head end reaches, where it signaled both a better certainty in irrigation water supply and also a risk-minimizing strategy in relation to pest attacks and marketing risks embodied in the growing of multiple cash crops.
- Differences in irrigation practices: (i) farmers in the head end and middle of the branch canal increased the number of rounds of irrigation as a means of storing water in the soil profile (whenever water is available), which led to over-irrigation (at least, as long as water is available), and also contributed to compounding water shortages for farmers located in the downstream reaches of the branch canal and/or *mesqas*; (ii) A significant number of farmers in the lower reaches of the branch canal owned more pumps, showed a higher frequency of night irrigation, and also depended more on drainage water as a secure water source, if they were able to access secondary drains; and (iii) while farmers acknowledged the inequity of water distribution along both the branch canal and its *mesqas*, no collective action to redress this state of affairs was observed at the *mesqa* level, except for the limitation of one pump for each *marwa* to access water. At the *marwa* level, however, farmers established collective irrigation rules to secure irrigation water for rice and vegetables to reduce conflicts.

The literature usually understands the responses of farmers practicing irrigation as spatially differentiated, according to the head-tail gradient in water scarcity along distributary canals (El-Shinnawi et al. 1980; Skold et al. 1984; Brugere and Lingard 2003; Tyagi et al. 2005; Bekchanov et al. 2010; El-Agha et al. 2011). However, a detailed analysis revealed a more subtle and intricate pattern of responses:

- Reuse of drainage water: This is not practiced only in the tail end reaches, as even farmers in the head end of the branch canal resorted to it. While drainage water is a necessary, complementary water source for farmers (growing rice and vegetables) in the head end reaches, those in the tail end reaches use it as their main available irrigation water source in the peak summer season. This shows the overall degradation of the quality of water supply. As the most water-consuming crop, rice was concentrated near the secondary drains rather than the branch canal, demonstrating the importance of a perennial water source.

- Night irrigation: This is also not limited only to the tail end reaches; even farmers in the head end reaches practiced frequent night irrigation. However, while night irrigation was an imposed option for farmers in the tail end reaches (for whom irrigation water was only available at night), it was optional for those in the head end reaches (and often a question of convenience for farmers with other activities during the day, who were willing to irrigate sensitive plants such as *luffah* or vegetables, or to also enjoy a flow that was large enough to be able to irrigate without interruption).
- Adaptation of *marwa*-level irrigation rules: It was expected that these rules would be stricter in the downstream areas, as water availability decreased. However, the cultivation of more water-intensive crops in the head end reaches also made it necessary to impose strict rules that had to be followed by farmers of the same *marwa*, such as a fixed duration for rice fields or the priority to irrigate vegetables.

Further, some of the farmers' crop choice strategies revealed unexpected responses, at least when seen through the lens of a single ecological, technical or economic factor:

- Low water-consuming crops in the head end reaches of the branch canal: Surprisingly, watermelon and melon (low water consumers in terms of irrigation frequency) were initially introduced by farmers who enjoyed the best water supply in upstream locations. One of the reasons for this is that the high nutrient uptake and degradation of the soil quality due to reduced leaching might be more critical in downstream areas, where water is not available for frequent leaching through rice cultivation. Another reason might be that market-oriented farmers in upstream areas introduced watermelon first, but the crop is now also being picked up in downstream areas.
- Water-consuming crops in the tail end reaches of the branch canal: (i) *Luffah* – a water-consuming and high-value crop – was mostly found in the tail end reaches. This possibly reflects how it spread from the farms which introduced it in the area, but also that the higher water table in the upstream parts makes the area unfit for semi-perennial crops; and (ii) grapes, a relatively water-consuming and high-value crop, would be expected to be more prominent in the upper reaches of the branch canal. However, the shift to grapes took place much earlier than the declared degradation in the quality of water supply, which shows that the water factor is not decisive. Key determinants were: i) farmers having the know-how in dealing with grape cultivation that was acquired by their family in their region of origin; ii) the lower water table induced by the lack of water and rice cultivation (in contrast, the higher water table found upstream is not favorable); and iii) the land fragmentation into smaller farms, which now makes it difficult for farmers in upstream areas to adopt such a crop (which cannot be cultivated in very small plots as done with vegetables).
- The collective dimension of crop choice is another very interesting finding of the study. Just as rice is often cultivated in clusters in order to limit the impacts on dry crops through seepage and a high water table, we found that grapes had to be clustered to spread bird damage and theft, and to also control the latter by the permanent presence of people in the field after maturation. This is reminiscent of the situation observed in many parts of Asia, where dry-season rice cultivation is often predicated upon a collective move to reduce overall seepage and the pressure from pests (notably rats) (see, for example, Luat 2001).
- However, it is also the impact of two different 'collective water regimes' that came out. Indeed, farmers in upstream areas are bound to a regime that prioritizes salinity control based on frequent rice cultivation, resulting

in a higher water table that is not favorable to grapes or semi-perennial crops such as *luffah*. In contrast, farmers in downstream areas are bound to a regime where rice and fodder crops are rare, the water table is lower and crops such as grapes could be established.

- Path dependency: Interestingly, the early adoption of grapes/*luffah* in downstream areas and vegetables in upstream areas has generated some path dependency, whereby farmers have partly opted out of pure subsistence strategies revolving around grain and fodder at a time when per capita land endowment was higher. It is now more difficult for farmers to diversify to cash crops because plots are smaller or under multiple holders (sons or grandchildren of farmers that originally settled).
- Tail end reaches are not necessarily in a poorer economic situation: Expectedly, farmer incomes decreased as one moves downstream when considering the same crop (rice or vegetables, for instance), which was mainly due to the additional costs related to pumping, purchasing a second pump, increased input intensity, and also because farmers in downstream areas cannot achieve the same yields as those in upstream areas. However, the survey showed that (at least some of) the farmers in the tail end reaches still had the opportunity to gain high profits – sometimes even higher than those in the head end reaches – by shifting to high-value cash crops, mainly *luffah* and grapes. Such findings contrast with numerous studies (e.g., El-Shinnawi et al. 1980; Skold et al. 1984; Perry and Narayanamurthy 1998; Brugere and Lingard 2003; Latif 2007; Sharma et al. 2008; Molle et al. 2010; Venot et al. 2010) that showed a decrease in high-value crops, cultivated areas and incomes as one moves downstream.

The case study changes our view of the traditional head-tail problem. The commonly observed head-tail opposition in terms of water availability and average income has become mediated by several other factors such as the reuse of drainage water, collective action around crop choice, and social and historical factors. These multiple factors mediate the head-tail dichotomy and determine how farmers cope with water scarcity.

Conclusion

The increasing water needs of Alexandria, as well as the growth of the rice area, have induced shortages in the tail end reaches of the Mahmoudiya Canal. At the time of concluding this study, new pumping stations were under construction to augment diversions to the city, as increased water scarcity was looming over the area. This study analyzed how farmers were coping with this situation in the al-Bayda secondary canal. A certain number of typical adaptation strategies and practices commonly found in the literature were first confirmed, including changing cropping systems, crafting collective irrigation rules, reusing drainage water, practicing deficit and night irrigation, and over-irrigating whenever water is available. While some responses and practices were expected to increase with water scarcity (when moving from upstream to downstream areas), several counter-examples appeared and were explained by bringing in other considerations (e.g., conjunctive water use, quality of drainage water, risk associated with cultivating vegetables, etc.).

This study also identified a number of more unexpected responses: low water-consuming crops (e.g., watermelon) were largely grown in the head end reaches of the branch canal, while high water-consuming crops were grown in the tail end reaches of the branch canal. Analysis of these anomalies revealed that farmers' adaptation to water scarcity was driven by several factors beyond water scarcity or profit maximization, which are generally considered as the overriding determinants: farm fragmentation, risk aversion, history and social capital of farmers, and, more unexpectedly, collectively established water regimes were shown to shape and constrain crop choice.

Of special interest was this collective dimension of farming, where the (upstream) possibility to grow rice associated with the need to do so in order to control soil salinity resulted in higher (average) groundwater levels, which were unsuitable for crops such as *luffah*, grapes or trees. In contrast, downstream areas could hardly grow rice, but could grow semi-perennial crops because of lower water tables (but not the otherwise desirable and adapted low water-consuming watermelon which requires soil leaching). Tree crops also came with a clustering collective logic, in order to reduce the occurrence of theft and bird damage.

The findings of this study help challenge the commonly accepted discourse that farmers are to be blamed for insufficient irrigation management and efficiency; they also expose the limitations of projects, modeling exercises or policy recommendations that are too often based on crop choice rationalities limited to income maximization.

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