REPORT

A Socio-Ecological Investigation of Options to Manage Groundwater Degradation in the Western Desert, Egypt

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Abstract Under increasing water scarcity, collective groundwater management is a global concern. This article presents an interdisciplinary analysis of this challenge drawing on a survey including 50 large and small farms and gardens in a village in an agricultural land reclamation area on the edge of the Western Desert of Egypt. Findings revealed that smallholders rely on a practice of shallow groundwater use, through which drainage water from adjacent irrigation areas is effectively recycled within the surface aquifer. Expanding agroindustrial activities in the surrounding area are socio-economically important, but by mining non-renewable water in the surrounding area, they set in motion a degradation process with social and ecological consequences for all users in the multi-layered aquifer system. Based on the findings of our investigation, we identify opportunities for local authorities to more systematically connect available environmental information sources and common pool resource management precedents, to counterbalance the degradation threat.

Keywords Groundwater management · Socio-ecological · Human–environment interactions

INTRODUCTION

In water scarce regions, the traditional constraints on agricultural production have been overturned by the introduction of groundwater pumping technologies, leading to a “groundwater revolution” (Giordano and Villholth 2007; Shah 2009). Farmers, who use an estimated 70 % of

global groundwater extraction per year, are depleting the natural reserves of groundwater that could otherwise buffer the effects of climate change for future generations (WWAP 2009). Until the 1980s, groundwater was not necessarily seen as an active part of the hydrological system, and it was believed that governments could control its extraction and use (Kovacs 1977; Falkenmark 1981). The privatization of agricultural activities in the desert areas of many developing arid regions, and the introduction of pumping technologies, has rapidly changed this situation, placing control of groundwater extraction in the hands of thousands of private individuals. The management issue is thus increasingly understood as an integrated social and ecological challenge (Mukherji and Shah 2005; Giordano and Villholth 2007; Shah 2009).

A socio-ecological conceptualization of groundwater systems and their management, following the principles of Folke et al. (2002) and Folke (2006), should take into account the fact that environmental and socio-economic processes are intrinsically inter-connected. Recognition of this point enables an analysis of the self-organizing dynamics of the socio-ecological system. Based on the analysis of causal dynamics, where interactions between social and ecological processes are identified to be leading to environmental degradation, management interventions can then be introduced to alter these dynamics (Belausteguigoitia 2004). According to the available literature on the management of groundwater as a Common Pool Resource (CPR), effective self-organization and adaptive management requires mutual trust, cooperation, and sharing of information to be established among different groups of resource users (Ostrom 1990; Moench 2004; Pahl-Wostl 2009).

In spite of the global shift in understanding of the human dimensions of environmental degradation threats, groundwater management has proved one of the hardest to reach

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resource management sectors. Research in this field remains heavily dominated by the geophysical research community, sparse datasets on subterranean conditions are zealously protected, and decision makers, particularly those in water scarce countries where groundwater is considered to be politically sensitive, are often sceptical regarding the utility of combining social and ecological research methods to investigate this issue.

Much of the literature from the developing world addressing the social dimensions of groundwater management in recent decades has focused on the disintegration of the sustainable traditional management systems of the past with the introduction of modern centralized national systems for legislation and regulation (Adams 1996; Attia 2002). Recent writing continues to focus on the “maladaptation” of current reactive strategies to cope with change, where “tubewell capitalists” respond to the falling water tables by digging deeper, higher capacity wells (Dubash 2002; Mustafa and Qazi 2007; Shah 2009), and regulatory institutions are unable to provide an effective response (Khater 2003; Hammani et al. 2009).

In the Western Desert of Egypt, there is a longstanding tradition of communal management of groundwater (described in MWRI 2005; IBRD 2007). Increasing groundwater extraction has been driven by land reclamation activities around the old communally managed areas of the Nile Delta and in the oases (CEDARE 2006). The most recent government reclamation targets, contained in the 2000 National Water Resources Plan, aim to expand the cultivated area by 3.4 million hectares before 2017. Land reclamation is increasingly supported by private investors, who use groundwater for irrigation. As extraction has increased, the groundwater table has fallen, salinity problems have emerged, and rapid losses of productive land are anticipated over the period 2007–2025 (World Bank 2007). In addition, further contamination threats have been associated with waste management failures in the area (MALR 2005; Attia et al. 2005).

Small farmers in the old cultivated areas of the Western Desert have observed the progressive degradation of their groundwater resources. Some have joined the pumping race, purchasing second-hand pumps imported from India. Others accept low-skilled employment on the farms and in the agricultural services sector. As the economy of the region becomes increasingly dependent on the expanding multi-million dollar agricultural export businesses, the Egyptian Government has considered various options to avoid the loss of productivity through environmental degradation, including the possibility of diverting water from the Nile Delta (Attia et al. 2007). Some very difficult choices will need to be made over the coming years to integrate improvements in groundwater management within the regional water resource management framework.

In efforts to cope with the contemporary scarcity of water resources in this region, the traditional institutions for common pool resource management have attracted renewed interest. However, the few internationally published accounts of experiments in participatory water user-engagement implemented through the Egyptian Ministry of Water Resources and Irrigation (MWRI) with external funding, have described participation as “reactive, mostly welcoming, and cooperative, but not usually self-organizing” (van Achthoven et al. 2004). A rare internationally published “success case” of self-organization among investors in a land reclamation area to the East of the Nile Delta quickly failed (van Steenberghe 2006). These examples hardly live up to the celebrated regional tradition of local groundwater management institutions (described in MWRI 2005; IBRD 2007).

In this study, we investigate problems of land and groundwater degradation, local coping strategies, and institutional options to improve local self-organizing resource management by long-term residents in a desert reclamation area to the West of the Nile Delta in Egypt. To do this, we have used an integrated socio-ecological approach, not previously applied in Egyptian groundwater research.

The approach used in this investigation is based on the idea that the key to understanding the social and ecological dimensions of the groundwater management problem rests in combining analysis of long-term data on the ecological function of the human–environmental system with the perspectives of land and water users concerning the observed changes and future management options. Previous studies have applied such integrated approaches to address a range of different environmental management challenges (e.g., Danielsen et al. 2007; Stringer et al. 2007; Dangles et al. 2010; Gebrehiwot et al. 2010). Nevertheless, despite some promising exploration of the social dimensions of groundwater use in other regions (Mukherji and Shah 2005; Lightfoot et al. 2009), the use of integrated socio-ecological methods to address groundwater management questions has so far been relatively limited globally, and particularly in North Africa (see discussion in Allan 2007; Hammani et al. 2009).

STUDY AREA

The village of Beni Salama is located on the edge of Egypt’s Western Desert (Fig. 1). It is situated in the Beni Salama depression, which is a subsection of the Wadi El Natrun depression (lowest point 23 m below sea level). The depression ensures a relatively sheltered climate, in contrast to the surrounding desert area. Mean annual rainfall is considered to be around 55 mm (Zahran and Willis 2009). The mean annual temperature varies from 22.8°C in January to 28.8°C in August. Mean monthly relative humidity

Fig. 1 Location of the study area

ranges from 52 % in May to 70 % in November–December. The depression forms an endorheic basin, receiving drainage water from the irrigated area of the Nile Basin through the Pleistocene sediments, recharging the Pliocene and Miocene aquifers (see RIGW 1990; Geirnaert and Laeven 1992). The Miocene aquifer also receives recharge from the deeper Nubian Sandstone Aquifer System to the South and West below the Western Desert. Deep faults bring water from the Miocene aquifer to emerge in the basin as springs (Idris 1996).

The natural habitats in the depression consist of saline drainage lakes, surrounded by salt marsh vegetation (*sebkha*), and sand and gravel desert, supporting wild assemblages of date palm and other salt-tolerant plants (Zahran and Willis 2009) (Fig. 2). This area has been cultivated with additional crops, such as wheat, alfalfa, beans, and various fruits and vegetables, which are traditionally watered from the shallow water table as it drains down the depression through the Pleistocene aquifer toward the *sebkha* system (LaMoreaux 1962; Idris 1996). Smallholders take irrigation water from shallow ditches and wells close to the edge of the *sebkha*, recycling it through their flood irrigation systems. All households in the village have access to small farms or gardens irrigated in this traditional way. Land ownership is often informal, particularly where the landholdings are small—e.g., <3 feddan (1.26 ha).

The reclamation of desert land for cultivation in this area dates back to the pre-dynastic period. Since the 1980s, land

reclamation has spread out from the Nile Delta to cover the higher elevations around the edges of the Wadi El Natrun depression, and new large farms have appeared on all sides of the village of Beni Salama (Attia et al. 2005). Due to the sloping landform, farms in these areas require deeper wells to access the Pliocene groundwater. From the 1990s, deeper wells directly accessing the higher quality Miocene groundwater have been installed on some of the larger farms. This aquifer receives minimal recharge from the surface, and is therefore classed as part of the non-renewable Post-Nubian Sandstone Aquifer System (CEDARE 2001). Extraction exceeding recharge has led to declining water tables and increased levels of salinity. Salinization is due to a series of processes, including: the mobilization of salts from clay lenses and deeper saline water strata, diminishing dilution capacity in the aquifer, and also to the return flow process leaching salts from the surface (Attia et al. 2005; World Bank 2007).

The large and small farms in the area exist within different regulatory systems. The larger farms register their land with the land registry of the Governorate of Behayra, and receive permits to extract groundwater from the Groundwater Management Office of the MWRI. Physical monitoring and enforcement of regulations concerning their groundwater use would require large in situ human resource capacities, which the authorities do not have. However, the legal and administrative requirements for land registration permits for groundwater use and

Fig. 2 Land cover in the study area, 2009

electricity supply for pumping groundwater are mutually reinforcing: to access cheaper electric-powered pumping systems, farms must obtain permits. Nevertheless, diesel-powered wells still proliferate, evading the need for permitted access to electricity.

As the small farms are often unregistered, they remain outside the formal regulatory system, under the traditional oversight of the Village Council “*Omda*”. Although this means that smallholders do not need to go through the bureaucratic process of obtaining permits to farm land that

they hold through traditional land rights, it also means that the responsible authorities have few records of their existence, resource management interests, and current needs for protection from resource degradation threats that are caused by the increasing presence of authorized large-scale groundwater extraction.

The focus on the perspectives of land and water users in this investigation is reflected in the use of local measurement units for the quantification of landholdings. The Egyptian feddan (0.42 ha) is a socially important unit of

spatial measurement, representing a minimum size of land needed to support a family (see Mitchell 2002, p. 114–115, 219). This unit was used by the cultivators interviewed in this investigation, and is the official unit of measurement for land area used in the Egyptian Agricultural Census. In this article, units of area are shown in both feddan and in hectares to enable both the social significance of the land areas and the physical dimensions to be intelligible to an international readership.

METHODS

The study incorporated a review of 50 years of hydrogeological studies, analysis of 40 years of satellite land cover imagery, a survey including 50 cultivated landholdings of varying sizes (ranging from large farms of close to 1000 feddan (420 ha) to small gardens of <1 feddan (0.42 ha) and 6 months of observation in the village). In preparation for the study, socio-economic information from the most recent 2006 national population census and 2000 national agricultural census was collected from the national statistics agency (CAPMAS) and the Ministry of Agriculture and Land Reclamation (MALR). The subsequent research process involved the following stages:

- (1) Field survey to record land and water users' observations of environmental changes and groundwater management practices in the different cultivation systems;
- (2) Compilation of secondary data on the state and trends of the resource from resource management institutions, analysis, and gap filling;
- (3) Interviews with selected key experts including local resource users, local and national decision makers, and scientists and international experts.

Field Observation and Survey

Field survey implementation and observation in the village stretched over the period 2008–2010, enabling observation

of resource management practices. The approach drew on available precedents in the application of ethnographic methods to ecological field research in the North Western Desert (Ahmed et al. 2002; El Bastawisy 2006; Salem 2008). Initial field visits were made to the study area to observe cultivation practices, leading to the generation of a typology of cultivation systems. This, together with maps, described below, provided the sampling frame for the survey (Table 1).

The survey aimed to capture the effects of falling groundwater levels and salinization on the studied community, and strategies employed by local farmers to deal with the situation. Ten questions covered three main topics: farming system characteristics, perceptions of changing groundwater resources, and household dependence on groundwater resources. The questionnaire was presented in a bilingual format in Arabic and English, including spaces for notes on the responses. Questions on water use were designed, reviewed, and reformulated through in-depth interviews with small-scale cultivators and farm workers, who advised on scientific methods needed to calculate the water requirements of the crops under cultivation. Different approaches to the estimation of water use were adopted for larger and smaller farms, reflecting their different management approaches.

The typology of cultivation was derived from initial observations in the village (Table 1). This typology included a category of farms and gardens of <3 feddan in size (1.26 ha), which was observed to be the most common size for farms and gardens in and around the village. These small farms and gardens are not usually considered in farm surveys conducted in the area (e.g., Yehia 2004; AFD 2008). Following the stratification of farms according to size and location in four areas around the village, survey participants were chosen at random. Willingness to take part in the survey was an important criterion, but all those approached were willing to take part. As the selection was discussed with local people, the sample may have been biased toward those farmers who were known in the village. However, no single person guided the choice of farms, and effort was made also to approach farms that were unknown or not recommended.

Table 1 Typology of cultivation in Beni Salama and surveyed farms and gardens

Farm size in feddan (equivalent in hectares)	Locally estimated % of farms	Locally estimated no. of farms	Estimated area cultivated (feddan)	Estimated % of total farm land area	Number surveyed
<3 (<1.26 ha)	10	200	400 (168 ha)	0.64	16
3–20 (1.26–8.4 ha)	25	500	5000 (2100 ha)	2.86	18
20–100 (8.4–42 ha)	60	1200	36 000 (15 120 ha)	47.73	8
>100 (>42 ha)	5	100	16 000 (6720 ha)	48.77	8
Total	100	2000	57 400	100.00	50

1 feddan = 4200 m² = 0.42 ha = 0.0042 km²

Cultivators from 50 farms and gardens and 35 different households in the village were interviewed during the field survey on a voluntary basis. Not all questions were fully answered. The interviews lasted on average half an hour, and were carried out on the cultivated land, or in adjacent houses. Coordinates of each location where the survey was administered were recorded. On large farms, the survey respondents were farm workers and managers. Workers were often living in the village. The owners of these farms were often living and working outside the area. In some cases, they were interviewed during their weekend visits to their farms.

Physical Data Compilation and Analysis

Information in gray literature on older wells dating back to the 1950s was compiled from local drilling companies and archived documents at the Egyptian Desert Research Center. A previously published study indicated that the groundwater table in the study area was falling by ~ 1 m/year and an estimation of the annual volume of groundwater extraction for irrigation was made, based on the per hectare water requirement ($50 \text{ m}^3/\text{ha}/\text{day}$) (Ibrahim 2005). Using a similar approach, in this investigation, it was possible to trace the trend in the expanding cultivated area, and the associated increase in the use of groundwater for irrigation over the past decade, supporting local people's accounts of the change.

A set of Landsat images at 30-m resolution taken with the TM sensor under clear atmospheric conditions during the months of August and September over the period 1984–2003 was downloaded from the United States Geological Survey (USGS).¹ Additional images taken with the ETM+ sensor (1999–present) were also used. The 8×8 -km study area around the village was unaffected by the failure of the scan line corrector (SLC) which occurred in the ETM+ sensor from 2003 onward.

Normalized difference vegetation index (NDVI) profiles were extracted using band 3 (R) and band 4 (NIR) of each image. Unsupervised classification was used to classify the NDVI values in each image into two classes of high and low NDVI using an iterative self-organizing data analysis technique (ISODATA). NDVI is used globally as a basis for discriminating between irrigated and non-irrigated lands in arid areas (Luedeling and Buerkert 2008; Thenkabail et al. 2009).² For a detailed discussion of the applicability of NDVI to the detection of irrigated land in the study region (see Bakr et al. 2010). The areas with high NDVI corresponded to vegetated

areas, including irrigated cultivation and naturally occurring saltmarsh vegetation. The areas of low NDVI included gravel desert and built areas. Through the field observation in the study area, and comparison to high resolution SPOT images available in Google Earth, areas of high NDVI were subdivided into salt marsh and irrigated crops. The non-vegetated land-covers included gravel desert and built areas.

Changes in the extent of irrigated cultivation were detected between images. A bimonthly dataset, GIMMS AVHRR, was used to establish a continual trendline for total NDVI across the study area over the period 1985–2006. Due to the coarse spatial resolution of this dataset, the entire 8×8 -km study area was captured in a single pixel. This dataset was compared to daily rainfall records available over the period 1996–2006, available from the US National Oceanic and Atmospheric Administration (NOAA) (<http://gis.ncdc.noaa.gov/map/gsod/>) to check for possible interference from rainfall.

Information on water quality obtained from private farms and gardens, local government monitoring of groundwater and an impromptu survey by local residents was mapped to identify spatially determined differences in quality. Well depths and usage identified through the typology and survey were compared to a georeferenced database of well permits held by the groundwater office, which lists permitted extraction volumes for some wells. This enabled comparison of groundwater users' accounts of changes observed in their wells to information concerning the hydrogeological conditions in the different parts of the study area.

Review of Findings

The survey implementation and results were discussed with local decision makers and responsible officials in the City Council of Wadi El Natrun and the Groundwater Management Office. These interviews provided insights concerning the institutional dimensions of local resource management as well as supplementing historical datasets. Finally, the field research findings were discussed with international experts in the field of land and groundwater management during a series of workshops. During these activities, experts offered suggestions concerning the conceptualization of management challenges, and the nature of solutions that might be explored.

RESULTS

Changing Groundwater Conditions in the Expanding Agro Ecosystems

During 1970–1980s, Beni Salama village was collectively irrigated from a well provided by the government. Local

¹ <http://edcns17.cr.usgs.gov/NewEarthExplorer/>

² Alternatives to NDVI proposed in the literature, e.g., the soil adjusted vegetation index (SAVI), bring with them additional interference and, are only as good as the supplementary datasets on which they are based). In this case, available datasets on soil conditions were not considered to be of a sufficient quality to improve significantly on the NDVI analysis.

people interviewed in the village described the jet of water that came out of this well under artesian pressure when it was first dug. According to these local accounts, the water was initially used to irrigate all of the small farms and gardens in the village, and salt-sensitive crops, such as oranges could be grown. However, the pressure gradually reduced, and from the late 1980s, the water was reserved for drinking use only. The government well is still used to supply drinking water to the houses in the villages with an electric-powered pumping system.

A rapid expansion of the reclamation area around the depression during the 1990s was described by local people, and is visible in the satellite data (Figs. 3, 4). This corresponds to the time when the Government of Egypt began permitting the allocation of land and water rights to private farmers to use groundwater for land reclamation, according to the 1990 Land use and groundwater development plan (RIGW/IWACO 1991). The new land reclamation was located in the former desert areas where large farms were created, using deeper groundwater reserves.

The analysis of a series of TM Landsat images 1990–1998 showed that the irrigated area in the 8 × 8-km study area around Beni Salama more than tripled over this period (Fig. 4), suggesting a corresponding increase in the volume of irrigation water applied. While the use of irrigation was increasing over the 1990s, rainfall records from these years were consistently below the long-term average. By 2005, the irrigated area, showing high NDVI, was five times its extent in 1990, but the analysis of the ETM+ image series showed that the rate of increase was decreasing. By 2009, the total extent of the high NDVI irrigated area had reduced slightly, by comparison to 2005. Although increases were continuing in some areas, these were offset by reductions in the extent of such areas elsewhere. The overall net loss in high NDVI vegetated cover over this period suggests degradation taking place in the irrigated area. This reduction could be attributed either to a reduction in the availability and quality of irrigation water, or to other factors affecting cultivation activities.

Individuals interviewed during the field survey gave different observations of falling water tables and salinization since the 1990s (Table 2). The effects observed varied according to the location of the farm or household and to the types of wells and farms. At the time of the survey in 2008–2009, the falling groundwater table and increasing salinity were affecting all parts of the study area. Considerable variation in levels of salinity was observed on both large and small farms, and was reflected in the collected datasets. The range of salinity, indicated by electrical conductivity (EC), in the deep wells, was slightly larger than it was in the shallow wells (Table 2). The quality of water in some of the wells remained suitable for cultivation, while in others salinity was high enough to constrain

or prevent cultivation use, depending on the choice of crop. Mean EC values from both small and large farms (Table 2) exceeded the thresholds for effects on soft fruits (Table 3). These are the most profitable commercial crops in the study area.

Farmers described the source of groundwater degradation problems that they had observed as related to the presence of salty lenses (Arabic: *tifla*), over-pumping and drawdown on the large farms. A gradual process of salinization was also reported to be affecting all of the shallow wells in the smaller farms and gardens over time. Most village land users were without facilities for chemical analysis, and therefore could not detect other suspected threats to water quality besides salinity. Large farms in the surrounding area either maintain their own laboratories for analysis of water, or rely on those that are available for commercial use. Some of the farm employees interviewed voluntarily provided copies of the chemical analyses which are held privately and not used to improve collective decision making.

Living with Changing Groundwater Conditions in Large and Small-Scale Cultivation Systems

On the large farms, particularly in the North of the study area, employees described the digging of new wells where groundwater had become salinized as a regular occurrence. When one well turned saline, it would immediately be blocked and replaced with another deeper well. To understand the economics of investment in new wells over the past decade, we examined a farm budget study from the year 2002, conducted by a student at the University of Alexandria (Yehia 2004). This study reported an average annual net income of 1080 US\$/ha³ on farms in the 20–100 feddan (8.4–42 ha) grouping, and 1516 US\$/ha⁴ on farms above 100 feddan (42 ha) in size. On these farms, each well will irrigate ~40 feddan (16.8 ha), therefore each one would have generated a net income of US \$18144 or US \$25469 per well, according to the calculations for the two farm types, respectively. The cost of replacing a well if it turned saline would have depended on the depth and drilling conditions, but might have been somewhere around US \$5000.

The economic comparison of the required investment for the new well, and potential profits to be secured (generating five times the investment cost within the first year) effectively explains the willingness of large farm owners to dig new and replacement wells on these farms whenever necessary over the past decade, as reported in this survey. More recent estimates of the annual income of the largest

³ LE 11 572 per feddan.

⁴ LE 16 252 per feddan.

Fig. 3 Changing land cover around the study area 1990–2005 (August–September, USGS Landsat)

horticultural export farms in the West Nile Delta are around US \$1680/ha (World Bank 2007). If we retain the assumption that a well serves 40 feddan (16.8 ha) that would equal US \$28 224 of profit per well. Furthermore, the export market is anticipated to continue to grow more profitable for large farms in the area as transportation, processing, and quality control infrastructure continue to improve (AFD 2008). However, income has not been consistent over the past decade, and farm managers interviewed described export farming as a speculative venture that only a limited number of investors could sustain. This is one of the reasons why small farmers do not export their produce.

On small farms and gardens surveyed in Beni Salama, the depth, and also the cost of a shallow hand dug well or ditch to be used to access and recycle surface drainage water are less than the cost of a well drilled in the land reclamation areas where the large farms are located. An indicative local price would be around US \$1000.⁵ However, in the farm budget study, referred to above, farms of 3–20 feddan (1.26–8.4 ha) were shown to only generate an

⁵ The cost of a well was estimated by smallholders at around LE 5000–6000. The conversion is made using an exchange rate of 5.5 LE to the US \$.

Fig. 4 Trend in NDVI in 8×8 -km study area visible in Landsat (high resolution, low frequency) and GIMMS AVHRR (bi-monthly frequency, low resolution, shown as annual average)

average annual income of 259 US \$/ha, with 62 % of farms of this size recording a negative net annual income (i.e., a loss), according to standard farm budget calculation practices. This finding offered a clear explanation as to why the smaller farmers are slower to dig new wells, even though these wells cost less; the small farms were generating far less net income per hectare against which to offset this cost.

Local people interviewed during the field survey nevertheless insisted that small farms were worthwhile. We concluded that the benefits of small farming for the dependent households in the study area, and the calculation determining the digging of a new well, were not effectively measured through the farm budget survey approach, and must incorporate other dimensions—e.g., the asset value of the landholding where ownership can be secured and the in-kind contribution of subsistence crops and livestock products within household budgets.

A small farm or garden of 1 feddan (0.42 ha) irrigated using recycled drainage water can produce a series of crops throughout the year, each time contributing to the household budget in avoided food expenditures or cash income. According to the survey results, estimates of the contribution of food grown on small farms and gardens to food budgets ranged from 20 to 75 % of the household food needs. Food expenditures commonly accounted for ~95 % of reported household income, which was around US \$329⁶ per month (Table 4). On a per capita basis, the average

reported income was around US \$27/person/month.⁷ It is to be considered possible that income reported through the survey, based on voluntary recollections, may not constitute a full account of all income and income sources.

Locally available sources of income other than farming mainly consisted of working on the surrounding farms as laborers, managers, and security providers, or in associated service industries, e.g., transportation, storage, and administration. Most economically active adult men in the study area have several occupations, usually including cultivation either of their own land, or that of someone else. This profile conformed to the information generated through the most recent population census, held in 2006. A basic wage reported during the survey was somewhere around US \$90 per month for work in farm security, which is one of the most common occupations in the village.

One of the households surveyed listed a female official. Otherwise, none of the women in the households visited had employment outside the family houses and gardens, which is the most convenient form of work for them to combine with childcare and other household responsibilities. The flat-rate calculation of labor costs in the farm budget survey may therefore have been inappropriate for the small farms and gardens, which are often maintained either as a leisure activity, or by people who do not have access to other forms of employment.

Two out of thirty-five smallholder households surveyed in this investigation had wells or pumping systems

⁶ LE 1811.8 at an exchange rate of 5.5 LE/US\$.

⁷ LE 148.2 per capita, at an exchange rate of 5.5 LE/US\$.

Table 2 Summary of survey observations and collected groundwater datasets

	Large Farms > 100 feddan (>42 ha)		20–100 feddan (8.4–42 ha)		3–20 feddan (1.26–8.4 ha)		<3 feddan (<1.26 ha)	
Area	North	South	North	South	North	South	Village	South
<i>Cultivation patterns</i>								
Mean well depth (m)	166	90	147	103	40	47	28	26
Range of well depths	89–200	75–110	60–200	70–120	35–42	5–78	16–40	25–29
Mean well age	6	29	16	6	10	9	12	9
Range of well ages	0–15	0–44	4–48	4–7	5–20	1–16	0–20	6–10
% use of electric pumps	83	50	65	0	0	33	0	0
Most frequent irrigation method ^a	D	D	D	D = 3	F > S > D	D/S	F > S > D	F = D = S
<i>Groundwater EC (dSm)</i>								
Source	(MWRI monitoring March 2009, <i>n</i> = 7)				(NA)		(Owners 04 2010, <i>n</i> = 12)	
Min	1.072						1.087	
Max	7.220						5.000	
Mean	3.586						2.458	
Std. dev.	2.610						1.054	
<i>Changes (% of surveyed)</i>								
Falling water table %	na	100	50	50	90	100	80	80
Salinization %	100	75	80	0	50	75	71	0

^a Irrigation methods: *D* drip, *S* sprinkler, *F* flood

Table 3 Characteristics of selected commercial crops (FAO 2002 and AFD)

Common name	Latin name	Local harvest period ^a	Threshold			Reduction in productivity				
			EC _e dS/m	Slope % per dS/m	Sensitivity rating	0 % EC	10 % EC	25 % EC	50 % EC	Maximum tolerance
Date palm	<i>Phoenix dactylifera</i> L.	October	4.0	3.6	T	4	6.8	10.9	17.9	32
Olive	<i>Olea europaea</i> L.	Sept–Oct	4.0	3.6	T	4	6.8	10.9	17.9	32
Guava	<i>Psidium guajava</i> L.	Sept–Nov			MT	2.7	3.8	5.5	8.4	14
Fig	<i>Ficus carica</i> L.		4.7	9.8	MT					
Pomegranate	<i>Punica granatum</i> L.				MT	2.7	3.8	5.5	8.4	14
Grape	<i>Vitis vinifera</i> L.	June–July			MS	2.7	3.8	5.5	8.4	14
Mango	<i>Mangifera indica</i> L.	July	1.5	9.6	MS	1.5	2.5	4.1	6.7	12
Apricot	<i>Prunus armeniaca</i> L.	June			S					
Pear	<i>Pyrus communis</i> L.	August	1.6	24	S					
Peach	<i>Prunus persica</i> (L.) Batsch	May–June			S					
Orange	<i>Citrus sinensis</i> (L.) Osbeck		1.7	21	S					
Alfalfa	<i>Medicago sativa</i>		1.3	13.1	S	1.7	2.3	3.3	4.8	8

T tolerant, *MT* moderately tolerant, *MS* moderately sensitive, *S* sensitive

^a Harvest periods based on local observation and AFD (2008)

that appeared to be failing, one had just replaced the well, and two had plots of land where wells had not yet been dug. Two new shallow wells were installed in surveyed village gardens during the period of the survey implementation. Those who expressed the most concern during the field survey regarding their vulnerability to groundwater-related threats were small-scale cultivators who had the fewest additional or alternative occupations, and whose livelihoods were, therefore, the most

dependent on cultivation using groundwater from shallow wells.

DISCUSSION

As described in the previous section, the observed changes in groundwater conditions were affecting large- and small-scale cultivators differently, depending on their ability to

Table 4 Monthly income and economic activities reported during the survey

	Household size	Percentage household income spent on food	Household reported income (US/month ^a)	Per capita income (US/month)	Income generating occupations in addition to cultivation of own land
Min	3	NA	600	33	0
Max	26	95	4000	208	5
Mean	14.4	(mode: 95)	1811.8	148.2	2
Total members in sampled households	389		30 800	2371.8	

^a Using 2009 exchange rate: 5.4754 LEE/\$ US

cope by digging new wells. Although the degradation process is driven by increasing groundwater use on the large farms and factories, local households increasingly also depend on these businesses to support their livelihoods through the provision of low-skilled employment opportunities for supplementary income generation. On a day-to-day basis, therefore, they are often employed to handle the machinery and chemicals that threaten their family farms and gardens close by. Viewing this situation through the theoretical lens of CPR (after Ostrom 1990; Schlager 2007; Shah 2009), as explored in this article, raises the question of the ability of local residents, smallholders and farm workers to self-organize to manage the shared natural resource and avoid a “tragedy of the commons”.

Is the Groundwater Pumping Race in the Village an Inevitable Socio-ecological Process?

The apparent lack of CPR management stood out to us as a curious finding in our research in light of the notably strong cultural precedents and associated beliefs in common responsibilities that we observed in the village, despite the surrounding degradation processes. During the field survey, village residents were observed to cooperate together in the maintenance of the village drainage and sewerage system. Cooperation between households took place continually, including the provision of financial and other means of support for disadvantaged households. The shared use of natural resources appeared culturally important and well respected. This was visible in the use of the communal grazing area “*wf*”, around the saline drainage lake “*mellahah*” close to the center of the village. In light of these observations, it became impossible to accept that a tragedy of the commons was an inevitable socially driven environmental phenomenon. In this case, there must be external factors limiting the degree to which local people could manage their shared resources.

Resource Management Information as a Key to Adapting Socio-ecological Processes

According to CPR theory, as introduced in the early sections of this article (after Ostrom 1990), involvement of all stakeholders in addressing resource management problems is essential to ensure their mutual cooperation. This is difficult under the present split formal and informal regulatory systems described earlier in this article. Furthermore, self-regulation by users needs to be based on mutual trust and sharing of effective information. Thus, complete (hydrogeological and resource use information) information and effective public monitoring have been identified as the keys to enabling a sound scientific basis for shared management. As Egypt is relying increasingly on privately conducted environmental impact studies to support environmental decision making, the public availability of accurate information becomes all the more important. However, our review of available public environmental information showed that although the State had published hydrogeological information on the study area (RIGW 1990), by the time of the investigation, this was already 20 years out of date, and considerable changes had taken place over the intervening years of intensive groundwater extraction.

Options to Improve Resource Management by Sharing Information Among Resource Users

A groundwater monitoring programme had recently been created by the MWRI. The sampling strategy focused on the deep aquifers that are of interest for commercial farming. On the other hand, monitoring data on the surface and shallow aquifers, which channel local recharge and provide irrigation water to the smallest subsistence farms, was not systematically collected. For the purpose of this study, water samples and some relevant data were rapidly volunteered by village residents. This confirmed the assumption, presented earlier in this investigation, that resource users can be willing to play a role in monitoring

and conserving the condition of their resource (e.g., van Steenberg 2006; Lightfoot et al. 2009).

With regard to the state and trends in the deep aquifers, the existing monitoring program had not yet been in operation long enough to identify any trends, only a limited number of parameters were included and the coverage was sparse at the local level in the study area. However, our interviews with farm owners and managers revealed that there was not, in any case, an absolute shortage of data concerning the deep aquifers and soil characteristics in this area. Many private individuals, laboratories, and drilling companies held environmental records dating back to the 1960s, although these were periodically lost and destroyed. This finding contrasted with the assumption of data scarcity that is made in the design of most public monitoring programmes and biophysical studies, requiring expensive public monitoring programmes to be set up and maintained by the local authorities (see Dawoud 2004).

Every large export farm is required to generate chemical analyses of soil and water, and possesses hydrogeological profiles of all of their wells. The largest enterprises have their own dedicated laboratories on site, while others use commercial facilities that are available in the area. This information was unavailable for use to support collective decision making at the time of this investigation because there is no institutional coordination instigated either by the State or by the international export certification bodies to enable local collation, analysis, and publication of it. Furthermore, private interests, particularly those in the drilling business, were benefiting from the scarcity of public information where they gained commercial advantage by claiming privileged access. As investors know that they will pay for drilling costs by the meter, and unforeseen hydrogeological complications will be costly, they pay a premium to the companies with exclusive knowledge of these environmental factors.

Following the CPR logic, an approach in which privately generated data concerning the condition of the common resource would be collected to complement existing monitoring efforts could be a cost-effective means to enhance collective decision making. To a limited extent, the beginnings of such a system had already been created at the time of this investigation by the MWRI. Requests for well permits were required to include privately generated basic information about the location, depth, and capacity of wells to be dug. These details were then stored in a database. However, once the permit was approved, there was no capacity for follow-up, information was not integrated with other existing data on monitoring of wells by the private farms and various agencies, and no systematic use was yet being made of the available dataset to support ongoing public decision making, through self-organizing CPR, or otherwise.

The Socio-ecological Approach to Investing Management Challenges in the Human Environment

As noted in the “Introduction”, the application of socio-ecological field research is an unusual approach in groundwater management, particularly in the Egyptian context, where groundwater management is most often addressed as a purely biophysical question, to be assessed using quantitative modeling approaches, fed by minimal biophysical data inputs, where available. The likely impacts of any given change, e.g., a new reclamation area depending on deep wells or a surface water irrigation project, are conventionally assessed using such approaches. However, the socio-ecological methods used in this study were found effective as a means to explore the processes of groundwater degradation, including the human roles and impacts in these environmental processes.

As described in the “Introduction”, quite a number of previous studies have demonstrated the relevance of social methods to address environmental problems (Mukherji and Shah 2005). Few studies focusing on groundwater management have explored the inverse idea—that changing the approach to physical monitoring and increasing participation in national activities for data collection and analysis could be the key to addressing the present institutional barriers to self-organization. This suggestion, as highlighted in this discussion has appeared in more integrated ecological approaches to dryland management questions in other regions (e.g., Stringer et al. 2007), but has proved challenging to put into practice, and is still a relatively under-explored option, globally.

CONCLUSIONS

The case investigated in this article concerning land and groundwater degradation threats in Beni Salama intersects with the current literature on common pool resource management, addressing the social and ecological challenge of groundwater degradation, observed in both developed and developing countries under increasing water scarcity. We summarize our findings as follows:

- Groundwater supplies to both large and small resource users were threatened by over extraction of the common pool resource;
- Smallholder cultivators were hit first and hardest because they relied on the more vulnerable shallow groundwater sources and were less able to pay for new wells to stay ahead of the pumping race. Large farms were exacerbating the degradation problem, but for smallholders, employment on these farms provided the best-available short-term coping strategy;

- Institutional disconnects between the high-tech regulatory systems for deep groundwater extraction, and the low-tech informal shallow groundwater recycling regime were preventing effective local self-organizing resource management.

To improve the engagement of local capacities to support regulatory compliance and resource conservation, we have recommended attention to increasing mutual trust and sharing of management-related information, including both large and small users of groundwater. No one is better placed than local residents to monitor good practices on the private farms in the study area that are their neighbors and employers. They also have a direct interest in doing this, as their households and smallholdings are affected by the degradation of groundwater.

We conclude that improved cooperation in resource management information generation, sharing and analysis could enable a cost effective and timely common pool resource management response to the growing management challenge of the global groundwater revolution, both in this case, and in other water scarce parts of the world where similar groundwater pumping races are emerging.

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