**Living with Environmental Change**

**in the Endorheic Oasis Systems of the Northern Sahara**

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**Short Abstract**

The oases of the northern Sahara illustrate the possibility that people and nature can work together to enhance life in a harsh and variable environment. This research investigates fifty years of experiences of living with environmental change in oasis systems, bringing together new data, archived environmental records and cultivators` observations. These are combined to gain insight into the environmental change processes, and the experiences gained by people through living with them in this regional context. Two detailed case studies deepen understanding of the socio-economic dimensions and significance of these changes over the past two decades.

The findings show how environmental changes constrained smallholders` traditional ecosystem management practices. Collective associations were weakened or disintegrated. National systems for environmental management and monitoring were overwhelmed. International recommendations for economic approaches to resource management and innovation to address water scarcity did not prove effective. On the other hand, instances where the international market transition appeared to be creating new opportunities for the restoration of common pool resource management were also identified.

This investigation enabled a new perspective on the global dryland management debate to be generated in a context where research has most commonly been concentrated on national sectoral objectives for productivity and desert reclamation. Theoretical insights regarding the application of interdisciplinary research to understand environmental change, further research needs, and potential solutions are directly transferable to other regions where desiccation, salinization and groundwater degradation are accelerating due to climatic and global market-driven changes in land and water use.

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**List of Abbreviations**

| | |
|---|---|
| AVHRR | Advanced Very High Resolution Radiometer |
| B $m^3$/yr | Billion cubic metres per year |
| CAPMAS | Central Agency for Planning, Mobilization and Statistics |
| CI | Complexe Intercalaire (aquifer) |
| CPR | Common Pool Resource |
| CRDA | Commissariat Régional au Developpement Agricole (Tunisia) |
| CT | Complexe Terminal (aquifer) |
| DELZOD | Local Development in Difficult Zones |
| DGRE | Direction Generale des Resources en Eau |
| DT | Tunisian Dinars |
| EC | Electrical Conductivity |
| ESRC | Economic and Social Research Council (United Kingdom) |
| GDA | Groupements de Developpement Agricole Water User |
| GIMMS | Global Inventory Modelling and Mapping Studies |
| Ha | Hectare |
| IMF | International Monetary Fund |
| INAT | Institut National Agronomique de Tunisie |
| IRA | Institut des Regions Arides (Tunisia) |
| JICA | Japanese International Cooperation Agency |
| Kg | Kilogram |
| l | litre |
| LE | Egyptian Pound |
| LULC | Land-use and land-cover |
| m | Metre |
| $m^3$ | Cubic metre |
| M $m^3$/yr | Million cubic metres per year |
| MA | Millennium Ecosystem Assessment |
| MALR | Ministry of Agriculture and Land Reclamation (Egypt) |
| MWRI | Ministry of Water Resources and Irrigation (Egypt) |
| NAS | Nubian Aquifer System |
| NDVI | Normalized Difference Vegetation Index |
| NERC | Natural Environment Research Council (United Kingdom) |
| NIE | New Institutional Economics |
| NOAA | National Oceanic and Atmospheric Administration (US) |
| NWSAS | North West Sandstone Aquifer System |
| PNAS | Post Nubian Aquifer System |
| SES | Social-Ecological System |
| SLM | Sustainable Land Management |
| TDS | Total Dissolved Solids |
| UNCCD | United Nations Convention for Combating Desertification |
| UNESCO-IHP | United Nations Educational, Scientific and Cultural Organization International Hydrological Programme |
| UNU | United Nations University |
| US | United States |
| USGS | United States Geological Survey |

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**Extended Abstract**

Perennial challenges faced by human societies in dryland environments include salinization and degradation of land and groundwater. These threats have been exacerbated through accelerating socio-economic activity in irrigated dryland areas over recent decades. Understanding and managing the dynamics of these environmental change processes is a shared challenge involving smallholder cultivators, policy-makers and global change researchers.

This thesis presents an interdisciplinary investigation of living with environmental change in the endorheic oasis systems of the northern Sahara. These socio-ecological systems represent a pivotal motif in global change research on arid environments. The oases illustrate the possibility that natural and anthropogenic forces can work together to enhance productivity in a harsh and variable environment. In the northern Sahara, long term environmental change processes heightening desiccation and salinization have been intersected by recent anthropogenic changes to land and water systems.

The northern Sahara is technologically advanced, and has inspired a rich scholarly literature in the environmental sciences, but the contemporary management of environmental change in this region has rarely been the subject of critical interdisciplinary investigations applying prevalent global change research frameworks. This research brings together new data, revisits available archives and generates an integrated analysis of the regional experience of living with environmental changes in

the oases of the northern Sahara. Cultivators` observations are combined with time-series datasets at various temporal and spatial scales to gain insight into the environmental change processes occurring over the past fifty years (1960-2010). Two detailed case studies deepen understanding of the socio-economic dimensions and significance of these changes over the past two decades (1990s-present).

The findings of this research show how environmental changes constrained smallholders` traditional ecosystem management practices. Collective associations were weakened or disintegrated. National systems for environmental management and monitoring were overwhelmed. International recommendations for economic approaches to resource management and innovation to address water scarcity did not prove effective. On the other hand, instances where the international market transition appeared to be creating new opportunities for the restoration of Common Pool Resource (CPR) management were also identified.

Several key themes or opportunities for enhancing the observed experiences of living with environmental change are highlighted through this research. The first concerns human capacity to overcome the constraints of heightening desiccation and degradation in oasis systems. Although innovation is considered to be a more important factor than aridity in determining experiences of living with environmental change, this investigation acknowledges that human institutional environments and arrangements at a range of scales affect these essential human capacities to innovate.

A second key related theme concerns the dynamics of environmental change in the oasis systems. Both local and global economic drivers of environmental changes and cultivators` resource management responses were identified. This suggested scope for consideration of the role of global economic measures as a means to enhance human capacities to live with environmental change in the oasis systems. However, such interventions should be based on a clear global understanding of environmental change processes, and should be subject to verification to ensure their positive effects on the environment and human well-being.

Tracing environmental change in cultivated environments is considered to be a shared responsibility. The third theme emerging through this research concerns systems for monitoring and understanding environmental change. The methods used in this investigation, and the findings produced demonstrated scope for such systems to be comprehensive, integrating effects on both land and water. The analysis underlined the need for such systems to be participatory, strengthening CPR management at different scales. Overall, the conclusions call for a reevaluation of land and water research and management institutions in the oasis systems of the northern Sahara, and in dryland environments more broadly.

Finally, this investigation enabled a new perspective on the global dryland management debate to be generated in a context where research has most commonly been concentrated on national sectoral objectives for productivity and desert reclamation. Practical lessons are directly transferable to other regions where

desiccation, salinization and groundwater degradation are accelerating, due to climatic and global market-driven changes in land and water use.

# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

In the contemporary global literature on dryland ecosystems, the cultivated oases of the northern Sahara represent an example of human ingenuity to secure water, food and comfortable living conditions in an otherwise arid and unstable environment (Safriel et al. 2005). Climatic change and variability taking place over the past millennia in this region have included periods of wetter conditions than today, but the dominance of dry conditions during the Holocene has contributed to regional drying, desiccating this region, and creating the present day desert ecosystems (Wendorf and Hassan 1980, Zahran and Willis 2009, Le Houérou 2002). Perennial challenges faced by human societies in such environments include salinization and degradation of land and groundwater (Midant-Reynes 2006, Bubenzer and Riemer 2007). These threats have been exacerbated through accelerated socio-economic activity that has taken place over recent decades (see e.g.MARH 2006b).

The expansion of irrigated cultivation in the northern Sahara has been led through national programmes since the 1950s (see e.g. Voll 1980). However, under market liberalization policies, particularly during the past two decades, the transformation of global export production has enabled an acceleration of land reclamation activities. Investors have secured land for private use and installed high capacity wells, using increasing volumes of non-renewable groundwater to irrigate the expanding productive area. The technology-driven transformation of the desert ecosystems around the traditional oases is visible from space. The local climate, productivity and function of these systems are increasingly regulated by human activity.

Although environmental threats to productive land and non-renewable groundwater reserves have been identified with agricultural exploitation, studies of the environmental change process in this region have rarely incorporated consideration of both social and ecological dimensions of ecosystem management. Objective research addressing land and water management information systems and agendas in their economic and institutional context is critical to enable practical improvements in local resource management. Such research should be interdisciplinary (Price 1990, Newell et al. 2005). Interdisciplinarity consists in:

> `interaction between two or more disciplines . . . (which) may range from simple communication of ideas, to the mutual integration of concepts, methodology, procedures, epistemology, terminology, data, and the organisation of research` (CERI 1971 p25)

Effective transfer of knowledge gained from interdisciplinary research is essential to improve the overarching policy frameworks within which resources are managed. The northern Saharan region has inspired a scholarly literature in the natural and environmental sciences, and regularly exports technological expertise for agricultural development, drilling[1] and the use of satellite imagery to other arid regions (e.g. El-Baz, Moores and E.Petrone 1989, Serageldin 1999, Serageldin 2002, Serageldin 2008). However, opportunities for interdisciplinary investigations to consider challenges faced by smallholders continuing the tradition of cultivation in this region are rare. In

[1] see eg: http://www.server2002.net/regwa1/company.html

the global scientific literature, interdisciplinary investigations of environmental change and degradation have instead more often focused on sub-Saharan Africa (see e.g. Adams 1996, Mazzucato and Niemeijer 2000, Reed, Fraser and Dougill 2006).

In the northern Sahara, the grey areas between `traditional` cultivation knowledge, and conventionally recognized scientific knowledge and expertise are different to those encountered by researchers in sub-Saharan Africa and other regions. Technological and scientific advances associated with agroindustrial development, hydrogeological exploration and other economic activities have affected the available knowledge bases in different ways. This region-specific context and perspective enables this thesis to present an original contribution to the global interdisciplinary literature on environmental change and local knowledge. The thesis draws on a series of contextual debates that have evolved in this region, and pursues the interrogation of the field observations through comparison to a long and extensive body of scholarship and grey literature, which is not otherwise widely published and is written often primarily in Arabic and French.

Simultaneously addressing both land and water management issues, this thesis makes a contribution across two key applied fields of the natural and environmental sciences. The thesis also aims to deepen consideration of the socio-economic regulation of groundwater within the global literature on land degradation and desertification. Conversely, water management has previously been the subject of extensive social science-based investigations. In addressing the water-development literature, the thesis aims to reemphasize elements of integrated ecosystem management (i.e.

integration of water management with the management of other biophysical elements of ecosystem productivity and function) at the interface with the Sustainable Land Management (SLM) agenda (Gisladottir and Stocking 2005).

The overall objective of the research is to provide an in-depth contemporary study of environmental change in the northern Sahara, observed through investigation with cultivators and local researchers, of evolving environmental parameters, including land and groundwater conditions. The research takes into account not only the ecological change processes, but also the effects of economic drivers and social institutions which regulate the experiences of people living with environmental change.

Following the model of Sternberg (2009), each chapter in this thesis is written to meet the standards of concise presentation demanded for an academic publication. Four papers capturing the research findings have been developed to stand in an academic framework. While the findings could have been presented through a conventional thesis structure, the data and research context is more rigorously examined through the development, independent peer review and publication of a series of articles. This approach connects the writing more tightly to current academic frameworks and debates at each step of the thesis. The choice of journals corresponds to the interdisciplinary reach of the research. The publication of articles will increase access to the research for the present academic and decision-making development communities, and for some of the children of the cultivators who took part. The thesis, as a whole, will also be made available through the research institutes in the study areas where the research was hosted.

In the thesis title `Living with Environmental Change....` connects the environmental and socio-economic interactions that shape the arid environment of the northern Sahara. The central theme of this thesis – interaction between the cultivating people and their changing arid, groundwater-irrigated environment – unifies the chapters, as each of the articles investigates and emphasizes varying dimensions of the socio-ecological oasis systems. The changing arid environment that conscribes cultivation, through aridity and salinization is the focus of the first chapter, and remains as an essential theme throughout.

The human interactions with the cultivated systems in this changing environment are pursued in more depth in two subsequent chapters, each focusing on a particular case and location. As the thesis progresses, increasing emphasis is placed on human choices and innovation as the key determinants of productivity and environmental conditions. The common assumptions of the socio-economic development agendas in the two cases are examined in the final paper. The discussion of the lessons and significance of the research highlights the critical role of international markets in driving ecological changes and options for resource monitoring and assessment processes to include enhanced participation by international market actors as well as other stakeholders. The concluding section reflects the need for further research to better enable human populations to live with environmental change in the future.

### *1.1.1 Background: Global environmental change research and the case of the northern Sahara*

Environmental change is increasingly understood as an interdisciplinary research challenge (Newell et al. 2005a, Adams 2009 p20, Turner and Fischer-Kowalski 2010, Adger et al. 2010). Such research moves beyond disciplinary bias (see Chambers 1974, Chambers 1997) to observe contemporary concerns, and better inform future decisions (Vitousek et al. 1997, Watson and Zakri 2005, Hassan, Scholes and Ash 2005c, Pachauri and Reisinger 2007). In contrast to the wider global literature on environmental change (e.g. Pachauri and Reisinger 2007), a more pronounced emphasis on human agency and artifice is inherent in an investigation of living with environmental change in the northern Sahara.

In the northern Sahara, landcover and climate have long been regulated by people, through the use of water for irrigation. In the human-regulated oasis systems, land management and groundwater use, rather than present climatic conditions, are the key factors determining productivity and survival. Over recent decades, interdisciplinary investigations based on observations of global landcover change have called socio-economic resource management decisions into question (Turner 1994, Lambin et al. 2001, Kijne 2003, Lepers 2005). This thesis responds to the opportunity to re-examine links between managed ecosystems, human institutions, and environmental learning, as these are understood by global change researchers in this novel context.

This approach to understanding environmental change drew on the work of scientists involved in the millennium ecosystem assessment (Hassan, Scholes and Ash 2005b, Safriel et al. 2005). Human-managed ecosystems, institutions, and environmental learning are themes that have been increasingly highlighted through global scientific efforts to understand environmental change (Ash et al. 2010, Young 2010). This recent literature has pursued an integrated interdisciplinary approach to understanding the problems of human development (IBRD 2010), agricultural production (McIntyre et al. 2009, IBRD 2008) and water scarcity (Bossio and Geheb 2008, WWAP 2009a, 2012). Within this global literature on environmental change, the northern Sahara represents a case that is relatively advanced in terms of its human development indicators, agricultural production technologies and outputs, and its state of acute water scarcity (IBRD 2007).

The findings of research conducted in such a context may provide insights for the management of increasing water scarcity in other environments, including those that are presently considered to be drylands (Safriel et al. 2005), and also others where water scarcity is increasingly of global concern (Pachauri and Reisinger 2007, WWAP 2012). These global scientific reviews focusing on the drylands have called for further attention to cases where societies have learned to enhance the life-supporting processes that provide food and favourable living conditions under changing environmental conditions (CGIAR 2011a, CGIAR 2011b). This has emerged as a central theme of a global literature on adaptation and resilience (Batterbury and Forsyth 1999, Folke et al. 2002).

In North Africa, the primary support to human innovation and productivity is provided by underground reserves of fossil water from more humid periods (Conrad and Fontes 1970, Edmunds and Wright 1979). While the rest of the world considers groundwater to be a silent resource (van der Gun 2012, Giordano 2007), this region has produced some of the most widely acclaimed scientific contributions to understanding its cycling over several millennia and transcontinental origins (Puri and Aureli 2009). The application of the ecosystems-institutions-learning lens brings a new dimension and perspective to these studies, shifting the focus of scientific attention from the identification of spatial and temporal limits to a fossil resource, to consider the cycling of groundwater in relation to other geophysical and socio-economic exchanges. This approach assumes a more dynamic and unstable equilibrium and searches for synergies between processes taking place in the ecosystems, both human-driven and natural.

The northern Saharan region has one of the longest histories of irrigated agriculture, enabling human populations to sustain productive agricultural systems in an otherwise arid environment (Clark 1980). In addition, this region has seen a particularly rapid expansion in its irrigated area over recent years. The expansion of irrigated agricultural production remains an under-investigated global environmental change of priority concern (Bossio and Geheb 2008, Thenkabail et al. 2009, WWAP 2009a). At the time of writing of this thesis, global and regional assessments of landcover change have not yet succeeded to definitively quantify effects associated with the expansion of irrigation and salinization (Helldén and Tottrup 2008, Bai et al. 2008). Nevertheless, the

need to do so has become widely apparent in studies of food and water security, particularly in the context of future climatic change (WWAP 2012).

Irrigation, where it is supported by pumped extraction of groundwater, can exacerbate water scarcity and other perennial problems affecting cultivation in arid environments. Groundwater naturally contains dissolved solids from primary salinization, by which salts accumulate in water due to weathering or transport processes from geological deposits. Under the effects of gravity, drainage water collects in low-lying areas, causing waterlogging. Aridity causes the water to evaporate, precipitating a build-up of salts at the land surface, known as secondary salinization. These land and water degradation challenges have been well-studied in the literature at both national and international levels over many decades (see e.g. Kassas 1995, Ghassemi, Jakeman and Nix 1995).

Over the years, many management solutions have been proposed to address these environmental problems (see a review in Hutchinson and Hermann 2008). Technologies such as solar powered desalination, hydroponic cultivation and artificial recharge of groundwater offer the potential to overturn all of the constraints presented by water, scarcity, salinization and other associated environmental change processes. However, socio-economic factors still restrict their applied development and widespread use. In North Africa, solutions proposed and applied to address water scarcity and salinization have included largescale water transfer projects, flooding areas of desert for the creation of artificial lakes in some locations, or pumping and draining others (see e.g. Sundborg and Nilsson 1985, Rizk and Davis 1991). Other

groundbreaking solutions such as reinjection of wastewater to aquifers, use of photovoltaic energy and reverse osmosis technologies for desalination have all been explored in this region (see e.g. RIGW 1999). These feats of engineering are the subject of technical feasibility studies, but more rarely interdisciplinary and participatory investigations.

It is important to underline that many simple technologies are also widely known and available in the Northern Sahara. These include traditional resource management practices to restore underground water reserves through floodwater spreading or rainwater harvesting. Manual techniques for water extraction (gravity or *shadouf*), filtration (sand or reed-bed), distillation (evaporation and capture of condensation) and precise application of water (hand-watering in kitchen gardens) are widely available, and have a history of use in the Northern Sahara (Laureano 2002). However, the economic dimensions of agricultural production scales, siting and labour requirements often render the use of these ecological technologies impractical (Hill and Woodland 2003).

This research addresses people *living with* environmental change. The adaptation literature has paid specific attention to the differentiation between adapting *to* and adapting *with* environmental change (Collins and Ison 2009). The further pragmatic shift to consideration of 'living with` rather than '*adapting with*` is understood to bring a broader, and less evolutionary perspective (Collins and Ison 2009). Survival (human and natural), encompassing work on vulnerability, adaptation and resilience, remains

as a fundamental concern. However, living is also more readily associated with the development vocabulary, including living standards and making a living.

Living with environmental change on the ground is necessarily different to mitigating or adapting to environmental change taking place in the atmosphere. Here, many complex natural and social processes are confounded. The challenge is to understand the socio-economic choices made by local and global populations who, through their actions, have played an integral part in environmental change processes over the past fifty year period. The people who are central to the research are smallholder cultivators. Cultivators are dependent on and steward natural resources.

Other groupings of people whose roles, perspectives and decisions affecting environmental change are explored in this research are policy-makers and scientists. North Africa provides an interesting case for the study of natural resource management decisions, due to the notably rapid pace of change and the considerable human capacity for the manipulation of natural systems that has been demonstrated. This multi-scale interdisciplinary approach reflects the current aspirations of global change research (an overview of the emergence of this trend through writing on political ecology during the 1980s and 1990s is provided in Adams 2009 p202-241, see also Adger, Brown and Conway 2010).

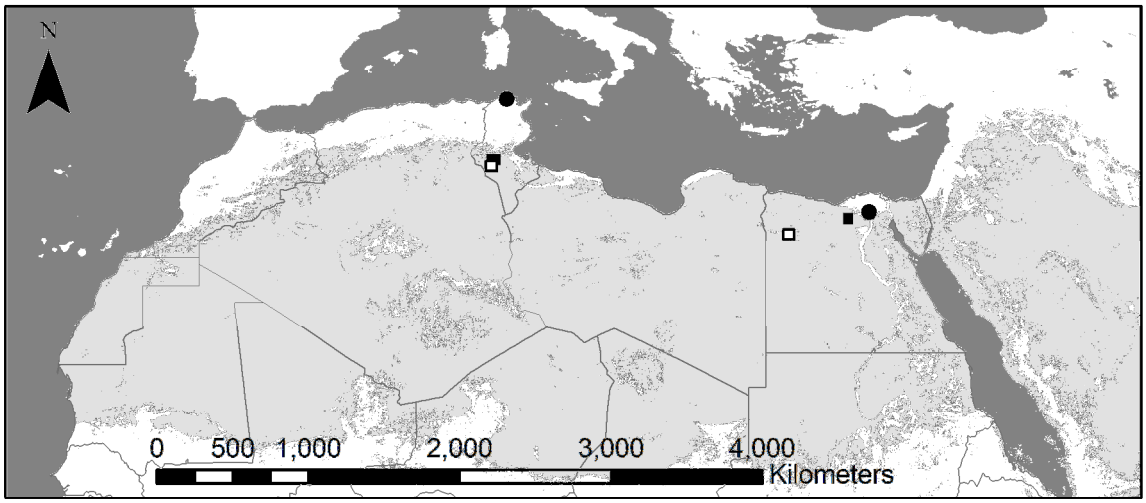
### *1.1.2 Social and economic characteristics of the northern Sahara*

The northern Sahara is governed from the capital cities of the separate States of North Africa. This research focuses on inland marginal desert areas located in two of these countries: Tunisia and Egypt. The South of Tunisia and the Western Desert of Egypt, where the Sahara begins, are arid areas, remote from the capital cities of Cairo and Tunis (see **Figure 1.1**). The shared traditions of the desert settlements, and the Berber, Bedouin and Sahrawi tribes who inhabit them, remain socio-economically and culturally important. Since the 1950s, the States of Tunisia and Egypt have brought security and stability to these areas, pursuing national agendas to settle the populations, and cultivate the desert land (Voll 1980). In light of their achievements in this regard, both countries have been influential in shaping international thinking on dryland development policy, particularly for the driest regions.

During the early years following independence in both countries, land reform and agricultural development were central to the national social agendas. In both countries, definitive studies for national resource management planning were launched. A series of maps of the study area from this period is presented in appendix 1. By the 1970s, ambitious investigations of national resources had been produced (Parsons 1962, Atwa 1968, AbdelSalam et al. 1972, El-Hinnawi and Atwa 1973, ERESS 1972). The development of the oil industry had a particular effect in stimulating hydrogeological investigation (e.g. Ezzat 1980, Sundborg and Nilsson 1985). However, as the oil industry overtook state-led agricultural development efforts, migration out of the marginal desert areas accelerated, and they remained socio-economically, as

well as geographically, marginalized (Abdelaziz 1979, Sghaier 1984, AOAD 1978, UNU 1979).

**Figure 1.1: Location of Study Areas in the Northern Sahara**




**Legend**
- Captial city
- Study area at/near administrative centre
- Study area distant from administrative centre
- Desert
- National bounary

During the 1980s, the development of the desert regions in both countries accelerated, due to the availability of new technologies, such as tubewells, which enabled increased private use of groundwater for irrigation, and the cultivated areas expanded (Kassah 1996a). Road building, urbanization and the provision of basic services also expanded in the desert regions (Allam 1991b, Allam 1991a). However, privatization policies introduced over this period, particularly in Egypt, appear – perversely - to have reduced the availability of definitive national resource management studies.

By the 1990s Egyptian and Tunisian research, based on the studies undertaken in previous decades, was formative in creating an international agenda for dryland

management (e.g.Kassas 1995, Le Houérou 2002). Resource scarcity and water management had emerged as matters of national and international concern, and new national institutions for this purpose had been created in both countries. Environmental policies were articulated (Gomaa 1997, MEAT 2000, MALH 2005). However, implementation was weak. Private groundwater use proved particularly difficult to regulate (Kassah 1996a, Khater 2003). At the same time, economic liberalization was growing, agricultural export and other industries were developing, and strains on natural resources continued to increase (MALH 2005, MARH 2006b).

In the new millennium, in line with Local Agenda 21, national agendas for environment and development have focused on decentralization and strengthening of the local and governorate level governments. Concepts of local knowledge and conservation, and participatory approaches that have become prevalent in global environmental change debates, are recognized by decision makers to be important. For example, there has been a revived interest in traditional knowledge and institutions such as water user associations and tribal associations (e.g. Selmi 1998, MWRI 2005). However, the challenge to incorporate these forms of social organization into practical resource management decision-making remains, even as established development agendas have been questioned in light of recent financial crashes and political changes (see e.g. Sghaier 2009).

### *1.1.3 Oasis cultivation in the endorheic basin systems of the northern Sahara*

In the desert regions of the Northern Sahara, cultivation traditionally takes place in endorheic basins. These are closed depressions situated at the natural termini of regional aquifer systems, where the water emerges through natural springs and a growing complex of engineered wells. This is a form of cultivation that has evolved from the earliest emergence of settled agriculture and urban civilization in the northern Sahara (Butzer 1960, Wendorf and Hassan 1980, Barker 1981, Hassan and Gross 1987).

In the natural environment of this region, xerophyte and halophyte vegetation establishes spontaneously in endorheic drainage basins (see El-Khouly and Zahran 2002, Zahran and Willis 2009). This has been adapted through human cultivation to increase the production of dates and other food and fodder crops, as well as ambient conditions for leisure and other economic or social activities. Thus, the cultivated oasis environment is the result of a combination of natural and socio-economic processes. These interactions create a socio-ecological system that has fascinated generations of geographers working in arid environments since the time of Herodotus (see e.g. Wilkinson 1978, Allan 1984).

Oasis cultivation traditionally takes place around springs or wells, shared through a rotational irrigation system. Cultivators have developed techniques to utilize shallow subsurface flows of water through endorheic basins, digging shallow trenches to capture drainage water. Variations on such techniques applied in a range of environments include *baali* agriculture (Richards 1982, Tomich 1992), water harvesting

systems (Ouessar et al. 2004) or water reuse systems, in cases where the drainage water is the result of irrigation further upstream (Nabil 2007). In the traditional oasis systems, practices in the construction of ditches and beds in the immediate area where crops are to be planted are adapted to further regulate and control water flows, evaporation and salt accumulation (Nabhan 2007, Forbes 1942).

Well-adapted species that can flourish in arid and saline environments, such as the olive (*Olea Europaea* L.) and the date palm (*Phoenix dactylifera* L.), dominate the cultivation patterns in the oases. Cultivators have learned where to plant them, and how to regulate the availability of water, sunlight and nutrients to enable them to flourish. The presence of vegetation regulates the climate at the land surface, enabling the retention of nutrients and water for soil formation (Sellami and Sifaoui 2008). Soils are further enhanced through the addition of manure and mulches made from wild plants and other available organic matter to improve fertility and increase the production of dates and other crops (Barker 1981). Once these favourable conditions for cultivation are established, other more sensitive crops can also be introduced to the planting pattern. Livestock husbandry and other economic activities are practiced alongside cultivation.

The cultivation of the oasis systems is enhanced through social organization (Brooks et al. 2005). Before the creation of the modern states, tribal institutions ensured collective resource management. Early accounts of these institutions provide a long-term record of their function and some benchmarks for investigation of changes in land and water use patterns and productivity over recent decades (e.g. Jennings-

Bramly 1897, Budge 1921). External systems for tracking the productivity of the oases were introduced for tax collection purposes (Stanley 1912). The strengthening of national regulatory systems over the past half a century (as described in the previous section) has changed the organization of local resource management and knowledge, tracking productivity and resource conditions from administrative and research centres based outside the regions.

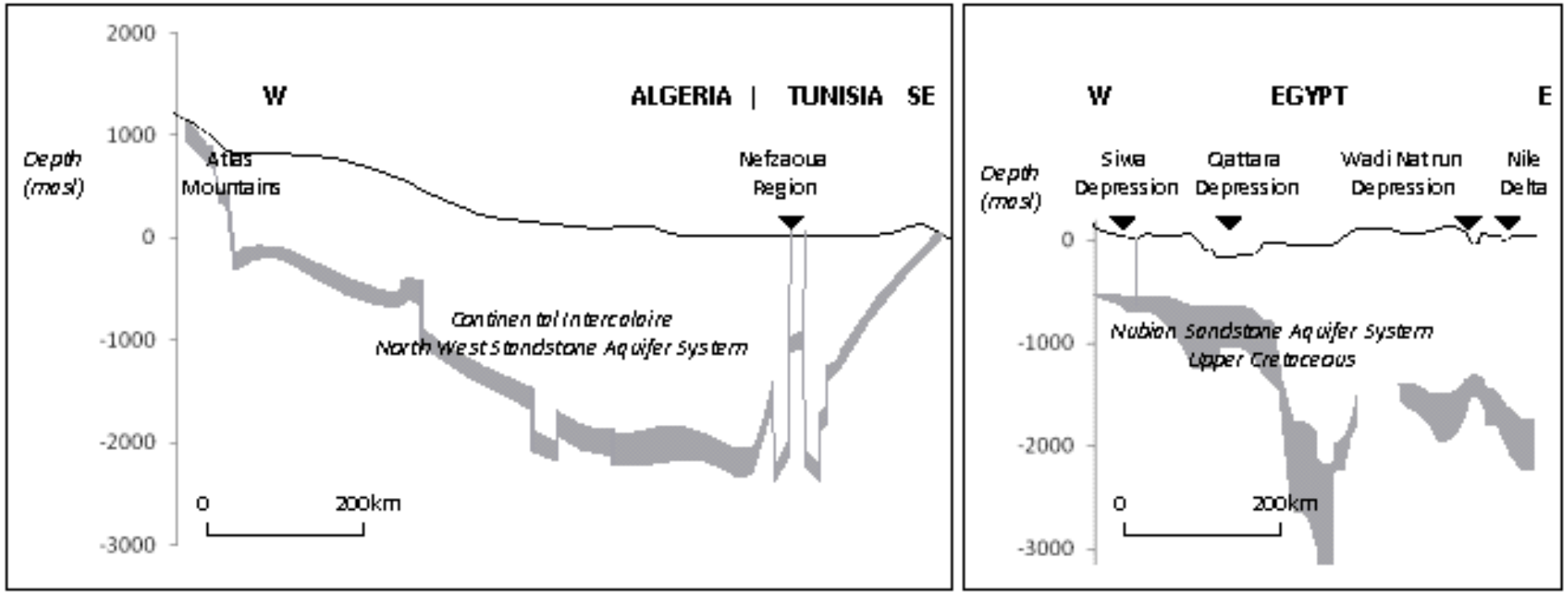
Whereas production of dates and olives for export is a traditional socio-economic activity in the oases, the increased availability of groundwater for irrigation from new wells and pumping systems has caused large-scale environmental changes in the nature and extent of the production systems. The concern that external market forces, or drivers, can drive environmental degradation is a common theme in global resource management research (see e.g. Barbier 1997a, MARH 2006b). Investigation of the potential interaction between market-based drivers and resource degradation requires analysis of long term trends in productivity and environmental parameters. In-depth research in the northern Saharan oases provides an opportunity to examine links between these international economic drivers and environmental change.

### 1.2 Study Sites

Two study areas were identified for investigation. Both are located in depressions in the desert landscape, at the natural termini of deep, non-renewable groundwater systems (**Figure 1.2**). Following consideration of a range of other oasis locations, the

similarity of the environmental conditions in these two low-lying endorheic basins led to their selection.

**Figure 1.2: Location of Study Areas in Endorheic Basins in the Northern Sahara** (based on Sundborg and Nilsson 1985, Edmunds et al. 2003)



### *1.2.1 Southern Tunisia*

In Southern Tunisia, the research was conducted in a region traditionally known as the Nefzaoua ($8^{o}30'$-$9^{o}15$ East and $33^{o}30'$-$34^{o}15$ North) (**Figure 1.3**). This region, covering an extent of 22,090 $km^2$, corresponds to the contemporary Governorate of Kebili. The landform contains a depression, forming a hydrologically closed basin with a complex of ephemeral salt lakes (*Chotts)* at the centre (Moreau 1947, Gautier 1953). Oases are located around the edge of the *Chotts*. These are then surrounded by steppe and desert systems. This region, together with that of the Djerid, to the North, is the principal region for Tunisian oasis cultivation and date production for export. A long enduring tradition of oasis cultivation exists in this region (see Sghaier 1984).

In the Nefzaoua, average annual precipitation is 85mm in the North at Kebili, and 71mm at El Faouar, to the South[2]. The region is dependent on non-renewable groundwater resources in the 1,019,000 $km^2$ North West Sandstone Aquifer System (NWSAS) (OSS 2003a, Puri and Aureli 2009). Underground reserves are stored in two principal deep aquifers: a) the Continental Intercalary (CI), in the lower Cretaceous formations (**Figure 1.2**); and b) the Complex Terminal (CT) in the Upper Cretaceous i.e. the Senonian, Eocene and the Mio-Pliocene. These aquifers both contain palaeogroundwater which dates back to the Pleistocene and early Holocene (ERESS 1972). They are overlain by the local phreatic (PQ) aquifers in the Mio-Plio-Quaternary sediments and the alluvial fillings of ephemeral river beds (Mamou 1990).

[2] according to compiled figures from CRDA annual reports 1995-2005. See Appendix 2 for rainfall data from National Oceanic and Atmospheric Agency.

Neither present nor planned pumping schemes for the region are anticipated to be sustainable (Siegfried 2004, Zammouri et al. 2007). The official estimate of the available deep groundwater resource flowing into the governorate of Kebili is 237.5 million cubic metres per year ($Mm^3/yr$), with an additional 5.5 $Mm^3/yr$ available in the shallow surface aquifer (ODS 2007). Each year, extractions in excess of this figure are published (Mamou and Kassah 2000, ODS 1997-2007). The CT is exploited most intensively, while further extractions are also made from the CI (Mamou and Kassah 2000). Increasing volumes of extraction from public wells for agricultural use are recorded annually (DGRE 1979-2006). However, these figures are recognized not to provide a full account of the total groundwater extraction volumes. Nevertheless, declining piezometric heads recorded in the same manner provide an effective confirmation that extraction exceeds recharge across the aquifer system.

Present day recharge from occasional rainfall in the Nefzaoua region enters the local PQ aquifers. However, this rainfall represents only a small fraction of irrigation requirements, and is often of poor quality due to the accumulation of salts at the soil surface. Since rainfall is erratic, much of it runs off or evaporates. The CT extends over a larger catchment area (670,00$km^2$), which includes an area of karstified outcrops around the Dahar uplands at the SE fringes of the basin, where recharge from rainfall has been observed to enter this aquifer directly (Guendouz et al. 2003, 2006, Abid et al. 2012a). Recharge volumes relative to precipitation in this region have been estimated using infiltration coefficient of 5% (Ben Baccar 1987). The recharge zone for the deeper CI (**Figure 1.2**) includes the Atlas mountains in Algeria (ERESS 1972). Water

from this source has only been detected in the aquifer within a distance of 100-150km from the recharge area, and not yet in the Nefzaoua region, which is further downstream (Edmunds et al. 2003, Moulla et al. 2012).

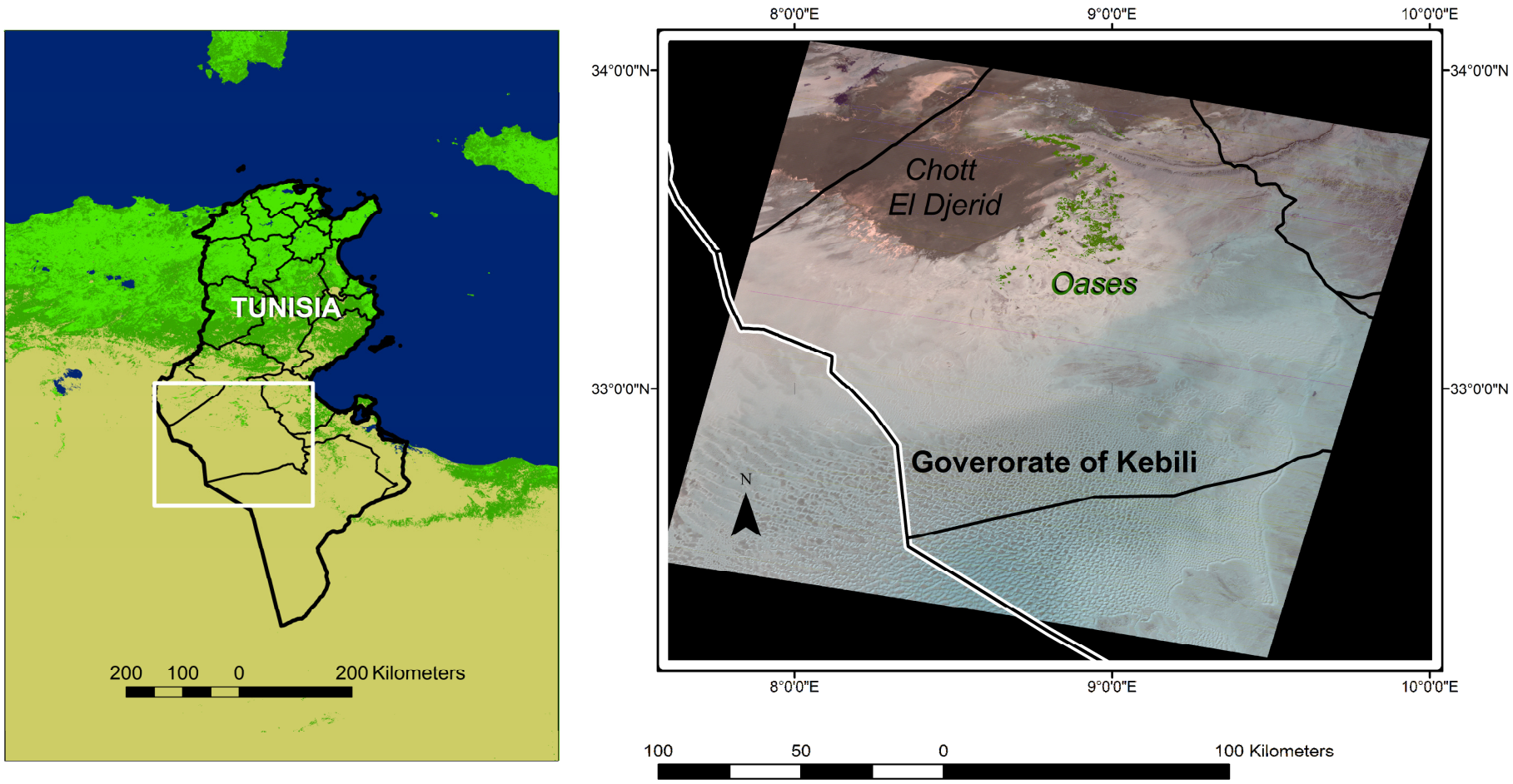
Once water enters the system, it may flow horizontally across the aquifer, or move either upward or downward, exiting one aquifer to recharge another (Tarki et al. 2011). These movements are difficult to generalize, predict and quantify because they are not uniform and are affected by the high degree of spatial and temporal heterogeneity affecting the lithology, hydrogeological and recharge conditions across the aquifers (see Ould Babasy 2005 for a discussion of the challenges of calculating recharge). Available studies of the interactions between the aquifer layers in this region have demonstrated that the CI and CT are connected, particularly in the northern part of the Nefzaoua (Gonfiantini et al. 1974, Abid et al. 2012b). Upflow from the CI and the CT to the PQ aquifers has also been identified (Kamel 2011a, Kamel 2011b). Such studies have been used in attempts to compute the volumes of recharge to the various aquifer layers, and across the system as a whole (Kamel 2011a, Al-Gamal 2011).

Recharge estimates are highly sensitive to seasonal and climatic changes in water availability or to changes in human water use. These factors will interact with the heterogeneous aquifer characteristics, affecting flow directions and volumes. Opportunities for human intervention to increase infiltration in the recharge zones of Southern Tunisia have attracted scientific attention (Ouessar et al. 2004, 2009, Fleskens et al. 2005, Schiettecatte et al. 2005), but no long-term impacts from these

processes on the NWSAS aquifer system and water availability in the Nefzaoua have yet been identified. More locally within the Nefzaoua region itself, drainage water reuse practices have been the focus of a range of studies (SCET-TUNISIE 2009, Nabil 2007). The poor quality of drainage water limits the use of this practice, constraining crop choices.

At the time of the field investigation, collective systems for groundwater management remained in place in this region, under the supervision of the State. Overall, this case was characterised by a strong State-led system for environmental monitoring and management of environmental change.

**Figure 1.3: Oases of the Nefzaoua Region in the Governorate of Kebili, Southern Tunisia** (Globcover 2005 (L) and Landsat TM (R))



### *1.2.2 Western Desert, Egypt*

The northernmost oasis depressions of the Western Desert of Egypt include Siwa ($25^{o}20'$-$25^{o}40$ East and $29^{o}19'$North) and Wadi El Natroun ($30^{o}02'$-$30^{o}30$ East and $30^{o}17'$-$30^{o}38$ North) (**Figure 1.4**). These two depressions are located on either side of the larger Qattara Depression, and fall in the contemporary Governorates of Matrouh and Behaira. In comparison to Southern Tunisia, the climate in the northern oases of the Western Desert is more arid, and continues to increase in aridity further to the South. The northern oases are, therefore, the most comparable to those of the Nefzaoua region in terms of environmental conditions. Rainfall in all of the study areas is scarce and erratic. Average annual precipitation is usually estimated at around 55mm at Wadi El Natroun and 10mm at Siwa, further to the West. Daily ground surface data over the past decade shows even lower annual averages and a very high degree of variability (see rainfall data in appendix 2).

The vegetation systems in the northern oases of the Western Desert remain composed of a complex of salt lake, sebkha, oasis, steppe and desert, similar to those of the Nefzaoua (Zahran and Willis 2009). Each depression contains a series of sub-basins, in which a string of small saline drainage lakes are formed. The underlying Nubian Sandstone Aquifer System (NSAS), originates in Chad and Sudan and flowing northward through Egypt and Libya, spans 828,000$km^2$ of the Western Desert (**Figure 1.2**)(CEDARE 2001).

The NSAS is divided into two major reservoirs: the deep Nubian Aquifer System (NAS), ranging in age from Cambrian to Pre Upper Cenomanian, and the Post Nubian Aquifer System (PNAS) ranging from the Upper Cenomanian to Recent (Puri and Aureli 2009, CEDARE 2001). In the Northern part of the Western Desert, the main water-bearing upper layers include the Moghra Miocene Aquifer and the Quaternary Pleistocene deposits (Sundborg and Nilsson 1985, RIGW 1990). There is also an additional local Pliocene aquifer at Wadi El Natroun (RIGW 1990).

In the 1960s the GDDO began a programme for drilling of wells for land reclamation at Wadi El Natroun (LaMoreaux 1962) and Siwa (Parsons 1962). Over the intervening period, continued drilling has extended progressively deeper through the Pliocene and Miocene, penetrating into the deeper layers of the NAS at Siwa and areas to the South of Wadi El Natroun (CEDARE 2001, Ibrahim 2005). Recent investigations have indicated that the greatest proportion of the NSAS water is fossil water, formed from *in-situ* precipitation during the Late Pleistocene to Early Holocene times (Thorweihe and Heinl 1993, Sultan et al. 2011, Patterson et al. 2005). Relatively recent studies concluded that present day recharge represented a small fraction – perhaps around 10% - of extractions from the NAS (Thorweihe 1990, Ebraheem et al. 2002, Gossel, Ebraheem and Wycisk 2004). This is confirmed by falling groundwater tables (see Khater 2003).

All management scenarios for the NSAS are considered to be unsustainable – ie discharge will exceed recharge, even without any anthropogenic extraction of groundwater (Ebraheem et al. 2002, Sultan et al. 2007). Saline intrusion from the Northern coastal areas has been observed over the past 140,000 years (Gossel,

Sefelnasr and Wycisk 2010). As a result, the deep layers of the system are saline at Wadi El Natroun (Hamza, Aly and Swailem 1984), while Siwa remains just to the South of the saline-freshwater interface (Himida 1970).

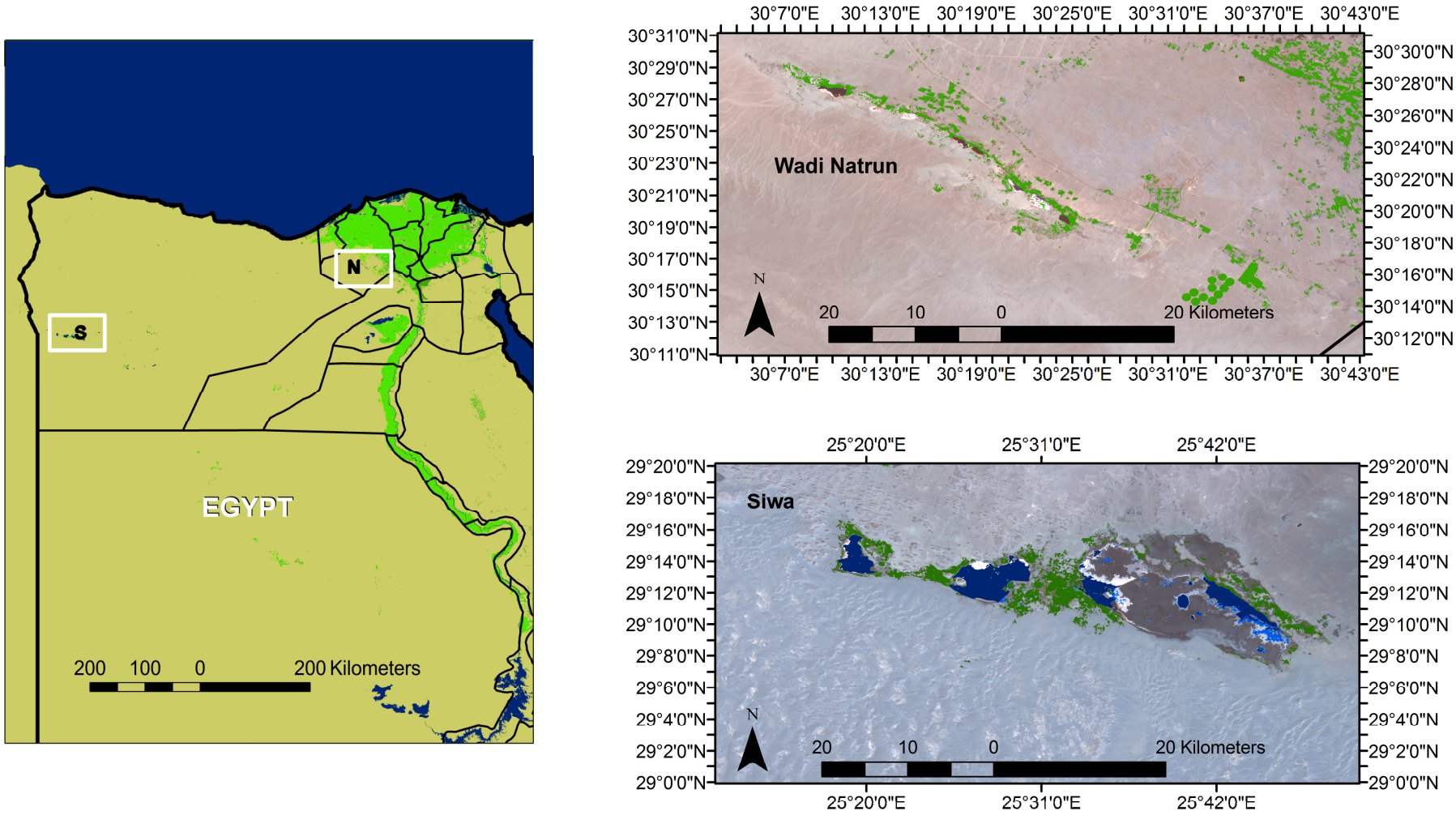
The main inflows to the NSAS in the Western Desert are considered to enter from Sudan. These are quantified at 0.5 billion cubic metres per year ($Bm^3/yr$) (RIGW 1999). Additional inflow volumes from the Kufra basin of Libya (Edmunds 1979) are less readily quantified in the available literature. The NSAS is hydraulically connected to the Nile Basin (Geirnaert and Laeven 1992, Dawoud and Ismail 2011). Since the construction of the High Aswan Dam, the exchange of groundwater along the Nile River in Egypt has been estimated at about 500,000 cubic metres per day ($m^3/day$). The most notable seepage to the NSAS in the Western Desert, estimated at $0.3Bm^3/yr$ per year (RIGW 1999), has been observed at Lake Nasser, to the south (Gossel et al. 2004, Kim and Sultan 2002, Hamdan 2011). At Wadi El Natroun, inflows from the Nile Basin enter the system through the upper layers, and travel west towards the discharge lakes (Geirnaert and Laeven 1992, Masoud and Atwia 2011, Fattah 2012). Some of the Nile water is thought to continue westward through the Moghra Miocene aquifer to discharge through the Qattara Depression (Geirnaert and Laeven 1992, Rizk and Davis 1991). None is anticipated to reach as far west as Siwa.

Surface drainage of locally used irrigation water recharges the shallow aquifers in the depressions at Siwa (Misak, Abdel Baki and El-Hakim 1997, Masoud and Koike 2006) and Wadi El Natroun (Geirnaert and Laeven 1992, Masoud and Atwia 2011, Fattah 2012). This water is often reused, although it is vulnerable to salinization and

contamination with agrochemicals, industrial and other waste products (Soliman 2007, Ahmed, Samie and El-Maghrabi 2011). Drainage systems have received scientific attention in areas prone to water-logging (Misak et al. 1997, Gad 1999). Potential recharge areas have been observed in the unconfined Moghra formation and unconfined Quaternary aquifer, where good infiltration characteristics prevail (Geirnaert and Laeven 1992). Rainfall harvesting structures are found in more northerly coastal regions, but none has been reported in the areas of the northern oases. No modelling of contemporary runoff in this area appears in the literature, but studies of the palaeodrainage systems are exploring the potential new development in upstream areas across the Western Desert (Robinson et al. 2007).

Alternative proposals for human intervention to increase water availability in the irrigation areas through the diversion of water from the sea to the Nile and overflowing drainage lakes have attracted decision-makers` attention (Sundborg and Nilsson 1985, Rizk and Davis 1991, Attia et al. 2007, Abo-Ragab 2008), but few detailed investigations on the possible long-term impacts from these interventions on the NSAS aquifer system and water availability in the Western Desert have yet been published. More locally within the cultivated areas, drainage water reuse practices are being explored, despite the generally poor quality of drainage water. A very notable tradition of saline agriculture and agroforestry in collective systems exists in this region (Nabhan 2007, CEDARE 2006). However, this has been changing rapidly in recent years.

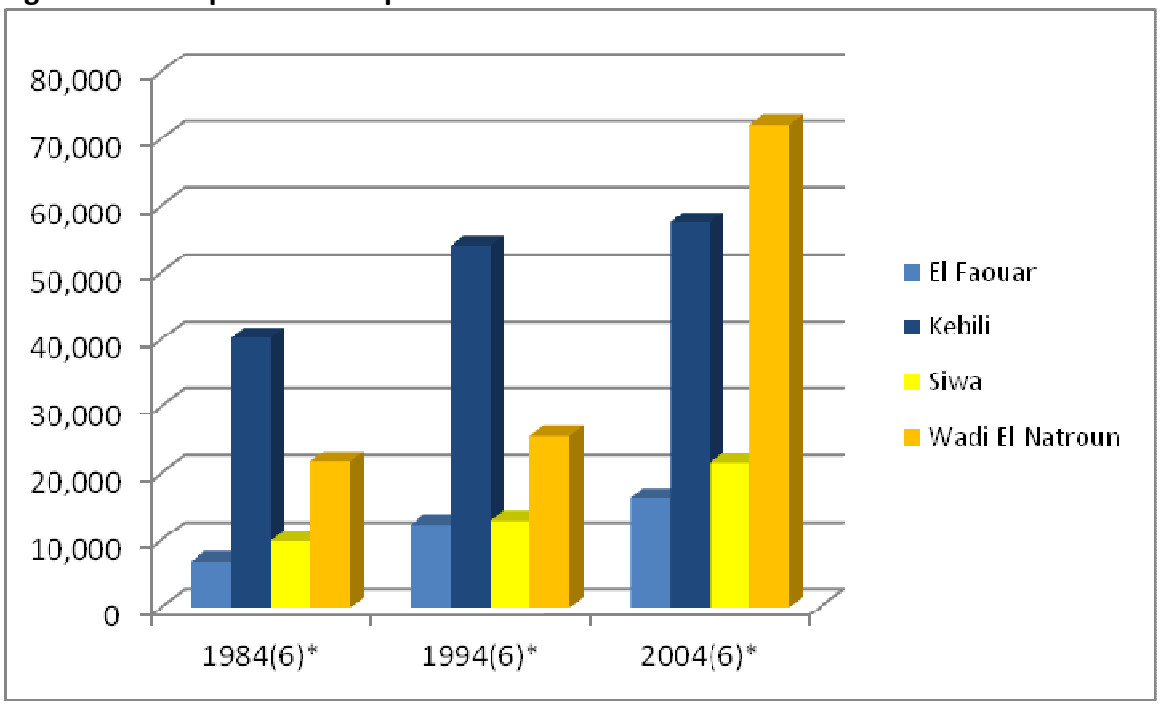
**Figure 1.4: Northern Oases of the Western Desert, Egypt: Siwa (S) and Wadi El Natroun (N)**



### *1.2.3 Population trends*

Within the case study areas in both regions, population growth rates have varied **(Figure 1.5).** In the Nefzaoua region, the more remote Southern Delegation of El Faouar has remained less populous than the regional capital of Kebili, in the North. In the Western Desert, the remote oasis settlement of Siwa, in the South West has grown more slowly than Wadi El Natroun, which is located closer to the Nile Delta, in the North East ( see also **Figure 1.4**).

**Figure 1.5: Comparison of Population Growth in Nefzaoua and Western Desert**




*Tunisian decadal census (Egyptian decadal census)

The physical similarities between the sites in the two endorheic basins throw into relief the more notable socio-economic and institutional differences, which have led to different cultivation patterns, shaping the recent environmental change processes explored through this investigation.

## 1.3 Thematic, Conceptual and Contextual Literatures: a selective review

### *1.3.1 Oases: interrupting arid ecosystems*

As localized natural or manmade areas of increased humidity in areas that are otherwise characterized by very low rainfall, oases are exceptional dryland ecosystems. In the natural and environmental sciences literature, dryland systems are usually defined in terms of the aridity index, which is based on precipitation and potential evapotranspiration (Thomas and Middleton 1994). Oasis systems, while located in arid environments, evade the constraints on human cultivation activities that are associated with meteorological aridity through the use of water sources that do not come directly from contemporary local rainfall (Clouet 1995). In the case of endorheic basin oases in the northern Sahara, this means that they are fed by surface or groundwater, arriving from other regions and time-periods (Ahmed 1999b, Dabous and Osmond 2001, Edmunds et al. 2003, Ould Babasy 2005, Kamel et al. 2005).

Oases have featured as an emblematic theme in the global popular literature on the survival or collapse of civilizations (e.g. Postel 1992). The case of the Garamantian oases, located in between the two contemporary study areas, has been analyzed as a case study in the collapse of civilizations under climatic change and salinizaton (Brooks et al. 2005). Oasis systems have also been the focus of considerable international policy-oriented literature on environmental conservation through the use of traditional or indigenous knowledge (Laureano 1988, 1999, 2005, 2002, Nabhan 2007, FAO 2007).

A global literature on traditional ecological knowledge in oasis systems includes contributions from many regions of the world (e.g. Yang, Zhou and Xiao 2007, Siebert et al. 2007). This literature was singled out for particular attention in the recent assessment of dryland systems as part of the millennium ecosystem assessment (Safriel et al. 2005):

> `In oases, for example, traditional management approaches are based on the appropriate usage of the physical and geomorphological factors. These include production and distribution systems for water management, architectures that regulate micro-climate, cultivation of salinity-tolerant fruit species such as the date palm, waste recycling systems, and sand dune stabilization techniques.` (Safriel et al. 2005 p655)

Nostalgic accounts of traditions for the cultivation of crops and regulation of the localized water cycles appear (Lightfoot 1996, Lightfoot and Miller 1996). The `oasis effect` has been observed as a biophysical phenomenon (Sellami and Sifaoui 1998, 2003, 2008). Some researchers consider `oasification`, achieved through positive interactions between environmental and social processes, to represent the reversal of the frequently observed socio-ecological dynamic of resource scarcity, poverty and resource degradation (Mongil Manso and de Azagra Paredes 2007).

However, in many cases, increasing demographic and investment pressures resulting in larger water abstraction are recognized to have led to soil salinization and loss of surrounding vegetation in the oases. Environmental degradation may be further compounded through overgrazing and fuelwood exploitation followed by soil erosion (Safriel et al. 2005 p641).

Areas considered oasis-like today in some cases may well represent ecologically destructive use of resources:

> `…… trying to ‘‘green’’ desert areas or make them ‘‘bloom,’’ (…) has often resulted in an aesthetically appealing landscapes of oasis-like patches of agricultural land set in sharply contrasting surrounding desert (Safriel 1992)—but with a loss of dryland biodiversity.` (Safriel et al. 2005 p633)

Experiences of living with environmental change in the oasis systems, which result from the application of human knowledge, innovation and ingenuity, can lead to either positive (resilience-enhancing) or negative (degrading) interactions between people and environmental change processes. These experiences therefore merit further attention through environmental change research.

While natural scientists continue to pursue improved understanding of changing arid environments, it is also well recognized that these systems are infinitely complex (Thomas 2003). Dynamic function, variability, change and instability are considered to be inherent characteristics of the arid environment and its ecosystems (Hutchinson and Hermann 2008). Analyses of how and why systems change, adapt or collapse are seen as useful in order to improve understanding of how they can be managed. In keeping with this view, in the new millennium, the focus in the conceptual literature on global environmental change has become oriented to discussion of resilience (Folke et al. 2002, Folke 2006a, Folke 2006b).

### *1.3.2 Understanding and living with environmental change in arid environments*

The global environmental literature has explored epistemological variations in approach to understanding environmental change, differentiating between top-down, exogenous scientific knowledge generated by experts and technocrats, and other bottom-up endogenous types of environmental knowledges that are termed traditional, ecological, indigenous, or local (Brokensha, Warren and Werner. 1980, Critchley 1989, Adams 1996, Mazzucato and Niemeijer 2000, Watts and Peet 2004, Agrawal 2005, Safriel et al. 2005, Sillitoe and Marzano 2009). Some commentators consider the difference in terms used for these alternative ways of knowing a matter of semantics (e.g. Ash et al. 2010), while others find interest in discussing the differentiation (Hamed et al. 2002, Briggs et al. 2007, Briggs 2005).

Small farmers` or cultivators` knowledge, as explored by Boserup (1965), has long been the subject of farming systems research (Chambers 1971, Chambers 1974), and a continuing interdisciplinary literature on induced innovation (see e.g. Turner and Fischer-Kowalski 2010). A recent international assessment of agricultural knowledge focused on distinguishing between a `mode 1` non-applied scientific knowledge generation process and `mode 2` applied simultaneous research and development processes (McIntyre et al. 2009, after Nowotny, Scott and Gibbons 2003).

Increasingly, `grounded` (see e.g. Glaser and Strauss 1967, Stringer 2007), iterative, adaptive processes of experience, observation, re-evaluation and repeated

experimentation (as practiced by cultivators *living with* environmental change), are considered to be required for empirical scientific knowledge generation. Such approaches may draw on one or more scientific disciplines in the generation of their research procedures.

Interdisciplinary approaches are used by many geographers, extension and fieldworkers, but are far less often published. Nevertheless, such approaches have generated a number of groundbreaking scientific contributions in the international literature on environmental change in land and water systems (e.g. Boserup 1965, Adams 1996, Mazzucato and Niemeijer 2000, Brookfield 2001, Brookfield, Parsons and Brookfield 2003, Manning and Seely 2005, Stringer 2007, Stringer, Twyman and Thomas 2007, Reed, Fraser and Dougill 2006).

When, at times, research approaches from the natural sciences and the social sciences appear to be at odds, the interdisciplinary literature on environmental change and knowledge generation provides a meeting ground for exploration. Depending on the degree of integration amongst the disciplines and methods, research at this interface may be multidisciplinary (less integrated) or transdisciplinary (highly integrated – to the extent that the features of individual academic disciplines are no longer distinguishable)(O'Sullivan 1980, Cernea 1984, Morse 2007). Such forms of knowledge appear to be increasingly popular, perhaps precisely *because* they can be undervalued:

> `approaches that, in addition to insights from a wide range of disciplines, include community and traditional knowledge of the kind that is produced 'on the job'. Knowledge generated through everyday activity within a community is usually seen as 'just common sense', a designation that reduces its value in the eyes of 'professionals' (Newell et al. 2005).

Acceptance of resource users` knowledge of their ecosystems within interdisciplinary frameworks brings with it implications for scientific research methods. Participatory approaches, seen as increasingly important in development research, are becoming ever more prevalent in investigations of environmental change, including those in arid environments (Stocking and Murnaghan 2001). Such approaches draw on techniques in anthropology to understand local environmental knowledge and practices (see e.g. Chambers and Conway 1992, Chambers 1997, Mazzucato and Niemeijer 2000). In this interdisciplinary investigation of human experiences of living with environmental change, such approaches are integrated with other data sources and analyses of processes taking place at other scales.

### *1.3.3 Environmental change scholarship in the Nefzaoua and the Western Desert*

During the last century, environmental scholarship in the northern Saharan region and its oases focused on discovering how the land was formed, where the groundwater came from, its age and recharge patterns (e.g. Beadnell 1909, Ball 1939, ERESS 1972). Ecological research has defined the habitats and species of the arid saline environment, and produced valuable information concerning plant characteristics and economic properties (see El-Khouly and Zahran 2002, Zahran and Willis 2009, Hassan et al. 2005a). Publications on the use of technologies for remote sensing, irrigation and agricultural improvement from this region are numerous (e.g. El-Baz et al. 1989). Many contributions have been made to research on hydrological modelling (e.g. Mamou 1990, Zammouri 2007, Robinson et al. 2007). These range from back of the envelope

water and salt balance calculations to dynamic multi-level aquifer models (Gad and Abdel-Baki 2002, Marlet, Bouksila and Bahri 2009, Askri, Bouhlila and Job 2010).

Research addressing environmental conditions and changes in this region is usually very technocentric and sectoral – i.e. studies of water management produced by employees of the ministries of water without reference to resource users, or agricultural development studies produced by employees of agricultural research institutions without access to data on water resource conditions. Applied research is highly valued, demonstrating expert researchers` skills and knowledge. However, such research generally does not devote critical attention to the characterization of the environmental problems to which it is often tasked to propose rapid solutions. Nor does there appear to have been the opportunity to ask long term questions as to the availability and quality of datasets to be used for public resource management.

The region has a long tradition of social research which could inform more social investigation of experiences of environmental change (e.g. Boris 1951, Clarke 1959, Abdelaziz 1979). This has included anthropological accounts of practices and traditions for resource management (Bedoucha Albergoni 1976, Abu-Lughod 1986., Bedoucha 1987, Bedoucha 2000, Battesti 2005, Hamed et al. 2002). Recent investigations of the changing oasis systems have focused on the economics of farm management (Belloumi and Matoussi 2004, 2006). Unemployment and migration have been explored as important socio-economic drivers of change (Sghaier 2000, de Haas 2001, Gammoudi 2007). However, very few such investigations have so far been oriented to national or international interdisciplinary environmental policy audiences, and very

few have been published in internationally peer reviewed journals (exceptional cases include Ouessar et al. 2004).

Critical literature questioning the application of expert knowledge in Egypt and Tunisia has included studies reconsidering the present order of land and water management disciplines (Mitchell 2002, Battesti 2005). At the policy level in both countries, emphasis on the importance of local environmental knowledge has grown since the 1990s. In the northern Sahara, as in other regions (see Stringer et al. 2007, INWEH 2010), the practical implications of this shift have been slow to feed back into the national environmental management systems and institutions.

Investigations of local environmental knowledge in the oases of the northern Sahara have tended to focus on its traditional past, separating between `scientific` and locally applicable knowledges (e.g. Parrish 1999, Hamed et al. 2002, Attia 2002b, MWRI 2005). Francophone contributions to this literature are relatively numerous (Battesti 2005, Haj Ahmed 2007). In keeping with the anthropological perspective, such research has often referred to knowledge that is `indigenous` (Hamed et al. 2002, Briggs 2005, Briggs et al. 2007). Such approaches have found application in the context of nature conservation in protected areas (Springuel 2006, Zalat and Gilbert 2008), and conservation agriculture, including water harvesting techniques in hilly areas (Ouessar et al. 2004, Ghazouani 2009), and agrobiodiversity in the oases (Neffati 2003, Nabhan 2007).

## 1.4 Research Question and Objectives

This thesis evaluates the experiences of living with environmental change over a period of half a century in the oasis systems of the arid northern Sahara, drawing on, and contributing to interdisciplinary research across the environmental and social science literatures. Long term datasets are used to identify environmental changes and original field research with decision-makers, scientists and cultivators to investigate experiences of living with and managing these changes.

**Research Question:**

What lessons for global environmental change research can be learned from interdisciplinary study of experiences of living with environmental changes in oasis systems?

**Research Objectives:**

Through two case studies in oasis systems:

- Identify environmental changes that have affected:
    - Land reclamation
    - Groundwater resources
    - Crop production

- Investigate how the environmental changes are managed by:
    - Individual cultivators
    - Local associations of cultivators
    - National and international experts and policymakers

**Expected Outcomes:**

The intended contribution of the thesis will be to interdisciplinary analysis and understanding of experiences of living with environmental change. Some of these findings will be policy-relevant, addressing policies for environmental monitoring on the one hand, and economic development, on the other. While the investigation was carried out in a manner that was cognizant of political ecology (see previous section and Robbins 2004), it did not set out to pursue any objective associated with social change. The objective was simply to reflect on the experiences of the past fifty years of environmental changes lived in the study region.

Overall, the thesis underlines the need for a more holistic and reflective integration between environmental assessment and human development objectives. The study engages participatory research addressing groundwater management issues in the northern Sahara, where pressures on non-renewable aquifers are increasingly recognized to threaten the agricultural productivity and basic water supplies. This suggests that similar approaches could be available to local scientists to deepen understanding of environmental change processes.

The thesis explores cultivators` understanding of environmental change. Established research techniques from other regions are used to override sectoral barriers and place the resource management debate in an interdisciplinary context. The data and conclusions are pursued through extensive field research. Survey data reflects cultivator perspectives and elucidates factors determining their responses to environmental degradation, either to regulate or exacerbate the problem. The thesis

then re-examines national policy decisions, identifying explanations as to why it has not been possible to prevent the aggravation of environmental change and enhance the achievement of development objectives.

While multidisciplinary research involves combining multiple disciplines in a single study, interdisciplinary research critically explores the tensions between the disciplines in an effort to draw lessons of interest to each. Transdisciplinary approaches, on the other hand, seek to move beyond the disciplines to build new frames of meaning and understanding in response to real world problems (Morse 2007, see p71McIntyre et al. 2009). Although this research sets out to address a real world problem, the interdisciplinary scope introduces an inherent tension between the varying methods, findings and articulation to different scientific audiences as an essential feature of the thesis.

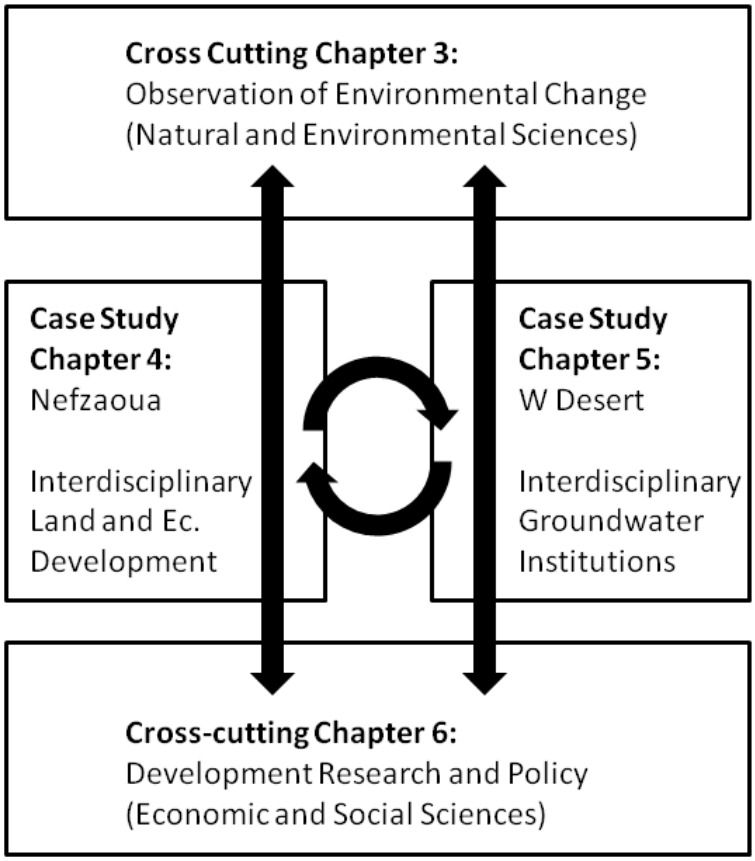
The study presents research outcomes to four international scientific research communities: environmental researchers in arid environments, development researchers, interdisciplinary researchers investigating land degradation processes and interdisciplinary researchers concerned with groundwater management challenges. The thesis maximizes the opportunity to inform the broader global change research communities of the insights for environmental change research gained through the experience of living with environmental change in the northern Saharan oasis systems. A coherent synthesis of this experience is distilled.

## 1.5 Thesis Structure

The thesis consists of two introductory chapters, four academic articles that have been published or submitted to relevant peer-reviewed journals, a discussion chapter, and a conclusion. Each paper is targeted to the disciplinary and thematic scope of the selected journal, and written in an appropriate style. A brief description of each of the chapters submitted as journal articles follows below, including an overview of the subject matter and the position of the paper within the overall structure of the thesis.

In the presentation of findings (chapters 3-6), a progression is orchestrated through the chapter structure (**Figure 1.6**), from chapter 3, which is oriented primarily to the environmental sciences, through the two interdisciplinary case study chapters, 4 and 5, towards the final paper in chapter 6, which synthesizes the findings for a development policy worldview.

**Figure 1.6: Schematic View of Thesis Chapter Structure**




In light of this evolving perspective, the conceptual, contextual and methodological dimensions of the research are briefly revisited in each chapter. This entails some repetition, but also underlines the progression in the thesis and enables each chapter to be read and scrutinized as a self-contained unit.

The remainder of this section presents a brief overview of the four chapters in which the thesis findings are presented and discussed, followed by a critical review of the conceptual orientation of the research as a whole.

## *Chapter 3: Overview of changing land and water systems in the oases of the northern Sahara*

This chapter provides an overview of the environmental changes that have taken place in the study areas in the northern Sahara over the past fifty years. The chapter focuses directly of the first objective of the research project, which is to identify the environmental changes that have affected the oasis systems. These changes are discussed in the context of the global debate on environmental change in arid environments, including concerns relating to both climatic change, and human-induced degradation processes affecting land and water resources. The chapter is based on a paper submitted to the Journal of Arid Environments under the title: `Monitoring landcover change and environmental degradation in the saline arid endorheic basins of the northern Sahara`.

`

Conceptually, the chapter is oriented to the global land change science agenda (Turner, Lambin and Reenberg 2007). It pursues current discussions in the international scientific literature regarding prevalent approaches to the analysis of environmental change processes in the arid environment. Methodologically, the paper focuses on land cover observation, using generically applicable techniques across both selected study areas to capture environmental changes. The chapter then considers opportunities for integration of the analysis with data from a range of other sources, including direct observations in the field and cultivators` accounts of environmental changes observed over time.

In the Tunisian case, public statistics on changing groundwater conditions shed light on the observation of salinization trends, whereas in Egypt, further analysis of the landcover changes had to rely on the use of increasingly high resolution satellite images, extended field observations and local knowledge. In each case explored, the integration of remote sensing data with other sources of local information enabled a revision of the prevalent views of salinization processes. Effects were attributed to a more complex and nuanced range of causes and localized salinization processes than previously considered in the available literature, leading to differentiated local management implications.

The discussion is concerned with the newly emerging conceptual and methodological orientations for the assessment of landcover changes that have entered the international scientific discussion amongst environmental scientists. The significance of these conceptual and methodological shifts is considered both in relation to the case study areas and more globally in light of trends in increasing use of groundwater for irrigation in arid environments. The overriding concern highlighted through all analyses focuses on the long-term over extraction of groundwater, leading to and exacerbating the effects of salinization. The conclusions and recommendations point towards further exploration of the social and statistical dimensions of this problem, which are picked up in subsequent chapters.

***Chapter 4: Southern Tunisia Case Study Paper***

The first of two detailed case studies is presented in this chapter. Environmental changes occurring in the oases of the Nefzaoua region over the period 1994-2009, and

smallholder cultivator's experiences of living with them, are explored. The chapter builds on the observations presented in chapter 3, adding detail and depth through a case study approach. The two studies complete the identification of environmental changes, which is the first objective of the research. They then move on to address the second objective, investigating how these changes are managed. This first case study chapter is based on a paper submitted to the Journal of Land Degradation and Development under the title: *Dates, degradation and development: international market effects on land and groundwater resources in the Nefzaoua Region, Southern Tunisia, 1994-2009.*

The role and perspectives of smallholder cultivators in managing environmental change through investing in irrigation and other inputs to production are explored. The discussion of environmental changes further develops the findings presented in chapter 3, considering the effects of degradation as experienced by the smallholders. Degradation is examined in terms of an externality of international economic activity driving the overexploitation of groundwater resources. Methodologically, the paper is interdisciplinary applying the recommendations identified in the international scientific literature , as discussed in the previous chapter. However, locally established research techniques, such as surveys of cultivators implemented through the water user associations, are also built into the approach used.

Local agricultural statistics, records of groundwater conditions, use and costs, and a temporal comparison between smallholder cultivators` farm budgets in the 1990s and at the present time are combined in the analysis. These provide insights towards

understanding the development of irrigated agricultural export production, associated degradation of land and water quality, and responses by cultivators and policy-makers living with and managing these effects.

The discussion of policy responses considers the efficacy of economic measures, including rising water prices introduced in this region to manage the environmental change. The effects of these measures on smallholder land management options are discussed. Other emerging economic policy responses under discussion during the study period are also identified. These included global market-oriented measures to address global market drivers – e.g. payments to resource-dependent communities from external actors responsible for driving degradation.

**Chapter 5: Western Desert Case Study Paper**

This chapter provides the second of two detailed case studies in this thesis. A socio-ecological process of groundwater resource degradation occurring in the Western Desert of Egypt over the period 1990-2009 is explored. The chapter deepens the observations presented in chapter 4, with emphasis more directly on changes in human-groundwater interactions than was the case in the two previous chapters. The scale is smaller, focusing on a single village. This chapter is based on a paper submitted to AMBIO: A Journal of the Human Environment under the title: *`A socio-ecological investigation of options to manage groundwater resource degradation in the Western Desert, Egypt`*

The chapter is interdisciplinary in focus, however, here, the social analysis precedes the environmental analysis in importance, framing the issue, and reversing the balance in the previous chapter. The socio-ecological conceptual framework draws on recent scholarship on resilience (Folke et al. 2002), and introduces a discussion of CPR management responses to environmental change (Mukherji 2005). Methodologically, the paper draws on a survey of smallholder cultivators, including similar questions to those asked in the Southern Tunisian case. However, the supporting archived statistical data in this case is more sparse. Instead, remote sensing is combined with environmental modelling techniques to reconstruct trends in groundwater use.

In this case, the investigation was not limited to consideration of smallholder cultivators, but also engaged with the presence of larger farming enterprises, exploring different farm budget models and attitudes to the risks of environmental degradation. The economics of cultivation on the large and small farms is contrasted, and impacts of the environmental changes on smallholders` household budgets since the 1990s highlighted. However, the smallholders in this case study were not simply victims of degradation, but had often also become part of the process, taking up employment on the large farms that were exacerbating the tragedy of their common groundwater resource through over extraction.

***Chapter 6: Synthesis of development policy implications***

This chapter provides a synthesis of the socioeconomic effects of environmental changes that have taken place in the study areas in the northern Sahara over the past fifty years. These changes are discussed in the context of international development

approaches focusing on the transition to international agricultural export production in water scarce environments, in which it is argued that technological and institutional innovation can overcome environmental constraints. The chapter is based on a paper submitted to World Development Journal under the title: ` *Why don't smallholders benefit from global export market development?*`

Conceptually, this chapter follows up on the CPR management theme, introduced in the previous chapter. The use of CPR management theories to support New Institutional Economic policies is interrogated, and an economic analysis of the impacts of environmental change on smallholder development is presented. Further investigation of the economics of international export production is pursued, building on the findings of the socioeconomic surveys presented in the case study chapters. Asymmetries encountered in the institutional settings for the survey in both countries are discussed. Additional socioeconomic contextual information is incorporated to the discussion of international market conditions and effects in both countries.

The chapter observes the disintegration of the collective institutions through which smallholders had traditionally managed environmental and market changes. This had been taking place at different rates in all of the study areas. Common problems encountered by smallholders are also identified. Aspects of the risks and costs of groundwater degradation are discussed. Tradeoffs between direct and indirect benefits to smallholders from the market transition, and costs in terms of resource degradation are interrogated. The discussion considers the logic of national strategies

and international development strategies in light of the observations made through this investigation.

Conclusions and recommendations highlight the need and the opportunity for national development programmes and global market institutions to enable smallholder associations and private companies to engage more effectively in CPR management. While this chapter is firmly oriented to the scope and priorities of World Development journal, it sets out to make a case as to why environmental change research is vitally important in the development context. This chapter therefore provides a development-oriented synthesis of the research findings presented in the earlier chapters of the thesis, leading into the broader interdisciplinary discussion in the following chapter.

Each of the chapters containing research findings (chapters 3-6), begins with an introductory preface, expanding on the summaries provided above. The purpose of the preface is to review the place of the chapter in the thesis as a whole, critically introduce the disciplinary scope to which it is articulated, consider the effect of this conceptual orientation on the discussion as presented within the chapter, and highlight aspects of the findings emerging for further discussion in the concluding sections of the thesis.

## 1.6 Conceptual Overview

Progressive shifts in the conceptual approach to understanding the northern Saharan experience of living with environmental change introduced with each chapter in this thesis are described in the previous section. The hybrid nature of the conceptual orientation is in keeping with contemporary interdisciplinary research assessing changing ecosystems:

> `Rather than adopting a conceptual framework entirely "off the shelf," a pragmatic approach that blends various frameworks and methods to balance strengths and offset weaknesses seems to be the most appropriate..` (Tomich et al. 2010 p72)

Building on the review of conceptual literature (in section 1.3.2), the blending of established frameworks and methods with localized perspectives from the two case study regions added depth to the study of human experiences of living with environmental change. A brief critical reflection on the overarching conceptual elements of the investigation, focusing on identified strengths and weaknesses, is provided in the remainder of this section.

### *1.6.1 Overarching Global Principles of Common Pool Resource (CPR) Management*

This investigation is oriented to the global literature on CPR management. This literature considers the institutions through which people adapt to, regulate or manage environmental change. Central to this theoretical work is the popular spectre of the tragedy of the commons (Malthus 1992, Hardin 1968), whereby a human population places excessive pressure on the natural resource base, leading to its eventual destruction. The contribution of CPR management theory is to argue that resource users who are threatened by a tragedy of the commons may organize themselves to regulate their collective resource use, avoiding the threat of degradation and collapse (Wade 1988, Ostrom 1990a, Moench 2002, Aggarwal 2006, Mukherji 2005, Janssen 2006).

CPR management analyses focus on institutional arrangements that include formal or informal systems of rules and behaviours. The organization of resource users living with environmental change in oasis systems, i.e. land and water users, can be analyzed through this lens. In the context of the northern Sahara, CPR management analyses can apply to the modern legal institutional systems, but also to the remaining traditional land tenure and resource rights institutions, including what are considered to be informal or illegal uses of resources – such as the use of land without a formal right to do so, or groundwater extraction without a legal permit (Hammani et al. 2009). The theory of successful CPR management is readily illustrated in the traditional management systems of the northern Saharan oases, where water is a shared resource ensuring the collective survival of the population (Attia 2002b).

Contemporary CPR management research perceives a social-ecological system (SES) that achieves sustainability or resilience through (social and ecological) self-organization (Ostrom 1990a, Janssen 2006, Ostrom 2009). In the contemporary global change literature investigating CPR management in SES, resilience is a key analytical concept integrating understanding of ecological and social processes (Gallopin 2006, Folke 2006, Enfors and Gordon 2007, Adger et al. 2010). Hollings' theory of resilience (1973 p14) defines resilience as ''a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables`'. Resilience has been further paraphrased as: `achieving desirable states in the face of change` (Engle 2011 p649).

Where production systems rely on non-renewable groundwater under increasing physical and economic scarcity and variability the persistence and robustness inherent in the natural vegetation of the northern Sahara and the ingenuity of the oasis cultivating society appear to relate well to the resilience concept. Sustainability, on the other hand, is a more problematic concept in relation to the oasis systems, which are inherently unsustainable, exhausting non-renewable reserves of groundwater, and therefore requiring continual innovation in resource management practices to achieve desirable states in the face of change.

CPR management scholars write about environmental change and socio-ecological resilience, but do not usually attempt to tangibly define, locate or quantify them in the physical environment. Instead, CPR management analyses most often focus on

theorizing the socioeconomic rules or principles that enable communities to cooperate in order to achieve CPR management. Nevertheless, the importance of an agreed body of facts regarding the state and trends in the shared resource is recognized to be fundamental to the achievement of consensus on resource management objectives, as demonstrated by Ostrom`s study of groundwater management in California (Ostrom 1990a). The missing element in research that is oriented to CPR management as a conceptual frame is that it rarely focuses on the shared environmental knowledge base that is needed. This critique reflects questions faced in practice by field workers, resource managers and decision-makers, i.e.: what are the resource impacts of your CPR management? (see also Walker 2005).

### *1.6.2 Identifying Experiences of Environmental Change with Cultivators*

While CPR management research generally focuses on resource users, this thesis specifically addresses resource cultivators and their experiences of environmental change in the oases. This difference between resource users, cultivators, and `farmer` (as used elsewhere by Brookfield 2001, Brookfield et al. 2003), is significant, since in the identification of "cultivators", the cultural and productive focus of those experiencing environmental change is emphasized. However, there are many overlaps and interchangeable uses of these terms in the respective literatures, as reviewed earlier in this chapter. Engagement with cultivators` experiences in the changing environment of the northern Saharan oases gives recognition to their dynamic and innovative applied knowledge systems, not excluding but moving beyond discussions

of indigenous or necessarily traditional knowledge systems (Tomich 1992, Briggs et al. 1998, 2005, 2007, Parrish 1999, Nabhan 2007).

Cultivators in the northern Sahara, and their ways of knowing, learning and making a living, are diverse, including men and women of varying ages and from different backgrounds, some with pastoralist heritages, e.g. Bedouin, who have adopted settled cultivation practices in the oasis systems relatively recently, as well as others who move from other rural or urban areas, or invest as absentees. All learn through trial, error, observation and experimentation, how to cultivate and live with the changing environmental conditions. Their knowledge generation is a continual work in progress. An approach to research with cultivators, focusing on their experiences, is therefore enriching in the study of environmental change (see e.g. Stringer 2004).

The main difficulty with research that is sensitive to multiple complex simultaneous knowledge generation processes is that it requires long periods of time spent in the field, following which, generalization becomes very difficult, due to the increasingly complex understanding that emerges. However, field research re-examining environmental change with cultivators through discussion of their experiences is valuable because it provides an epistemologically sensitized `reality check` as a counterpoint to received wisdom from policy-makers and scientists.

This can enable a researcher to develop a deeper understanding of the significance of environmental changes, identify and to fill gaps in the availability or understanding of information. The approach encourages the researcher to read aggregated statistics

critically, recognizing the complexity that is necessarily masked through the compilation and aggregation. It also encourages critical reading of scientific accounts of the environmental conditions and changes. The methodological implications of this orientation are described in the following chapter.

# CHAPTER 2: METHODOLOGY

## 2.1 Introduction

This research integrates natural and social science research techniques to examine how ongoing environmental changes and socio-economic interactions have been experienced in the oasis systems of the northern Sahara. The methods used may be summarised to include three major components. First, research focused on time-series datasets that could capture environmental changes. Second, field investigations added depth to the understanding of observed changes, using a survey questionnaire, participatory environmental sampling, and *in-situ* observation. Third, analysis was pursued, extrapolating from collected data, comparing and combining with additional contextual datasets.

The multi-method approach adopted in this DPhil research project drew on previous studies conducted in other regions (e.g. Batterbury, Forsyth and Thomson 1997, Olson et al. 2004, Stringer and Reed 2007, Reed, Dougill and Taylor 2007). Multiple different approaches to data collection and analysis were applied iteratively. Each step was preceded by a consultation with supervisors, colleagues and local people in the study areas. Following each step, results obtained were reviewed in the same way.

Each discipline and research method brings with it a range of preconceptions, and sources of potential bias. Triangulation amongst data from different sources can reveal such effects (Mazzucato and Niemeijer 2000). For example, cross-checking with meteorological data and different survey instruments or focus groups is recommended for validation of perception data collected in cultivator surveys (Bandyopadhyay, Wang

and Wijnen 2011). The multi-method approach also enables integration of datasources at different scales, connecting cultivators' knowledge at the field scale to global and national processes.

The design of the investigation as a comparative study to be implemented in two countries, each with a range of pre-established scholarly traditions provided an array of alternative, locally tried and tested methods that were adapted to support the investigation. This introduced new elements that had not been included in the previous studies conducted in other regions. In addition to these, the investigation also drew on more recent global scientific debates that were evolving during the study period concerning methods for the assessment of Land Degradation and SLM (Stocking and Murnaghan 2001, Niemeijer 2006, Vogt et al. 2011).

In the remainder of this section, a comprehensive overview of the methods used is presented. Each of the subsequent results chapters 3-6 adds a brief summary description of particular methods used to obtain the data and analyses presented in that chapter. Some elements of the methodological description are therefore further elaborated in these chapters. This increases the internal coherence and clarity of each chapter. It also builds the methodological progression through the thesis, starting out from a Land Change Science toolbox in chapter 3, and working towards the use of more socioeconomic approaches addressing water scarcity and development issues in chapter 6.

## 2.2 Use of archived long-term environmental data sets

Environmental datasets covered agricultural productivity, water resource conditions, and the supporting landcover and land management systems through which these are regulated. Time series datasets were sought throughout each step of the study, beginning from the literature review and initial desk-based research during the preparatory phase of the investigation, proceeding to a series of visits to national and local archives in the two countries. Field survey interviews and preliminary discussion of findings with other researchers led to the further identification of time series datasets as the study progressed.

### *2.2.1 Changing productivity of oasis systems*

Reviewed literature (MALR 2005, MEAT 2000, MARH 2006b, MEDD/GTZ 2006) indicated that crop productivity would have risen in both study areas, until recent decades when it was believed to be falling, due to the effects of environmental degradation. However, initial consultations in the study areas threw doubt on this expectation. Time series datasets on the extent and condition of agricultural production were, therefore, anticipated to provide an essential reference point for the study of environmental change in the oasis systems.

In both countries, systematic records concerning the extent and characteristics of the cultivated oases were available through the national decadal agricultural censuses

(MA 1963, MARH 2006a, MARH 1996, MALR 1961, 1982, 1990, 2000). Together with early agricultural development plans (e.g. LaMoreaux 1962, Parsons 1962), and historical accounts of cultivation (Clarke 1959, Forbes 1921, 1942, Bedoucha Albergoni 1976), these provided an important source of time series information, documenting the progressive expansion of irrigated cultivation in each case. In both cases, the decadal agricultural census has been consistently in operation since the creation of the State (with a pause in Egypt caused by war during the 1970s), documenting volumes of production of major crops on a regional scale. In Nefzaoua, annual surveys of agricultural productivity in the oases were also available (MoA 1977, 1978b, 1978a, 1980, 1981, DIS 1982, 1983, DG/PDIA 1989, 1995). For most recent years (1994-2010) UN COMTRADE lists the volumes and values of each crop exported by the case study countries.

During the study period, the Commission Regional de Developpement Agricole (CRDA) in Nefzaoua was in the process of analyzing annual agricultural statistics, while in Egypt, the 2010 Agricultural Census was being carried out at the time of the field investigation. Methods for conducting, compiling and analyzing data from the agricultural censuses were discussed with local officials in both countries in order to ensure a clear understanding. Statistics did not include crops that were consumed domestically. Most of the published statistics are aggregated to regional or national level and none are georeferenced.

Disaggregated time series statistics on agricultural production 1994-2005 were located at the Regional Agricultural Development Commission (CRDA) in Nefzaoua. These

enabled comparison of trends in crop productivity to changes in water quality and availability at the individual wells that were being used to irrigate them. The resulting analysis, taking into account crop water requirements and salinity tolerances, as published by FAO (2002) is presented in chapter 5. In the Egyptian case, disaggregated time series statistics were not available through the national agricultural census. Greater use of other data sources, e.g. high resolution satellite images and cultivators` knowledge was made in this case. These are further described and analyzed below and in chapters 3 and 5.

From the compiled statistical information alone it was not possible to determine whether the changes observed in agricultural production were due to environmental factors, or whether they resulted from socioeconomic drivers, influencing crop choices and cultivation patterns. It also appeared desirable to verify compiled information on changing productivity with cultivators. These gaps informed the design of survey and field observation activities described below.

### *2.2.2 Changing water resource conditions*

Data on rainfall, soil and groundwater salinity were obtained from national archives. These datasets were anticipated to account for changes in agricultural productivity. For the Nefzaoua region, continuous published monitoring observations of climate (1982-2006) from the Kebili, Douz and El Faouar meteorological stations were compiled (DGRE 1982-2006). Annual rainfall 1995-2005 was also compiled from the annual reports of the CRDA. Since the late 1980s, daily climate data from Kebili are

available from the United States (US) National Oceanic and Atmospheric Administration (NOAA)[3]. Observations of Total Dissolved Solids (TDS) (1979-2006) in wells used by smallholder cultivators` water user associations (DGRE 1979-2006) were compiled and analyzed spatially and temporally. A number of other groundwater quality parameters are monitored and published, but only from selected wells (DGRE 1998-2006). Since these did not provide a time series of conditions in the selected parts of the region, the analysis was not pursued.

Basic information on water resource availability and quality is published by the Egyptian Government (EEAA 2010b, EEAA 2009). NOAA daily global surface data on climatic conditions were available from Siwa since 1959, and from Wadi El Natroun since 1996. Investigation through the archives of the Egyptian Desert Research Centre and the MWRI confirmed that the national programme for monitoring groundwater quality had been established more recently than the Tunisian one (Dawoud 2004, EEAA 2009, 2010b). Technicians were accompanied in the field during their sampling activities in Wadi El Natroun, and available data from monitoring over the period 2009-10 was obtained and analyzed with their assistance. In Siwa, during the field research period, local government technicians were engaged in a campaign to block excess wells with concrete. These activities were also accompanied and observed.

Georeferenced databases generated through the issuing of permits for groundwater extraction in Wadi El Natroun were obtained and analyzed, but none could be found in

[3] http://gis.ncdc.noaa.gov/map/gsod/

the more remote part of the study area at Siwa, where the groundwater office reported more local resistance to the implementation of the permit system. Further unpublished data were obtained through interactions with agricultural workers, drilling companies and private farmers in Wadi El Natroun, where there are commercial laboratories analyzing soil, water and farm produce. Local farmers also provided some records of water quality analyses from their wells over additional recent years.

Information in grey literature on older wells dating back to the 1950s was consulted from local drilling companies and archived documents in both regions (e.g. REGWA 2000, SCET-TUNISIE 2000a, 2000b, 2003b, 2003a, 2009). The theses of previous students also provided valuable sources of information (e.g. Hossary 1999, Gad 1999, Ibrahim 2005, El Fahem 2003, Siegfried 2004, Ould Babasy 2005). A published time series data set on Electrical Conductivity (EC) in 44 wells and springs, beginning in 1998 was resampled using a simple handheld conductivity meter (after Abd El-Rahman Aly 2007).

Where hydrological data were sparse, volumes of groundwater extraction and use are often estimated as a function of the increasing extent of the cultivated area (see e.g. Gad 1999, Ibrahim 2005). These methods focus on calculation of water use per hectare, either on the basis of crop-water requirements for evapotranspiration (see Golombek, Gebauer and Buerkert 2007, Siebert et al. 2007), or local generic estimates of irrigation water use.

The knowledge of water users regarding their water resources has been demonstrated in other regions (Lightfoot et al. 2009). Water use patterns were further investigated through the field surveys in each study area, as described in the following section. These provided georeferenced information on land and water use practices, observation of rising or falling water tables and changes in water quality including salinization. Interviewees were also asked for their opinions concerning the causes and processes of salinization. This produced additional insights concerning the water resource conditions and trends affecting them.

Estimates of the rate of the falling groundwater tables were available in both regions (Abdel Mogheeth 2004, Ibrahim 2005, Zammouri 2007). This is the change most readily observed by water users, whose access to water is reduced where the water table has fallen, necessitating the use of pumps to extract groundwater for irrigation. In Wadi El Natroun, initial local consultations in the study area cast doubt on a 1m per year trend in the falling water table that had been observed in the previous studies. Wells where such trends had not been observed were identified. Further investigation was therefore required to explore whether or not the previously observed trend could be accepted as a generalized regional assessment.

In order to examine accounts of wells in the study areas where the water table had been reported to have declined, and those where it had not, an examination of the topographical and hydrogeological factors that might be affecting the rate of lowering in the groundwater table was necessary. Well depths identified through the cultivation typology and survey were compared to a database of well permits held by the Ministry

of Water Resources and Irrigation (MWRI), which lists permitted extraction volumes for some wells. Overlaying the datasets on well types, locations and trends in water resource conditions with the known horizontal and vertical locations of the aquifers was explored in order to support understanding of the nature of the environmental change processes taking place.

The objective of this examination of the combined data from different sources was not to compare reliability through any statistical analysis of correlations between local perceptions and other datasets. The focus remained on the more fundamental need to deepen understanding of the different processes likely to be taking place simultaneously at different rates across the different layers of the aquifer systems. Most of these spatial comparisons were done very simply, using Google Earth™. ARCGIS™ was also used in order for comparison to landcover change analysis.

### *2.2.3 Landcover change datasets and analysis*

The land cover change toolbox (Olson et al. 2004, Turner et al. 2007) provided an important methodological support to this investigation. Spatially referenced datasets on landcover generated through remote sensing techniques enable analysis of conditions and trends not only in vegetation cover, but also in land and water resources, and in human well-being. In this investigation, these methodologies are integrated. Land-use and land-cover (LULC) change studies are increasingly used as a basis for global environmental research (Lepers 2005, de Jong et al. 2011, Bai and Dent 2006). They therefore provide an important common reference framework for global environmental change researchers, capturing both effects, and drivers of other global changes (Safriel et al. 2005). The use of relatively simple techniques in this investigation renders the findings repeatable, readily comparable in relation to global scientific assessments in other publications, and comprehensible to researchers working across a range of disciplines.

The most commonly and widely used land cover index in global land change research is the Normalized Difference Vegetation Index (NDVI) (after Rouse et al. 1973, Tucker 1979). NDVI quantifies relative biomass (green-ness) by contrasting the characteristics of two bands from a multispectral raster dataset—the chlorophyll pigment absorptions in the red band and the high reflectivity of plant materials in the near infrared band. NDVI is calculated from the Red Band (R) and the Near Infrared Band (NIR) of the image using the equation:

$$NDVI = \frac{NIR-R}{NIR+R}$$

NDVI is globally comparable because it compensates for changing illumination conditions, surface slope, aspect, and other extraneous factors that otherwise affect images from different times and locations. This index works particularly well for differentiating irrigated areas with dense tree cover from other more sparsely vegetated landcovers (Olalla, Calera and Domınguez 2003, White 2007, Alhammadi and Glenn 2008). Differentiation between barren land, temporarily fallow, or immature crops is more difficult (Huete 1987). Because NDVI is correlated with vegetation density and reflectance, it is also used as an indicator of vegetation productivity and health. Most current investigations use NDVI either directly, or propose in an adjusted version (see de Jong et al. 2011, Masoud and Koike 2006, Alhammadi and Glenn 2008, Bai and Dent 2006) [4].

NDVI is commonly used for the detection of cultivated areas at the regional scale (Golombek et al. 2007, Siebert et al. 2007, Toomanian 2004, White 2007, Bakr et al. 2010). In this investigation, NDVI was used to detect the extent of vegetated areas and, based on this, to assess the changing extent of cultivation and irrigation around the oases in the study areas. Agricultural productivity was estimated by multiplication of the extent of the cultivated area by the volume of production per spatial unit.

[4] Alternatives 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).

Likewise, water use volumes were estimated, based on the extent of the irrigated area, multiplied by the irrigation water requirement per spatial unit.

Changes in NDVI can be caused by climatic conditions. Because of this, much of the current global methodological discussion on NDVI focuses on the rainfall effects on NDVI (see e.g. Tucker 1986, de Jong et al. 2011, Evans and Geerken 2004, Helldén and Tottrup 2008, Bai et al. 2008, Bai and Dent 2006). A discussion of the possible effects of rainfall on NDVI in the study areas is presented in chapter 3. This discussion was required in order to publish the analysis for a global scientific readership. However, since irrigation water volumes applied in one week exceeded the volume of annual rainfall in all of the study areas, the assumption that no correlation would be identified was already reasonably clear.

Effects on NDVI can also be caused by soil conditions and land management practices. Although NDVI is sometimes also adjusted for soil characteristics, where data are available (e.g. Alhammadi and Glenn 2008, Masoud and Koike 2006), since, no effective time series datasets on soil conditions were identified in this investigation, no such adjustments were attempted. However, the effects of soil management practices are considered in some detail in chapter 4.

Two very commonly used time series sets of remote sensing imagery, available at different spatial and temporal resolutions and over different time periods were used:

1. 1982-2006: high temporal frequency (bimonthly), coarse spatial resolution (8x8km)

2. 1972 - present: lower temporal frequency, higher spatial resolution (60-30m)

***Landcover analysis at high temporal frequency with low resolution (8x8km)***

A global dataset was obtained from the Global Inventory Modelling and Mapping Studies (GIMMS) through the University of Maryland Global Land Cover Facility. GIMMS contains NDVI data for 1982 – 2006 at 8km resolution, at a bimonthly frequency (Cracknell 2001). The dataset is derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17.

The dataset has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change. The low resolution increases the possibility that variations in reflectance from soil, rock, desert areas and water bodies might affect the pixel values, offsetting the effects of cultivation. However, assuming that such interference would be minimal, the use of high frequency data such as the GIMMS dataset enables smoothing of seasonal effects and anomalies, and has therefore provided the basis for recent land degradation and desertification assessments (e.g. Helldén and Tottrup 2008, de Jong et al. 2011).

Reflecting the approach in the current global assessments, the NDVI analysis was intended to show whether land and water degradation had taken place at the regional scale. A curve was anticipated – showing a rising trend as the cultivated land area expanded, and finally, a decline as productivity peaked, land and water resource capacities were exceeded, and salinization affected land and water resources.

Using the GIMMS AVHRR dataset, with ERDAS Imagine$^{TM}$ software, 27 pixels around the cultivated areas of the Nefzaoua, and on each side of the Western Desert at Siwa and Wadi El Natroun were selected for analysis of the regional trend in NDVI. Bi-monthly NDVI profiles were extracted from these areas over the 24-year period covered by the GIMMs dataset. An annual average was taken from the 24 NDVI values obtained from each selected pixel for each year. These were then averaged across each area to obtain a single annual value for NDVI from each region for each year, enabling trends to be plotted and compared.

A somewhat more complex approach to combining the bimonthly GIMMS AVHRR data is used in the global assessment literature by Wessels et al (2007). These authors apply a statistical filter to interpolate cloud flagged or atmospherically affected data whenever a relative decrease in the signal of 5% or more was followed within 4 weeks by an equivalent increase. The composite is then weighted by the actual number of days left in each period, to generate an annual value for ∑ NDVI. Wessels et al. argue that this procedure helps to reduce atmospheric effects on the NDVI. This technique could have been adopted in the present investigation, had atmospheric effects been suspected to be interfering with the result obtained. However, no such interference was identified as a relevant cause for concern in the interpretation of the results in this case. Further discussion on the analysis of high frequency time series images at coarse resolution is provided in other studies (Pax Lenney et al. 1996, White 2007, de Jong et al. 2011).

Overall, the anticipated rising trends in regional level NDVI were identified. The recent reductions were not as sizeable as expected. Within each region analyzed, several pixels were then selected for further analysis and plotted separately, enabling a more disaggregated view of the regional trends**.** The scale of the 8x8km pixels is such that in each region, the field survey activities conducted fit within a single pixel. In the currently available global landcover maps that are built on these datasets (Helldén and Tottrup 2008, Bai et al. 2008), these single pixel areas of irrigated cultivation in the desert environment are practically invisible. Because the scale of the dataset is so coarse in relation to the size of the study areas, many indistinguishable factors can affect the observed trends. It is therefore desirable to combine this dataset with analysis at higher spatial resolution.

***Landcover change analysis at higher resolution (60m and 30m resolution)***

In 2008, the United States Geological Survey (USGS) released the Landsat image archive for public use (http://edcsns17.cr.usgs.gov/EarthExplorer/). This includes 239 georeferenced MSS images of the selected study areas at 60m resolution over the period 1972-87. A further 285 TM images at 30m resolution cover the period 1984-2003, in the Western Desert, and continue to the present for Southern Tunisia. Finally, 435 ETM+ images at 15m resolution were identified, covering the period 1999-present for both regions. From 2003-present a fault in the scan line corrector obscures some of the pixels in these images. Fortunately, parts of these images covering the centre of both areas of interest were left undamaged.

In total, 959 images were reviewed to locate image sets for each study area in comparable months in order to minimize the possible effects of seasonal variations. In the case of Nefzaoua, which receives higher winter rainfall than the Western Desert, images taken during the months of July and August were selected. The MSS images required geocorrection to match the TM images. This was carried out using ERDAS Imagine$^{TM}$ software.

Simple rectangular areas of 48x72km were identified in each Landsat image. NDVI was analyzed in each pixel and NDVI profiles were extracted. Unsupervised classification was then used to classify the images into areas of high and low NDVI using an iterative self-organizing data analysis technique (ISODATA) provided by ERDAS Imagine$^{TM}$ software. This analysis created two clusters of highest NDVI, representing vegetated areas, and lowest NDVI, representing non-vegetated areas.

Previous investigations in the study areas had concluded that it was not possible to use a more complex classification to differentiate effectively between different vegetation types: i.e. separating salt marsh vegetation from irrigated cultivation, or to differentiate between gravel desert landcovers and built surfaces, such as roads and residential areas (Awad 2002). This was confirmed through some experimentation in the present investigation, and the simple two-class classification was therefore retained. Comparison of recent images classified in this way to observations in the field and to high resolution images viewed in Google Earth confirmed that the simple classification was correctly identifying vegetated and non-vegetated areas.

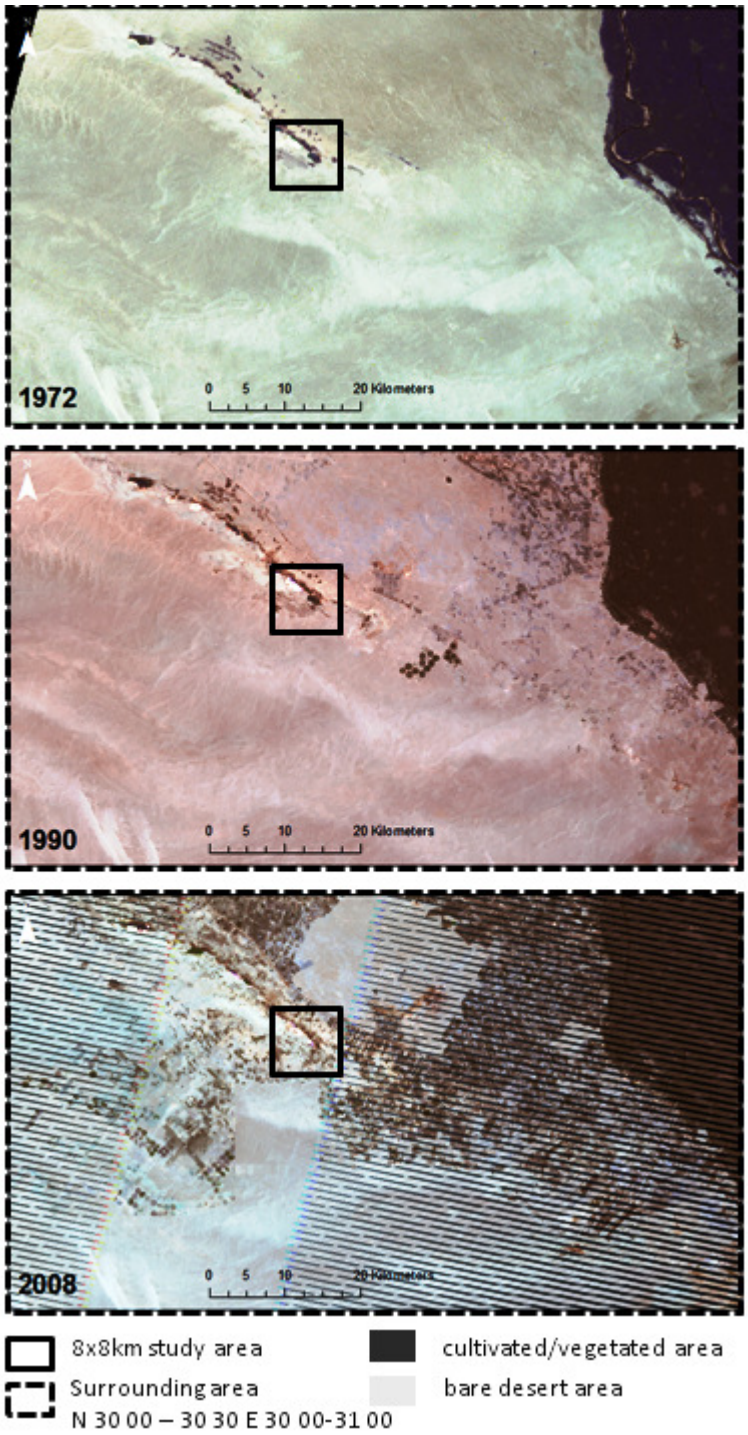
In the case of Siwa, the presence of drainage lakes with very low NDVI values disrupted the classification. It was therefore necessary to introduce a third class in this case to accommodate the water bodies. The same problem occurred with drainage lakes in the images taken in Wadi El Natroun until the late 1980s, after which time the level of water in the lakes is believed to have fallen. In later years at this location, the third class separated different levels of reflectance within the cultivated areas, whilst in the Nefzaoua region, the introduction of a third class differentiated between desert surfaces, rather than between the land and dry *Chott* (ephemeral saline lake) areas. Neither of these differentiations was pursued further in this study, since the main objective was simply to capture trends in the extent of the irrigated area.

The classification of the MSS images from all three areas required five classes to be used rather than two or three, in order for vegetated areas, bare land and water bodies to be effectively differentiated. The two- and three-class TM classifications and the five class MSS classification were not equivalent. This was confirmed through comparison of two images taken of the same location in the Nefzaoua region by the two sensors on 21 August 1987. The MSS dataset and analysis did not generate quantitative results that could be considered comparable to the subsequent TM and ETM+ datasets. In addition, at 60m resolution, the images generated were of relatively low quality. The MSS dataset therefore provided background information in the form of a qualitative representation of the extent of the cultivated areas during the 1970s. However this is not referred to in the quantitative comparisons presented in the following chapters .

A full time series of images from one of the selected study areas at Wadi El Natroun, Egypt is presented in **Figure 2.1.** showing the magnitude of the land cover changes observed in this most extreme case. This includes the MSS image from 1972, the TM image (1990) and ETM+ image (2008), showing the hatched effect on a large part of the image that is caused by the broken Scan Line Corrector. The 8x8km study area is unaffected by this effect.

In addition to the visual inspection of the accuracy of the images, comparison was made to the extent of the cultivated area, as recorded in available agricultural statistics. However, through this comparison it was concluded that the agricultural statistics did not capture all cultivated areas. Overall, remote sensing analysis is considered more reliable than the available agricultural records. In light of these issues, no statistical evaluation of the accuracy of the image classifications was made. While acknowledging that questions regarding the degree of accuracy in the classification must remain, the image classification was adopted as the best available consistent measure of temporal trends in cultivated landcover.

**Figure 2.1: Time series of Images from Wadi El Natroun**




Change detection using ERDAS Imagine™ was used to pinpoint areas where vegetation had been gained and lost over the years in each study area, and where increases or decreases had taken place in the extent of the lakes. The change detection was

performed between successive Landsat 5 TM images from each location 1987-2003, and also between the series of Landsat 7 ETM+ images 1999-2009.

Overall trends in the extent of the vegetated area were identified based on the results of the change detection, taking into account the vegetation types. Based on the findings of the field survey interviews, it was concluded that the area of salt-marsh and small farms and gardens had remained more or less constant over the study period, and therefore, subtracting these areas provided an estimation of the change in the extent of the large farms in the area. This method has been previously used in this vicinity for estimation of the extent of expansion of the large farms (Bakr et al. 2010).

Appendix 1 contains maps of the study areas as they were in 1954 before the expansion of the agricultural areas. Other mapping resources used to generate, compare and review maps of the study areas included internal administrative subdivisions of the two case study countries, obtained from a geographic database of global administrative areas (boundaries) GADM, (http://www.gadm.org for details) and a map of the extent of the Sahara in 2005, from the GlobCover dataset, produced by the European Space Agency and Partners. A range of mapping materials were consulted for this purpose at the University of Oxford Map Room and the Royal Geographical Society of London. These are not reproduced in this thesis.

## 2.3 Field survey design and implementation

Field investigations provided an essential component to the study of environmental changes, enabling first-hand observation and discussion with cultivators and their families. Four intensive two week field study periods were spent in the Nefzaoua in the spring and autumn of both 2008 and 2009. The remainder of the academic year 2008-9 was spent in residence in Egypt, enabling continuous field observation to be interspersed with the archive work and analysis. Additional visits to the study area in Egypt continued into 2010. The field investigations generated information directly covering this period, and also indirectly covering a period of around a decade that could be recollected by those who were interviewed. This information provided an essential counterpoint to the secondary time series data described in the previous section.

In line with the overall study design, social and environmental research methods were combined (after Stocking and Murnaghan 2001). The techniques used during the field investigations included a survey questionnaire, participatory environmental sampling and ethnographic observation. The design of the survey activities was informed by generic guidance on household survey design (Grosh and Munoz 1996, Whittington 2000), and surveys of environmental change developed in other regions .

Locally established precedents in the use of participatory research techniques were followed (Sghaier 2000, Ahmed et al. 2002, El Bastawisy 2006, Salem 2008a). In the

most remote area of Siwa, a greater degree of sensitivity in the use of social research methods was found necessary. In this case, the survey questionnaire was applied much more loosely, providing general insights to chapters 3 and 6, but no quantitative findings or dedicated case study chapter.

The implementation of the field investigations was carried out through hosting arrangements with research institutions that were active in the study areas in each country. These were the Institut des Regions Arides in Tunisia, and the University of Alexandria in Egypt. This was necessary in order to obtain permission to carry out the research, and entailed a process of discussion of the research objectives and methods with the host institution. Following these discussions, further contact and discussions were initiated with other associated national institutions engaged in environmental management and research. A non-exhaustive listing of the numerous institutions that provided inputs to the investigation is included in the acknowledgements section of the thesis.

Since the investigation was conceived as a comparative study, field investigations followed a uniform approach across the two regions, wherever possible. However, in each case, different constraints and opportunities were encountered. For example, the institutional arrangements in Tunisia favoured a rapid approach to data collection, in order to minimize the burden placed on the host institution, which was a national research institute with the capacity to implement rapid secondary and field data collection. On the other hand, in Egypt, the host institution was a University. The logistical arrangements for the field study took more time to put in place in this case.

However, it was possible to increase the geographical extent of the investigation and the time spent in the collection of observations, enabling two locations to be included, and a greater degree of local interaction.

The design of the survey in each location included an initial series of interviews with local scientists, decision makers and cultivators. These offered opportunities for wide-ranging discussions of the research topic and survey design. These conversations identified a range of additional potential sources of bias in the survey, and helped to reshape the questions.

### *2.3.1 Design of survey sampling framework and connection to environmental datasets*

The sampling frameworks reflected the available profile of degradation ascertained through the initial literature review, collection of locally archived data, and consultation of local decision-makers. Relevant institutional arrangements were also identified through this process and built into the sample frame. The selected study areas were distributed across each region, ranging in aridity of environmental conditions, as described in section 1.2, and in degrees of remoteness from the regional centres and markets. Less remote oases in both cases were less then 10km from the regional capitals, while more remote oases were over 70km away in the South of the Nefzaoua region, and the oasis of Siwa was over 200km away from the nearest governorate capital at Matrouh in the Western Desert (see **Figure 1.1**).

Institutional arrangements for land and water management varied amongst the study areas, and were reflected in the sampling frames applied. In Nefzaoua, six collective water user associations were surveyed. In Siwa, 14 *Hattiyat*[5] were explored and in Wadi El Natroun the survey focused on a single village. Further descriptions of the field sampling in each location are provided in chapters 3, 4, and 5.

The sample of cultivators (see **Table 2.1**) was structured in relation to the available profile of land-holdings within each system. In the Nefzaoua case, effective lists of cultivators and long term datasets on environmental conditions in the public oases were available, but this was not the case in the Western Desert of Egypt. In Siwa available datasets on the collectively managed systems were out of date and inaccessible, and in Beni Salama, where no collectively managed systems existed on a comparable scale, no lists of cultivators or public monitoring of environmental conditions associated with their activities existed at all. In this case, a cultivation typology was developed through field observation and local consultation to guide the survey sampling and analysis.

[5] local name for collective irrigated area

**Table 2.1: Characteristics of Surveyed Cultivators**

| | Nefzaoua | | Western Desert | |
|---|---|---|---|---|
| | **North Kebili** | **South Douz and El Faouar** | **South west (Siwa)** | **North east (Wadi El Natroun)** |
| **Number of cultivators interviewed** | 28 | 32 | 26 | 34 |
| **Max land-holding (ha)** | 5.37 | 1.63 | 3.36 | 7.14 |
| **Min land-holding (ha)** | 0.01 | 0.01 | 0.25 | 0.42 |
| **Mean land-holding (ha)** | 0.35 | 0.20 | 0.82 | 3.00 |

The field investigations were, to a large degree, guided by the cultivators, particularly those who were senior, holding positions of responsibility in the water user associations, agricultural development services, or agricultural research centres, through which the investigation was guided. Nevertheless, numerous young cultivators were also interviewed. Often, they had only recently begun farming, and were learning through experimentation, growing crops that previous generations had not known, and introducing different technologies, such as drip irrigation. Older and more experienced smallscale cultivators also described an ongoing process of continual experimentation, through which they tried new varieties, and techniques for applying water, observing how they performed.

### *2.3.2 Questionnaire design*

A survey questionnaire was developed in Beni Salama, Egypt, and subsequently adapted for use in the other study areas (see appendix 4-5). The questions aimed to capture the effects of increasing groundwater scarcity and salinization on the cultivators, and their options and practices to deal with these environmental changes. The questionnaire was structured in three main sections:

(I) farming system characteristics, including e.g. use of fertilizers and labour investments in irrigated/non-irrigated fields

(II) state and trends in groundwater conditions

(III) household livelihoods

Questions, presented in a bi-lingual English and Arabic format were designed, reviewed and reformulated through in-depth interviews with smallscale cultivators and farm workers in Wadi El Natroun. The multi-lingual format made the questionnaire accessible to supervisors, institutional hosts and local people. The survey was adapted for use in Southern Tunisia in consultation with local researchers and decision-makers, and pilot tested in one part of the study area before implementation. The principal differences between the questionnaires used in the different study areas concerned the additional translation into French for the Tunisian questionnaire, adjustment of the listing of crops to match local cultivation patterns, and rephrasing of questions concerning water use to reflect collective rather than private water management systems.

### *2.3.3 Implementation*

The administration of the questionnaire was undertaken through interviews requiring around 15 minutes with each cultivator. However, in many cases, particularly in the Western Desert of Egypt, this was followed by a longer, less structured discussion. In this case, problems with the identification of effective sampling frames led to the lengthening of the survey implementation in Wadi El Natroun and replacement of much of the survey questionnaire with less structured interview techniques in Siwa. These continued intermittently throughout the research period, 2008-10. In Nefzaoua, the survey was implemented in cooperation with the local agricultural development service. This enabled use of vehicles and drivers to survey cultivators from six water user associations located on different sides of the region, but imposed a more rapid timeframe, which constrained interaction with the cultivators interviewed. Some additional questions were introduced through a number of less formal interviews with cultivators who were willing to provide further information.

In both cases, interviews were often carried out in cultivators` fields. This provided an opportunity for additional observations and insights to be gained. During the survey implementation, residence in the village of Beni Salama also enabled further informal observations to be gathered, during the course of daily life. These observations informed the analysis of the survey data, and guided the ongoing compilation of supporting background information on themes that emerged from the analysis.

The implementation of the questionnaire offered an opportunity for a range of other observations to be collected, particularly in the Egyptian case, where the

implementation period was longer, and more notable gaps had been encountered in the availability of published environmental datasets.

In this case, the hosting arrangements for the research specifically ruled out the option of collecting field data through sampling activities. This constraint was partially overcome by working with local researchers, who provided their own field sampling results. Without taking any samples, some simple analyses of EC in groundwater were conducted in the field, using a handheld conductivity meter. On occasion, cultivators interviewed asked why, if the study was addressing environmental conditions, it did not include environmental measurements. Some of them proceeded to provide samples of water from their own wells, unrequested. In these cases, EC was measured in a similar manner to the *in situ* analyses. Original environmental data collected during the field investigations were compared to the collected secondary datasets. This was helpful in order to give an insight regarding current water quality conditions and constraints to cultivation. The location of analyses was entered rapidly into Google Earth™ and compared to other geographical information.

At the end of each day, questionnaire responses were checked and entered into an Excel database. Coordinates of the sampled locations were entered to Google Earth™. On completion of the survey period in each location a report on the survey results was prepared for discussion with institutional hosts and supervisors. Supplementary data collection and analyses were designed to address issues emerging from the survey implementation and preliminary analysis of results.

### *2.3.4 Factors affecting the reliability of questionnaire survey data*

It is important to acknowledge that the data on farming system characteristics, state and trends in groundwater conditions and household livelihoods based on the respondents` knowledge and perceptions are subject to the various forms of bias that are widely recognized to affect social surveys more generally. These may include strategic bias (false reporting in expectation of a reward), politeness bias (anticipating what the interviewer wishes to hear) and recall bias (accuracy is affected by elapsed time or sequence of events) (Iarossi 2006).

In Southern Tunisia, local officials warned of possible effects of strategic bias on the reporting of increases in water scarcity and salinity that might be due to expectations that the local authorities would respond to the survey findings by providing more wells or other social programs for income support. The same effect was not considered likely in Egypt, where there was no expectation of such interventions from the local authorities. In both cases, care was taken through the presentation of the survey and its objectives to avoid such expectations. Nevertheless, in the Tunisian case, the availability of datasets on environmental conditions generated by officials and independent scientists were helpful for cross-checking.

Politeness bias may well have influenced the survey results regarding the occurrence of environmental changes. This problem has been identified in numerous surveys focusing on changes in climate, where cultivators have been observed to claim that the climate is getting hotter and drier if they anticipate that this is what the interviewer wishes to hear (Bandyopadhyay et al. 2011). Repeating and reframing of

questions during the pilot testing of the survey in Egypt revealed the risk of this effect, and the importance of careful presentation of the questions so as not to invite it. Nevertheless, potential for bias due to the politeness of cultivators cannot be ruled out.

Sources of bias that became apparent in the survey results included commonly identified recall errors, referred to as telescoping, heaping, and recall decay (see Beegle, Carletto and Himelein 2011). These affected different parts of the survey, depending on the topic, the framing of the question and the variation in time periods for recollection that were required for different questions. Telescoping refers to inaccurately identifying the date of events – eg digging of a well or observation of a change in environmental conditions, either forward or backward into the recall reference period.

The recall period for environmental changes in our survey was much longer than the one-year period used in many agricultural surveys (Beegle et al. 2011). The time periods over which cultivators could recall environmental changes conformed to expectations in the literature, ie a 10-year period for changes in farming systems (eg tree stock) (McCarthy 2011) and a period of 0-5 years for changes in water scarcity. It has been argued that longer-term perceptions of climate trends (e.g. over 20 years) are likely to be unreliable, except for the timing of extreme events (Bandyopadhyay et al. 2011). Problems concerning cultivators` ability to recall productivity levels achieved and practices used have been observed in previous surveys in the study region (Meddeb 2003).

When respondents are asked to recall larger amounts of information, from a longer recall period, they will shift from summing the total of individual remembered events to estimating the overall total, unless the information is of some particular interest (saliency). This effect is known as heaping (Beegle et al. 2011). A range of techniques can be used to overcome recall problems, eg breaking down the volume of items to be recalled into manageable component parts. The 15 minute duration of the survey interviews in Nefzaoua was too short to devote much time to this, but in Beni Salama, this technique was used to encourage cultivators to recall the volumes of irrigation water they applied. No attempt was made to use this technique to improve accuracy in reporting of income in either case.

### 2.4 Combined analysis of primary and secondary datasets

In order to analyse the significance of environmental changes for the populations living with them, environmental time series data and information collected through the field investigation and compiled datasets, as described in the two previous sections, were compared to other available socio-economic datasets.

Regional profiles and data presented in the population census concerning occupational activities provided an important point of reference in both countries (CAPMAS 1986, 1996, 2006, INS 2006). Insights into the relationship between the surveyed smallholders and the larger population were also enabled through these datasets.

Comparison to the agricultural data provided further insights concerning landholdings, cropping patterns and productivity levels.

### *2.4.1 Connecting environmental change to changing productivity and income*

Changing farm budgets under different environmental conditions were compared using data presented in previous studies, and comparison to the findings from the survey. This enabled the tracking of effects of the environmental changes over time on the cultivators' income and other activities. In the Tunisian case, the availability of a regional scale farm budget investigation from the early 1990s (JICA 1996) enabled a temporal comparison to be made at the regional level.

Changing cultivation models as well as changing environmental conditions introduced complexity to this analysis, due to cultivators' adaptations to living with environmental change. In both regions, variations amongst farm budget models could be identified (Belloumi and Matoussi 2004, 2006, Yehia 2004). In the Tunisian case, the survey and analysis focused on the smallholders. However, the investigation in Egypt examined the differentiation between large and small cultivators, and explored the different patterns for living with environmental change that were adopted by these groups. In both cases, the analysis was informed by discussions with cultivators concerning the effects of environmental changes, and their response options.

In order to support the analysis of changes that had affected the farm budgets, and to place them in context, additional economic information was needed to trace the

evolution of export prices. These were obtained with analysis of the datasets obtained from FAOSTAT and COMTRADE. Exchange rates and inflation were included in the analysis using archived datasets available from the IFS online database maintained by the International Monetary Fund (IMF). Regional productivity and export statistics provided further insights concerning the national economic significance of productive activities.

Cultivators` comments concerning pricing at different points in the marketing chain were followed up through use of previous studies and rapid checks on local and international markets. Different attitudes to capital investments, risk and discount rates observed during the survey were analyzed in relation to the farm budget models. Some gaps in these models that were identified could not be addressed during the investigation. For example, it was not possible to obtain data on real estate prices, and to consider the effect of the changing value of land, even though this was identified as a relevant factor in cultivator decision-making.

### *2.4.2 Calculating the costs of environmental degradation*

Changing environmental conditions had an effect on input prices, and therefore an effect on the farm budgets. Trends in water pricing were analyzed in the Tunisian case, where compiled time series data were available. Falling water tables resulted in rising volumes of fuel required for pumping. These changes could be observed both through the environmental data collected on water levels and artesian pressure, and also on the depths of wells and hours of pumping.

The Tunisian water user associations (known as GDAs) recorded the costs for energy that were transferred to their members as a component of their user fees. The increases in these costs were compared to the rising costs of fuel over the same period. In the Egyptian case, such records were not identified. However, increases in costs for agricultural production were described by smallholders. These were associated both with falling groundwater tables and increasing fuel costs for pumping. In this case, an economic modelling approach (after Croitoru and Sarraf 2010, Bolt, Ruta and Sarraf 2005) was used in order to estimate the cost of groundwater degradation to smallholder farmers living in the village of Beni Salama.

The calculation was based on the combined costs for digging replacement wells and the marginal increase in costs for pumping of irrigation water as the groundwater table lowers (column 15). The time period considered in the model (column 1) was similar to that of the Tunisian dataset, covering the period 1994-2005. The total area of smallscale cultivation (hectares) (column 2) was calculated based on the landcover map and estimates provided during the survey. It was assumed that the area concerned had remained constant since the 1990s. Although wells and plots were abandoned in some parts of the village, new ones had been established elsewhere.

Similarly, the total number of wells on small farms and gardens (column 3) was assumed to remain constant in the area of smallscale cultivation, with replacement wells replacing those that fail, but no overall increase in the number of wells. This assumption is consistent with the findings of the present investigation, in which

neither an overall increase in smallholder cultivation, nor a definitive reduction could be identified, although individual wells and farms were continually abandoned, and others created.

### *2.4.3 Cost of replacement wells*

The calculation for the cost of replacement wells included the following elements:

-number of wells replaced per year (#/yr)

-average depth of replacement wells in meters (m)

-local price of drilling in Egyptian Pounds (LE/m)

-exchange rate for US dollar (LE/US$)

-price of drilling for replacement wells (US$/m)

-annual total cost for replacement wells (US$/yr)

*Number of replacement wells per year (column 4):* During the survey period, three new wells being dug were identified. Based on this observation, it was estimated that 10% of all wells might be replaced on an annual basis. This percentage is assumed to remain constant throughout the study period.

*-Average depth of replacement wells in meters (column 5):* The increasing depth of the new wells is calculated, based on the progressive lowering of the groundwater table. As described previously, this was observed to be occurring at a rate of 1m per year up until 2005 (Ibrahim 2005). During the field investigations, smallholders reported observations of the decrease, depending on their recollections and opinions. These

observations varied above and below 1m per year. Changes in water levels observed from measurements reported in 1997 and 2006-7 in the larger area around the village between have since been cited by other researchers (Masoud and Atwia 2011). The reported decline was 15 and 2m for the northwestern and southeastern zones, respectively. This result contrasts with local accounts and previous work, which describe a more rapid fall in the water table occurring in the South. The increase in depth of wells is included in the model at 1m per year, taking into account the likelihood that cultivators might dig slightly deeper than the present level of the water table, in order to ensure that the well did not fail too quickly.

*Local price of drilling (column 6):* smallholders interviewed in the village reported the cost of drilling new wells in terms of cost per metre of depth, plus other costs to be paid to the drilling company, including labour and pipes. A specific estimate for the cost of drilling per metre of depth was provided as LE 50/m. The price was considered to have risen steadily over the past decade. The price rise is therefore modelled at LE 1 per year.

*US$ exchange rate (column 7):* The LE has weakened over the study period. Exchange rates were calculated based on archived statistics obtained from the IMF.

*Price of drilling for replacement wells US$/m (column 8):* The price of drilling in US$ was calculated by converting the local price of drilling, using the US$ exchange rate. Although the cost of drilling expressed in local currency rose, due to the exchange rate, the cost in US$ has reduced over the study period, according to this calculation. It

would be desirable to check on this price history with drilling companies in the study area, however, this was not possible during the field research period.

*Cost for replacement wells US$/year/well (column 9):* Based on local information, the total annual cost of replacement wells includes the cost of drilling, plus other costs, including pipes and labour. A rough estimate for the cost of the well to the smallholder cultivator during the study period was provided locally at LE 5,000-6,000. It was therefore estimated that the total cost for drilling a well was around four times the drilling cost, as calculated in column 8.

*Total cost for replacement wells US$/year (column 10):* The cost per well is multiplied by the number of replacement wells.

### *2.4.4 Marginal cost of increased pumping*

The marginal cost for increased pumping needed, due to the falling groundwater table (column 16) was calculated according to the cost of the additional fuel requirement for pumping the same amount of groundwater from progressively increasing depths. Irrigation water requirements are multiplied by the additional fuel requirement for pumping from greater depth, and by the cost of fuel. The following inputs were required to enable the calculation:

-annual rate of decline in the water table (m)

-total annual groundwater requirement in cubic metres ($m^3$)

-additional annual fuel requirement in litres (l)

-international price of diesel (US$/l)

*Annual rate of decline in the water table (m) (column 11):* Although the rate of decline of the water table has been estimated locally at 1m per year (Ibrahim 2005), this estimate was generated on large farms away from the centre of the depression, and was not supported by all of the accounts collected during the field survey. It is possible that continued drainage of water through the shallow aquifer from irrigation activity in the surrounding area could have attenuated the effect of the falling water table in and around the village. Therefore, a more conservative estimate of 0.5m per year for the actual rate at which the water table was lowering over the study period was adopted.

*Additional annual fuel requirement (l/$m^3$) (column 12):* for pumping one cubic meter of groundwater, the average fuel consumption is around 0.004 litres per meter of depth (Croitoru and Sarraf 2010). This requirement is calculated by multiplying the total water requirement (column 11), by the annual rate of decline in the groundwater table (column 10), and by 0.004. The additional fuel requirement is calculated in relation to the baseline year, of 1994. The amount is therefore cumulative from year to year.

*Total annual groundwater requirement ($m^3$) (column 13):* The requirement for groundwater to be used by the smallholder cultivators for irrigating their land was calculated by multiplying the cultivated area by the per hectare water requirement, as identified through the interviews with the smallholders. A value of 50$m^3$/day/ha was

used. In this model, the cultivated area and the water requirement are assumed to remain constant over the study period. This assumption reflects the information collected through smallholder interviews. Although changes in individual smallholders` use of water were identified through the field survey, particularly through introduction of alternative irrigation methods such as sprinklers (increasing water applications) and drip systems (reducing water application), it was not possible to identify any overall trend in the volumes of water being applied.

*Total additional annual fuel requirement for all wells (l) (column 14):* The additional cost of pumping per cubic metre is multiplied by the total annual water requirement.

*International price of diesel (US$/l) (column 15):* Archived information on the international price of diesel covering the study period has been compiled and published by the US Energy Information Administration[6].

*Total marginal cost of the additional pumping of groundwater* (column 16) is calculated by the additional volume of diesel needed for to pump from the additional depth, multiplied by the cost of the diesel fuel.

Total annual cost of groundwater degradation (column 17) is the sum of the cost of digging replacement wells, plus the additional pumping cost. The total cost of

[6] http://www.eia.gov/oog/info/wohdp/diesel.asp

groundwater degradation over the period 1994-2005 may then be calculated from the sum of the costs incurred each year.

If the calculation had been made in 1994, a discount rate would have been applied to the estimation of the future costs of groundwater degradation. However, since the calculation is made retrospectively, no discount cost is used in this calculation. It is also important to acknowledge that the calculation of the costs of degradation focusing only on costs incurred in terms of replacement wells and additional costs for pumping does not take into account a range of other direct and indirect costs associated with reduced water availability and quality and reduced productivity of the land.

**Table 2.2: Model of Groundwater Degradation Costs to Smallholders in the Village of Beni Salama, 1994-2009**

| Study area | | | Annual cost of replacement wells | | | | | | | Annual increase in pumping costs | | | | | | Cost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | **10** | 11 | 12 | 13 | 14 | 15 | **16** | **17** |
| **Year** | area (ha) | total # wells | # new wells / yr | av depth (m) | price of drilling (LE/m) | US$ exch. Rate | price of drilling (US$/m) | total cost per well (US$) | **sub-total (US$/yr)** | fall in water table (m) | incr. fuel need (l) per $m^3$ | total water needs $m^3$/yr | incr. fuel need (l) | price of diesel (US$/l) | **subtotal (US$/yr)** | **TOTAL: Cost of Degradation (US$/yr)** |
| **1994** | 50 | 35 | 3.5 | 19 | 39 | 3.391 | 12 | 874 | **3,059** | 0 | 0 | 912500 | 0 | 0.29 | 0 | **3,059** |
| **1995** | 50 | 35 | 3.5 | 20 | 40 | 3.39 | 12 | 944 | **3,304** | 0.5 | 0.002 | 912500 | 1825 | 0.30 | 548 | **3,851** |
| **1996** | 50 | 35 | 3.5 | 21 | 41 | 3.388 | 12 | 1017 | **3,558** | 1 | 0.004 | 912500 | 3650 | 0.33 | 1,205 | **4,762** |
| **1997** | 50 | 35 | 3.5 | 22 | 42 | 3.388 | 12 | 1091 | **3,818** | 1.5 | 0.006 | 912500 | 5475 | 0.32 | 1,752 | **5,570** |
| **1998** | 50 | 35 | 3.5 | 23 | 43 | 3.388 | 13 | 1168 | **4,087** | 2 | 0.008 | 912500 | 7300 | 0.28 | 2,044 | **6,131** |
| **1999** | 50 | 35 | 3.5 | 24 | 44 | 3.405 | 13 | 1241 | **4,342** | 2.5 | 0.01 | 912500 | 9125 | 0.30 | 2,738 | **7,079** |
| **2000** | 50 | 35 | 3.5 | 25 | 45 | 3.69 | 12 | 1220 | **4,268** | 3 | 0.012 | 912500 | 10950 | 0.40 | 4,380 | **8,648** |
| **2001** | 50 | 35 | 3.5 | 26 | 46 | 4.49 | 10 | 1065 | **3,729** | 3.5 | 0.014 | 912500 | 12775 | 0.37 | 4,727 | **8,456** |
| **2002** | 50 | 35 | 3.5 | 27 | 47 | 4.5 | 10 | 1128 | **3,948** | 4 | 0.016 | 912500 | 14600 | 0.35 | 5,110 | **9,058** |
| **2003** | 50 | 35 | 3.5 | 28 | 48 | 6.153 | 8 | 874 | **3,058** | 4.5 | 0.018 | 912500 | 16425 | 0.40 | 6,570 | **9,628** |
| **2004** | 50 | 35 | 3.5 | 29 | 49 | 6.131 | 8 | 927 | **3,245** | 5 | 0.02 | 912500 | 18250 | 0.48 | 8,760 | **12,005** |
| **2005** | 50 | 35 | 3.5 | 30 | 50 | 5.732 | 9 | 1047 | **3,664** | 5.5 | 0.022 | 912500 | 20075 | 0.64 | 12,848 | **16,512** |
| **2006** | 50 | 35 | 3.5 | 31 | 51 | 5.704 | 9 | 1109 | **3,881** | 6 | 0.024 | 912500 | 21900 | 0.72 | 15,711 | **19,591** |
| **2007** | 50 | 35 | 3.5 | 32 | 52 | 5.504 | 9 | 1209 | **4,233** | 6.5 | 0.026 | 912500 | 23725 | 0.77 | 18,155 | **22,388** |
| **2008** | 50 | 35 | 3.5 | 33 | 53 | 5.504 | 10 | 1271 | **4,449** | 7 | 0.028 | 912500 | 25550 | 1.00 | 25,494 | **29,943** |
| **2009** | 50 | 35 | 3.5 | 34 | 54 | 5.475 | 10 | 1341 | **4,694** | 7.5 | 0.03 | 912500 | 27375 | 0.66 | 17,938 | **22,632** |
| | | | | | | | | **subtotal** | **61,336** | | | | | **subtotal** | **127,977** | **189,314** |

# CHAPTER 3: CHANGING LAND AND WATER SYSTEMS

## 3.1 Preface and abstract

***Preface***

This chapter presents a cross-cutting overview of the conceptual orientation and methods used to investigate environmental changes including desiccation and salinization effects occurring in the study areas in southern Tunisia and the Western Desert of Egypt. The Journal of Arid Environments, to which this chapter has been submitted, publishes original scientific and technical research articles on physical, biological and anthropological aspects of arid, semi-arid, and desert environments. The chapter considers the introduction of multidisciplinary research approaches within the natural and environmental sciences for observation of environmental change in the arid environment.

Methodological issues in the assessment of environmental changes affecting the land surface in arid environments are a particularly popular current theme amongst scientists working on the arid environment (see Verón et al. 2006, featuring amongst both the top ten most cited articles and most frequently downloaded of all articles published in this journal over the past five years). The perennial challenge of salinization problems in the cultivation of the irrigated environment, has been a longstanding preoccupation (Brookes 1989, Thomas and Middleton 1993, Kassas 1995). This chapter presents a fresh look at this issue, in light of emerging conceptual and methodological perspectives in global change research.

Previous articles published in this journal have showcased the state of the art in techniques for landcover change observation in the arid environment (Masoud and Koike 2006, Wessels et al. 2007). This article engages a discussion of the significance of the availability of these techniques to be used in conjunction with data from other sources to support interdisciplinary investigation of environmental change. Simplified methods intended to be accessible to other students and researchers are presented, applied and discussed. A requisite degree of scientific rigour in their presentation and application to the case studies has been ensured through the journal peer review process. The chapter connects these methods to the interdisciplinary conceptual discussion. The approach to the observation of environmental change that is developed in this chapter is then pursued further in the following case study chapters.

***Title of journal submission***

Monitoring landcover change and environmental degradation in the saline arid endorheic basins of the northern Sahara

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***Abstract***

Salinization caused by irrigation mismanagement is a major cause of desertification. Monitoring of land degradation caused by salinization and other processes has been subject to international scientific debates ever since the United Nations Convention for Combating Desertification (UNCCD) engaged global decision-makers to address these threats collectively. This paper discusses the experience of monitoring land and water degradation in the salinity-prone irrigated arid environments of the northern Sahara in light of current international scientific developments affecting both conceptual and methodological approaches.

The paper draws on the results of a multidisciplinary analysis of irrigation and salinization. The integrated methods used included remote sensing, use of national research archives, interviews with decision-makers and direct surveys of cultivators. Revised assessments of the extent and ecological processes of salinization emerge from the analysis. As irrigated areas expand globally, the new conceptual and methodological techniques in dryland development science have the potential to enable global efforts to monitor degradation effects caused by desiccation, salinity and human responses.

keywords: *salinization; desertification; oases; dryland development science*

## 3.2 Introductory sections

### *3.2.1 Introduction*

The extent of irrigated agriculture in arid environments is growing globally (Kijne 2003, WWAP 2009). The main drivers are increasing demand for agricultural production, growing climatic threats to rainfed production, and the spread of groundwater extraction technologies. Salinization caused by irrigation mismanagement is well-recognized as a major cause of desertification (Worthington 1977, UNCCD 1994). Salinization is a process whereby the proportion of salt content in soil or water is increased. This is detrimental to agricultural productivity because it disrupts plant water-use patterns, and leads to increased requirements for water and labour to leach or replace salt-affected soils (Kijne et al 2003, Ghassemi et al 1995). Irrigated systems are not usually adaptable to increasing water scarcity, which can trigger deepening cycles of overexploitation and degradation (Puigdefábregas and Mendizabal 1998). A generic desertification pathway through salinization has been conceptualized as follows: `*Traditional oases > large scale irrigation > booming non agrarian uses > water degradation > vegetation degradation > sandification*`(Geist 2005).

During the 1980s, the loss of agricultural land through waterlogging, salinization and alkalinization was estimated at 1.5 million hectares annually (e.g. in Brundtland 1987). Had this been correct, and had the trend continued, 1,577,880 hectares would have been lost each year over the past 15 years, amounting to an area of 236,682 square kilometres, an area close to the size of the British Isles (244,820 square kilometres). More recent global and regional assessments of landcover change do not attempt to

quantify effects associated with the expansion of irrigation and salinization (e.g. Helldén and Tottrup 2008, Bai et al. 2008). In response to international pressure to improve the monitoring of global trends in land degradation and desertification, the international scientific community has searched for new conceptual and methodological approaches to better inform decision-makers (Reynolds 2007, Stafford Smith and Reynolds 2002, Vogt et al. 2011).

This paper takes a fresh look at the salinization-desertification challenge in light of both conceptual and methodological developments that have been introduced for monitoring and assessment of salinization as a land degradation process over the past twenty years. The question is approached through two case studies in the northern Sahara, a region where salinization has been recognized as a perennial cause of land degradation (Kassas 1995). The paper investigates the following questions:

-what insights have been enabled through the increased availability of materials and methods for land cover change detection?

-how do these insights connect to other ongoing national and scientific efforts to monitor, model and assess land salinization and degradation trends in the two selected cases?

-what conclusions can be drawn from these cases for international scientific efforts to contribute to the monitoring of land degradation in arid regions under threat from salinization?

### *3.2.2. The new conceptual approach to dryland development science*

Over recent decades, research and practice in dryland development science have converged into a set of general lessons concerning the condition and dynamics of human environment systems (Reynolds 2007, UNCCD 2009). These are conceived to guide more effective monitoring and assessment of land degradation, including salinization:

> *(a) Both researchers and practitioners need to adopt an integrated approach; ecological and social issues are fundamentally interwoven, as are the options for livelihood support and ecological management;*
>
> *(b) There needs to be heightened awareness of slowly evolving conditions; short-term measures tend to be superficial and neither resolve persistent problems nor deal with continual change;*
>
> *(c) Nonlinear processes need to be recognized. Dryland systems are often not in equilibrium, have multiple thresholds, and thus often exhibit multiple ecological and social states;*
>
> *(d) Cross-scale interactions must be anticipated; problems and solutions at one scale influence, and are influenced by, those at other scales;*
>
> *(e) A much greater value must be placed on local environmental knowledge.*

This conceptual approach is helpful in highlighting the need to consider both temporal and spatial patterns of flux. It also enhances the range of social and ecological research tools through which these changes can be pursued. Points b) and c) reflect the prevalent view that scientific understanding of environmental change in drylands has

lagged behind science in more temperate areas because it took time to understand disequilibrium theories regarding long term change (Thomas and Middleton 1994). In light of this, recent scientific contributions have emphasized the importance of monitoring "internal controlling drivers", such as water availability, which are termed "fast" changing, and connecting them up to "slow" external drivers resulting from processes on a wider scale, such as landscape function, land use and climate change relating to persistent changes in ecosystem function (Gunderson and Holling 2002, Stafford Smith and Reynolds 2002). Salinization has been conceptualized as a slow change, resulting from fast increases in productivity achieved through irrigation (Verstraete 2009).

Salinization is observable through simple conventional methods for field sampling of SEC (Specific[7] Electric Conductivity) or Total Dissolved Solids (TDS) (Hem 1985)[8], or through remote observation of trends in vegetation cover. Thresholds for salinity effects on fruit yields of various crops (eg EC 4dSm (4000 $\mu S/cm^{-1}$) for *Phoenix dactylifera*, L. (date palm) have been published (FAO 2002). However, reflecting point c), above, the effects of salinity on plant productivity are not linear, and can interact with other stress factors (FAO 2002, Flowers and Colmer 2008).

Geist (2005) classifies increases of salt content in water from a given baseline as follows: (<25% = slight, 25-50% = moderate, 50-75 % strong and 75-100% extreme). The same classifications are applied for increases in a salinized area or vegetation

[7] In the case that the specific temperature is known
[8] This source refers to the non-linear relationship between these parameters

change. Extreme changes according to this classification can conceivably take place in the space of a year. Therefore, while salinization may be conceptualized as “slow“, the timeframe within which changes may be observed is not necessarily an obstacle to scientific measurement. Although time series of data over decades are desirable to determine processes and trends in salinization, a few years of consistent monitoring can sometimes be enough. This is fortunate, since once an area of land or a well is too saline to use, monitoring tends to cease.

In light of points a) and e), above, it has been argued for some time that land degradation should be understood differently by scientists (Reynolds 2007, Stafford Smith and Reynolds 2002, Vogt et al. 2011). Few physical processes are irreversible. This is true of salinization. Some of the most effective techniques for soil conservation and salt removal have been practiced for centuries (Rhoades et al 1992). Other innovations, such as hydroponics, are changing the fundamental requirements for soil and water for cultivation. Salts can be flushed away from soils, or desalinated out of water. Waterlogged areas can be pumped. Even salinized aquifers can be remediated through artificial recharge. This renders the available definitions of degradation in terms of biophysical irreversibility ever more socio-economic, bringing with them questions as to who might or might not pay the costs to reverse the degradation.

### *3.2.3. Description of study areas*

Climate change in North Africa over multi-millennial timescales has led to the region experiencing multiple episodes of conditions wetter than today, interspersed with dry phases. The surface water resources available in this region today are limited under

arid conditions, and thus groundwater resources, representing a legacy of groundwater recharge under wetter conditions during the late Quaternary, are a significant asset. The major regional aquifer systems are at depths of around 1000m (see **Figure 1.2**). In the North West Sandstone Aquifer System (NWSAS) beneath the Nefzaoua region, the deep Continental Intercalaire (CI) aquifer is overlain by the Complexe Terminal (CT). In the Western Desert, the Nubian Sandstone Aquifer System (NSAS) in the Upper Cretaceous is overlain by the Miocene Aquifer in the Post-Nubian Aquifer System (PNAS). The groundwater systems feed springs that emerge through geomorphological depressions in the desert landscapes, contributing to water in endorheic, or closed, basins around saline lakes and sebkhas. Local micro-climates are altered through the presence of water bodies and irrigation. These environments support *Phoenix dactylifera* L., other halophytic vegetation, and salt-tolerant crops.

Two study areas in the Northern Sahara have been included in this investigation: the Nefzaoua region in Southern Tunisia, and the North of the Western Desert of Egypt (see **Figure 1.1**). Each extends from a relatively developed and accessible area to a more remote and less developed area. In the Nefzaoua region, the North-South extent of the study area is 72km. The South is more arid, receiving an annual average close to 50mm of rainfall per year, compared to 100mm in the North. Since the area of the study region is approximately 3,456km$^2$, the average annual volume of rainfall is around 26 million cubic metres. However, a conservative estimate of the volume of groundwater used for irrigation each year from the 1990s would be somewhere around 350 million cubic metres, based on available national statistics. The Western Desert is even more arid and dependent on irrigation. At its North-Eastern edge, Wadi

El Natroun, is relatively close to the Nile Delta, and receives below 50mm of rainfall on average per year. Siwa, 600km to the South-West, is more remote and receives below 10mm on average per year. Farmers using traditional flood irrigation systems apply around 10mm of water *each time* they irrigate. In the summer, this may be several times per week. In both regions, daily mean temperatures vary between 10°C in the winter to 32°C in the summer, with the hottest temperatures in August.

Scientific investigations of the causes and processes of salinization have identified water-logging in the low-lying areas close to the *Chott* in the Nefzaoua region, and at Siwa in the Western Desert (Misak et al. 1997, Masoud and Koike 2006). In these diagnoses, the inefficiency of water use by farmers has often been blamed for causing land secondary salinization (Askri et al.2010, Gad and Abdel-Baki 2002, Marlet et al. 2009). Such diagnoses justify the installation of extensive drainage structures, energy-intensive pumping systems, and controversial proposals for water-transfer projects, threatening the surrounding desert habitats (Abo-Ragab 2008).

Where the salinity of groundwater has increased over time, inappropriate well-design has sometimes been blamed, leading to suggestions for the improved engineering of wells (Gaame 2005). On the other hand, regional salinization processes taking place across the aquifer systems due to falling water tables, upconing of saline under-layers or potential movement of fresh-salt interfaces, leading to saline intrusion, have also been suggested in both regions (see e.g. Pallas 1991, Zammouri et al. 2007). Close to the Nile Delta, salinization processes have been considered to justify the diversion of

water from the Nile in order to recharge depleted groundwater supplies (Attia et al. 2005).

### *3.2.4. Materials and methods*

#### *Monitoring Changes in Vegetation Cover and Productivity*

Analysis of satellite images using the Normalized Difference Vegetation Index (NDVI) (after Rouse et al. 1973, Tucker 1979) has been demonstrated as a globally applicable measure for discriminating between vegetated and non-vegetated landcovers. In arid environments, where rainfed vegetation is sparse, irrigated areas show a much higher level of vegetation cover, and therefore a higher NDVI signal. This method can therefore be used for differentiating between irrigated and non-irrigated areas (after White 2007). Recognized limitations include failure to differentiate between barren land, temporarily fallow, or immature crops that produce sparse vegetation cover (Huete 1987). Also, where vegetation is affected by salinization, a reduction of NDVI is observed (Alhammadi and Glenn 2008).

285 TM images of the selected study areas at 30m resolution were identified in the online database of the US Geological Survey (USGS), covering the period 1984-2003, in the Western Desert, and continuing to the present for Southern Tunisia. Also, 435 ETM+ images at 30m resolution were identified, covering the period 1999-present for both regions (although from 2003-present a fault in the scan line corrector obscures some of the pixels). Image sets taken in comparable months were selected for each study area in order to minimize the possible effects of seasonal variations (**Table 3.1**).

In the case of Nefzaoua, which receives higher winter rainfall than the Western Desert, images taken during the months of July and August were selected.

**Table 3.1: Selected USGS Landsat Scenes of Study Areas**

| | | TM | ETM+ |
|---|---|---|---|
| | **Landsat** | 5 | 7 |
| | **WRS** | 2 | 2 |
| | **Resolution (m)** | 30 | 30 |
| **Nefzaoua** | **Path Number** | 191 | 191 |
| | **Row Number** | 37 | 37 |
| | **Dates** | 11 July, 1984<br>21 August,1987<br>24 August, 2003<br>04 August, 2010 | |
| **Siwa** | **Path Number** | 180 | 180 |
| | **Row Number** | 40 | 40 |
| | **Dates** | 11 October, 1987<br>23 October, 2003 | 7 November, 2000<br>15 October, 2009 |
| **El Natroun** | **Path Number** | 177 | 177 |
| | **Row Number** | 39 | 39 |
| | **Dates** | 26 August, 1984<br>18 July, 1987<br>30 July, 2003<br>16 September, 2003 | 12 August, 1999<br>24 September, 2009 |

An additional global dataset was obtained from the Global Inventory Modelling and Mapping Studies (GIMMS) through the University of Maryland Global Land Cover Facility. GIMMS contains NDVI data for 1982 – 2006 at 8km resolution. This dataset is not atmospherically corrected, and is more coarse than the Landsat data, but provides a higher (bimonthly) frequency. The dataset is derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17. The dataset has been corrected for calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change. Use of high frequency data such as the GIMMs dataset enables

smoothing of seasonal effects and anomalies, and has therefore been used for recent land degradation and desertification assessments (e.g. Helldén and Tottrup 2008).

Simple rectangular areas of 48x72km were identified in each Landsat image, and NDVI was analyzed in each pixel. Using ERDAS Imagine$^{TM}$ software, the NDVI values were classified through an unsupervised iterative clustering process into two clusters of highest NDVI, representing vegetated areas, and lowest NDVI, representing non-vegetated areas.

The results were inspected visually to determine whether the areas identified were consistent with other available information from each time period on the location of lakes and cultivated areas, including agricultural development statistics, previous scientific and technical accounts and higher resolution images available in Google Earth. A comparison of results obtained from the classification of images taken in the same place and time period by two different sensors (TM and ETM) found that results for the study area as a whole were very similar (less than 10% difference), although variations were observed between pixels (e.g.: pixel E of study area in **Table 3.2**).

**Table 3.2: Comparison of % Classes in WRS-2 Path 180, Row 4 Landsat 5 TM (23/10/ 2003) and Landsat 7 ETM+ (16/11/2003)**

| | 48x72km Area | | 8x8km Pixel W of study area | | 8x8km Pixel E of study area | |
|---|---|---|---|---|---|---|
| | **Landsat 7 ETM+** | **Landsat 5 TM** | **Landsat 7 ETM+** | **Landsat 5 TM** | **Landsat 7 ETM+** | **Landsat 5 TM** |
| **Class 3 (Cultivated Area)** | 1.65 | 1.77 | 15.50 | 16.69 | 18.65 | 18.91 |
| **Class 1 (Lake)** | 1.91 | 1.65 | 26.94 | 25.80 | 18.65 | 12.76 |
| **Class 2 (Other)** | 96.44 | 96.58 | 57.56 | 57.51 | 62.70 | 68.33 |

In the case of Siwa, the presence of drainage lakes with very low NDVI values disrupted the classification. It was therefore necessary to introduce a third class in this case to accommodate the water bodies.

Change detection was performed between successive Landsat 5 TM images from each location, and also between the series of Landsat 7 ETM+ images 1999-2009 in order to pinpoint areas where vegetation had been gained and lost. Using ERDAS Imagine™, changes (positive or negative) of 10% or more in the NDVI value were highlighted.

For the GIMMS AVHRR dataset, 27 pixels around the cultivated areas of the Nefzaoua, and on each side of the Western Desert at Siwa and Wadi El Natroun were selected for analysis. An annual average was taken from the 24 bi-monthly NDVI values assigned to each selected pixel for each year. These were then averaged across each area to obtain a single annual value for NDVI from each region. Within each region, several pixels were then selected for further analysis and plotted separately.

***Comparison of landcover changes to other datasets***

National archives containing data on rainfall, soil and water salinity were consulted, and available time-series datasets obtained. For the Nefzaoua region, published statistics on climate ranging over the period 1981-2006 from the Kebili, Douz and El Faouar meteorological stations were compiled. The spatial distribution of in TDS levels recorded from publicly monitored wells in the region (DGRE 2006) was compared to

the landcover change maps using ERDAS Imagine™. Temporal trends in the records of TDS (DGRE 1979-2006) at selected wells from each part of the region were plotted and compared using Exel.

Public statistics held at the Regional Agricultural Development Commission (CRDA) on the extent and productivity of cultivated areas in Nefzaoua over the period 1979-2004 were compiled and analyzed in the same manner. A questionnaire survey focusing on environmental conditions and changes affecting cultivators was carried out with cultivators who were using the land and water resources featured in the public datasets (see description in chapters 2 and 4 and questionnaire in appendix 5).

In the Western Desert of Egypt, all water-related datasets, including those for climatic data were difficult for researchers to access during the period when the archive visits were made (2008-10). Climatic data from the US National Oceanic and Atmospheric Administration (NOAA), 1958-present[9] were consulted. The archives of the Egyptian Desert Research Center and the MWRI confirmed that the national programme for monitoring groundwater quality had been established more recently than the Tunisian one.

Technicians of the Ministry of Water Resources and Irrigation (MWRI) were accompanied during field activities in Wadi El Natroun and Siwa, and available data from monitoring over the period 2009-10 were obtained with their assistance.

[9] http://gis.ncdc.noaa.gov/map/gsod/

Although these available datasets were too sparse and brief in duration to enable the identification of any spatial or temporal trends, additional well inventories available and accompanying chemical analyses have been published through a number of graduate theses (e.g. Gad 1999, Hossary 1999, Ibrahim 2005, Abd El-Rahman Aly 2007). These are otherwise not monitored continuously.

Where the available datasets were georeferenced, these were plotted using Google Earth. Where a series of readings had been taken from the same locations in successive years, these were resampled using a simple handheld conductivity meter. A series of semi-structured interviews were carried out with cultivators at these locations. A questionnaire survey was also implemented with cultivators to obtain information on environmental changes (see detailed descriptions in chapters 2 and 5 and questionnaire in appendix 4). Local farmers also provided some records of water quality analyses from their wells over additional recent years. The results were added to the geodatabase created in Google Earth, enabling spatial analysis and comparison between the different datasets.

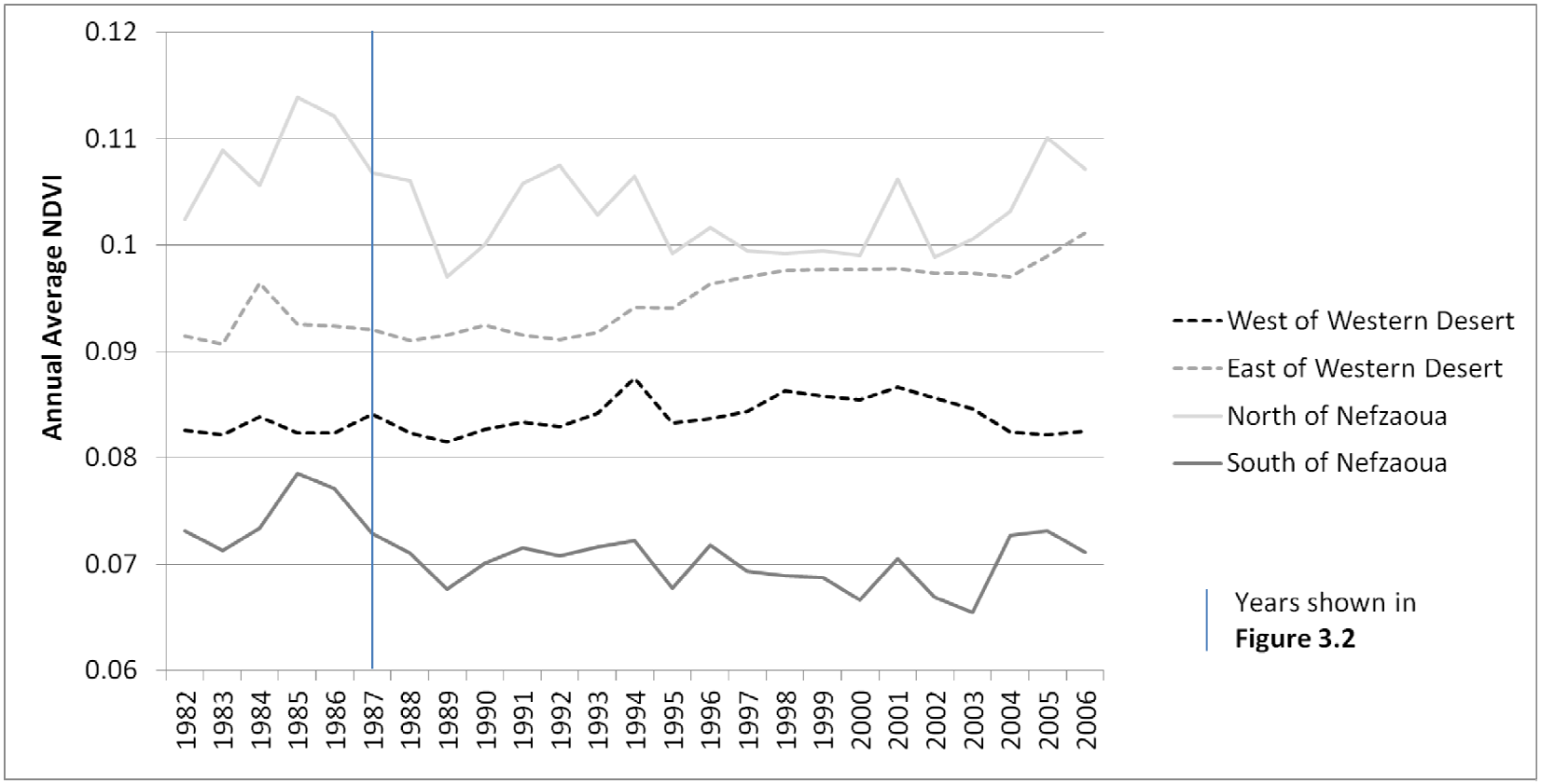
## *3.3 Results*

### 3.3.1 Inter-regional Comparison of Expanding Irrigated Areas: Overview

Over the period 1984-2006, it is notable that average annual NDVI observed using the coarse resolution GIMMS AVHRR datasets fluctuated from year to year, and did not increase as much as the extent of the irrigated high NDVI areas (**Figure 3.1**). Considerable intra-annual variations were also visible in this dataset *(*not shown in

**Figure 3.1***)*. There was a 17% rise in the average NDVI value in the AVHRR dataset for the Nefzaoua region. Published annual rainfall from weather stations located across Nefzaoua fluctuated, but showed no overall increase over this period.

**Figure 3.1: Trends in Average Annual NDVI, 1982-2006**



The overall increase in the area of high reflectance vegetation in the Nefzaoua 1987-2003 detected using the TM image series was 51%. In the Western Desert, areas of high NDVI increased from 3,263 hectares in Siwa and 3,707 hectares in Wadi El Natroun in 1987 to 5,734 hectares and 11,869 hectares in 2003[10]. The combined increase was therefore 153% (**Figure 3.2**). However, considerable spatial and temporal variations were apparent within both cases.

**Figure 3.2: Overall Increase in the Area of High Reflectance Vegetation 1987-2003**

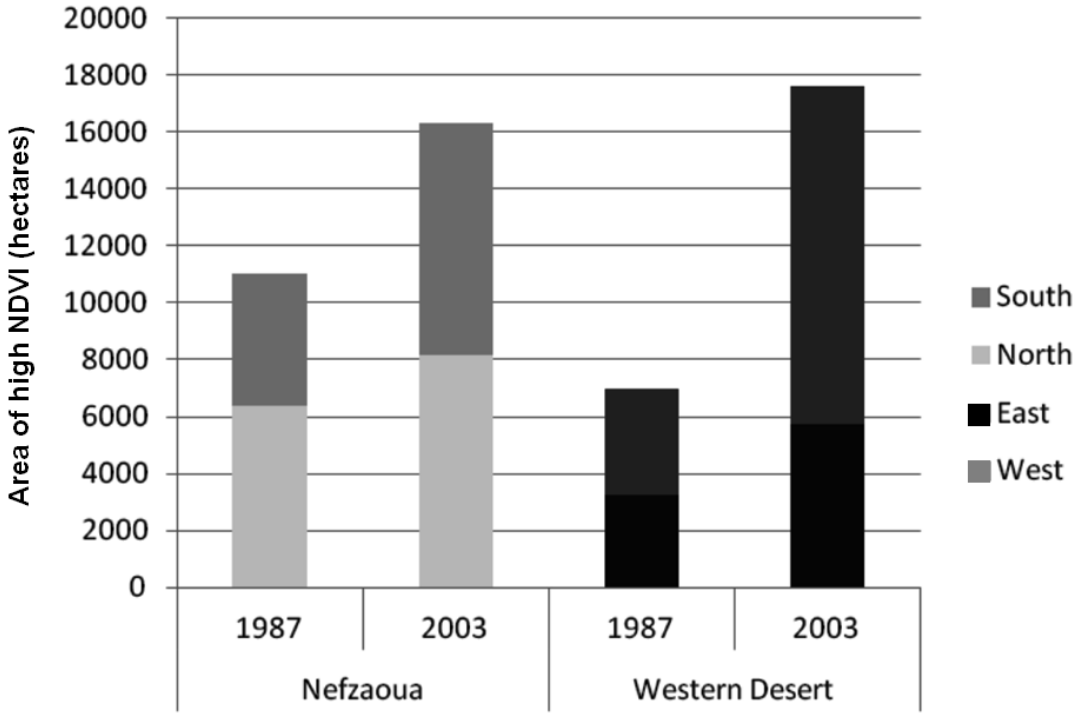



**Figure 3.3** shows a comparison between the trend in NDVI averaged across the Nefzaoua region and official statistics on groundwater extraction for irrigation use. The

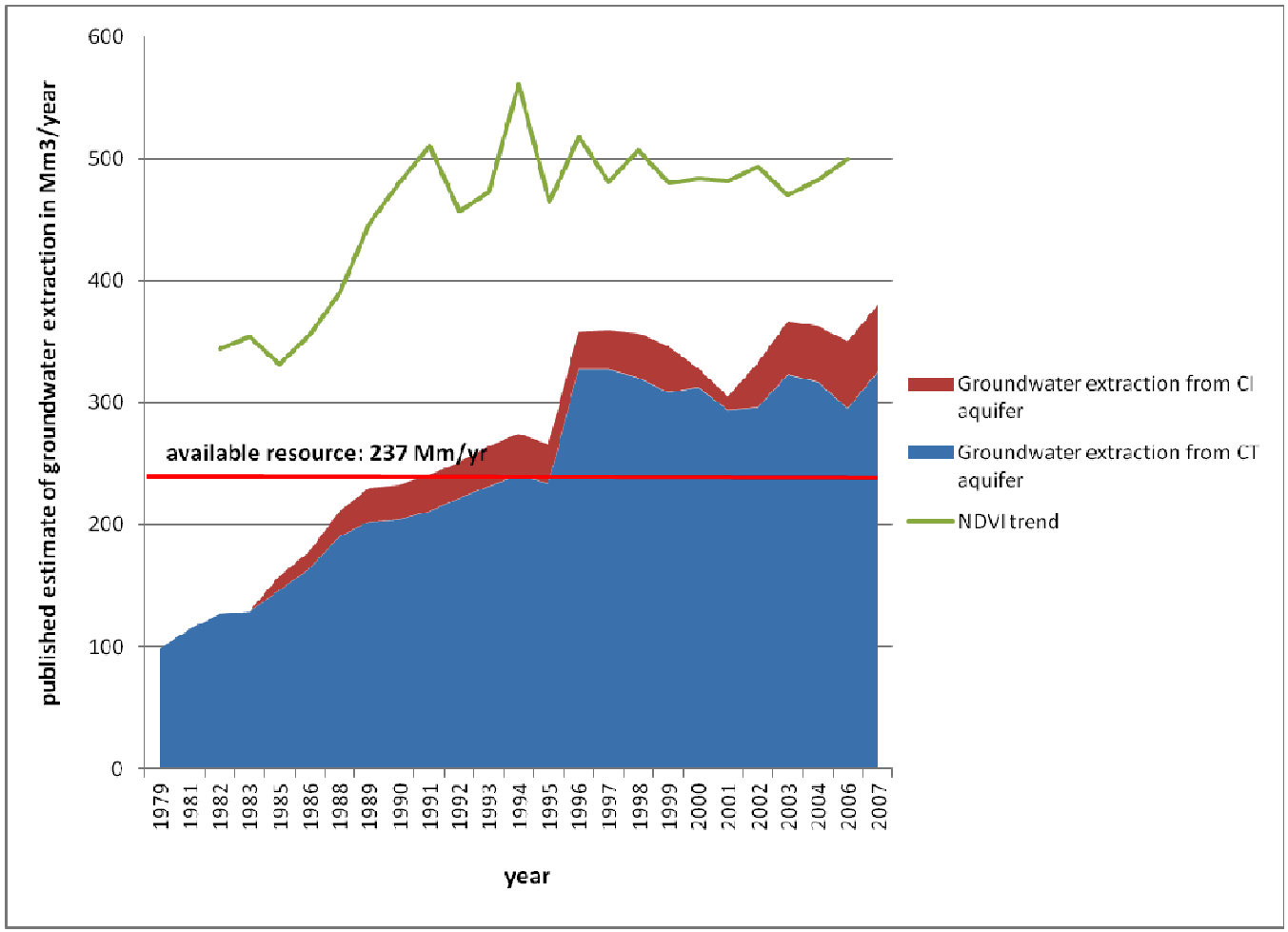
[10] since areas of young or sparse vegetation would not have been detected, these figures are to be considered conservative

trend is well correlated, particularly during the 1980s. The correlation coefficients for the entire period for which data were available (1982-2006) and for the second half of the 1980s, were 0.79 and 0.95, respectively. The acceleration of the trend in increasing NDVI corresponds to the timing of a period of increased groundwater extraction under the Southern Water Resources Development Plan (PDES) during the 1980s, and the arrival of the hand dug well technology from the late 1980s, which led to the proliferation of illegal private wells. A notable increase in official estimates of extractions from the CT and CI aquifers of the Nefzaoua region was recorded through a one-off field survey of illicit wells carried out by the local authorities in 1996. This showed that official estimates of groundwater extraction had been around 30% below the actual level of extraction, due to the unrecorded presence of illicit wells. The illicit extraction, as observed in the 1996 survey took the total extraction volume well above the threshold of the available renewable water supply (**Table 3.3** and **Figure 3.3**). The balance of over extraction has been published by the local authorities each year (DGRE 1979-2006), based on comparison of estimates for available extractions compared to inflows to the Kebili Region, including the Nefzaoua oases, and an area immediately to its SouthWest (Rejim Maatoug) (**Table 3.3**).

**Table 3.3: Official Estimation of Deep Groundwater Resources in the Governorate of Kebili, 2006** (ODS 2007, Source Listed: CRDA, 2006)

| Aquifer Name | Available Resource ($Mm^3$/year) | Exploited Resource ($Mm^3$/year) | Number of Wells |
|---|---|---|---|
| **CT Nefzaoua** | 142.00 | 259.44 | 195 |
| **CT Rejim Maatoug** | 64.00 | 36.06 | 30 |
| **CI** | 31.50 | 54.71 | 48 |
| **TOTAL** | **237.5** | **350.21** | **273** |

**Figure 3.3: Groundwater Extraction for Irrigation Use (ODS 1997-2007) and Trend in NDVI, Nefzaoua**



### *3.3.2 Tracking Salinization in Irrigated Areas in Nefzaoua, Southern Tunisia*

Over the most recent decade (late 90s-2000s), a slower trend in the increasing extent of high NDVI (ie: irrigated) areas is apparent. This has previously been associated with the effects of degraded land and water quality caused by salinization (OSS 2003b, Zammouri et al. 2007). Analysis of the spatial distribution of land cover change (**Figure 3.4**) showed that more vegetation losses affected the north than other parts of the region. Both land users and published statistics indicate that the groundwater table has fallen, increasing water scarcity and pumping costs in this area. Simultaneously, water-logging has occurred in low-lying areas. Groundwater quality, as recorded in the official monitoring results, has deteriorated somewhat in this part of the region (**Figure 3.5**). This has been associated withupwelling of saline water from the CI (see El Fahem 2003).

This mix of different degradation processes affecting groundwater availability and salinity, and resulting degradation of land quality and productivity may explain some of the observed land cover changes in the north.

The most rapid and extensive growth of the vegetated area was in the southeast, in the Delegation of Douz (**Figure 3.4**). The groundwater of the CT had become more saline, reaching levels well above the FAO threshold for effects on datepalm (**Figure 3.5**). In this region, over-pumping appears to be a likely cause of salinization. Backflow of drainage water has also been observed as a significant process affecting water quality, due to drainage conditions around El Hsay (see El Fahem 2003).

**Figure 3.4: Changes in NDVI and Spatial Distribution of Land Cover Change, Nefzaoua**

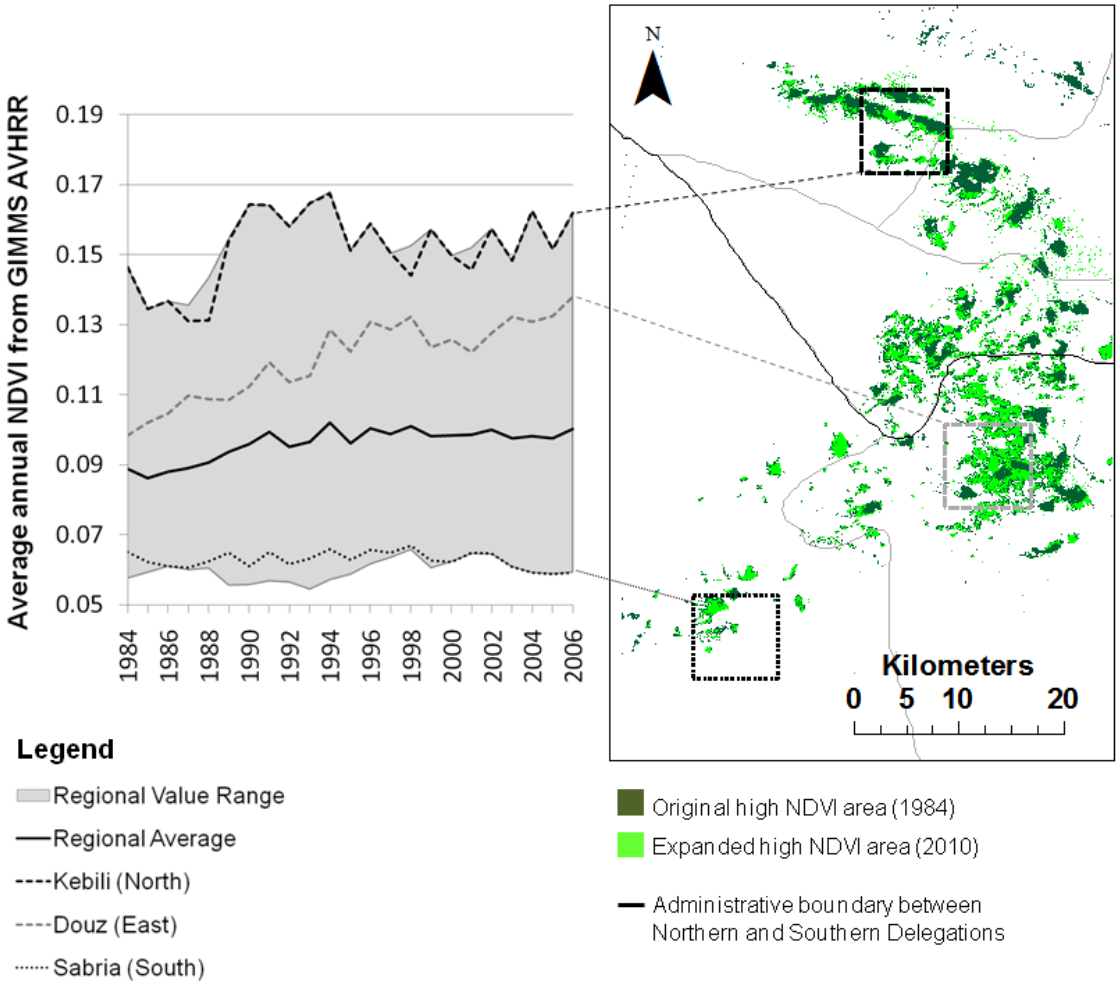
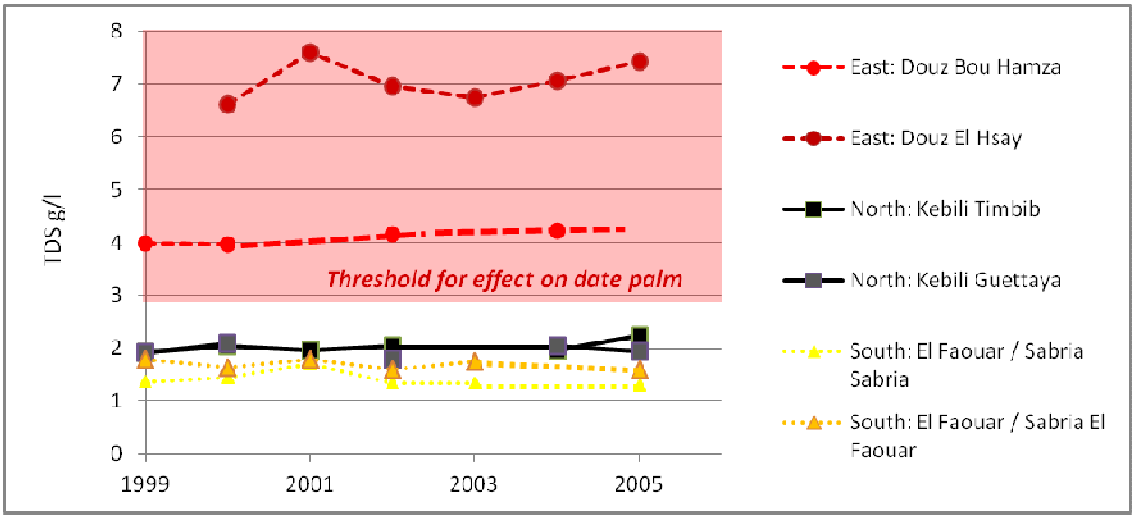


**Figure 3.5: Salinity Levels and Trends in the Nefzaoua Region** (source: DGRE) [11]




Surveyed cultivators from different parts of the region described problems due to increasing salinity, and also to scarcity of water occurring over this period. Survey results recorded infrequent irrigation water applications. Losses of productivity in *Phoenix dactylifera* L. and the death of other fruit and vegetable crops were described. Cultivators blamed malfunctions in the water distribution systems, the age of their wells, and the generalized scarcity of water for these problems. However, interviews also revealed that economic factors influence their salinity management practices. Furthermore, new economic opportunities weighed against falling international date prices may have affected investments of labour in water management and soil improvement (these factors are further explored in chapter 5).

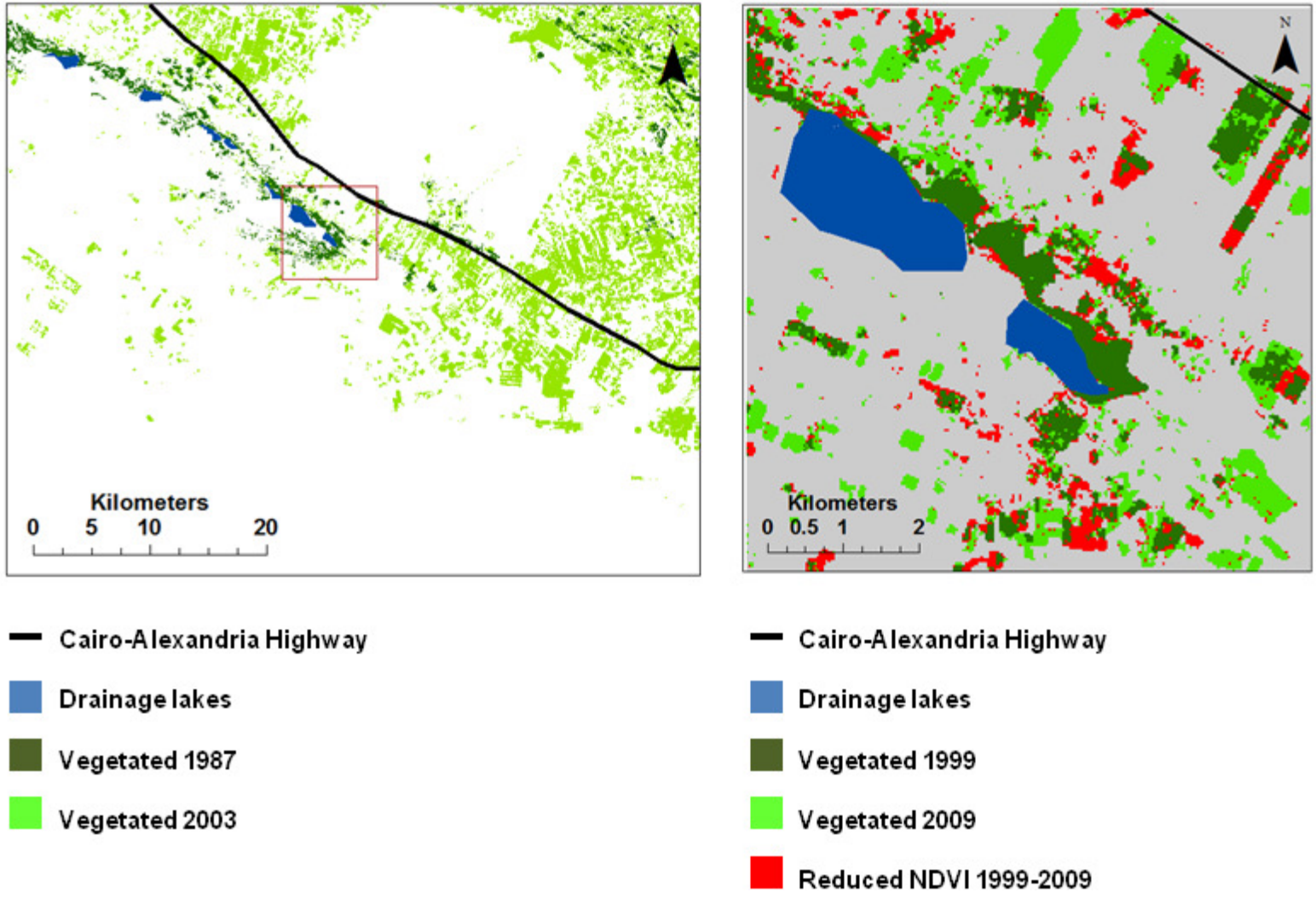
[11] We calculated the threshold value for effects on date palm approximately through conversion from the FAO threshold value of EC 4 dS/m (4000 µS/cm$^{-1}$) to an approximate TDS value. This is based on a previous investigations in this region by Marlet et al. 2009, in which average values EC and TDS from analysis of 237 local groundwater samples were reported. However, conversion from TDS to EC are non linear, and subject to effects by the composition of salt assemblages (see Hem, 1984). In light of this, the conversion is approximate and conversion of the full dataset from TDS to EC is not attempted.

### *3.3.3 Tracking Salinization in Irrigated Areas in the North Western Desert, Egypt*

Since the late 90s, increases in the extent of the high reflectance area have been visible in the Landsat images from Wadi El Natroun, in the Western Desert of Egypt. However, our results show vegetation losses in some areas, as well as continuing gains in others. On large farms in this area, employees interviewed during the questionnaire survey could each recall numerous wells on their farms that had previously become too saline to use, and been replaced over recent years. No records are kept when this occurs. It is therefore important to recognize that monitoring wells still in use might not provide a full picture of the extent of salinization. Water users, who monitor and observe water quality continuously as it is applied and affects their crops are therefore an important source of information concerning salinization processes.

Vegetation losses observable in Landsat 5 images over the period 1984-2003 seemed to have been spread across the region, showing no particular spatial trend (**Figure 3.6**, left). But in the higher resolution Landsat7 dataset available for over the period 1999-2009 (**Figure 3.6**, right), it could be observed that vegetation losses had been particularly concentrated close to the drainage lakes in the base of the depression. This is the location of the older cultivated lands. On the other hand, increases in the area of newly cultivated land continued to accelerate across the surrounding area away from the center of the depression**.**

**Figure 3.6: Change Detection, Wadi El Natroun, Based on Landsat 5 and 7**



The significance of this new analysis, in which the higher resolution images pinpoint the effect of degradation on the older cultivated land becomes clear when it is compared to the results of the survey of farmers. This reveals that this is the area where the smallest farms are located. Therefore, it can be concluded that degradation is affecting productivity on the smaller, older farms in this area more than it is affecting the larger, newer farms.

According to the farmers on the small farms, their greatest concern is most often not salinity (Electrical Conductivity in their wells remaining under use varied from 1-5000 $\mu S/cm^{-1}$, with a mean value of 2500 $\mu S/cm^{-1}$), but the falling water table. This reduces their access to water, thereby impairing their options for managing salinity increases, unless they can afford to pay the cost of deeper drilling and pumping. Where salinity cannot be managed, wells are simply abandoned (these aspects of the degradation problem are further explored in chapter 5)

Further to the West, at Siwa, water-logging, was clearly taking place, confirming the accepted interpretation of salinization processes described in section 3 . This is visible in the NDVI images as an expansion in the low NDVI lake areas at the centre of the depression (**Figure 3.7**). However, during semi-structured interviews conducted in the field cultivators said that deep wells were also affecting water quality and pressure in neighbouring springs, traditionally used for irrigation.

The evidence from resampling of the wells where data on salinity was available over a ten year period confirmed increasing the salinity levels at these locations (e.g. from

4000 µS/cm$^{-1}$ to 7000 µS/cm$^{-1}$ in 2009 at Lehrek Spring and from 4000 µS/cm$^{-1}$ to 9000 µS/cm$^{-1}$ at the neighbouring Shaker Well over the period 1998-2009). Re-analysis of higher resolution satellite images (**Figure 3.7** confirmed that vegetation loss was not located only in low-lying areas likely to be affected by water-logging, as indicated in previous investigations, but has also been taking place at higher elevations. This, together with the results from available water quality sampling (**Figure 3.8**), confirms local cultivators` theories of another explanation for the salinization process – i.e. hydrogeological change caused by accelerated groundwater extraction. However, given the notably elevated salinities recorded in some of the wells and springs in this area, it appears surprising that more degradation has not taken place in the cultivated area. One possible reason for this, observed through the interviews with cultivators, is the highly developed state of local knowledge concerning techniques for cultivation under saline conditions.

**Figure 3.7: Change Detection, Siwa, Based on Landsat 5 and 7**

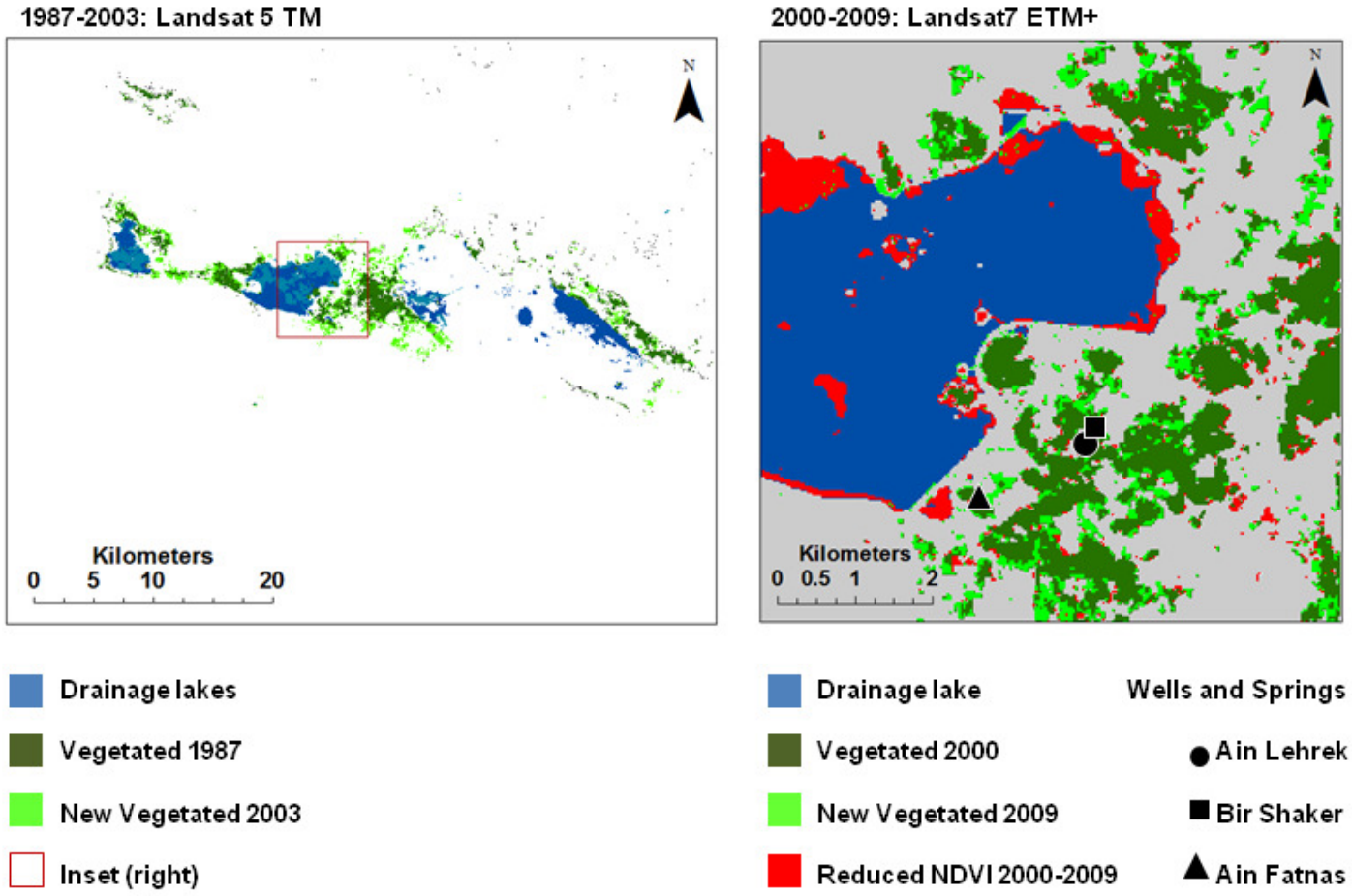
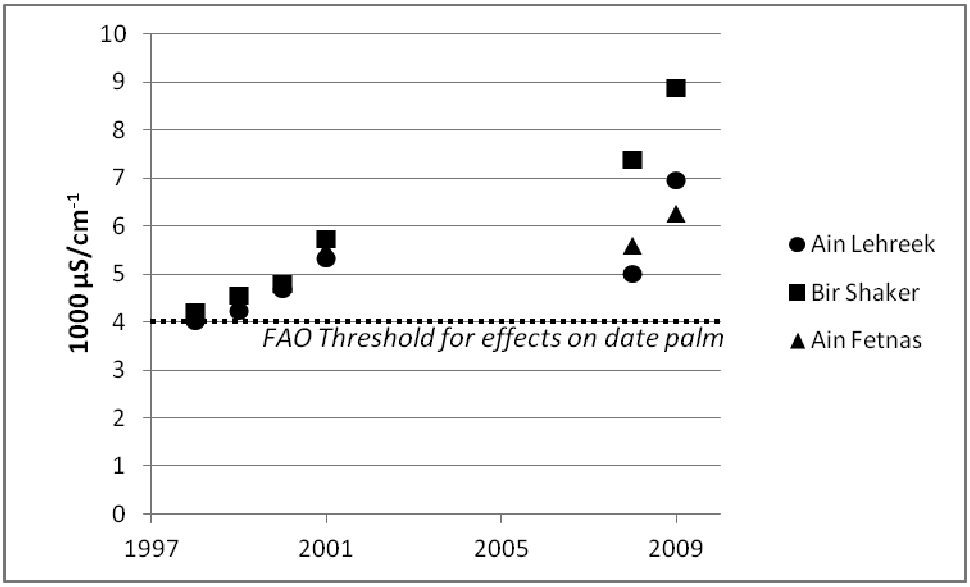


**Figure 3.8: Trend in Salinity at Wells and Springs in Western Siwa, Egypt (after Abd Al Rahman)**




## 3.4 Discussion and conclusions

### *3.4.1. What insights have been enabled through the increased availability of materials and methods for land cover change detection?*

As demonstrated in this paper, land cover change analysis offers new options for scientists to pursue and further interrogate salinization effects on land and water resources through observation of spatial and temporal changes in vegetation cover. The analyses are relatively simple and low-cost, and the resolution, frequency and range of spatial and temporal scales at which such analyses can be drawn are continually improving. As researchers continue to progress the use of these methods, it may, in time, be possible to integrate such analyses within ongoing global assessments of land degradation (e.g. Bai et al. 2008, Helldén and Tottrup 2008). At 30m, the resolution of the Landsat TM images used in this paper is still too coarse to

be used in isolation to pinpoint degraded areas and to identify potential salinization processes. To address this uncertainty, the remote sensing datasets are therefore effectively combined with other available information, including groundtruthing and time-series analyses of water quality. This is very much in keeping with the new conceptual approach understanding the condition and dynamics of human environment systems (Reynolds 2007).

In each case explored in the previous sections, the integration of remote sensing data with other sources of local information enabled a revision of the prevalent views of salinization processes. While the overriding concern highlighted through all analyses remained focused on the long-term over extraction of groundwater, leading to and exacerbating the effects of salinization, these effects were attributed to a more complex and nuanced range of causes and localized salinization processes, leading to differentiated local management implications. In addition to the local management challenge, where aquifers are shared across several countries, effective monitoring is a shared challenge. Public capacities to design and sustain the necessary environmental monitoring, data management and analysis are necessarily limited by practical and cost-constraints. Remote sensing of land cover changes could help both to target monitoring of both deep and shallow groundwater quality, and to improve regional and global assessments of environmental change.

### *3.4.2. How do these insights connect to other ongoing national and scientific efforts to monitor, model and assess land salinization and degradation trends in the two selected cases?*

Socioeconomic datasets have sometimes been integrated into the large-scale groundwater assessments, enabling modelling of water demands on a broad scale (e.g. Attia 2002a). However such approaches have not yet been connected to local management databases or data collection strategies. Nor are available participatory approaches to local environmental monitoring and decision-making systematically utilized in either region. As demonstrated in this, and many previous participatory investigations, land and water users are aware of changes affecting their resources (see e.g. Lightfoot et al. 2009), and use ecological management techniques where they can to mitigate these changes. However, based on recollections by water users alone, and without time series data consistently sampled from the same wells, it is difficult to quantify the extent, trends and processes of salinization. It is therefore impossible to consider any comprehensive regional approach to remediation, or to determine who might or might not pay the costs to reverse the degradation process.

Individual land and water users cannot effectively conduct wider systems analyses of degradation trends and management alternatives unless they collaborate and use regional datasets. However, it is important to observe that there is not an absolute scarcity of data on salinity in soils and water in either of the study areas. This observation runs counter to convention in scientific publications on environmental monitoring in the arid environment (e.g. Masoud and Koike 2006). In this investigation, it was observed that where monitoring including chemical analysis is

conducted privately by well owners, the information is not publicly collated and analyzed. However, some public databases are beginning to incorporate privately generated data. In Wadi El Natroun, for example, data generated by users for well permit applications is stored electronically. Periodic analysis and publication of this information in accessible and durable formats could enhance its availability and use by scientists and decision-makers undertaking environmental impact assessments. Periodic publication would also minimize the inevitable loss of data, generated for the public benefit, due to database management failures.

### 3.4.3. Conclusions

The global scientific challenge to monitor and manage salinization effects in irrigated arid areas increases every day with the growing extent of irrigation systems. Current global investigations of land degradation have focused on assessing ecosystem function through comparisons of NDVI to rainfall, and have not yet addressed the possible effects of irrigation in temporarily increasing productivity, or the consequences of these increases, where they are already resulting in degradation (Bai et al. 2008, Helldén and Tottrup 2008). The present situation and experiences with regard to monitoring landcover change and salinization discussed in this paper highlights the need to address these issues in this and other arid regions where irrigated agriculture is expanding. The paper also presents the conceptual and methodological tools that are readily available to achieve this purpose.

Overall, the new integrated conceptual and methodological toolbox of dryland development science appears to work well for monitoring and assessing salinization in the irrigated desert environments. Similar approaches may be applicable to address other less easily detected chemical degradation threats that may be emerging to affect land and water quality in these environments, due to expanding industrialization, urbanization, agrochemical use and waste disposal problems. As highlighted in this paper, improvements in hydrogeological datasets may be under development. However, we observe that the conceptual shift proposed by dryland development scientists has not yet led to the realization of large-scale improvements in participatory monitoring and evaluation of salinization trends in this region, and a notable degree of expert scepticism regarding participatory monitoring approaches remains to be overcome.

***Acknowledgement***

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# CHAPTER 4: SOUTHERN TUNISIA CASE STUDY

## 4.1 Preface and abstract

### 4.1.1 Preface

The chapter presents an investigation of environmental processes and smallholder well-being in Southern Tunisian oases. The chapter is based on a paper submitted to the Journal of Land Degradation and Development[12]. Progressing on from chapter 3, an increased engagement with the social dimensions of environmental change is introduced in this chapter. Land degradation is explored both in terms of environmental quality, but also in economic terms, as the loss of utility or potential utility through the reduction of or damage to physical, social, cultural or economic features, and reduction of ecosystem diversity. The overall scope of the chapter remains interdisciplinary, including a balance between environmental and social research.

The chapter draws on statistical data compiled through field investigations and archive research. It is informed by the perspectives of a large group of local experts and decision-makers at the host institutions, and draws on an extensive grey literature. In this case study, institutional support for environmental data collection and management was demonstrated to be notable, as evidenced by the archived datasets that were incorporated. On the other hand, smallholders appear in this case study as victims of degradation, reliant on State support to continue cultivating, and with few options to reverse the degradation trend that is overtaking them. A comparison of

12 (see: http://onlinelibrary.wiley.com/journal/10.1002/%28ISSN%291099-45X/homepage/ProductInformation.html).

trends in groundwater degradation between this case and those recorded in the Western Desert of Egypt is presented in appendix 8.

Findings include identification of a relationship between the international market price for dates, groundwater extraction, and degradation. This reflects the complex and indirect causes of land degradation, and the increasing consideration given to economic approaches for the assessment of land degradation that have appeared over recent years. A critique of economic policy measures is presented. Prospects for new economic measures such as payments for ecosystem services or premiums for organic agriculture are discussed as global market-based measures to address global market driven degradation problems.

The chapter introduces some key issues concerning smallholder capacity for innovation and the management of land degradation threats emerging through international markets. These issues are pursued further in chapters 6 and 7 and in the concluding discussion of the thesis. In particular, the conclusions to this chapter suggest that in order for economic measures to be effective, systems for tracking environmental processes and verifying their effects on smallholder land management practices need to be in place. The concluding discussion raises the need for strategic action through international market regimes and development strategies to strengthen local social and environmental monitoring capacities against further international market-driven degradation processes.

Title:
**Dates, degradation and development: international market effects on land and groundwater resources in the Nefzaoua Region, Southern Tunisia, 1994-2009**

Short title:
Dates, degradation and development

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Keywords:
*economic drivers, groundwater, environmental degradation, policy responses*

**Abstract:**

Land degradation associated with the over extraction of groundwater in the oasis systems of the Nefzaoua region, Southern Tunisia, is investigated through a combination of methods, including a survey of cultivators, analysis of available long term environmental datasets, and consultation of local experts and decision-makers. Over the period 1994-2009, a close relationship is observed between trends in groundwater extraction and the international market price for dates. However, the findings also show that rising water prices offsetting export price rises over this period did not provide an effective response to slow the over extraction and accompanying degradation process. Instead, economic constraints on the maintenance of smallholder land management practices increased, thereby exacerbating degradation effects on the economically disadvantaged. The concluding discussion considers the need for strategic action through international market regimes and development strategies to strengthen local social and environmental monitoring capacities against further international market-driven degradation processes.

## 4.2 Introductory sections

### 4.2.1 Introduction

The production of high value agricultural exports is an important element in development strategies in many fragile resource-dependent regions (IBRD 2008, OECD/FAO 2009). These strategies aim to generate rural jobs by diversifying into high-value resource-efficient export production (Agrawala and Fankhauser 2008). This has contributed to a large-scale expansion of the global extent of irrigated areas, placing new stresses on land and water resources, and leading to land degradation through salinization, desiccation and groundwater depletion (Giordano 2007).

The identification of international market drivers of land degradation in drylands represents a departure from the emphasis on either biophysical (e.g. climatic) or local socio-economic (e.g. resource-dependence) drivers of degradation that is prevalent in the literature (see e.g. Safriel et al. 2005). This has implications for land and water management improvements: where the cause of degradation is attributed to an external economic driver, a logical response could be to introduce an economic measure aiming to redress the degradation effect– e.g. through a payment to the resource dependent community from the external actor(s) responsible for the degradation.

Recent literature focusing on the interpretation of land degradation as an externality of economic activity located or driven from outside the degraded area has drawn on investigations of extractive `frontier development` patterns of agricultural expansion

(see e.g. Barbier 1997a). According to this perspective, reversing the extractive and degrading land management pattern requires resource conservation to be integrated with land management practices. Economic investigations of non-degrading agricultural activities in dryland environments have most often focused on conservation agriculture, rather than production for international (Reij, Scoones and Toulmin 1997, Brookfield 2001, Pingali 2001, FAO 2007, Fu et al. 2010).

While recent research on sustainable land management has begun to identify possible positive effects on local resource management and sustainability under global export regimes (e.g. Pretty et al. 2006, e.g. Ambinakudige and Choi 2009), few such investigations have been published from regions where biophysical water scarcity (i.e.: aridity) determines land management options. This paper therefore proposes a contribution to the available literature on the international drivers of land degradation with a particular focus on the dry regions.

This investigation of international market effects on land and groundwater resources focuses on a case in southern Tunisia, a region that is relatively advanced in the implementation of the-export-led development approach. Conceptualization of land degradation as an externality of international economic activity fits well to the situation in the Nefzaoua region, where salinization effects have been associated with the agroindustrial transition. Since the turn of the last century, date export production has progressively replaced the ecological complex of desert, spring-fed oasis and pastoral steppe systems traditionally maintained in this region (Sghaier 1999), with a monoculture of high value *Deglet Nour* dates (MEAT 2000, MEDD/GTZ 2006). In light

of the notably arid conditions that are prevalent in this region, this case enables us to address the gap that we have identified in the literature on international market-drivers of land degradation where the dry regions are concerned.

As a forerunner in the dryland horticultural export sector, the Nefzaoua experience offers both a cautionary tale, and an enlightened perspective on the need for greater environmental sustainability in this sector. this region has been widely represented as an exemplary demonstration model in global efforts to address the water scarcity agenda through strengthening water pricing making (Agrawala and Fankhauser 2008). Further examination of the role of the global export market for dates as a driver of land and water degradation in this case therefore has a particular significance within the growing literature on the economic dimensions of land degradation and sustainable land management.

In this paper, we investigate land degradation effects accompanying the expansion of the groundwater irrigated desert area of Nefzaoua, 1994-2009. This period corresponds to the major period of Tunisian export-market development[13], and the emergence of a water-use efficiency agenda in Tunisian policy-making (Mamou and Kassah 2000). The investigation tracks the economic drivers (date export prices), economic policy responses (water pricing), and effects on the small farm budgets and land management practices in the region. The final discussion weighs the effect of water pricing policies on the drivers and impacts of land degradation over the fifteen

[13] Tunisia joined the World Trade Organization in 1995

year period, and considers the broader lessons to be extracted from this case for global efforts to understand and manage new land degradation threats emerging through international market-oriented development strategies.

### 4.2.2. Methodological Approach, Context and Methods

***Local consultation and long term datasets***

Our investigation set out to include an interdisciplinary approach, in line with the current state of the art in land degradation research, combining field investigation, social research methods and use of available long-term environmental datasets (after Howes and Chambers 1979, Stocking and Murnaghan 2001, Ouessar et al. 2004, Nkonya et al. 2010). The study methods were adapted for implementation through reference to a signficant body of local expertise at the Tunisian Institut des Regions Arides (IRA). Published and unpublished data, commentaries and analysis on regional land and water management reviewed in preparation for this study included a detailed investigation of the water user associations, including household and farm budget survey work, compiled in 1994 by the Japanese International Cooperation Agency (JICA). This previous work provides the main source for temporal comparison in this paper.

Field research for the study was implemented in consultation with the Commissariat Régional au Developpement Agricole (CRDA) in the Governorate of Kebili. The CRDA provided local long term records of agricultural productivity, groundwater extraction and quality and management information on the water user associations, as well as an

extensive archive of grey literature on land and water management in the study area. The principal environmental and social datasets are published annually (DGRE 1979-2006, DGRE 1998-2006, ODS 1997, 2007).

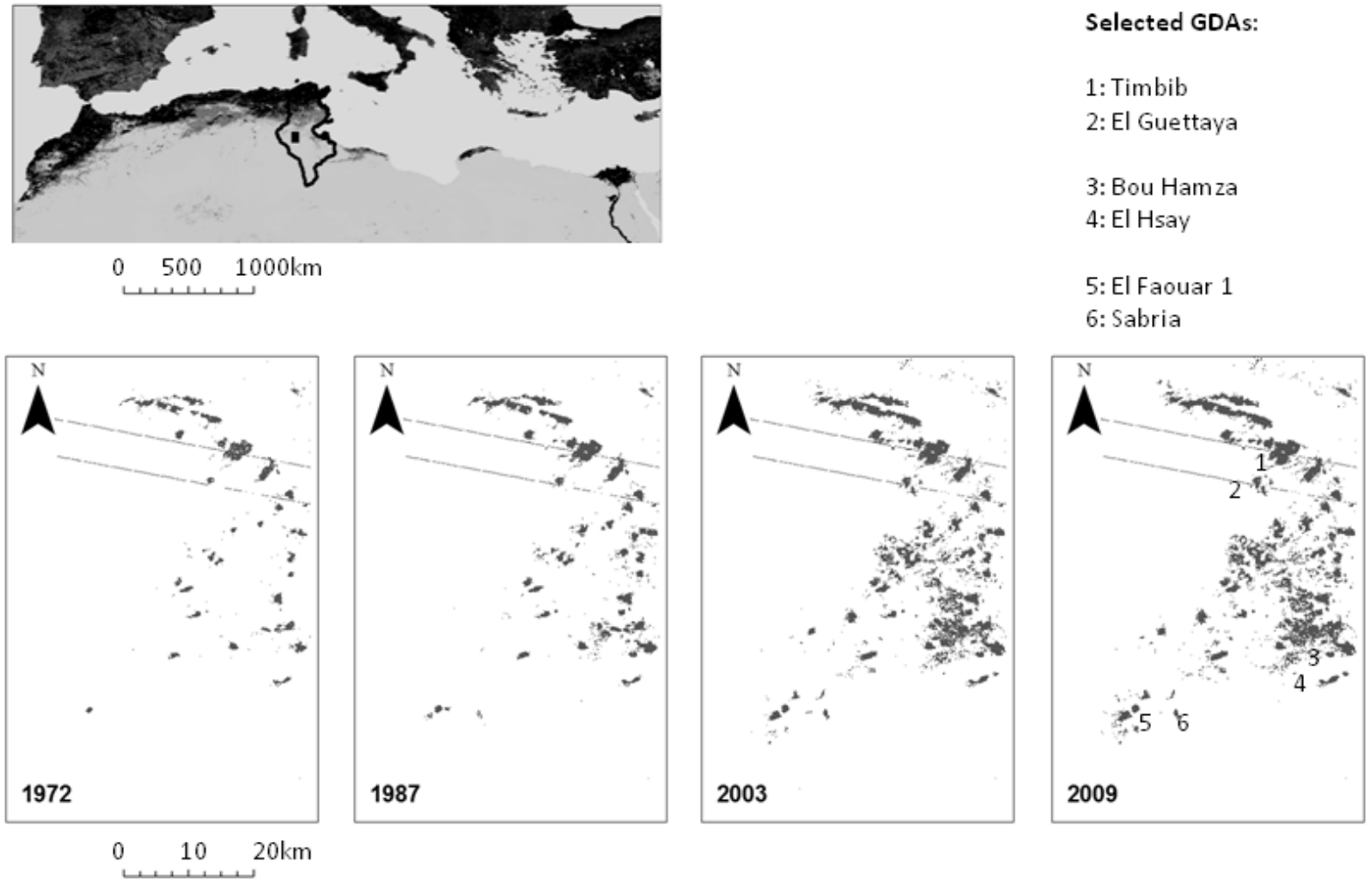
Internationally available long term environmental datasets and other relevant background information were incorporated to the study, building on previous local research and validation wherever possible. Vegetation cover was assessed using the AVHRR GIMMS dataset (See chapters 2 and 3 and methods in King and Salem 2009). Generic information on water requirements and salt tolerance of crops was compared to levels of Total Dissolved Solids (TDS) in groundwater, monitored by the CRDA over the study period. A salt tolerance threshold for Electrical Conductivity (EC) of 4 dS/m (4000 $\mu S/cm^{-1}$) published by FAO for effects of salinity on date palm *(Phoenix dactylifera,* L.*)* (Allen et al. 1998, FAO 2002), was approximately converted for comparison to the TDS values based on an EC:TDS ratio previously identified in the region (Marlet et al. 2009). Producer prices for export commodities 1994-2010 were obtained from the Tunisian Ministry of Agriculture and FAOSTAT and compared to those listed in the 1994 study. Historic exchange rates were obtained from the IFS online database, maintained by the IMF.

***Study area: the date producing and exporting oasis region of the Nefzaoua***

The Nefzaoua region, in the Governorate of Kebili, Southern Tunisia, is located on the edge of the Sahara Desert Erg (**Figure 4.1)**. The climate is arid and has experienced long term drying trends (Abdelaziz 1979). Average annual rainfall over the period 1995-2005 was 85mm in Kebili in the north and 71mm at El Faouar in the south, but

variability is high, ranging between maximum values of 155mm and 145mm and minimum values of 15mm and 12mm, respectively (CRDA). Annual evapotranspiration calculated by the Penman-Monteith method is 2124mm (Omrani 2005).

**Figure 4.1: Nefzaoua Region Location and Expansion of Oases** (Inset Source: GIMMS AVHRR and Image Series Source: Landsat)



The region is bounded by the Dahar mountain range to the North and East, forming a drainage basin around the *Chott El Djerid* depression, with a lowest point at around 25m below sea level. Present-day runoff in the study area provides limited recharge to the shallow Mio-Pliocene Quaternary aquifer. However, since rainfall is minimal, human cultivation relies on groundwater from the deeper fossil aquifer systems of the North West Sandstone Aquifer System (NWSAS), flowing upward towards the *Chott* from reserves held across an area of 1.100.000 $km^2$ beneath the Sahara to the South, East and West (Mamou 1990, OSS 2003b, Ould Babasy 2005).

The traditional pattern of oasis cultivation taking place around collectively managed springs and wells is characterised by intercropping of date palm, fruit trees, and vegetables and fodder crops (Lasram 1990). Groups of cultivators share water from a single well or source, distributed through a series of channels. Each cultivator takes water from the channel in turn, measuring the allocation of water by **duration**. When the allocated time of the irrigation duration is up, the opening from the main channel into the cultivator`s plot is closed, and water flows on to the next plot. This continues until the water has been distributed to all of the plots in turn, when the cycle begins again. The **interval** between each irrigation event for any given plot depends on the total number of plots in the system, the length of time of each allocation, and the effectiveness with which the cycling of water is collectively managed by all of the other cultivators.

The operating costs for pumping water, maintaining the distribution infrastructure, staffing, administration and other expenses are divided amongst the members of the

collective water user associations proportionally to the size of their land-holdings. The associations operate under the supervision of the CRDA, and are legally termed `Groupements de Developpement Agricole` (GDAs), although they are still popularly referred to as Water Associations `Jamaiyya Maaiya` (Selmi 1998, Mouri and Marlet 2006, Romagny and Riaux 2007, Zekri and Easter 2007). Water extraction and quality in each of the associations is recorded annually by the CRDA (DGRE 1979-2006, DGRE 1998-2006).

Physical mechanisms of salinisation include natural processes, and those caused by overextraction and poor management of groundwater. These environmental processes, often working in synergistic combination, vary across the region according to climate (including intra-annual variations), topography, hydrogeological, and management conditions (for further concise discussion, see Zammouri et al. 2007, and additional contributions from this region by Kriaa 2003, Siegfried 2004, El Fahem 2003, Bouarfa et al. 2009, Marlet et al. 2009, Askri et al. 2010, Kamel 2011b).

Surrounding the traditional public oases, private farms have sprung up. Extensions to the irrigated areas across the region (including both legal and illegal expansions) have taken place at varying rates over the past thirty years, with the most rapid growth visible in the east (**Figure 4.1**). The trend in increasing vegetation cover observed through remote sensing showed a rapid increase occurring earlier in the 1980s and 90s (King and Salem 2009). This corresponds with the timing of the introduction of hand-held technologies for drilling wells in the region (Kassah 1996a, Brochier-Puig 2004).

Official data on groundwater extraction also shows a sudden rise in 1996, due to the inclusion of data from illegally-sunk wells from this year (Siegfried 2004).

In the past decade, the extraction of groundwater is recognized to have continued well beyond the present recharge capacity (Mamou and Kassah 2000, ERESS 1972). The official estimates of the balance of available resources and extractions is published annually by the local authorities, acknowledging the deficit (**Table 3.3**). This has been widely accepted as the cause of salinization affecting both land and water resources, leading to losses of productivity, biodiversity and resilience to pests (Siegfried 2004, El Fahem 2003, Zammouri et al. 2007, MEDD/GTZ 2006).

The Tunisian national land degradation assessment identified market drivers as the cause of degradation: `*The oasis agriculture has become a market-oriented agriculture, demanding increased productivity and extraction of resources*` (MARH 2006b p28). In response, increasing prices for water use were introduced under the national water-use efficiency agenda (Sghaier 1995, Mamou and Kassah 2000, Belloumi and Matoussi 2004, 2006, Zekri and Easter 2007).

***Survey design and administration***

Methods used for the field survey were adapted, based on the findings of previous local surveys and ethnographic work (Sghaier 1984, Bedoucha 1987, Sghaier 2000, Meddeb 2003, Battesti 2005, Ghazouani 2009), to ensure relevance to the study context, and to build in possible comparisons with previous studies. The survey was conducted through a series of face to face interviews. Fundamental issues in surveying

cultivators` perceptions of productivity in the Southern Tunisian oases concern the subjective distance between the external interviewer and the cultivator (Battesti 2005), problems of recollection for the cultivators (Meddeb 2003), and a `chorus line effect` observed amongst groups of farmers influencing one anothers recollections (Ghazouani 2009). Consultation of local experts and decision-makers and comparison to multiple data sources were undertaken to identify and cross-check for these potential effects of bias. Additional less structured interviews with cultivators, decision-makers, and other local people not part of the survey, contributed further information and insights.

Through consultation with the CRDA, a series of six GDAs were selected in which to carry out more detailed survey investigations. The criteria for selection included the presence of degradation threats to land and groundwater resources, and also the continuation of cultivation activities. The selection was regionally distributed: two associations were selected in the North in an area at low elevation that was prone to waterlogging (Timbib and El Guettaya), two in the East in an area of very rapid development and salinisation of deep groundwater (Bou Hamza and El Hsay), and two in the South under more water scarce conditions (Sabria and El Faouar 1) (**Figure 4.1** and discussion of environmental degradation processes in different parts of the region presented in chapter 3). The investigated GDAs varied in size, membership and access to water resources (**Table 4.1**). El Hsay and Bou Hamza, in the rapidly developing East, are located further away from the *Chott*, and drain to separate drainage basins, located close to the oases.

**Table 4.1: Characteristics of Selected Agricultural Development Associations (GDAs)**

| GDA | Total # members | Total area* | Total # landholdings | Minimum landholdings size (ha) | Mean size of landholdings (ha) | Max size of landholdings (ha) | Trees per ha (1994) |
|---|---|---|---|---|---|---|---|
| El Guettaya | 403 | 154 | 747 | 0.015 | 0.383 | 5.377 | NA |
| Timbib | 365 | 114 | 914 | 0.014 | 0.313 | 2.00 | 217 |
| El Hsay | 321 | 91 | 396 | 0.04 | 0.29 | 1.25 | 148 |
| Bou Hamza | 264 | 81 | 320 | 0.063 | 0.308 | 1.625 | 151 |
| El Faouar 1 | 562 | 85 | 785 | 0.015 | 0.152 | 1.55 | 133 |
| Sabria | 384 | 66 | 503 | 0.021 | 0.172 | 0.875 | 158 |

* to the nearest hectare. Many landholdings are less than one hectare in size.
NA=Not Available

The selected GDAs each have at least one well pumping water at around 80 l/s per well. Rates of discharge and numbers of wells in the selected GDAs have varied over the study period. Bou Hamza and Timbib have both been using their wells since 1973, and El Faouar 1 has maintained a single high capacity well since 1985, while the numbers of wells available in use at the other GDAs have varied. In all of the cases, there has been increasing need for pumping as artesian pressure has reduced in the region. In most GDAs, the transition from artesianism to the use of pumping took place during the mid 90s, although in the eastern oases, it began earlier, in 1988. In addition to pumping from wells, in low lying areas, such as El Guettaya and Timbib, pumping can also be required to remove excess drainage water.

The survey questionnaire was prepared through consultation at IRA, Medenine and Kebili, and at CRDA, Kebili. The questionnaire was pilot-tested in the GDA of El Guettaya through a meeting of cultivators coordinated by the GDA President. The content of the survey included questions on the following:

-cultivation patterns: land-holdings, water use and crop production

-observations of changes affecting groundwater: availability and quality

-household characteristics: occupations and use of crops

Due to increasing emphasis on organic production in the region, survey questions concerning the use of agrochemicals were not considered likely to yield useful results in 2009, and were discarded following the pilot investigation. Instead, generic observations on these issues were collected from agricultural experts in Kebili.

The implementation of the survey took place in October, 2009, shortly before the harvest period for *Deglat Nour* dates. At this time, it was possible to observe where protective mosquito nets were used, as recommended for dates intended for export to the EU, or plastic wrapping to keep off the rain. Interviews were carried out with GDA managers of four of the selected oases during March 2009 and October 2009. With their assistance, eight or more cultivators were selected from each GDA to take part in the survey (Total n = 60). In all cases, except for El Hsay, the interviews took place at the GDA offices, near to the oasis, and were followed by a visit to selected plots. In the case of El Hsay, the GDA does not have an office, and therefore the interviews also took place in the field. The duration of each interview was around 15 minutes, including introductions, questions and follow-up on salient points raised. This enabled around eight interviews to be conducted in succession in a single visit to each selected location.

## 4.3 Results

### *4.3.1 Tracking two decades of land and water degradation 1994-2009*

Cultivators in all six surveyed GDAs expressed concern over the increasing scarcity of water experienced during the past decade. Water extractions in each of the surveyed GDAs, as for those across the region as a whole, had not reduced in volume, according to local statistics (DGRE 1979-2006 and CRDA unpublished data). Scarcity was therefore, at least in part, the result of management practices. Comparison to the earlier JICA study confirmed that irrigation intervals in each GDA had grown longer, even though the areas recorded as under irrigation, and the numbers of formally

registered users, had not changed significantly. Other possible explanations for the lengthening of the irrigation intervals would include technical failures in water delivery, or increases in the duration of irrigation allocated to each cultivator.

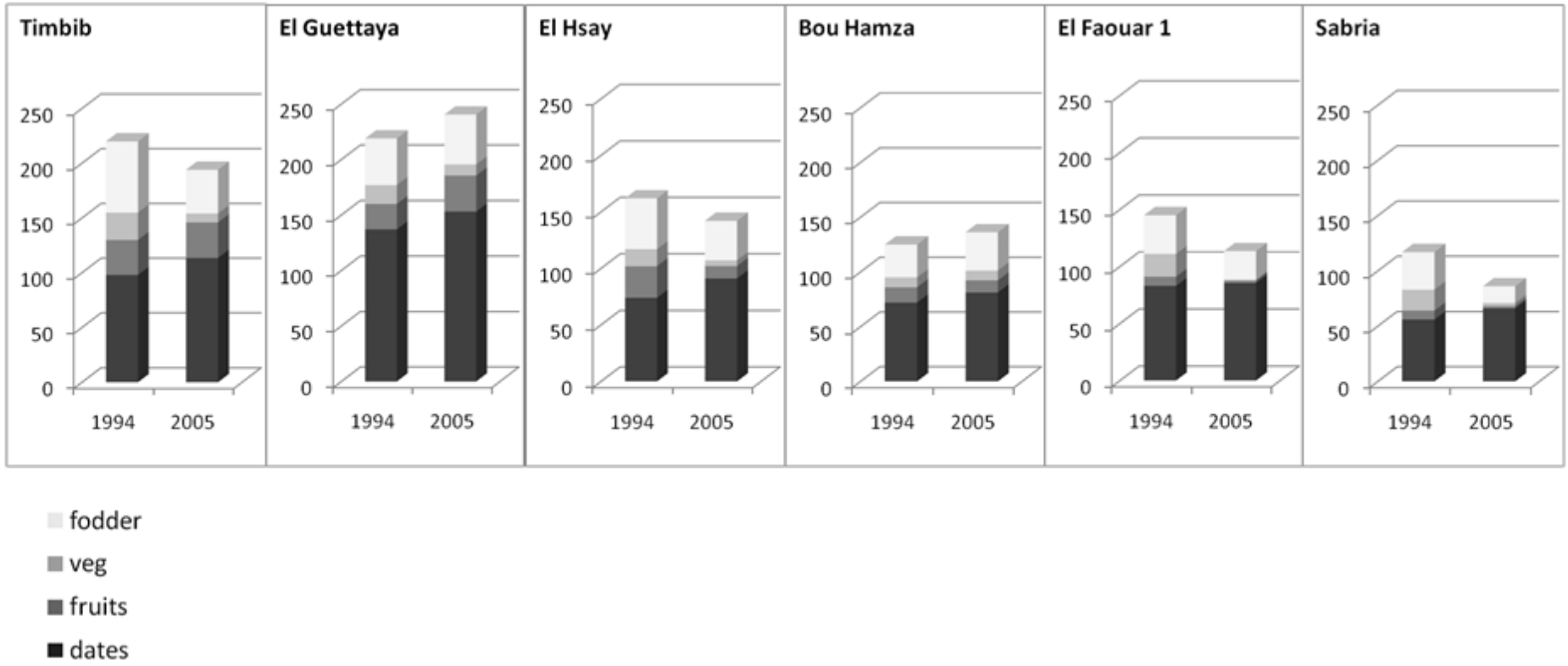
Cultivators in the eastern part of the region reported problems of water salinization, with the highest recorded levels of TDS in irrigation water at over 8g/l TDS at El Hsay and over 6g/l TDS at Bou Hamza, where clear rising trends were apparent. Degradation of water of quality can exacerbate water stress by reducing the ability of plants to take up the available water. The high salinity levels were well in excess of the threshold for effects on date palm: 2.9 g/l. Salinity in the wells at the other selected oases has remained below 2g/l TDS (**Figure 3.5**). However, even these lower levels exceed

generic published thresholds for effects on more sensitive soft fruits, such as apricots (FAO 2002).

The combined effects of the long irrigation intervals and saline conditions, had increasingly ruled out the production of crops other than date and olive, and even these may under produce under such conditions. Losses of some or all varieties of fruit trees, were reported in all GDAs. With the exception of olives observed in Timbib and El Guettaya, and described by the Director of El Faouar 1 GDA, the few remaining trees did not produce good quality fruit. All of the interviewees explained that the diversity of intercropping with fruits, vegetables and ground crops in addition to the date palm had been reduced due to the lack of water. Most indicated that they had previously grown vegetables, but that this was no longer possible.

Cultivators` accounts of lost productivity in the date crops were compared to crop production data collected at the six case study oases, and the one hundred and three other oases under the supervision of the CRDA over the period 1994-2005. Changes in the area under different crops in each case over the period 1994-2005 are recorded in local agricultural statistics for all of the case study oases (**Figure 4.2**). The area of date production increased slightly in each case, while the areas of fruit production were reduced.

**Figure 4.2: Change in Extent of Different Crops (ha) 1994-2005 (JICA 1996 and CRDA 2009)**



A healthy mature date palm can produce around 200 kilos of dates but in 1994, average productivity levels from each of the surveyed oases, and across the region as a whole, amounted to less than 6 tons per hectare (less than 60 kilos per tree). The maximum productivity was 6.4 tons per hectare, and the standard deviation from the mean was 0.6. By 2005, the statistics had become much more differentiated between oases: the maximum productivity had reached over 20 tons per hectare, and the standard deviation was above 3, however the mean regional productivity had reduced to just below 5 tons per hectare, since the gains in productivity in some cases were outweighed by the losses recorded in others. In the case study oases, the findings of the 2009 survey reconfirmed that productivity had remained low, with a pronounced long term declining trend in date production apparent in the salinity affected eastern oases (**Table 4.2**).

Our analysis of the CRDA regional datasets showed that neither water scarcity nor salinity, individually or combined, fully accounted for the changes in productivity recorded over the period 1994-2005 across all of the oases in the region**.** Nor were the losses in productivity in salinized areas, such as El Hsay and Bou Hamza, proportional to the recorded increases in salinity. Furthermore, although over the intervening period, improvements had been made to the water quality in El Hsay, this had not yet translated into a reversal of the loss of date productivity.

**Table 4.2: Reported Date Production in 2009**

| | Trees per hectare | | | Fraction Deglet Nour | | | DT** per tree | | | Tons per hectare | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | max | min | mean | max | min | mean | max | min | mean | max | min | mean |
| **Timbib** | 300 | 115 | 172 | 0.96 | 0.25 | 0.70 | 50 | 0 | 26 | 7.5 | 1.6 | 3.9 |
| **El Hsay** | 129 | 92 | 105 | 0.94 | 0.77 | 0.89 | 67 | 21 | 41 | 9.0 | 1.5 | 3.8 |
| **Bou Hamza*** | 240 | 39 | 124 | | | | 60 | 30 | 40 | 6.5 | 1.0 | 4.1 |
| **Sabria** | 384 | 44 | 174 | 0.91 | 0.60 | 0.73 | 89 | 8 | 18 | 13.3 | 1.3 | 5.1 |
| **El Faouar** | 244 | 67 | 136 | 0.98 | 0.82 | 0.91 | 81 | 18 | 50 | 10.0 | 3.0 | 7.6 |

*Results in Bou Hamza for deglet nour only

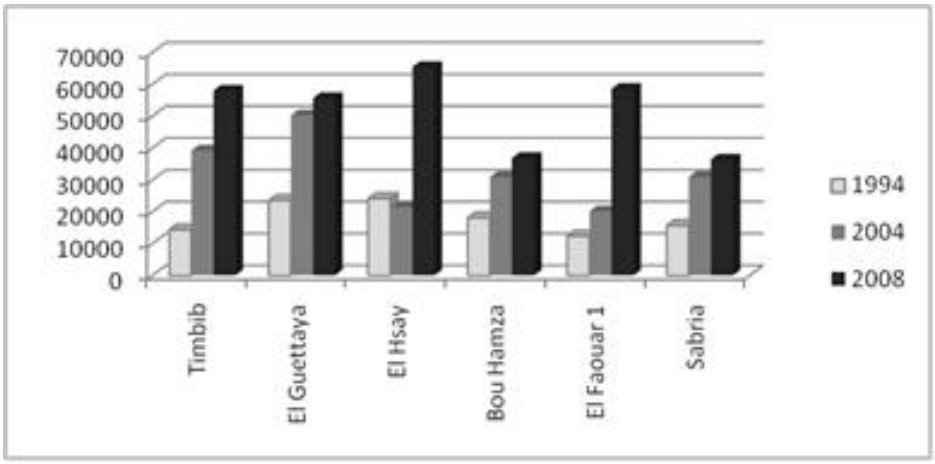
**DT = Tunisian Dinars

It has been suggested that in some cases cultivators might be succeeding to mitigate effects of increasing salinity on productivity through land and water management practices, while mismanagement could have exacerbated negative effects in others (see e.g. Meddeb 2003). Thus the continued low productivity at El Hsay could either be due to the lasting effect on the trees of the exposure to high levels of salinity in previous years, or to reduced interest amongst cultivators in investing in labour and other inputs when the salinity levels became excessive. Traditional practices for managing salinity include flushing excess water through the soil to remove salts, which may further exacerbate water scarcity problems (see e.g. Marlet et al. 2009). Use of this or other practices for managing soil quality and salinity is an economic choice made by cultivators. These choices are discussed in the remaining parts of this section, in light of the changing international price drivers over the period 1994-2009.

### *4.3.2 Increasing water prices to address the economic drivers of degradation: The water scarcity policy agenda during the 1990s*

In all of the GDAs studied, with the exception of El Hsay, operating budgets, including costs for energy, maintenance and other infrastructure, had doubled over the period between 1994-2005, and continued to increase until the survey period **(Figure 4.3**). The rising costs reflected both the increasing physical scarcity of water and rising energy costs for pumping under falling artesian pressure. The increases were slower in the salinity affected oases of El Hsay and Bou Hamza, but in 2004, El Hsay obtained a new well, enabling operations, and therefore also costs, to pick up again.

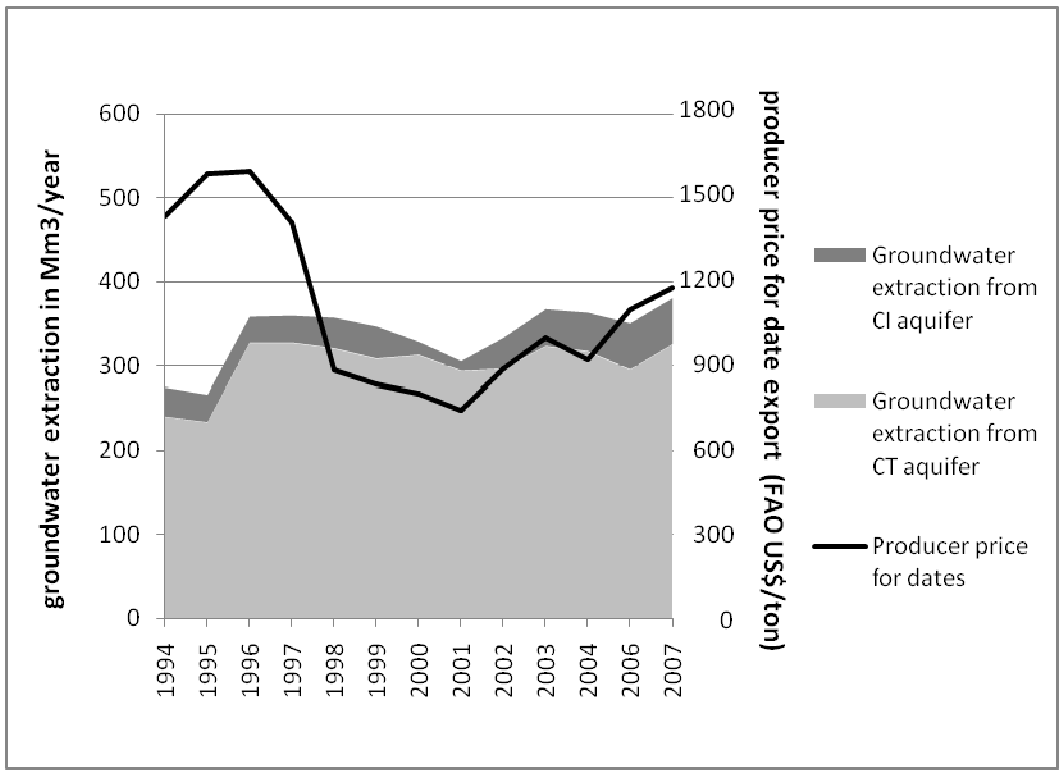
**Figure 4.3: Operating Costs of Water Distribution by GDAs (DT) 1994-2008**




Analysis of the regional trend in water extractions shows that despite the rising prices, the only year in which the water extraction rate fell noticeably was 1998, when a global price crash hit the international date export market. Following recovery from the crash, water extraction followed a trend that is even more closely correlated to that of the international date prices, suggesting that the international price has become an increasingly important driver of groundwater use patterns over the past decade (**Figure 4.4**). From this analysis, we conclude that since the late 1990s, the rising costs of water for cultivators in the Nefzaoua region have not reduced water use, but have instead been offset by the simultaneously rising price of dates for export. Overall, the survey results indicate an increase in local prices for dates of well over 20% since 1995[14].

[14] At the time of the 2009 survey, the official reference price published by the *Union Tunisienne de l'Agriculture et de la Peche* (UTAP) was 1.55 DT/kg, and *Deglat Nour* dates would be sold from the oases at around 1.5 DT/kg (close to US$2 at 2009 exchange rates). This was more than double the 1994 farm gate value of 0.90 DT/kg (below US$0.9) recorded in the JICA study.

**Figure 4.4: Trends in Groundwater Extraction and Producer Prices for Date Exports from the Nefzaoua Region**




Cultivators interviewed in 2009 described shifts occurring in the systems for marketing of dates from the Nefzaoua region that had further enhanced the local effect of international price rises. These were due to recent policy attention to the gap between international market prices and farm-gate prices (see Bachta et al. 2006, Le Gal, Gendre and Rhouma 2007, Le Gal et al. 2009). For example, infrastructure for stocking dates in the region had recently been increased, through subsidies offered by the CRDA for the local installation of additional refrigerators to store dates and transfer them to the markets.

### 5.3.3 The changing economics of smallholder land management

When the observations collected during the survey in 2009 were compared to earlier accounts, it appeared that smallholder farm budgets and associated resource management choices had been affected by a range of factors since 1994. In addition to the increasing cost of water for irrigation, the cost of labour and the use of non-water inputs to cultivation had also been affected. In light of suggestions in previous local investigations (particularly Meddeb 2003), that land management practices may be a key determinant of productivity under water scarce and saline conditions, we examined the possible relationship between the observed changes in the smallholder budgets and their choice of land management practices.

***Changing non-water inputs 1994-2009***

Physical inputs other than water that are required for soil management in oasis cultivation include addition of sand to improve drainage in some areas, application of farmyard manure, chemical fertilizers, insecticides and fungicides (**Table 4.3**). In the 1990s, costs for water inputs were already estimated to represent on average around 50% of the total physical input costs for oasis cultivation borne by individual cultivating households, while water management accounted for around 30% of labour costs.

**Table 4.3: Changing Non-Water Inputs for Oasis Production 1995-2009**

| | 1994 | 2005-9 | Reason for change |
|---|---|---|---|
| **Fertilizers** | FYM/ compost: 1.56 ton/ha x 10DT = 15.6<br>super 45 TSP: 65 kg/ha x 0.238DT = 15.47<br>ammonium nitrate: 115 kg/ha x 0.23DT = 26.45 | 150 DT per load + transportation<br>Phosphate: 50 kg / quarter ha x 24DT = 96 DT/ha | Increased reliance on manure<br><br>Reduced use of agrochemicals for organic market |
| **Other chemicals** | Insecticide: 2 litres/ha x 18.7DT = 37.4<br>Fungicide: 2.4 kg x 25.2DT = 60.48 | Mosquito netting and plastic covers<br>6 DT per tree for plastic rain covering = 600 DT/ha | Plastic covers to prevent rain damage<br>Mosquito netting to reduce insecticide use |

Cultivators interviewed in 2009 described the quantities of each physical input used, other than water, as flexible, and the associated expenditures, to a large extent, determined by the availability of cash, rather than vice versa. Each year, a household will spend as much as it can afford on land improvement and inputs, and will also make use of available in-kind inputs, e.g. manure from animals owned by the family and neighbours. Because the timing and degree of use of these other inputs are controlled by the cultivators themselves, where household budgets are limited, if additional cash must be spent on irrigation water, less is available for investment in agricultural inputs such as land improvement.

The main input for soil improvement described by cultivators interviewed during the 2009 survey, and observed in the field, was manure. In the traditional oasis cultivation model, these costs are avoided through integrating livestock raising activities and composting, however, commercialisation appears to have introduced new practices and increased the scarcity of manure. In the 1994 JICA farm budget survey, market costs of manure were recorded at 10 DT per ton (just under US$10 at 1994 exchange rates), whereas by 2003 this price had already more than doubled (see detailed investigation in Meddeb 2003). Cultivators interviewed during the present survey reported that a tractor load of manure cost 150 DT (US$100), plus the hire of the tractor. The context-dependent cost for transportation of manure to the farm by tractor had become more significant in their calculations than the unit cost of the manure. Thus, both the input cost, and the calculation through which it should be expressed had changed over time, shifting from practices enabling the use of in-kind local resources to a growing requirement for cash investment to maintain cultivation.

Regarding agrochemicals, two contrasting trends were described during the survey**.** On the one hand, those cultivators who have access to sufficient and reliable water supplies, and can afford to do so, said that they routinely used around 200 kilorams per hectare (kg/ha) of phosphate, at a cost of 96 Tunisian Dinars per hectare (DT/ha) (US$126). This is noticeably more than the amount recorded in 1994 (65kg/ha at a cost of 15.5DT or US$15). Also, use of chemical weed killers to reduce unnecessary water consumption was described as an option for coping with increasing water scarcity during the 1990s. On the other hand, cultivators interviewed in 2009 said that more recently they have been reducing their use of chemicals in order to access the organic

export markets. They explained that phosphates are no longer recommended for date production, and the introduction of protective netting rather than the use of insecticides was observed in the field.

***Changing labour inputs 1994-2009***

The most significant cost in the production of dates and other oasis crops during the 1990s was labour. This is usually provided by the cultivators and their families, although it is sometimes contracted to others. In the 1990s, the wage for a day`s agricultural labour in Nefzaoua was 5.2 DT/day (US$5 approx. at 1994 exchange rates), whereas in 2009-10 it had more than doubled, reaching around 12 DT/day (around US$16 at 2009 exchange rates). Over the period 1990-2005, labour has become more expensive in Kebili, as other sectors have increased in size. In 1989, agriculture accounted for 38% of economic activities in the region, whereas in 2007 it had reduced to 34%, while the share taken up by other sectors increased (ODS 2007). This is part of a longer process of reduction in the agricultural labour force due to migration as well as to the growth of other sectors of the economy (Sghaier 1999).

As is inevitable in a voluntary survey, those who were available for interview were likely to be the least occupied in alternative income generating activities, and the information supplied voluntarily concerning income was likely to be underestimated. Despite this, cultivators were rarely working full-time in the oasis, but had other jobs during week-days, were over retirement age, or were students earning pocket-money**.** 66% of cultivators who answered questions relating to income sources during the survey reported another source of income to their household besides agriculture.

These included work in tourism, food processing and real-estate, as well as transporting, storing and processing dates.

While the 1994 study estimated that around 106 man-days per hectare annually were invested in date production, and more for the cultivation of other crops, discussions with cultivators during the present survey indicated that smallscale cultivating households have found ways to minimize labour requirements and/or the amounts paid for them. Overall, a reduction in labour inputs to the various tasks required for oasis cultivation could be observed from the comparison of estimates made in 2009 to figures from the 1990s (**Table 4.4**). This corresponds to the findings of the 2002 survey, which reported that cultivators were frequently investing as little as 25-50 man-days per year (Meddeb 2003).

**Table 4.4: Estimated Labour Requirements for Oasis Cultivation (man days/ha) (JICA 1996 and present study)**

| | 1990s labour for mixed crop system | 1990s labour for date only | 2005-9 labour for date only |
|---|---|---|---|
| **land preparation** | 34 | 28 | 15 |
| **transport seedlings** | 7 | 1 | NA |
| **transplanting** | 30 | 1 | NA |
| **fertilizer application** | 7 | 7 | 7 |
| **weeding** | 17 | 5 | 4 |
| **cleaning of plant** | 10 | 10 | 10 |
| **pollination** | 8 | 4 | 4 |
| **water management** | 36 | 30 | 10 |
| **harvesting** | 49 | 15 | |
| **post-harvest** | 13 | 5 | |
| **TOTAL # DAYS** | **210** | **105.8** | **50** |
| **Daily wage rate (DT)** | **5.2** | **5.2** | **12** |
| **TOTAL COST** | **1092** | **546** | **600** |

The reduction of labour inputs is part of a longer trend identified from agricultural calendars from times when labour was more often exchanged or paid for in-kind (Bedoucha 1987). In the earlier accounts, tasks such as weeding and trimming were undertaken much more often than in the 1990s. On the other hand, the use of chemical weed killer, as described by some agricultural experts interviewed in 2009, was not reported in either of the accounts of cultivation practices predating the most recent decade.

In the 1990s, the largest annual requirement for labour associated with date cultivation was for water management. But as the frequency of irrigation events halved over the period 1994-2005, the requirement reduced correspondingly. With the exception of pollination, most other tasks are flexible in the amount and timing of labour required, enabling smallscale cultivating households to manage them in such a way as to minimize the involvement of hired labour, or to avoid it altogether.

Finally, harvest and post-harvest labour costs are increasingly handled by local middle men. These costs, therefore, do not necessarily occupy the same place in the household farm budget that they did formerly.

## 4.4 Discussion and conclusions

### *4.4.1 Water pricing as a policy response to the economic drivers of degradation 1994-2009*

Our results clearly show a strengthening relationship between international prices for export produce and groundwater extraction (see **Figure 4.4**). Therefore, directing economic measures to address this driver of the land and water degradation problem through water pricing was a logical response. However, as shown in the previous section, not only did the volume of extractions *not* reduce with increasing water prices, but extraction actually continued to rise with international date export prices**.** Furthermore, rather than reducing degradation effects, the price rises led to land management practices which may in fact have exacerbated degradation by reducing smallholder investment in land improvements, increasing agrochemical use, and deepening vulnerability to land degradation.

Our examination of the projected generic smallholder farm budgets for different crops, as calculated during the 1990s, showed that reductions in agrobiodiversity, reduced investments in land improvement and increased use of agrochemicals by some cultivators over the intervening period made a profit in the short term. For those who were able to apply this strategy, the output of dates per unit of water increased, apparently improving the economic efficiency of water use. Soft fruits, on the other hand, generated little or no profit, due to high labour requirements. At the same time, our analysis of local productivity statistics showed that between 1994 and 2005, the variation between the highest (efficient) producers and the lowest increased from a

little over 2 tons per hectare in 1994, when productivity was uniformly low, to vary across a range of more than 20 tons per hectare in 2005. Therefore, the water use efficiency agenda had the unanticipated effect of deepening inequality in terms of productivity.

The 2009 survey demonstrated that where degradation trends had already been affecting smallscale cultivation systems in 2005, by 2009 these effects had gained increased momentum. Effects of degraded water availability and quality hit the GDA members interviewed particularly hard because they depend on the collective distribution systems that are vulnerable to degradation in the timing and quality of irrigation water. Also, the higher the price of water, the greater the need to maximize economic output per unit of input, and therefore, the tighter the relationship of cultivation decisions to international prices became. Thus, although water pricing policies targeted the main driver of degradation, they did not take into account the full range of factors and conditions affecting the economics of small-holder investment in land management practices. Because of this, they are likely to have exacerbated, rather than reduced, land degradation.

While our results would confirm the observation in previous studies, cited earlier in this article, that the smallholders were `inefficient` in terms of economic crop-water productivity – attaining a low and degrading level of economic output per assigned unit of water input- we have also concluded that pricing measures aimed at increasing efficiency led to land degradation, by preventing cultivators from investing in land improvement, conserving crop diversity and supporting food consumption by their

households. These other dimensions of smallholder land management were not assessed in the previous studies focusing on the water use efficiency agenda. However, we found that the past farm budget studies provided a valuable source of information concerning the changing economics of smallscale cultivation and land degradation in this region, enabling such an analysis to be supported in the present investigation.

### *4.4.2. Significance of findings to global literature on land degradation in dryland environments*

The study findings concerning the Nefzaoua experience in the management of international market drivers of degradation have a series of clear implications for the wider literature. First of all, we observed that water use efficiency in crop production is not socially neutral, but can negatively affect economically-disadvantaged smallholders, reducing their land management capacities. Increasing economic water use efficiency tightened the profit margins in groundwater-irrigated oasis agriculture, and impacted smallholders` ability to invest in land management. We observe that alteration of the economic incentives for cultivators practicing traditional cultivation and resource management methods can exacerbate land degradation while failing to curtail over extraction. This observation must be taken into account in ongoing discussions of water use efficiency.

Second, our study has clearly demonstrated that use of datasets from sustained monitoring of local productivity, in conjunction with independent field investigations, can enable the tracking and analysis of trends in land degradation. However, field

observations confirmed that the activities of the private sector were not fully reflected in the official statistics, and that `illicit` cultivation activities, as well as water use in other sectors, were increasingly compromising the accuracy of official resource management datasets, necessitating the cross-checking approach.

We agree with previous studies arguing that measures to address the international economic drivers of land degradation can only be effective where there are sufficient institutions in place to monitor and manage these trends (Kumar 2010). We note that in many other dryland regions such institutionalized environmental data collection systems have never been in place at all. We therefore further recommend that international market-oriented development strategies must be underpinned by strategic policy action to ensure systematic provisions for environmental monitoring, within an integrated cross-sectoral local resource management framework.

The emergent organic sector, as observed in the Nefzaoua case, appears to offer potential to ensure a premium for sustainable production methods practiced by smallholders. This could provide a basis for payments to support ecological cultivation methods. Local decision-makers and cultivators interviewed during our survey expressed interest in this approach, underlining the centrality of traditional land management practices to the family-oriented culture of the Nefzaoua region, and the social value of promoting them. However, as yet, provisions for the generation of local environmental and social information through the organic export regimes are limited to selected producers, and do not systematically strengthen local resource management capacities. Further attention to this issue at the international level may

be useful to better enable local decision-makers to maximize strategic opportunities in response to degradation threats driven through international market development.

### 4.4.3 Conclusions

This study in the Nefzaoua region confirmed that the economics of international export production had driven land degradation over the period 1994-2009. At the forefront of the dryland horticultural export sector, the Nefzaoua region appears to be undergoing a shift in management objectives from water-use efficiency towards a more holistic agenda for sustainable land management. Strategic local and international action to support systematic monitoring of social and environmental trends will be essential to support this transition. Within the wider global literature on sustainable land management and development, the generalization of this recommendation is particularly pertinent to the articulation of forward-looking strategies to build in and ensure environmental and economic development benefits from the agroindustrial transition, while avoiding potential land degradation outcomes.

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Mamou, Observatoire du Sahara et du Sahel and Dr. Brahim BenBaccar, Direction Generale des Resources en Eau (DGRE), Tunis and M. Aissa at the CRDA in Kebili.

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Participants in the 9th conference on Desert Technologies, organized by IRA, 11-16 November, 2008, and the International Colloquium on Societies in Transition and Local Development in Difficult Zones (DELZOD), organized by IRA, 22-24 April, 2009, provided insights and reflections on current policy debates.

# CHAPTER 5: WESTERN EGYPT CASE STUDY

## 5.1 Preface and abstract

### Preface

A second in-depth case study is presented in this chapter. The chapter is based on a paper submitted to AMBIO: a journal of the human environment.[15] In comparison to the interdisciplinary case study presented in chapter 5, here the focus shifts towards a more human-centred investigation of a socio-ecological change process. Whereas chapter 4. addressed changes in landcover, and chapter 5. considered land degradation, which was caused by over extraction of groundwater, in this chapter, more emphasis is placed on the groundwater resource and its management by the human population. The degradation of land and groundwater is viewed through a multidisciplinary lens, placing it in the perspective of international environmental research and policy.

Whereas six villages are included in the previous case study, this case study chapter focuses on a single village in the Western Desert. As described in chapters 1 and 2, research in Egypt focused on the Northern oases of Siwa and Wadi El Natroun, in which biophysical conditions are the most similar to the those in the Southern Tunisian oases. At the time of the 1961 agricultural census, the cultivated areas in these two oases were 1,072 hectares and 191 hectares, respectively year (UAR 1961). By 2010, the cultivated area in Siwa had more than tripled in size, reaching an extent of 3,833 hectares. Over the same fifty year period, the cultivated area of Wadi El Natroun had

[15] see http://www.springer.com/environment/journal/13280

increased to fifty times its original size, extending to cover 9,200 hectares by 2010. One of the fastest-growing areas on the outer edge of Wadi El Natroun is the village of Beni Salama. Over the period 2000-2010 the average annual increase in the cultivated area was over 216 hectares per year (based on MALR 2000 and personal communication from MALR). In addition to the final paper, further findings from the field survey are included in appendices 3, 6 and 7.

Smallholders` adaptations and alternative livelihoods are investigated in this chapter, drawing on the socioeconomic survey findings, and also taking into consideration institutional disconnects encountered during the survey implementation. The chapter raises some key issues, subsequently addressed in chapter 7, and in the concluding discussion of the thesis, concerning the management of groundwater degradation threats emerging through the acceleration of private market-oriented development processes. The observations presented include consideration of the smallholders` role as agents in the environmental degradation process which is explored as a tragedy of the groundwater commons. The discussion introduces a Common Pool Resource management (CPR) perspective.

It is argued that in order for CPR management to be effective, the engagement of both private investors and smallholders in a CPR management framework enabling collective environmental monitoring activities is needed. The concluding discussion highlights the importance of shared knowledge and trust to harmonize the social

drivers within the socio-ecological resource management process. In order to pursue this argument further, in chapter 7, a synthesized economic representation of the case study findings is presented.

**Title**

A socio-ecological investigation of options to manage groundwater degradation in the Western Desert, Egypt

**Authors: Caroline King and Boshra Salem**

**Abstract**

Under increasing water scarcity, collective groundwater management is a global concern. This paper presents an interdisciplinary analysis of this challenge drawing on a survey including fifty 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*

## 5.2 Introductory sections

### 5.2.1 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 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 ensure future generations against the effects of climate change (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 (Falkenmark 1981, Kovacs 1977). The privatisation 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 2005, Giordano 2007, Shah 2009).

A socio-ecological conceptualization of groundwater systems and their management, following the principles of Folke et al (2002, 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 CPR, effective self-organization and adaptive management requires mutual trust, cooperation and sharing of information to be established amongst different groups of resource users regulation (Ostrom 1990a, 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 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 2002b). 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). However, increasing groundwater extraction has been driven by land reclamation activities around the old cultivated areas to the West 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 in order 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 CPR 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` (vanAchthoven et al. 2004). A rare internationally published `success case` of self-organization amongst investors in a land reclamation area to the East of the Nile Delta quickly failed (van Steenbergen 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. In order 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, Dangles et al. 2010, Gebrehiwot, Taye and Bishop 2010, Stringer et al. 2007). Nevertheless, despite some promising exploration of the social dimensions of groundwater use in other regions (Mukherji 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).

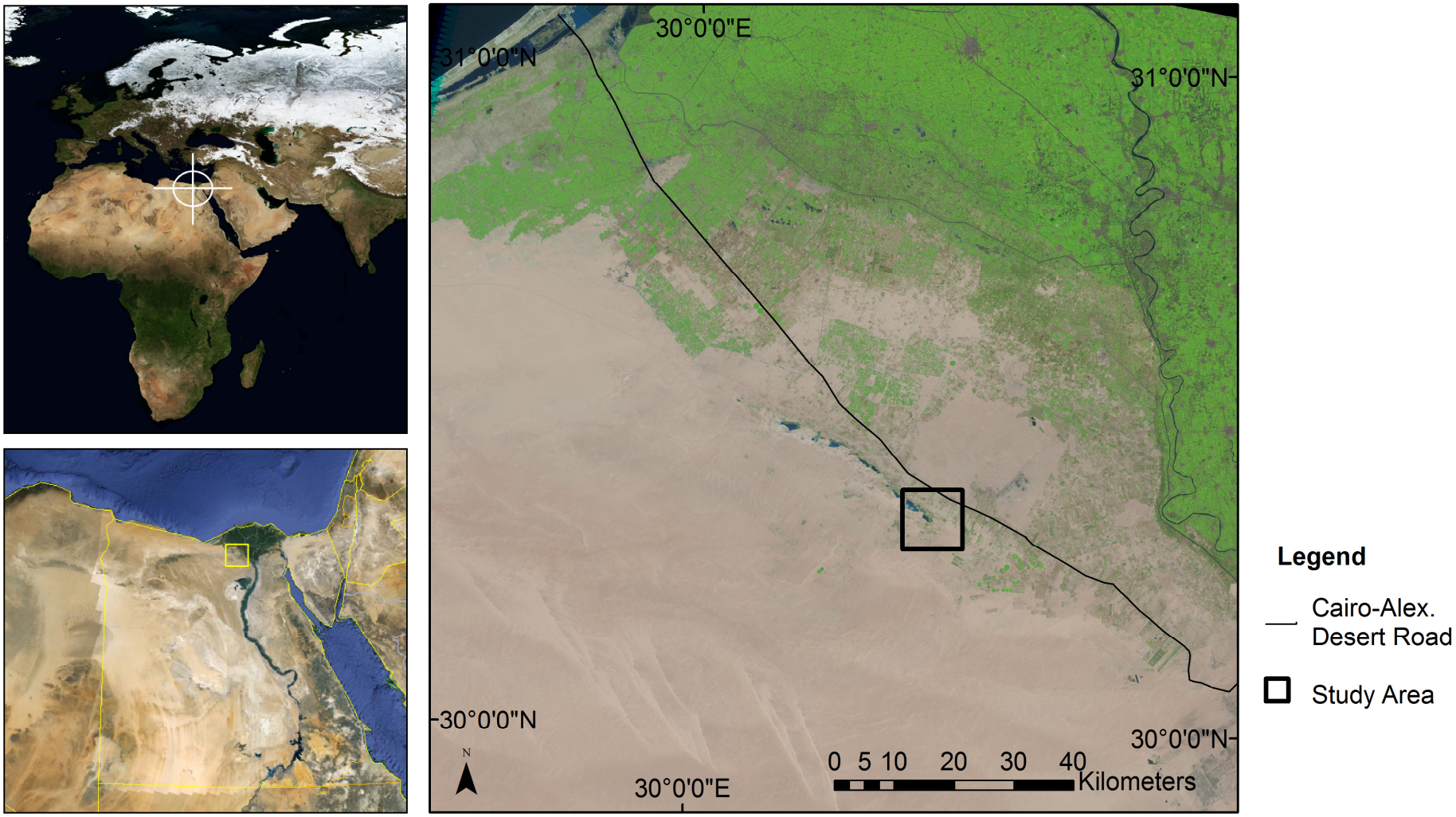
The focus on the perspectives of land and water users in this investigation is reflected in the use of local measurement units for the quantification of landholdings. The Egyptian feddan (0,42ha) is a socially important unit of spatial measurement, representing a minimum size of land needed to support a family (see Mitchell 2002p114-5 and 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 in order to enable both the social significance of the land areas and the physical dimensions to be intelligible to an international readership.

### 5.2.2 Study Area

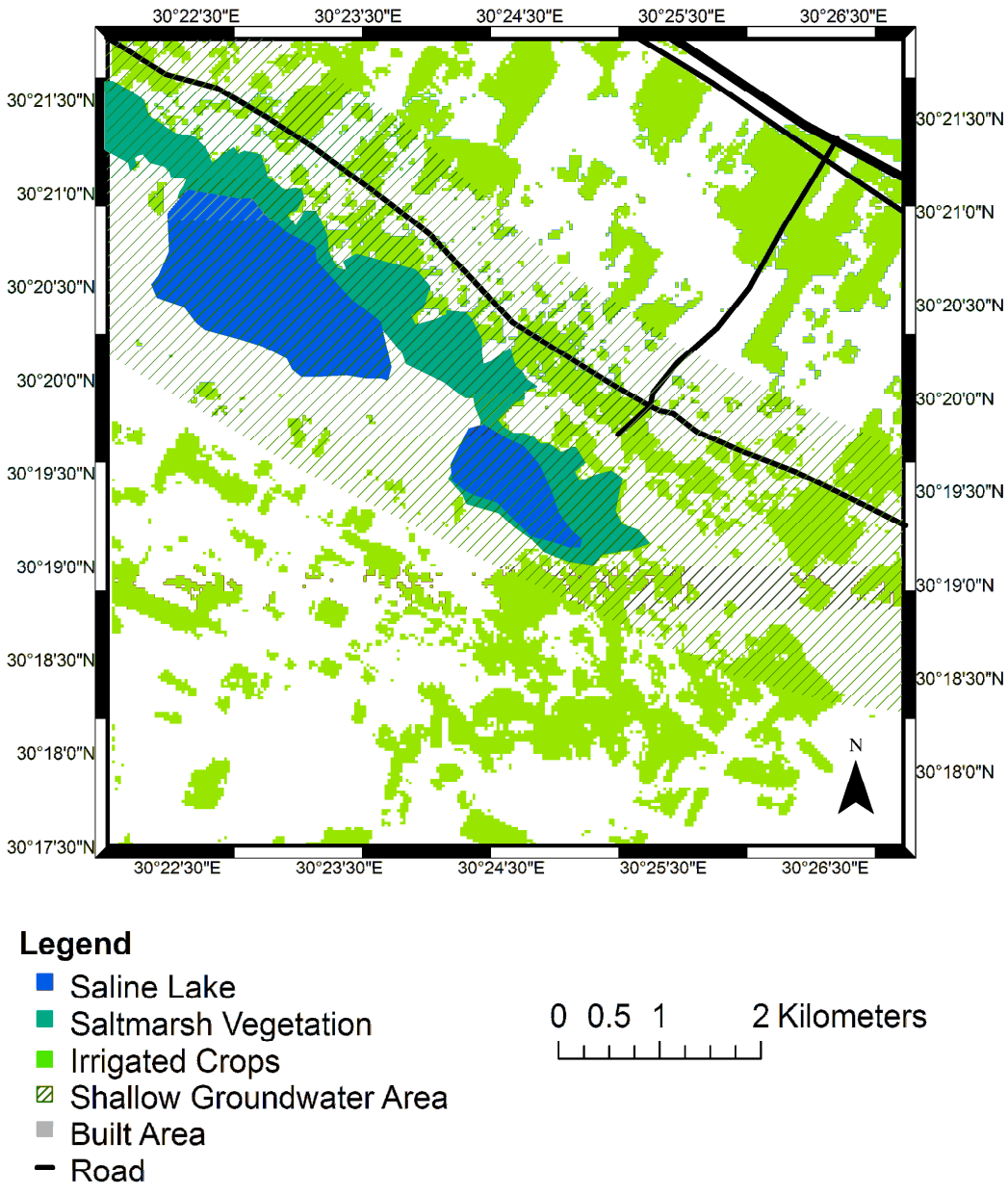
The village of Beni Salama is located on the edge of Egypt`s Western Desert (**Figure 5.1**). It is situated in the Beni Salama depression, which is a subsection of the Wadi El Natroun Depression (lowest point 23m below sea level). The depression ensures a relatively sheltered climate, in contrast to 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 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)**.**

**Figure 5.1: Location of the Study Area, Western Desert, Egypt**



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) (**Figure 5.2**).

**Figure 5.2: Land Cover in the Study Area, 2010**



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 towards 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. less than 3 feddan (1.26 hectares).

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 Natroun 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 Behaira, 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 electricity supply for pumping groundwater are mutually reinforcing: in order 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.

Because 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.

### 5.2.3 Research Methods

The study incorporated a review of fifty years of hydrogeological studies, analysis of forty years of satellite land cover imagery, a survey including fifty cultivated landholdings of varying sizes (ranging from large farms of close to 1000 feddan (420

hectares) to small gardens of less than one feddan (0.42ha) and six 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 2008-10, 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 area (Ahmed et al. 2002, El Bastawisy 2006, Salem 2008a). Initial field visits were made to the study area in order 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 5.1**).

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 smallscale 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 5.1**). This typology included a category of farms and gardens of less than 3 feddan in size (1.26 hectares), 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. Because the selection was discussed with local people, the sample may have been biased towards 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.

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.

**Table 5.1: Typology of Cultivation in Beni Salama and Surveyed Farms and Gardens**

| Farm size in feddan (equivalent in hectares) | Locally estimated % of farms | Locally estimated # 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 (2,100 ha) | 2.86 | 18 |
| 20-100 (8.4-42 ha) | 60% | 1200 | 36000 (15,120 ha) | 47.73 | 8 |
| >100 (>42ha) | 5% | 100 | 16000 (6,720 ha) | 48.77 | 8 |
| **TOTAL** | **100%** | **2000** | **57400** | **100** | **50** |

1 feddan = 4200$m^2$ = 0.42ha = 0.0042$km^2$

**Physical Data Compilation and Analysis**

Information in grey literature on older wells dating back to the 1950s was also 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 approximately 1 meter per year and an estimation of the annual volume of groundwater extraction for irrigation was made, based on the per hectare water requirement ($50m^3$/ha/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 30m 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)[16]. Additional images taken with the ETM+ sensor (1999-present) were also used. The 8x8km 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. 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).

[16] http://edcsns17.cr.usgs.gov/NewEarthExplorer/

NDVI is used globally as a basis for discriminating between irrigated and non-irrigated lands in arid areas (Thenkabail et al. 2009, Luedeling and Buerkert 2008)[17]. 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 trend line for total NDVI across the study area over the period 1985-2006. Due to the coarse spatial resolution of this dataset, the entire 8x8km 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/) in order 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

[17] 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.

was mapped in order 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 MWRI, 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 Natroun and the Groundwater Management Office in Tanta. 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.

## 5.3 Results

### 5.3.1 Changing groundwater conditions in the expanding agro ecosystems

During the 1970s-80s, Beni Salama village was collectively irrigated from a well provided by the government. Local 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 (**Figure 5.3** and **Figure 5.4.**). 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 8x8km study area around Beni Salama more than tripled over this period (**Figure 5.3**), 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 slowing.

**Figure 5.3: Changing Land Cover Around the Study Area 1990-2005 (August-September, USGS Landsat)**

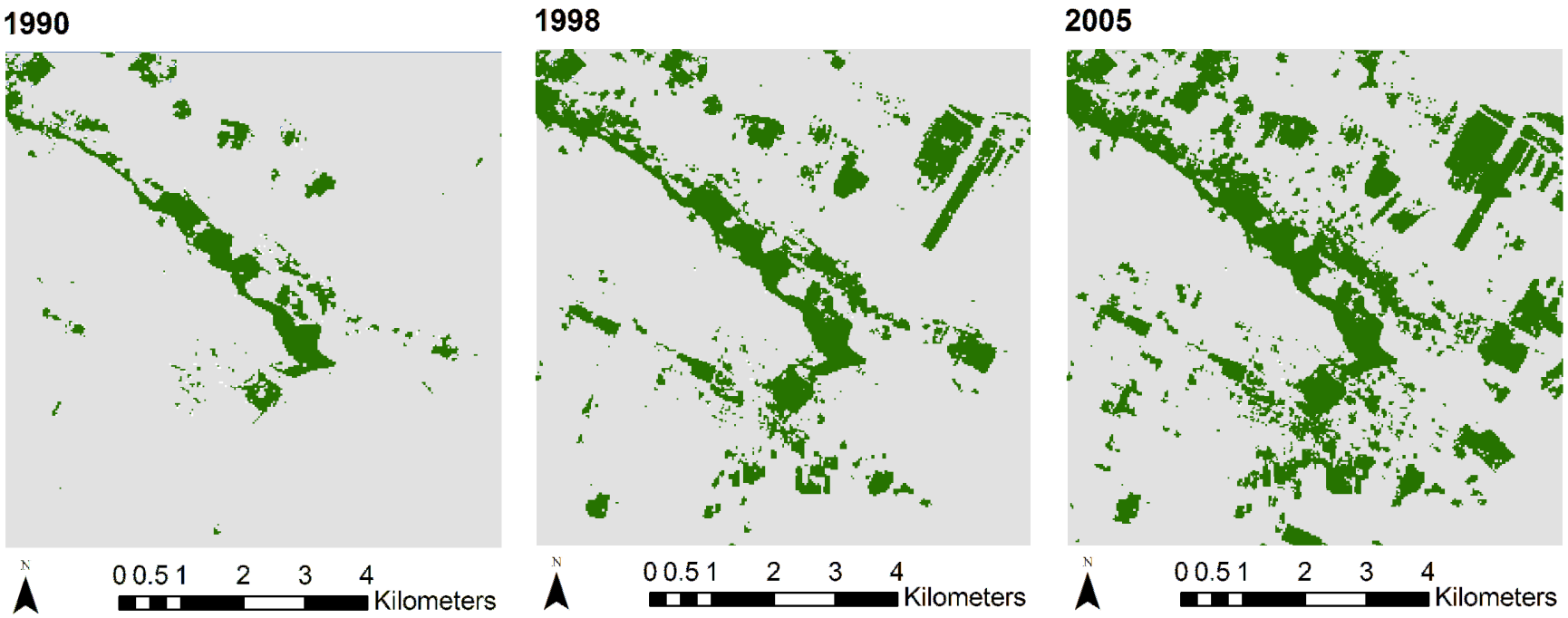
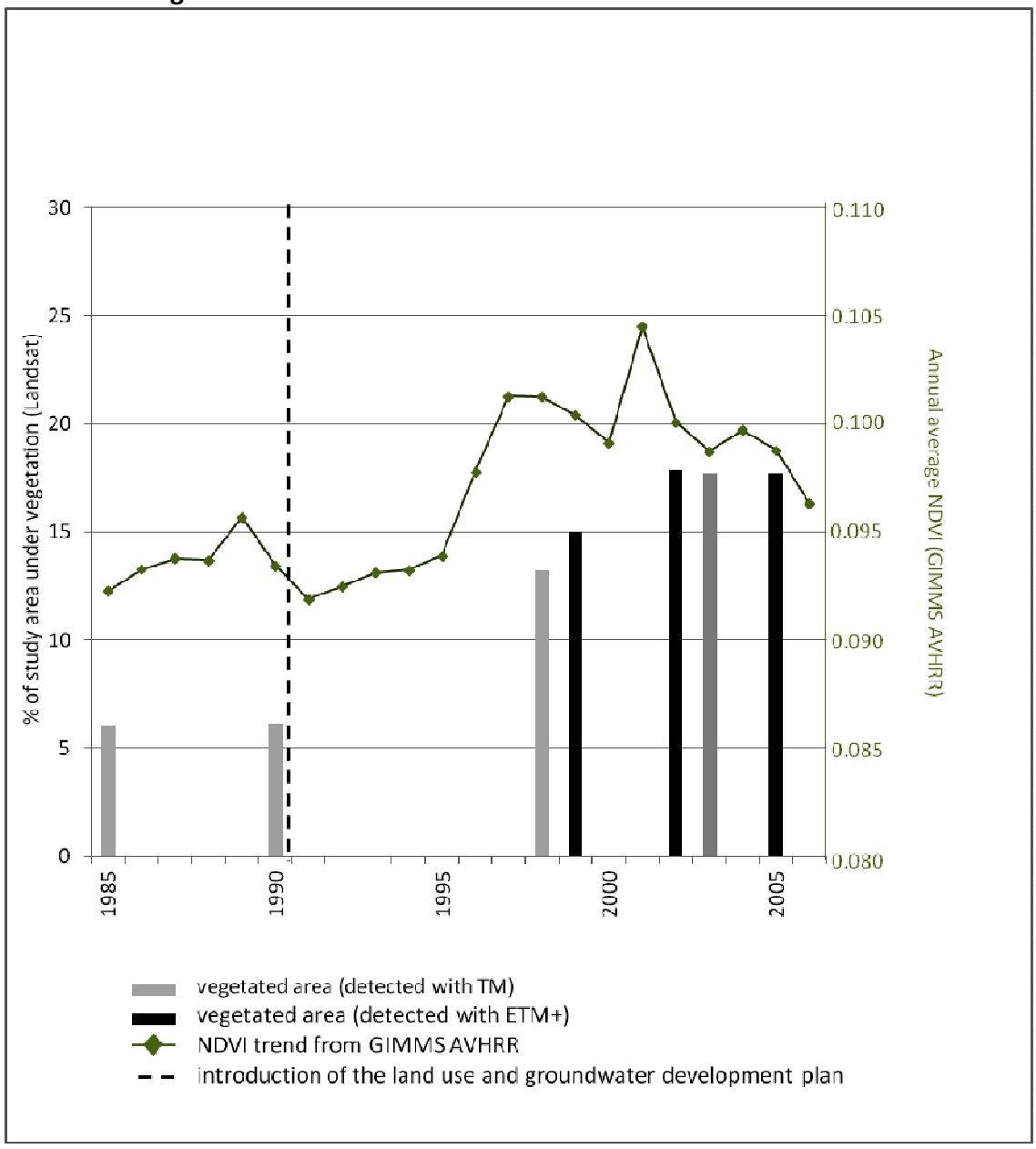


**Figure 5.4: Trend in NDVI in 8x8km Study Area Visible in Landsat* and GIMMS AVHRR** images**




* high resolution, low frequency
** low resolution, bi-monthly frequency shown as annual average

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 5.2**). 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 2008-9, 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. Salinity, indicated by the range of Electrical Conductivity (EC) in the deep wells was slightly larger than it was in the shallow wells**.** 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 exceeded the thresholds for effects on soft fruits (**Table 5.3**). These are the most profitable commercial crops in the study area.

**Table 5.2: Summary of 2009 Survey Observations and Collected Groundwater Datasets**

| | | ***Large Farms >100 feddan*** (>42ha) | | ***20-100 feddan*** (8.4-42 ha) | | ***3-20 feddan*** (1.26-8.4 ha) | | ***<3 feddan*** (<1.26 ha) | |
|---|---|---|---|---|---|---|---|---|---|
| **Data source** | **Area** | ***north*** | ***south*** | ***north*** | ***south*** | ***north*** | ***south*** | ***village*** | ***south*** |
| | | | | | | | | | |
| Cultivators` responses to questionnaire survey (no physical measurements) | **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*** | D | D | D | D=3 | F>S>D | D/S | F>S>D | F=D=S |
| | | | | | | | | | |
| Other datasets (physical measurements) | **Groundwater EC (µS/cm$^{-1}$):** | | | | | | | | |
| | **source** | (MWRI monitoring March 2009, n=7) | | | | (NA) | | (Owners 04 2010, n=12) | |
| | **min** | 1072 | | | | | | 1087 | |
| | **max** | 7220 | | | | | | 5000 | |
| | **mean** | 3586 | | | | | | 2458 | |
| | **Std dev** | 2610 | | | | | | 1054 | |
| | | | | | | | | | |
| questionnaire survey (no physical measurements ) | ***Changes (% of surveyed):*** | | | | | | | | |
| | **Falling water table %** | na | 100 | 50 | 50 | 90 | 100 | 80 | 80 |
| | **Salinization %** | 100 | 75 | 80 | 0 | 50 | 75 | 71 | 0 |

*Irrigation Methods: D = Drip, S = Sprinkler, F = Flood

**Table 5.3: Characteristics of Selected Commercial Crops** (FAO 2002)

| Common name | Latin name | Local harvest period* | Threshold | | | Reduction in productivity | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *EC* 1000 $\mu S/cm^{-1}$ | Slope % per 1000 $\mu S/cm^{-1}$ | Sensitivity rating | 0% EC | 10% EC | 25% EC | 50% EC | Maximum tolerance |
| **date palm** | *Phoenix dactylifera* L. | October | 4000 | 3.6 | T | 4000 | 6800 | 1090 | 17900 | 32000 |
| **olives** | *Olea europaea* L. | Sept Oct | 4000 | 3.6 | T | 4000 | 6800 | 1090 | 17900 | 32000 |
| **guava** | *Psidium guajava* L. | Sept Nov | | | MT | 2700 | 3800 | 5500 | 8400 | 14000 |
| **fig** | *Ficus carica* L. | | 4700 | 9.8 | MT | | | | | |
| **pomegranate** | *Punica granatum* L. | | | | MT | 2700 | 3800 | 5500 | 8400 | 14000 |
| **grapes** | *Vitis vinifera* L. | June July | | | MS | 2700 | 3800 | 5500 | 8400 | 14000 |
| **mangoes** | *Mangifera indica* L. | July | 1500 | 9.6 | MS | 1500 | 2500 | 4100 | 6700 | 12000 |
| **apricots** | *Prunus armeniaca* L. | June | | | S | | | | | |
| **pears** | *Pyrus communis* L. | August | 1600 | 24 | S | | | | | |
| **peaches** | *Prunus persica* (L.) Batsch | May June | | | S | | | | | |
| **orange** | *Citrus sinensis* (L.) Osbeck | | 1700 | 21 | S | | | | | |
| **alfalfa** | *Medicago sativa* | | 1300 | 13.1 | S | 1700 | 2300 | 3300 | 4800 | 8000 |

* note: harvest periods based on local observation and AFD (2008)

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

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.

### *5.3.2 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. In order 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$/hectare[18] on farms in the 20-100 feddan (8.4-42 hectares) grouping, and 1,516 US$/hectare[19] on farms above 100 feddan (42 hectares) in size. On these farms, each well will irrigate approximately 40 feddan (16.8 hectares), therefore each one would have generated a

[18] 11,572 Egyptian Pounds (LE) per feddan
[19] LE 16,252 per feddan

net income of US$18,144 or US$25,469 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$5,000.

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 the present survey. More recent estimates of the annual income of the largest horticultural export farms in the West Nile Delta are around US$1680/hectare (World Bank 2007). If we retain the assumption that a well serves 40 feddan (16.8 hectares), 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$1,000[20]. However, in the farm budget study, referred to above, farms of 3-20 feddan (1.26-8.4 hectares) were shown to only generate an average annual income of 259 US$/hectare, 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 land-holding 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 one feddan (0.42 hectare) 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 20-75% of the household food needs. Food

[20] The cost of a well was estimated by smallholders at around LE 5-6,000. The conversion is made using an exchange rate of 5.5 LE to the US$

expenditures commonly accounted for approximately 95% of reported household income, which was around US$329[21] per month (**Table 5.4**). On a per capita basis, the average reported income was around US$27/person/month[22]. 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.

[21] LE 1811.8 at an exchange rate of 5.5 LE/US$
[22] LE 148.2 per capita, at an exchange rate of 5.5 LE/US$

**Table 5.4: Monthly Income and Economic Activities Reported During the Survey**

| | Household size | % household income spent on food | Household reported income (US/month*) | 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** | | **30800** | **2371.8** | |

* using 2009 exchange rate: 5.4754 LE/$US

Locally available sources of income other than farming mainly consisted of working on the surrounding farms as labourers, 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 labour 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 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**.**

## 5.4 Discussion and conclusions

### 5.4.1 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 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 management (after Ostrom 1990a, Schlager 2007, Shah 2009, etc), as explored in this paper, raises the question of the ability of local residents, smallholders and farm-workers to self-organize in order 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 *`ᶜurf`*, around the saline drainage lake *`mellahah`* close to the centre 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 management theory, as introduced in the early sections of this paper (after Ostrom 1990a), 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 paper. 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 twenty 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 amongst 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 to commercial farming for exploitation. 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, were 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 (RIGW 1990).

With regard to the state and trends in the deep aquifers, the MWRI 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. Since 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 for their knowledge of these factors.

Following the CPR management logic, an approach in which privately generated data 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 by the MWRI. 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, MWRI and other Agencies, and no systematic use was yet being made of the available dataset to support ongoing public decision-making, through self-organizing CPR management, 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 modelling 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 to this paper, quite a number of previous studies have demonstrated the relevance of social methods to address environmental problems (Mukherji 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.

### 5.4.2 Conclusion

The case investigated in this article concerning land and groundwater degradation threats in Beni Salama intersects with the current literature on CPR 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 CPR;
- 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 system for deep groundwater extraction, and the low-tech informal shallow groundwater recycling regime were preventing effective local self-organizing resource management

In order 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 neighbours and employers. They also have a direct interest in doing this, since 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 CPR 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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# CHAPTER 6: SYNTHESIS OF DEVELOPMENT POLICY IMPLICATIONS

## 6.1 Preface and abstract

### 6.1.1 Preface

This chapter synthesizes the socioeconomic findings of the investigation, and is based on a paper submitted to *World Development,* a multi-disciplinary journal of development studies[23]. The chapter reconsiders development strategies proposed for the study region, which focus on the opportunities created through the development of agricultural export markets. The chapter asks why these strategies do not appear to have succeeded in reducing poverty, environmental degradation, and lack of popular participation in economic and political life, and how these continuing problems could be addressed.

The development concerns addressed in this chapter concern `social and economic processes of change involving nations, economies, political alliances, institutions, groups, and individuals`. The chapter explores these processes occurring at a range of scales inside the family, the agroindustrial firm and the farm; locally, provincially, nationally, and globally. The consideration of these issues is presented with a view to the international development debate, rather than focusing on regional concerns. The world view is global, both in the problem definition - in terms of the international export markets -, and also in the solutions. A more concentrated examination of global market-oriented development strategies is presented, whereas, these themes appear only peripherally to the discussion in chapters 4 and 5.

[23] see://www.elsevier.com/wps/find/journaldescription.cws_home/386/description.

The synthesized findings of the two case studies address not only the relatively low level of income generated by smallholders through cultivation or alternative activities, but also the loss of long term income generating opportunities through environmental degradation, and loss of participation in resource management through smallholder institutions. The overall tenor and articulation of messages is intended to reach decision-makers beyond the circle of environmental scientists with a predetermined interest in the study region. The condensed analysis is forceful in connecting the environmental degradation problem to the development policy agenda. Environmental degradation is presented in simplified economic terms. Institutional breakdown is visually illustrated. This approach to analysis is further considered in the discussion section of the thesis.

**Title**

**Why don't resource dependent smallholders benefit from global export market development?**


**Abstract**

Recent international development strategies have built on the assertion that in a global market economy, resource scarcity can lead to innovation, enabling development benefits for resource dependent populations. This theory has provided a basis for a New Institutional Economic (NIE) approach in international development policy. This agenda is explored drawing on the experiences of resource dependent smallholder cultivators in the marginal desert regions of Western Egypt and Southern Tunisia in the Northern Sahara. In both countries, we observe that NIE policies refer to regional Common Pool Resource (CPR) management traditions to illustrate the precedents for institutional responses to scarcity. However, at the same time, these policies constrain the CPR management functions of existing smallholder associations. This situation has permitted the alienation of the smallholders` resource bases and limited the achievement of the anticipated development benefits. The global market-oriented development agenda could do more to reengage CPR management principles and practice, both locally and from the global level.



**Keywords:** *Smallholder; Common Pool Resource (CPR) Management; Global Agricultural Export; Egypt, Tunisia; North Africa*

## 6.2 Introductory sections

### 6.2.1 Introduction

Market openness is widely believed to drive innovation and resilience under resource scarcity (e.g. Collier 2007, IBRD 2010, Bekaert 2011). In marginalized, water-scarce areas, where the largely State-led Green Revolution and other rural development agendas failed to take root, export-oriented development strategies are now proposed to support development (WDR 2007, IBRD 2007, Molden 2007, Lipton 2010). Improvements in income generation for marginalized groups of resource dependent smallholders are anticipated. These are expected to arise either through the creation of new high value markets for their produce, or through increased employment opportunities in agro industries and other associated sectors of the economy with rising GDP. In this article, we set out to question this assumption. The aim is not to argue against global trade with resource scarce regions, but to consider why existing institutions in these regions, and globally, have not yet achieved the anticipated development benefits to smallholders from their export-led development strategies.

Previous analyses have explored the question as to why the global markets do not benefit smallholders in terms of cash income (see e.g. Raynolds 2004, Reardon 2009, Wiggins, Kirsten and Llambí 2010). These critiques have focused primarily on the problem of smallholder farmers` access to the global markets in order to obtain higher prices for their produce. As a result, development projects increasingly incorporate efforts to improve smallholder market access for income generation (e.g. IFAD 2008). However, as global understanding of development shifts (see e.g. Stiglitz, Sen and

Fitoussi 2009), the nature of development benefits sought from the global markets to resource dependent smallholders requires refocused attention.

Attention to tradeoffs between increased income on the one hand, and losses of natural resource and social capital on the other, is noticeably absent from recent contributions to the debate on emerging market-oriented development strategies (Henson, Masakure and Cranfield 2011). In the development literature, measures of natural resource availability, subsistence use value and social security in the form of naturally sustained food and water supplies are rarely considered. A relatively progressive approach proposes that these assets might be partially considered in the future as an intangible capital residual (World Bank 2006). Participation in resource management decision-making is well-recognized as a key dimension of development status in resource scarce environments (Pretty and Ward 2001, Cleaver 2005, Blaikie 2006, Krishna Prasad Adhikari 2010). However, the effects of export-oriented development strategies on the function of local resource management institutions evade measurement, and therefore have not been comprehensively assessed (an interesting illustration of this point is presented in Mustafa and Qazi 2007).

In this investigation, we seek to reconnect international development strategies focusing on export-led development to the literature on CPR management. The analysis focuses on current global development strategies targeting resource dependent populations in water-scarce environments. Recent development strategies (e.g. IBRD 2007) have placed a strong emphasis on the essential role of institutions in managing resource scarcity, drawing on CPR management theory to support the

argument that resource scarcity can lead to innovation where effective institutions are in place (Wade 1988). These ideas provided the basis for a New Institutional Economic agenda that emerged over the recent decades in international development research and practice (Nabli and Nugent 1989a, North 1990, Bardhan 1989). In this paper, following the distinctions drawn in contemporary usage in the development field, we consider institutional arrangements consisting of organizational structures, while the institutional environment consists of the rules governing the behaviour of actors (after North 1990, further conceptual discussion is presented in Pahl-Wostl 2009).

Following a review of the theoretical work in the CPR management literature, and its use to underpin international development strategies in this environment (IBRD 2007). we examine the trajectories of a series of associations of smallholder cultivators in the resource scarce environment of the Northern Sahara. The wider institutional environments, includes national systems allocating land rights, groundwater extraction permits and payments to regulate natural resource use. The observations on which the paper is based are drawn from field research conducted in the Governorate of Kebili, in Southern Tunisia, and the Governorates of Matrouh and Behaira in the North of the Western Desert of Egypt. The essential scarce natural resource under consideration is groundwater. Observed effects on smallholder cultivator associations in the two cases, and effects on incomes are examined in section 6.3. National and global strategies are discussed in section 6.4.

### 6.2.2. Institutional approaches for development and innovation under resource scarcity

Under all environmental conditions, critical research tends to suggest that benefits to smallholder cultivators are underachieved. This is partly due to the lack of critical mass and capital investment that is inherent in smallholder cultivation. Two main themes have appeared in the general literature, both aiming to address this problem. One focuses on market access for smallholders directly - through strengthening the institutional arrangements for fair trade (e.g. Raynolds 2009, Barham et al. 2011). The other accepts that smallholders cannot benefit from direct access to global markets, and instead argues that they should benefit from `knock-on` benefits provided by other producers` contributions to economic growth (see e.g. Henson et al. 2011).

The rationale of export development based on resource extraction from fragile environments has been called into question through a number of contributions to the environmental economic literature (Bardhan 2006, Barbier 1997b, Aggarwal 2006). These studies have argued that the allocation of resources to high value export uses has to be weighed against alternative resource needs for subsistence, basic food production and existing resource dependent livelihoods. Methodological approaches required to present such analyses to policymakers are gradually emerging through the literature on environmental services (e.g. Croitoru and Sarraf 2010, Bolt et al. 2005). However, these methods rely on the use of nationally available data sets that mask effects on resource dependent smallholder cultivators, since these effects are indistinguishable from regional trends in areas dominated by larger agro industrial resource users.

Our analysis of global market benefits under resource scarcity proposes to reconnect the literature on export-led development to the notable body of scholarship on CPR management (Ostrom 1990b, Pahl-Wostl 2009). This theoretical literature addresses the theme of resource use under scarcity and population pressure, for example, proposing, a curvilinear relationship whereby collective organization increases with resource scarcity initially, but becomes more difficult under extreme scarcity (Araral 2009). Since the 1990s, this work has become increasingly influential in development policy-making (Mustafa and Qazi 2007, Wade 1988). In this article, we are primarily concerned with groundwater users in North Africa. In this context, CPR theorisation of institutional mechanisms for managing scarce water resources, refers back to the longstanding traditions of collective resource management in the region (see Attia 2002b, CEDARE 2006, MWRI 2005). These reference points have provided the basis for arguments supporting a New Institutional Economic agenda (IBRD 2007).

The institutional elements of local innovation, enabling populations to manage pressures on scarce resources, have been explored extensively in various regions since the 1960s and 70s (Chambers 1971, 1974, Brokensha, Warren and Werner 1980, Ruttan 1989, Adams 1996). The basic principle, countering the inevitability of Malthusian effects anticipated from population growth, is often attributed to Esther Boserup (1965) for her work in Sub-Saharan Africa. The nature of innovations considered in these investigations has been both technological and social. In North Africa, however, scholarly contributions have tended to focus on the technological

dimensions of innovation (e.g. Tomich 1992), shifting the definition of scarcity constraints through the modernization of irrigation and drainage technologies, rather than institutional solutions. Global development scholars have characterized this North African regional development model as `agrarian` (Shah 2009). Criticisms have focused on a troubling perceived dialectic between the central authority and the interests of local associations (e.g. Attia 2002b) This perspective corresponds to more anthropologically oriented development studies in other regions (Mosse 1997, Mosse 2006).

CPR management principles and examples have recently been reengaged in international development strategies to support the argument that groups of smallholder cultivators can self-organize to achieve the necessary critical mass to compete directly in a global market-place, access seasonal finance and determine prices (Poulton, Dorward and Kydd 2010). Under the resulting fusion of CPR management and NIE development theories, smallholder associations are expected to manage their own water allocations, maintain infrastructure and pay the cost of any water supply services provided by the State (Agrawala and Fankhauser 2008). They must also overcome the scale challenge in order to achieve marketing, logistical and other requirements for participation in global export markets. If they are to do this, they must perform more like private firms than traditional social institutions.

The global export-development literature considers the growth of market-oriented village associations (e.g. Bernard et al. 2008), but does not weigh these gains against

the loss of the broader development focus, including CPR management responsibilities, in the traditional community institutions. Thus, the emphasis on income generation and market access for smallholders obscures the broader need for strategic institutional frameworks to address long term local resource and development impacts driven by the global markets (see e.g. Mustafa and Qazi 2007). The relations between agricultural export market development strategies, escalating resource scarcity and smallholder benefits achieved through institutional arrangements in the NIE environment in North Africa have been viewed as critical, but opaque over the past two decades (see e.g. Biggs 1990, Kuper et al. 2009, Shah 2009, Hammani et al. 2009).

### 6.2.3. Research setting in the northern Sahara and methodology

Research findings on which this paper is based were collected through a period of field investigations conducted in 2008-9 in the Governorate of Kebili in Southern Tunisia, and in the Governorates of Matrouh and Behaira in the North of the Western Desert of Egypt. In each country, the selected areas included both a relatively accessible area, and a relatively inaccessible area. The Southern Tunisian Delegation of Kebili North is adjacent to the Governorate capital, while the Delegation of El Faouar is 70km away by road. The subdivision of Beni Salama in the North Western Desert is adjacent to the main highway connecting the cities of Cairo and Alexandria, while the subdivision of Siwa in the Western Desert is 300km from the Governorate capital of Matrouh (See **Figure 1.1**).

National plans for desert reclamation and irrigated cultivation have been pursued in these areas. This has contributed to national development objectives in both countries, enabling the settlement of growing human populations and the extension of service provision for improved quality of life (World Bank 2007). Although at the national level, other sectors have grown more rapidly over recent decades, irrigated agricultural production is still considered to provide the mainstay of the local economies in the marginal desert areas. In the year before the field investigations, it was estimated that around the most developed area on the edge of Egypt`s Western Desert, close to the Cairo-Alexandria Desert Road, every hectare of land reclaimed for export horticulture production generated an annual contribution to the economy of US$4667, plus the creation of 2-3 permanent jobs (Hassan 2005, ODS 2007, Handoussa 2010).

Until the 1980s, the land development processes and markets for agricultural produce were government-controlled in both countries. Tunisia and Egypt joined the World Trade Organization (WTO) in 1994 and 1995, respectively. Tunisia immediately created a Free Trade Zone with the EU. Egypt did the same in 2004. As international market liberalization took hold, cultivation patterns shifted, and land development accelerated. From the 1980s, technologies for private well digging became available, causing numbers of wells to accelerate rapidly (Kassah 1996b, Khater 2003). Rapid growth took place in the extent of the cultivated areas in both countries. In 1987, healthy mature date palm covering an area of 10,942 hectares could be identified in Kebili region in southern Tunisia. In the same year in the North Western Desert of Egypt, a total of 6,970 hectares could be detected in the cultivated oases of Siwa and

Wadi El Natroun, combined. By 2003, a 44% increase in the densely vegetated area under irrigation had taken place in Kebili, and a 153% increase had taken place in the two Northern oases of the North Western Desert.

The traditional export products from the Northern Sahara, dates and olives, are increasingly popular as health-inducing luxury food items on international markets. Overall, in 2007, Tunisian date exports, primarily from the south, generated just below US$165 million (FAOSTAT 2010). International producer prices for *Deglet Nour* dates from the south of Tunisia have remained higher than those for Egyptian dates (US$973.5/ton compared to US$409.6/ton, respectively, in 2008 (FAOSTAT). In the same year, the value of date exports from the whole of Egypt reached a value little over US$3 million, however, horticultural exports from the North of Egypt`s Western Desert have become more diversified, following the recommendations of international development strategies. Other agricultural produce in the reclaimed land to the West of the Nile Delta alone was valued at US$3-500 million (World Bank 2007).

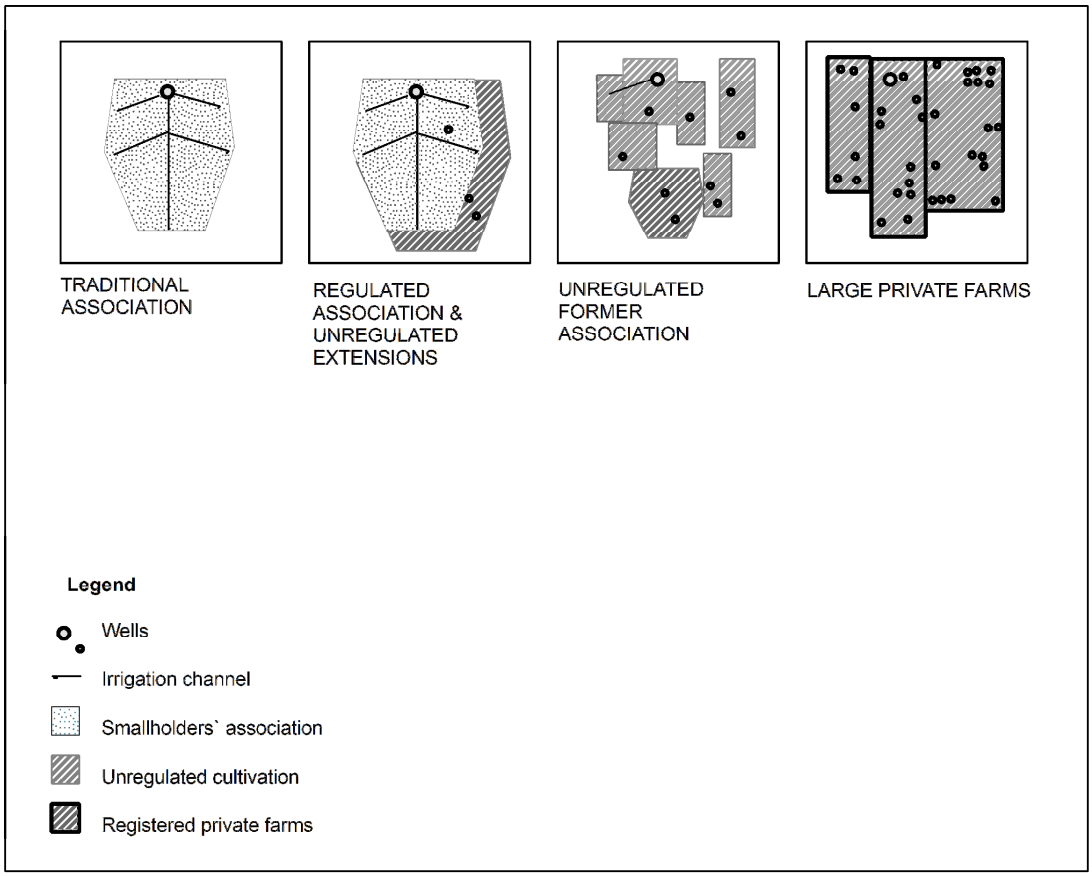
Global market demand has driven an agroindustrial transition in the methods of production and marketing of crops. Larger enterprises own refrigerated storage and transportation facilities, directly supplying air freight shipments of high quality internationally known varieties to buyers from Europe and the Gulf countries. In contrast, where smallholder produce reaches international markets, this usually takes place through a chain of stockists, processing facilities and other intermediaries. Previous investigations have observed differentials between farm gate prices for smallholders` produce and the international market prices, transferring attention away

from local resource management issues to focus on opportunities at other points on the global marketing chain (Bachta et al. 2006, Le Gal et al. 2007, IFAD 2008).

Smallholders are traditionally organized around collective systems for water management. At the time of the survey implementation, associations providing irrigation water to smallholders through traditional timed rotation systems were still in place in every village surveyed in Southern Tunisia. In the surrounding area, land irrigated from private wells was also in use. In Egypt`s North Western Desert, traditional collective irrigation associations structured around the shared management of water resources were also observed through the field investigations in the remote Western areas of Siwa. However, the membership of these associations was already smaller than those in Tunisia, while in the fastest-developing areas close to the Desert Highway, where once a collective association had been in operation amongst cultivators, the shared irrigation systems had been entirely replaced by private wells.

The Western Desert Highway case, identified in the village of Beni Salama, appeared to be the most advanced in a generalized regional trend towards the disintegration of traditional collective water resource management arrangements at the village level in the study region (see simplified illustration in **Figure 6.1**). In this case, although instances of cooperation amongst small groups of neighbours were identified, active village associations engaging entire communities of smallholder cultivators in a shared resource management agenda were no longer in evidence. Instead, new farming associations rented larger plots of land and water to farmers.

**Figure 6.1: Schematic Representation of Progressive Disintegration of Village Level Water Resource Management Arrangements in the Northern Saharan Oases**




Field survey designs and sampling frames were developed in consultation with local decision-makers. A series of previous surveys conducted in each region informed the survey design (Sghaier 1984, Meddeb 2003, Yehia 2004, El-Kadi 2009). The survey constituted the administration of 120 questionnaires to cultivators and their households living in villages or hamlets in the selected study areas, and cultivating plots of land ranging in size between 0.01-7.14 hectares (**Table 2.1**). Each cultivator was interviewed individually.

The same primary investigator carried out the survey in all locations. In each case, the questionnaire and mode of administration was adapted according to the local context. In each case, a local institution supported the implementation of the survey and a local person was selected to accompany the primary investigator. In Tunisia, the survey implementation was facilitated by the availability of lists of smallholders maintained by the Regional Agricultural Development Commission (CRDA), and with support from local associations to contact participating cultivators. In Egypt, logistical support was provided by various institutions, however none maintained lists of cultivators. The survey sampling frame was therefore generated iteratively through local observation. This process took place through an intensive period of three months spent living in the village of Beni Salama, March-May, 2009, in addition to a series of preparatory and follow-up visits.

The longer research period based in Beni Salama enabled more observations of village life to be collected in parallel to the survey activities. In Southern Tunisia, the study had to rely on experiences described by local researchers and in the available literature for contextual information. These secondary observations including the perspectives of different individuals, provided a rich body of insights to be revisited and verified through the survey. The institutional asymmetry between the two simultaneous research processes, resulting from the different institutional and logistical constraints encountered, created a discursive tension between the investigations in the two countries.

The criteria for selection of the respondents during the survey comprised their occupation in smallscale cultivation and their willingness to be interviewed. Efforts were made to include both young and old cultivators and those who had other occupations in addition to farming. Those who were employed on neighbouring farms as well as cultivating their own land provided information concerning both activities. Where collective water user associations had office facilities (five out of the total six cases in Tunisia), these were used to conduct interviews in series, followed by field observation visits. No office facilities were available at the remaining collective irrigation systems in Egypt. Interviews were therefore conducted entirely in the field, or in private offices and houses belonging to individual cultivators.

Building on the field survey findings, the value of agricultural exports for smallholders was further assessed using local statistics on productivity and prices, together with international economic data sources[24] and Landsat imagery showing the expanding cultivated areas. Changes in land under agricultural use, productivity, prices and exchange rates were identified over the period of the market transition during the 1990s-present. The significance of these changes in regional export production were examined using locally available accounts of farm budget models from the study period, and comparison to observations collected through the field survey activities. Trends in increasing water scarcity and degradation were identified directly through regional groundwater monitoring datasets from the DGRE in Southern Tunisia,

[24] See http://comtrade.un.org and http://faostat.fao.org for timeseries data tracing international producer prices, and http://www.imf.org/external/data.htm for exchange rates and inflation

whereas in the Egyptian case, the analysis relied more heavily on the survey data, grey literature and landcover change detection.

Information on costs of degradation for smallholders in terms of the increased costs of water supply was identified directly in the Tunisian case, where the CRDA maintains a database on water user association operating costs and fees paid by their members. In the Egyptian case, the increasing costs for water supplies to smallholders were estimated based the increased cost of pumping, and the cost of replacement wells. For this purpose, information on water requirements, well characteristics, observed changes and replacement rate collected through field surveys were supplemented with international data on diesel price trends from the US EIA and exchange rates from the IMF. These data were used to construct a model of the costs of groundwater degradation following methods described by Croitorou and Sarraf (2010) (See sections 2.4.3-2.4.4).

**Table 6.1: Model of groundwater degradation costs to smallholders in the village of Beni Salama, Western Desert of Egypt, 2000-2008** (after Croitoru and Sarraf 2010)

| Year | area (ha) | total # wells | # new wells / yr | av dept h (m) | price of drilling (LE/m) | US$ exch. Rate | price of drilling (US$/m) | total cost per well (US$) | sub-total (US$/yr) | fall in water table (m) | incr. fuel need (l) per $m^3$ | total water needs $m^3$/yr | incr. fuel need (l) | price of diesel (US$/l) | subtotal (US$/yr) | TOTAL: Cost of Degradation (US$/yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2000** | 50 | 35 | 3.5 | 25 | 45 | 3.69 | 12 | 1220 | **4,268** | 0 | 0 | 912500 | 0 | 0.40 | 0 | **4,268** |
| **2001** | 50 | 35 | 3.5 | 26 | 46 | 4.49 | 10 | 1065 | **3,729** | 1 | 0.004 | 912500 | 3650 | 0.37 | 1,351 | **5,080** |
| **2002** | 50 | 35 | 3.5 | 27 | 47 | 4.5 | 10 | 1128 | **3,948** | 2 | 0.008 | 912500 | 7300 | 0.35 | 2,555 | **6,503** |
| **2003** | 50 | 35 | 3.5 | 28 | 48 | 6.153 | 8 | 874 | **3,058** | 3 | 0.012 | 912500 | 10950 | 0.40 | 4,380 | **7,438** |
| **2004** | 50 | 35 | 3.5 | 29 | 49 | 6.131 | 8 | 927 | **3,245** | 4 | 0.016 | 912500 | 14600 | 0.48 | 7,008 | **10,253** |
| **2005** | 50 | 35 | 3.5 | 30 | 50 | 5.732 | 9 | 1047 | **3,664** | 5 | 0.02 | 912500 | 18250 | 0.64 | 11,680 | **15,344** |
| **2006** | 50 | 35 | 3.5 | 31 | 51 | 5.704 | 9 | 1109 | **3,881** | 6 | 0.024 | 912500 | 21900 | 0.72 | 15,711 | **19,591** |
| **2007** | 50 | 35 | 3.5 | 32 | 52 | 5.504 | 9 | 1209 | **4,233** | 7 | 0.028 | 912500 | 25550 | 0.77 | 19,551 | **23,784** |
| **2008** | 50 | 35 | 3.5 | 33 | 53 | 5.504 | 10 | 1271 | **4,449** | 8 | 0.032 | 912500 | 29200 | 1.00 | 29,136 | **33,585** |

## 6.3 Results

### 6.3.1. Social effects of agricultural export development on smallholder associations

The compiled information from secondary sources and field investigations in the two study areas revealed the following accounts of the social effects of agricultural export development on the smallholder associations.

**Nefzaoua Region, Governorate of Kebili, Tunisia**

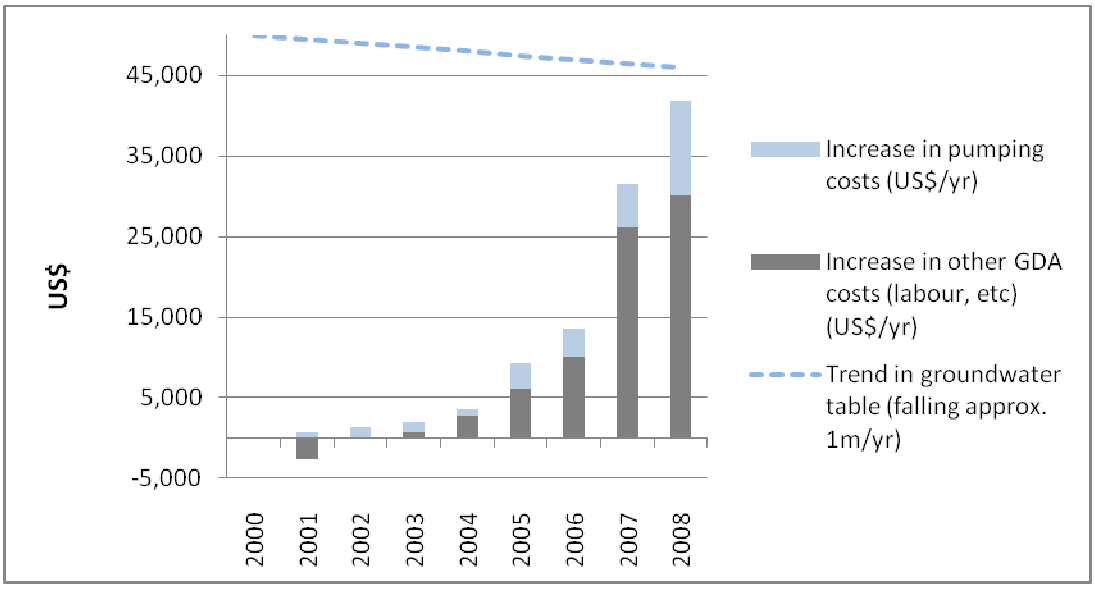
The traditional water user associations of the Nefzaoua, through which communal springs and wells were shared amongst users on a timed rotational basis had been reformed during the colonial period when the French Protectorate nationalized water and put in place a new legal framework to regulate the associations. Over the following decades, the associations` legal status was successively modified (Mouri and Marlet 2006, Selmi 1998, Romagny and Riaux 2007). These legal interventions restricted membership, formally separating the water user associations from the village councils *(Omda*), placing them instead under the supervision of the Ministry of Agriculture.

During the 1970s and 80s under the *Plan Directeur des Eaux du Sud* the government had installed wells for land reclamation to be shared by smallholders through the reformed associations. This enabled the establishment of new settlements, particularly in the South of the region, where previously cultivation had been maintained on a seasonal basis by mobile pastoralist and trading communities. As regional water extraction increased, and artesian pressure fell, the associations became increasingly dependent on the power and infrastructure provided by the

State. In the 1980s, the arrival of new technologies for digging private wells accelerated this process, enabling private individuals to bypass the associations through private and `illicit` groundwater extraction (Kassah 1996a).

Since the 1990s, the associations had been encouraged to reduce their financial dependence on the State. Law # 99-43, introduced in 1999, amended in 2004, and applied in 2006 in Kebili, redefined the water user associations as Agricultural Development Associations, `*Groupements de Developpement Agricole*` (GDA). This legislation required that the associations should be modernized to shift their focus more towards objectives for export production. At the time of the survey, the associations were still referred to locally as `*Jamaiyya Maaiya*` (water associations), and understood as such.

**Figure 6.2: Change in Members` Fees in a in Southern Tunisian GDA (562 Cultivators, 865 ha)**



The associations appeared to have been weakened by the private and illicit water use surrounding them, and the resulting escalation of resource scarcity. The falling regional groundwater table, together with rising fuel prices, were reflected in the rising annual GDA membership fees (see example in **Figure 6.2**). Technical and financial oversight provided through the Regional Agricultural Development Commission were enabling the associations to continue providing water distribution infrastructure services to fee-paying members, but not to exceed this function.

The GDA Presidents were continuing to lobby the regional government to provide them with more wells and infrastructure, as they had always done. But those interviewed during the field surveys did not identify their association with any potential to access new global market opportunities. Fees were rising with growing energy costs, and yet the associations still could not ensure sufficient frequency and quality of water supplies to produce high value crops. In the meantime, the traditional CPR management context and rationale of the water associations had been alienated by the *`foudawi`* (chaotic) cultivation surrounding them, which was proving more profitable.

**North Western Desert, Governorates of Matrouh and Behaira, Egypt**

The traditional groundwater management systems in the Western Desert enabled water from communal springs and wells to be shared amongst users on a timed rotational basis, providing a structure for communal decision-making and conflict resolution similar to the associations in Southern Tunisia (MWRI 2005). At the time of the survey, the Government of Egypt, however, had not legislated and supported the

function of the traditional informal local water user associations, as the Tunisian government had done. A superstructure of Water Boards for associations was created around canals in the Nile Delta area, but not in the desert areas.

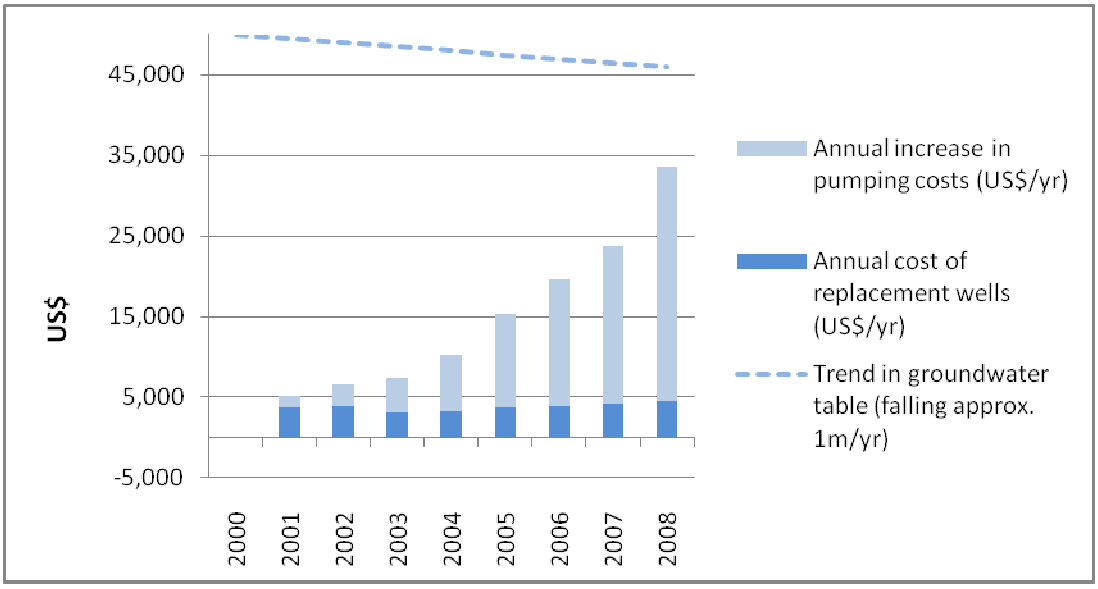
Until the 1980s, efforts to use groundwater for collective irrigation and land reclamation, including areas in the North of the Western Desert had been pursued, first by the State (LaMoreaux 1962, Parsons 1963, Voll 1980), and then from the 1990s, by privatized companies (Sherbiny, Cole and Girgis 1992). Groundwater levels had fallen, water pressure weakened, and smallholders resorted to digging their own private wells for irrigation. As in Southern Tunisia, the proliferation of wells and improved water storage reservoirs rendered the old collective water management associations increasingly obsolete. The process took place faster close to the urban centres and export markets in the Nile Delta, putting an end to collective irrigation in the study area at the village of Beni Salama in the mid 1980s. In the remote Western areas, over the 1990s-2000s, the government continued to drill new wells and encourage investors to share them.

From the 1990s, export producer associations, sometimes including smallholders, had begun emerging in the form of private enterprises or Non Governmental Organizations (NGOs) through a State-controlled registration process. As such, they were devoid of any role in resource monitoring and management. These functions remained dependent on the State, which had limited capacities to fulfil them. In the remote west at Siwa, the government contracted the privatized former State drilling company to dig deeper wells, arguing that this would consolidate water use patterns (Sakr

2001). This approach was accompanied by a series of campaigns to block flowing wells with concrete. This strategy was acknowledged to be ineffective, however, it was still the principal strategy observed under implementation during the field survey.

A system requiring permits for groundwater extraction had been introduced, however compliance was limited, particularly in the remote areas (see Khater 2003). Without the engagement of local institutions and private individuals, both groundwater users and policymakers interviewed agreed that private well-digging was practically impossible to monitor and manage. Export production by both large and small producers was considered to be threatened by degradation in resource availability and quality. Lower costs for electric-powered pumping enabled some producers to benefit from compliance through the permit and land registration system. Smallholders whose land was not formally registered could not apply for well licenses or cheap electricity supplies. For them, prices for pumping groundwater rose with the increasing cost of diesel, and rose further with the lowering of the groundwater table following the escalation of cheap electric powered-pumping by their neighbours (see **Figure 6.3**).

**Figure 6.3: Modelled Costs of Groundwater Extraction Borne by Smallholder Cultivators in the Village of Beni Salama, Western Desert, Egypt (35 Cultivators, 50ha) (based on replacement cost model – see section 2.4.3-4)**




The most viable option identified for association open to smallholders in this region was to form small private enterprises, which would not be able to assume any CPR management functions. This phenomenon, which appears in the more developed areas close to the Cairo-Alexandria Desert Highway, may be the shape of the future for the region as a whole. Even in the remote areas, the role of the tribal associations had shifted away from CPR management, becoming reengaged by the State in guaranteeing loan repayments for the provision of land equipped with electric-powered wells to young smallholders -who otherwise frequently defaulted (SEAP 2002).

Overall, our investigations with smallholders in the two countries revealed that similar traditional associative models, structured around CPR management systems, had been in place in the study areas. However, these institutional arrangements and

environments had evolved differently in each case. The institutional factors had shaped the status and capacities of the smallholder associations to respond to changing market and environmental conditions in order to secure development benefits in each case. In the Desert Highway study area, where export production is the most developed, the disintegration of the village association had been observed.

### 6.3.2 Economic effects of agricultural export development on smallholder income

Despite the differences between the institutional contexts in the two regions, the investigation of the effects of agricultural export market development on smallholder cultivators revealed some common observations. In the remainder of this paper, shared problems affecting smallholders` opportunities to benefit from the development of agricultural export markets are identified and discussed. This discussion considers the broader context of agricultural development in the study regions, including the growth of large farms offering employment, before turning attention back to the global logic of the international development strategies in the concluding section.

Under the traditional cultivation models still employed by smallholders, although income generation was low, capital investment and input costs for non-purchased manure and labour from the household were also low, and compensated by outputs of fodder, vegetable and cereal production, to be consumed or sold by the household. In such cases, any sales of dates as a cash crop could be considered as profit. Smallholders` subsistence resource uses, and to some extent local markets also, are relatively insulated from financial shocks. In contrast, medium and large export

farmers interviewed in the Western Desert often had to survive through a series of consecutive bad years before a profit could be made. Where farms belonged to absent outside investors, employees described frequent changes in ownership. International horticulture price patterns are characterised by considerable inter-annual variations. For example, international producer prices for Tunisian dates fell by 37% 1997-8 and Egyptian olive prices reduced by almost 34% over the year 1998-9 (FAOSTAT).

Cultivators in both regions reported the perennial problems of low farm-gate prices. Prices for local sale of dates anticipated by smallholders taking part in the survey in Kebili were around US$0.67/kg. The Tunisian national reference price, set by the Union Tunisienne de l'Agriculture et de la Peche (UTAP) was US$1.04/kg for dates that had been covered with mosquito netting, or US$0.84/kg without. The average value of Tunisian date exports to the UK in 2009 listed by UN COMTRADE was US$3/kg. The retail price of dates in UK supermarkets during Ramadan in 2010 was US$13.96/kg. Price differentials – although inevitable in export activity -are of interest because they signal opportunities for greater value-added that producer communities may be able to capture. However, none of the interviewed smallholders reported any engagement in activities at other points on the marketing chain.

In 2009, smallholders reported an average gross annual income per hectare of US$3,650 in the Nefzaoua region from dates alone, and US$3000/ha/yr in the remote West of Egypt's Western Desert at Siwa. In areas closer to the more developed Desert Highway, smallholder cultivators more often focused on the production of crops for

home consumption, therefore, their cash income from their own landholdings was negligible. A previously published estimate of income per hectare generated on larger export farms in this area was around 50% higher than the income on the smallholdings in other areas that were exporting their produce. Lack of direct income from cultivation did not mean that the cultivation of smallholdings lacked value for the households. Their value consisted of subsistence food production, the social value of family cultivation activities, and, notably the security of the land asset close to the Desert Highway.

Based on farm budget studies and comparison to our study findings, we observed that capital investments for land reclamation, agricultural inputs and labour increased with farm size in both regions. Furthermore, as the farm budget models become more capital-intensive with increasing farm size, higher value cash sales per hectare were required to break even. Most previous studies including both large and small farms had routinely concluded that small farms generated less income per unit of input, and were therefore inefficient in comparison to the larger farms (Yehia 2004, Belloumi and Matoussi 2006). However, the models used to calculate input costs per hectare had not been adjusted in these studies to accommodate the variation in cultivation strategies that we observed between large and small farmers.

The difference in attitudes to investments in high value and high risk production between smallholders and large agroindustrial producers is exacerbated by requirements for quality produce in order to obtain the higher prices. The achievement of quality necessitates precise and regular applications of irrigation water

of low salinity. Land and water quality problems have accompanied the expansion of cultivation in both regions at comparable rates[25]. Overall losses of date productivity recorded in local production statistics for the Nefzaoua region over the period 1993-2005 averaged around 6%, however, in some of the smallholder systems the recorded losses were around 80% of the total commercial production volume. In Egypt`s Western Desert, losses of production due to degraded land and water quality over a similar period have been estimated at around 19% (Abo-Ragab 2008). Without continual renewal of infrastructure, losses in total annual productivity of fruit crops from the export areas close to the Western Desert Highway over the coming 12 to 20 year period have been anticipated at 25-33% (World Bank 2007).

Continual renewal of wells and pumping infrastructure was observed close to the Desert Road in Egypt, where large farms could afford to invest. The ability of resource-dependent households to afford increased expenditures required to continue cultivating (see **Figures 6.2 and 6.3**) depended both on their assets, and on any institutional arrangements in place to mediate these costs. In the Southern Tunisian case, the presence of the smallholder associations presented a means through which increases in resource access costs by smallholders could be routinely smoothed, since the fees covering the infrastructure and pumping costs could be distributed across the year – rather than requiring immediate payments, and in a limited number of cases assistance in the provision of infrastructure might still be provided by the local

[25] Depletion rates reported during the survey and grey literature ranged up to 1m per year. Considerable intra regional variation existed. It is essential to bear in mind while using regional level observations that water levels, and therefore the required depths of new wells and drainage systems, are highly dependent on environmental context-specific factors such as elevation and hydrogeological conditions. Allowing for these effects, depletion appeared most rapid close to the Egyptian Desert Highway.

government. However, in the Western Desert, unless external development assistance was provided to them, individual smallholders would be required to pay the costs, or absorb the production loss.

In both regions, smallholder households depended on additional sources of income besides cultivation of their own land. Where additional income sources were not available, households were considered by their neighbours to be poor. This was expressed through the provision of assistance amongst households. Smallholder households in both regions have benefited to some extent from growth in other sectors supporting agricultural export, such as transportation, storage and farm security. In one year, a typical smallholder engaging in local on-farm employment providing in Egypt`s North Western Desert earns around US$1051.80, which is supplemented from continued part-time work on the smallholding for household food production, and sometimes also cash.

In the short term, employment opportunities were enabling young people to remain in the area, and to continue part-time cultivation activities with their families. However, it was observed that through this process, smallholder cultivation, even as a secondary economic activity, was becoming less viable, due to the stresses on land and water resources that were created by the presence of the larger neighbouring export farms. This situation was most pronounced in the most developed part of the Western Desert, close to the Desert Highway. However, where similar export production models were pursued, other areas could well be anticipated to follow a similar development pathway.

## 6.4 Discussion and conclusions

### 6.4.1. The New Institutional Economic (NIE) policy agenda for smallholder associations

In all cases investigated, national policies had responded to the New Institutional Economic development agenda focusing on water use efficiency and regulatory reform in the water sector by withdrawing from the physical provision of water to smallholder associations, requiring cultivators to invest in private wells in order to ensure the timing and quality of their water supplies, rather than managing and maintaining shared infrastructure. In both countries, the potential for smallholder associations to be reshaped into producer associations or export corporations was under exploration. At the same time, however, the original CPR management function and *raison d'être* of the existing associations was undermined through their lack of participation in the evolving regulatory systems governing resource access. Until regulatory provisions for effective CPR management secure the resource dependent smallholders` environmental assets and livelihoods, their vulnerability prevents them from benefitting directly from the new export market opportunities.

In some cases the alienation of the traditional resource management base and functions of the associations had led to their collapse. Where the associations survived, they no longer fulfilled a collective resource management function, since they had no means through which to comprehensively monitor and coordinate resource use by private operators outside, around, and in some cases, even inside their resource systems. Where they remained, the reformed associations simply

enabled smallholders to pay escalating prices for dwindling and degraded water allocations, while larger private users gained the lion`s share of the available resources and market benefits. Thus, the new institutional economic policies had enabled market driven accelerations in resource extraction in all of the study areas, particularly by larger private users who paid to receive private groundwater extraction permits, ensuring the quality of their export production, independently of local associations or any responsibilities to secure basic resource availability or other benefits to smallholders.

In both countries, there is an urgent need to reengage the principles of CPR management, securing the cooperation of all resource users through full information sharing regarding the state of the shared resources. Officials interviewed during investigations in both regions expressed awareness of needs for improved local participation in the enforcement of regulations (see e.g. MWRI 2005), but tended to view monitoring and analysis of resource conditions and regulatory compliance as the (unmanageable) task of technical authorities, rather than as a shared responsibility involving all resource users. In this context, the mutual trust and cooperation amongst stakeholders that is required to address shared resource management and development challenges proved impossible to achieve. The growing private and informal sectors were preventing effective resource management information flows and blocking the necessary scientific scrutiny of environmental effects accompanying the development of the export economy.

Summarizing why the smallholders` associations could not transform themselves, we have observed in both cases, national-level failures to engage the smallholder associations in the resource-development management process, despite their centrality to theoretical models of CPR management. If our assessment is correct, rather than continuing to focus on market access alone, national development strategies should put more emphasis on achieving participatory resource management by fostering information exchange between smallholder associations and other resource users in the private sector, supporting effective coordination of shared resource management priorities and local capacities, both institutional and technological. Through the field studies described in this article, it was observed that significant capacities and technologies necessary to revitalize the smallholder associations are present on the surrounding private farms. These could be made available for mutually beneficial CPR management purposes at minimal or no cost.

We conclude that the national level institutional arrangements and environment within which smallholder associations must operate could do a lot more to support their CPR management function. National institutions, in the form of landholding, resource access permitting and export certification systems structure incentives for the behaviour of private resource users, as well as generating income for local authorities. These systems should send a clear message that private enterprises using CPRs are expected to contribute to local CPR management, either financially, or through occasional technical support activities. In order to convince resource users that they are participating in a CPR management framework, rather than in a tragedy of the commons, national regulatory systems that are all designed to operate in a fair

and transparent manner, must publish the existing evidence that they are doing so effectively. If this was achieved, smallholders might indeed access development benefits – including *both* well-being and income-related benefits - from the global markets in the way that national and international development specialists anticipate they should.

### 6. 4.2 Implications for rethinking global NIE

Just as the New Institutional regulatory frameworks effectively prevented the essential conditions for CPR management and smallholder innovation for development in the two cases from the Northern Sahara examined in this paper, the same combination of institutional arrangements must be considered likely to have a similar effect in other developing regions pursuing global market transition strategies. This is not only due to the global reach of the strategies, or to the presence of the growing export of technical and commercial expertise from companies operating in the Northern Sahara to areas across Sub-Saharan Africa. It is because the challenge of ensuring environmental responsibility in the developing global market economy is a global challenge that has not been comprehensively addressed, either in the international development literature, or in practice, through the existing international institutions.

Export market development in the two cases investigated may be considered to be ahead of the curve in comparison to other marginal dryland areas– providing a possible vision of the future elsewhere. Our empirical results confirmed that gross income benefits from the global markets to smallholders were being generated in

different ways under different management regimes – either directly from smallholder export cultivation, or through on-farm employment. Global development strategies encourage governments to use economic evaluation to assess these different resource allocation options in relation to GDP. These analyses are then used to formulate national level strategies for resource allocation and pricing that will determine whether or not resource dependent cultivators continue cultivating their own land or move into employment on the land of others.

Our analysis of farm budget models similar to those used at the national level to consider the efficiency of production at various scales of operation revealed a number of problems. These models did not place sufficient value on smallholder cultivation. The models tend to include valuation of input costs such as labour or manure that do not have a cash value, and may become either more or less valuable through being invested. However, they routinely ignore the subsistence value of food production, the social value of family cultivation activities, and the asset value of the landholding. Therefore, this approach, focusing on calculated net income of smallholders as a measure of benefit was inappropriate. This is of considerable global concern, since the assessments used were in line with the prevalent global approach to economic evaluation of contributions to GDP and smallholder income generation.

In contrast, the contribution of large farms supporting smallholder employment has been over-valued. `Knock-on` benefits from employment were accepted by smallholder households against the alternative of diminishing returns from the degrading resource base, which they could not control. We have observed that this

was due to the failure of national level institutions, despite the focus of the international strategies on this issue. It therefore appears that international strategies should be more explicit concerning the imperative for CPR management to include all resource users, large and small. If this was achieved, households might take a different view of employment in an industry that paid them less for access to their resources, cultivation knowledge, local security and labour over the period of one year than it routinely paid for one day of white collar work by an international technical consultant.

Interestingly, no established international institutions are yet mandated and equipped to tackle the regulation of global market effects on CPR management institutions. This appears, however to be an urgent necessity. International financing and trade-related institutions have a key role to play in requiring not only rhetorical use of CPR management theories, but the national level publication of tangible, independently verifiable physical evidence of resource management. This can only be achieved through implementing CPR management on the ground with the engagement of resource users.

### 6.4.3 Conclusion

This paper provides an analysis of the lack of global market benefits to resource dependent smallholders. The following insights could be drawn from experiences in the northern Sahara, where global markets development did not drive innovation under resource scarcity. *First,* our field surveys in the marginal desert areas of the two countries revealed that farm budget models used in current development project appraisals did not correctly characterise the benefits of smallholder cultivation. *Second,* while better opportunities for smallholders have been sought through associations, these have been constrained under national policies that fail to recognize the importance of the CPR management function of these associations in ensuring local environmental security. *Third*, `knock-on benefits` to resource-dependent smallholders achieved through low-waged employment in other sectors came at the cost of food, water, livelihood security and participation in resource management decision-making.

Whether the cultivators` associations were supported by the State, as in the Tunisian case, or left to fend for themselves, as they were in Egypt, the increasing presence of externally regulated (and un-regulated) private operators weakened the CPR management frameworks. The debilitating effect of institutional and environmental marginalization on the smallholder associations underscores the need for an integrated view of the market/resource access question that includes improving smallholder export cultivation and employment opportunities but also providing for more effective CPR management in the process.

Our findings suggest both the need, and the opportunity, for a global rethink of international development strategies in relation to the market transition. Global development strategies should require national development programmes to enable smallholders to configure their collective associations, not only to access to export markets, but also, more fundamentally, to fulfil their traditional CPR management aspirations. Smallholder associations and private companies should support improved national decision-making by effectively monitoring, guiding, and sustaining development outcomes as they cultivate and innovate in the resource scarce regions of the developing world.

# CHAPTER 7: DISCUSSION

## 7.1 Introduction

The preceding chapters have detailed the approach and findings of the research, identifying environmental changes in the endorheic basin oases, and examining experiences of living with them. This chapter moves beyond data and analysis to consider the wider significance and implications of the research findings. The overall objective of the investigation was to draw lessons for global change research. This interdisciplinary discussion is intended to identify the relevance of the research findings to both scientists and decision-makers working in a range of different fields and regions.

The overarching preoccupation of global environmental change research concerns the challenge to enhance human capacities to live with these changes (Engle 2011). The oases are, on the one hand, emblematic of resilience achieved by human populations in a harsh and changing environment through common pool resource (CPR) management. They are, admittedly, also increasingly unsustainable in terms of non-renewable natural resource extraction, particularly of groundwater. And yet, there is a belief amongst environmental change scientists that the oasis systems could somehow continue to achieve resilience through renewed social, institutional and technological innovation. Three main themes of relevance to global change research emerge from this study of the oasis systems.

The first theme thrown into relief through this investigation concerns human capacities to apply technological innovation to live with environmental change. Under very similar natural and climatic conditions, the options open to smallholders for innovation to improve their experiences of living with environmental change were determined by institutional factors. Institutional arrangements, including local associations of smallholder cultivators, were key in differentiating between the experiences in the two cases observed. National and global institutional perspectives on environmental change were also critical in determining conditions for innovation.

The second essential theme emerging from this research addresses the global economic drivers of environmental change affecting the oasis systems. These can constrain options for innovation, and have implications for the re-evaluation of international and regional economic development strategies. Reassessment of the economic drivers of environmental change can bring about fundamental shifts in understanding as to how best to address them (Hassan et al. 2005b, Stern 2006, UNEP 2009, Brink 2011). The research presents a contribution to the ongoing global discussion as to how an economic analysis of the effects of the environmental changes on smallholder cultivators might be approached, focusing on the oasis systems.

Third, the thesis identifies new practical challenges and opportunities to trace and understand environmental change processes affecting land and water in the oasis systems. Findings revealed that there is considerable scope for national and global environmental monitoring systems to be enhanced at very low cost by making use of human and technological capacities already in existence in the oasis study areas. The

need for this knowledge of environmental change processes and effects to inform development decision-making at all levels is very clearly demonstrated in this thesis.

These observations connect to the growing global challenge of land and groundwater management (Giordano 2007, Bossio and Geheb 2008, WWAP 2009). The observations drawn from the research concerning opportunities to enhance understanding and human capacities to live with environmental change in the northern Sahara are relevant to various other regions experiencing water scarcity, and pursuing similar development pathways (see e.g. Bossio and Geheb 2008, CGIAR 2011a). They are also relevant to areas undergoing land and water management challenges more broadly (Akhtar-Schuster, Bigas and Thomas 2010, Buenemann et al. 2010, Nkonya et al. 2010, UNEP 2012).

## 7.2 Significant Themes Emerging from the Research

### *7.2.1 Redefining environmental constraints: human innovation and institutions*

Although the study areas were relatively comparable in terms of their altitude, temperature, natural vegetation types, and cultivation traditions, the findings revealed a wide variation in environmental change processes within each location. These were sometimes related to natural and environmental factors, such as topography, affecting groundwater levels, drainage and water-logging effects. In other cases, the variations resulted from social, economic and institutional differences, determining the nature and pace of cultivation, groundwater extraction and the application of human ingenuity to improve options for living with environmental change.

Through the field research period, it was observed that some potential solutions to water scarcity and quality constraints – such as water treatment through desalination, groundwater recharge, reuse of drainage water and other technological innovations were not applied in the areas investigated. Global environmental change scholarship focuses on the manner in which human societies understand and react to environmental changes through innovation in some cases, or in others, collapse because they fail to do so (see Turner and Fischer-Kowalski 2010, review of selected literature in Section 1.2.3 and overview of conceptual framework in Section 1.6.1).

In this investigation, constraints that were preventing cultivators from organizing themselves to test and apply such solutions included the disintegration of traditional smallholder resource management institutions, as well as institutional arrangements and environments at other scales. This observation connected to a wider literature regarding the negative effects of centralized regulation on traditional CPR management institutions, including scholarship in the two countries under study (Mitchell 2002, Kassah 1996a), and also in other dryland contexts (e.g. Wade 1988, Mosse 1997, Shah 2009). In order to make effective use of cultivators` knowledge and capacities for innovation, it would be necessary for institutions at all scales to strengthen, rather than weaken, resource users` and consumers` ability to participate in resource management (after Ostrom 1990a, Janssen 2006, after Ostrom 2009).

A particularly salient parallel was identified between the tragedy of the groundwater commons in the northern Sahara and previous studies of the groundwater revolution

in India (Shah 2009). Beyond the similarity observed in the breakdown of local institutions, closer observation through the fieldwork period revealed that the pumping technologies themselves were being imported to the oases of the northern Sahara from India and China. In light of this, the changing environment in the northern Sahara should be seen as part of a globally integrated socio-economic process.

The analysis of the Indian case found the smallholders innovative and national regulatory systems ineffective, concluding in a celebration of the anarchy of the Indian groundwater revolution. The findings of the present investigation in the northern Sahara, reaffirmed the role of smallholder cultivators in understanding and managing their resources in this region, similarly to the Indian experience. However, the research observations also suggest that the degree and range of technological innovation that has already taken place amongst smallholder cultivators in North Africa has not yet been fully recognized.

In contrast to the previous impression, a very cosmopolitan generation of smallholder cultivators was observed to be emerging in the northern Sahara during the period of this investigation. Not only did they import the smallscale pumping technologies of the groundwater revolution from other regions of the world, but they could also market their produce on the internet and through mobile telephones. Their outlook is much more open to global economic trends than the Indian farmers appeared in the earlier account, and so are their options for innovation. The global literature on smallholder innovation (e.g. Turner and Fischer-Kowalski 2010, McIntyre et al. 2009) has not yet

fully engaged with these new conditions in the changing environments of the northern Sahara, or elsewhere.

As the development of high value agricultural exports continues, an anarchical situation, where smallholders innovate, and the tragedy of the groundwater commons deepens, as observed in India, is not the only conceivable management scenario. The millennium ecosystem assessment (MA) presented a broadly favourable scenario for the future of innovation for living with environmental change, which it named `techno garden` (Cork et al. 2005). To a considerable degree, the oases increasingly resemble this scenario, which:

> `..depicts a globally connected world relying strongly on technology and on highly managed and often-engineered ecosystems to deliver needed goods and services. Overall, eco-efficiency improves, but it is shadowed by the risks inherent in large-scale human made solutions.`

The key difference between the northern Saharan experience so far and the MA techno-garden scenario is that in the scenario, technology and market-oriented institutional reform are used to achieve solutions to environmental problems. At present, in the northern Sahara, globally connected environmental management institutions are not in place to verify and readjust eco-efficiency. However, the MA scenario opens up some questions as to what might be the risks if they were.

### *7.2.2 Responding to economic drivers of environmental change at different scales*

This thesis identifies the agricultural export market as the global economic driver of recent environmental change in the oases. The concern that external market drivers can drive environmental degradation is a common theme in global resource management research (see e.g. Barbier 1997a, Ambinakudige and Choi 2009, Mayrand 2006).

Examinations of changing farm budgets presented in both case studies indicated that during the 1990s management choices leading to environmental degradation could have been predicted on the basis of simple economic projections, since investment in diverse resilient smallscale cropping patterns were not bringing as high a return as extractive agroindustrial farming methods.

As demonstrated in this investigation, environmental degradation can constrain the options available to cultivators. Cultivators` decisions concern volumes of irrigation water to apply to their crops, groundwater pumping rates, use of chemicals, spreading of wastewater for artificial recharge, soil improvement techniques, conservation of biodiversity, pruning, weeding and planting patterns, and, indeed, whether or not to continue cultivation at all (see a similar discussion in Twyman, Sporton and Thomas 2004). These played an integral role in shaping the nature and magnitude of environmental changes in the oasis systems. Analysis of cultivators` resource management choices can enable prediction of the effect of policies and institutional arrangements or environments, including measures targeted to address

environmental degradation such as rules against the digging of new wells, the costs of pumping water, or transferring it over a dispersed area.

Economic analyses applied in the two case study chapters focused on the estimated value of crop production, while in chapter 6, the replacement costs of degraded groundwater provision were valued. These analyses separated smallholders` experiences from those of larger export producers. This contrasted with available regional scale assessments (e.g. Croitoru and Sarraf 2010 in Southern Tunisia, Eid, El-Marsafawy and Ouda 2007, EEAA 2010a), which mask the variation in the effects of environmental change on large and small cultivators.

Most economic assessments of environmental change are necessarily undertaken using secondary datasets which are available at a regional scale. These investigations do not necessarily include extended periods of field observation. The research presented in this thesis included a long period spent in the field learning to recognize the contextual specificity of varying environmental conditions and temporal changes affecting them, as experienced by different individual cultivators. Once such an understanding has been gained, on a personal level, it is very counter-intuitive to reduce it to the level of an economic analysis, where so many levels of specificity must remain obscured. The choice to make an economic analysis of environmental change also runs counter to wider debates in the literature concerning the nature of development, in which many non-economic aspects of human well-being are recognized (Sen 1999).

It is notable that few experienced fieldworkers attempt to present economic analyses of the effects of environmental change. Such assessments are made sometimes to justify a proposed intervention, but rarely to value the effects achieved. Nevertheless, at the policy level, *de facto* economic assessments are used to support decision-making every day. Where the available economic assessments do not include environmental factors, these cannot be taken into account (see e.g. Requier-des-Jardins, Adhikari and Sperlich 2011). The potential for effective economic assessments of environmental change to lead to far-reaching shifts in policy is widely recognized at the global level (after Stern 2006). An economic analysis, as presented in chapter 6, was therefore considered to be more communicative than early reports on the complexity of the fieldwork findings.

Interestingly, global export production is still widely seen both as part of the social and environmental problem, *and* as a potential entry-point for solutions to achieve income benefits for land stewardship through producer associations and organic production (IBRD 2007, Cork et al. 2005). In the preceding chapters, it has been argued that global market regulation and standardization offer new institutions that could strengthen the existing capacities for living with environmental change (after Pretty and Ward 2001, Pretty et al. 2006, Pagiola, Artcenas and Platais 2005). This argument corresponds with the global literature on emerging economic instruments, such as payments for environmental services (see section 2.4), and to the MA scenario described in the previous section. In the context of the oases, relevant environmental services might include e.g. spreading of drainage water to reduce water logging and increase groundwater recharge. Means of payment might include direct subsidies for soil and

water conservation activities or price premiums for certified organic and ecologically friendly produce.

Based on the analysis of past failures in economic regulation of environmental change identified through this study, the need to test assumptions is an important lesson. Until effective systems are in place for verifying anticipated effects on cultivator behaviour and environmental processes, new economic policy instruments, such as payments for ecosystem services, cannot be tested. Without such testing, these new economic measures will be empty panaceas, based on unverifiable assumptions. Comprehensive, integrated and participatory systems required for tracing and understanding environmental change are considered in the following section.

### *7.2.3 Tracing environmental change in cultivated environments: a shared responsibility*

The research project set out to track environmental changes affecting the oasis systems of the northern Sahara since the 1950s. The discussion of changing land and water conditions in dryland areas connected to longstanding and current international scientific debates on monitoring the impacts of land management projects, programmes and policies (e.g. Bossio and Geheb 2008, Nkonya et al. 2010, INWEH 2010). In the 1950s and 60s, the oases were remote, marginalized places with resource dependent populations maintaining traditional resource management practices through local institutions. However, the findings of this investigation reconfirmed that

rapid changes have occurred over the recent decades through national policies and private investments in land reclamation and development.

The background literature review revealed that integrated assessment of environmental change affecting both land and groundwater resources is relatively rare in the northern Sahara. This was borne out through the activities for collection of secondary datasets and archived information in both countries. Environmental research tends to be carried out by researchers who are either attached to a Ministry of Agriculture or a Ministry of Water Resources and/or Drainage. Although Ministries of Agriculture have access to considerable information regarding water use for irrigation, they did not produce and refer to comprehensive assessments of the state and trends in the resource in planning ongoing land and water management.

The research findings point to new opportunities to complement existing national data collection systems. The combination of datasets and analytical approaches used by the two sectoral land and water management communities was demonstrated to be effective. The use of landcover analysis enabled estimation of groundwater extraction volumes, while use of data on groundwater conditions enabled more effective assessment of land degradation processes and effects. In both cases, the incorporation of insights and additional data provided by land and water users offered key insights for understanding the environmental changes, as well as the experience and role of human populations living with them. The field data collection also helped to give an understanding of the multiple causal explanations for the changes and the nature and degree of variations.

Received wisdom that data on environmental conditions in the study areas are scarce (e.g. in Masoud and Koike 2006) was refuted by the findings of this investigation. Shortcomings in available databases and institutionalized data management systems for monitoring land degradation, particularly those concerning groundwater management, were overcome through surveys of water users, use of new data sources such as satellite data and collection of privately generated and held data from export farms and drilling companies. This suggests a third lesson for global change research, regarding the potential for such solutions to be more systematically used on a long term basis through the responsible institutions.

Around the time of the investigation, a prevalent view in the international research community was that environmental monitoring programmes must work from the basis of unpopulated maps, designing expensive field sampling programmes (e.g. Dawoud 2004, Schuster-Wallace et al. 2008). In light of these anticipated costs, international agencies and governments had a tendency to avoid measuring land management effects on the environment in evaluating their environmental management programmes (Bigas 2010).

In this investigation, environmental changes were tracked using data obtained from resource users and local archives. This took time, but did not otherwise require a large financial outlay. Considerable logistical and substantive support was volunteered from the resource users themselves because they were interested in the environmental changes that were affecting them. This demonstrates that unexploited potential exists

for intelligent low-cost public strategies to coordinate, compile, analyse and progressively enhance the quality of available data and understanding of environmental change processes in the studied areas of the northern Sahara, and in other marginal dryland environments.

Various discussions of the merits in enabling local people`s accounts of groundwater conditions to inform environmental management studies have been presented to the literature (e.g. Moench 2004, Lightfoot et al. 2009). This study drew intensively on local people`s observations of environmental change. These often appeared contradictory. Repeat questioning and further checking for bias was undertaken in the more detailed case study in the Western Desert of Egypt. Overall, combination of the data from these sources with the remote sensing and archived datasets and observations taken from a longer observation period provided a range of opportunities to counterbalance possible bias.

At the time of the survey, in Tunisia, a notable volume of information on water resource availability and quality was systematically collected, published and archived by the MWRI. In Egypt, the coverage and public availability of the MWRI datasets appeared to have been less comprehensive since privatisation took place. Relevant information generated privately was not systematically used. The private sector, including both small and large land and water users, was becoming increasingly influential, creating both a need and an opportunity for the generation of environmental data through privately funded impact assessment studies and certification requirements.

Following recent changes in both countries, the question as to whether, and in what form, institutionalized collection of data on productivity and environmental conditions will be sustained in both Egypt and Tunisia may have taken on some new dimensions, previously unconsidered in this thesis. As argued above, global economic institutions may well be an important factor in both countries` efforts to shape the level of provisions for environmental monitoring and management that will remain in place for the future. The role of other global environmental institutions is still under debate (Najam, Papa and Taiyab 2006).

The review of current scientific literature on landcover change revealed that the majority of scientific contributions at the global level (e.g. Bai et al. 2008, Helldén and Tottrup 2008) have focused on the rainfed dryland environment, and are not able to account for the effects of the growing area of drylands that is under groundwater-irrigated cultivation, as is the case in all areas considered in this investigation. It is widely accepted that it will not be possible to address this and other land and water management issues in global scientific assessments until more integrated data collection systems are in place at other scales to support them. This chapter, and the thesis as a whole, suggests that such an objective is not as far off as it has often appeared to previous global change researchers (e.g. as in UNCCD 2011).

## 7.3 Significance of the Emerging Themes to Global Environmental Change Research

The significance of the research findings extends to comparison with the literature from other regions. Other accounts of dryland countries undergoing large-scale changes in cultivation patterns, including a shift towards groundwater use for export production include an extensive literature on cases from northern Asia, some of which informed the conceptual section of this thesis are explored earlier in this section (Wade 1988, Mustafa and Qazi 2007, Shah 2009). Similar concerns appear in the growing literature on the effects of environmental degradation in the northern Chinese oases (Yang, Zhou and Xiao 2007).

A particularly closely related body of work addressing the theme of environmental change affecting land and water resources, with an orientation to resource users and their management practices, was located in Namibia (e.g. Manning and Seely 2005, Stringer et al 2007, Newsham and Thomas 2011). The shared characteristic of extreme water scarcity in the Namibian case renders the comparison with the northern Saharan oases environmentally salient, despite the large geographical distance, and numerous other natural and social factors that otherwise differentiate between the northern Saharan and Southern African regional contexts. The emergence of the global market-oriented producers` associations in Namibia has been more directed towards ensuring their resource management function, through the concept of the Forum for Integrated Resource Management (FIRM) organizations (Manning and Seely 2005).

The northern Saharan oases have had a head start on Namibia in terms of the establishment of international markets for horticultural export. However, the strategic focus in the Namibian case on institutional development and participatory research to be engaged in the further development of this sector have been influential in recent international debates on dryland development (Seely, Klintenberg and Shikongo 2007). This model is reflected in the approach and recommendations presented in this study. In relation to the Namibian case, study findings in the northern Sahara paint a vision of the shape of a possible future, if efforts to enable smallholder associations to fulfil their role in environmental management and economic productivity are not maintained. This may provide a useful point of reference for Namibian decision-makers, who have formulated participatory strategies, but are now faced with the challenging task of putting them into practice, and finding out how well they work (GoN 2010a, GoN 2010b).

Another relevant parallel body of work on land and water management associations in liberalizing (post-socialist) economies was identified in the former Soviet countries, where a similar development approach, encouraging cultivators associations to explore the development of horticultural produce for export is also growing. This literature deals with the disintegration of organization amongst cultivators, and recent efforts to restore collective systems in the context of new market opportunities (USAID 2010, Abdullaev et al. 2010, Sehring 2009). Once again, the northern Saharan case appears to be ahead of the curve – since the socialist period in this region, for the most part effectively ended in the 1970s, particularly under the `Open Door` policies of Sadat – even if traces of the social agendas for the development of smallholder

cultivators do still remain in the planning of ongoing land reclamation and settlement activities.

In the dryland countries, particularly those of the former Soviet Union, a large-scale change is taking place in cultivation patterns (Conliffe 2010). Groundwater use is clearly increasing, and the systems in place for monitoring resource conditions are not prepared for the new market-driven environmental changes (see case studies from Tajikistan and other countries in INWEH 2010). The findings from this study in the northern Sahara represent one possible shape for the future. The available options to manage this likely future scenario therefore, have a wider relevance across other such cases.

# CHAPTER 8: CONCLUSION

## 8.1 Summary of findings

This thesis explored cultivators` experiences of living with environmental change in the endorheic basin oasis systems of the northern Sahara from a global dryland research perspective. The objectives were to investigate the environmental changes experienced in the field study region, particularly increasing water scarcity and degradation of land and water resources. The research then explored cultivators` resource management and socio-economic strategies through field surveys and observations. The discussion and analysis situated the findings within the national policy context in each of the two countries, and drew conclusions of interest to the international research community. The work consisted of four chapters, each of which was presented in the form of an article submitted to a relevant academic journal. In each chapter, the constant themes of global economic development and cultivators` experiences of environmental change are reconfigured.

Due to the relative openness of the study areas to international markets and applied commercial technological expertise in this region, land management parameters are commonly defined by government and private sector assessments, rather than through academic endeavour. Lack of critical interdisciplinary investigation prevents distinctive aspects of the experiences gained in the cultivated oases from informing global dryland research, despite the centrality of the oasis as a pivotal motif in recent interdisciplinary work on dryland systems and global environmental change (Safriel et al. 2005).

The research provides a critical investigation of the experience of human populations in living with environmental change, emphasizing the interplay between the natural environmental and socio-economic factors in the changing environment. Through localized investigation of these factors, the thesis projects topical global debates concerning economic development policies into the local geography of the northern Sahara. The regional case studies connect the ongoing work of scientists in applied disciplines across the study regions into the wider global scientific debate, with the intention of contributing a research product of potential interest to both.

Interdisciplinary work on regional land and groundwater management is long overdue, in the northern Sahara, and also in other regions. Such research is the key to understanding processes that influence productivity and development in the arid regions of the developing world, as elsewhere. Groundwater degradation was analyzed as an environmental change that impacts cultivation, exemplifying how physical conditions and human management approaches interact. While remote sensing results established a land cover change chronology, the field survey data revealed insights to explain these changes. These insights concerned the effects of international market drivers such as commodity prices on resource management by smallholders and other resource users.

An unexpected volume of environmental data were identified in private companies operating in the Egyptian desert. This implied that there are new opportunities for public and private sectors to collaborate in the improvement of environmental monitoring arrangements. This was an unusual finding, which was not apparent in the

review of previous studies from this, and other regions. This is therefore considered to represent a unique and original contribution to the ongoing global discussion of land and water management. Further research examining the potential to use this opportunity should be a high priority for the international research community, in order to prevent global market drivers from bringing about a tragedy of the land and water commons in the dryland regions.

Overall, this thesis demonstrates the scope for improvement of systems for environmental monitoring through action at the international level to consider the global market drivers of environmental change. This is necessarily connected to action at other levels to reengage institutions for CPR management, including users in the private sector and smallholders whose resource uses sometimes remain under informal or traditional regulatory arrangements. As has been argued in regional development strategies (IBRD 2007), cultivators need to be reengaged in resource management, in some cases reducing expectations of government to provide them with irrigation water, and managing their own economic development strategies.

The research confirms that interdisciplinary methodological approaches spanning the natural and social sciences in drylands research as developed and applied in one dryland region (e.g. Mazzucato and Niemeijer 2000 in Burkina Faso, or Stringer 2007 in Swaziland) can effectively inform investigations undertaken in other regions (in this case, the northern Sahara). It is argued that the integrated natural-social scientific approach could be applied more widely across the northern Saharan region, deepening global knowledge of dryland change processes and experiences. Intensified

utilization of such global environmental research approaches could further enrich international scholarship on environmental change in dryland environments.

### 8.2 Recommendations for implementation and further research

The northern Sahara is a vast region where contemporary studies of environmental processes, including human-environment interactions are rarely published, preventing dissemination of research and analysis amongst the global community. Recent environmental and socio-economic transitions have driven new cultivation technologies and resource cultivation patterns. If resource management is to improve, it is essential that environmental changes and changes in management level understanding of them are critically documented and published. By addressing key regional issues of water scarcity and land and water degradation, and assessing smallholder engagement in addressing them, this thesis highlighted forces shaping the cultivated environment. Cultivator-oriented and driven resource monitoring and management is a theme that merits continued research for the future.

Research increases understanding of ecological processes, how cultivators manage them, and how human (social and economic) management systems determine the interactions between these two. As rapid land cover change is increasingly observable across the northern Sahara, regional and global scientific understanding of the nature and implications of interacting environmental and economic change processes requires documentation and analysis. This study makes a contribution by providing an objective discussion of socio-economic and environmental processes affecting the

region. While the field surveys focused on two marginal desert regions in southern Tunisia and western Egypt, as highlighted in section 6.3.3, techniques employed could be replicated in other areas, nationally and internationally, to track environmental changes, and strengthen knowledge from economic development experiences gained in the cultivated desert ecosystems.

Environmental research in the northern Sahara has often been conducted by private technical consultants, who are dependent on sporadic international funding or, more often, private investment projects. Public research institutes and university departments are often disconnected from this process. Improved coordination amongst national governments, global companies and consumers is needed in order to better connect the existing demand and available capacities for effective environmental management and research programmes. The case studies indicate that the condition and trends in resources are monitored by resource users at the local level, by State institutions at regional levels (eg EEAA 2010b), and by private businesses on individual farms (Amekawa 2009). However, these discrete monitoring systems are not sufficiently integrated and inclusive to identify shared management imperatives and to drive changes in CPR management practices.

As yet, integrated resource assessments are seldom published from this region. Where available, they are irregular and less than comprehensive. Intelligent low-cost public strategies to coordinate, compile, analyse and progressively enhance the quality of available data and understanding of environmental change processes will be crucial in order to better evaluate the impacts of potential future policies involving economic

measures or other innovations to respond to environmental change. This is the key short-term implementable recommendation from this thesis.

A recent strategic analysis considers and compares the roles of seven separate Ministries involved in resource monitoring in Egypt, each working through a series of different Agencies and Departments (Abdel Dayem 2011). The situation in Tunisia is similarly fragmented. In addition, the preceding chapters have also identified a need for participation by additional stakeholders, including private sector resource users and consumers, in resource management data collection, analysis and decision-making.

This thesis has not set out to make recommendations to any particular group of local or national resource-managers or policy-makers, nor to propose a new national project. Who takes the lead in coordination of resource assessment may be less important than the overall inclusiveness of the processes. The remaining coordination challenge represents a gap or an opportunity for institutions and individuals working within them to take the initiative and self-organize. It also leaves considerable space open for independent researchers to contribute a more lively discussion of resource assessment challenges, engaging both national and international scientific communities.

It is important to admit the limitations of the investigation of environmental changes presented in this thesis. The available information supported observation of falling water tables, salinization of deep aquifers, and effects of waterlogging and salinization in low-lying areas. Other local reports of water contamination with agrochemicals and

burial or dumping of wastes could not be investigated, do not feature in published environmental datasets in either region, and are not addressed in this thesis. However, once the movement and fate of salts in the environment is understood, that of most other elements can be modelled on this basis, even where data on these other parameters of interest may remain sparse and infrequent. Since the discussion in this thesis addresses methodological and institutional dimensions of environmental monitoring as a generic activity, it provides insights of relevance to the monitoring of other parameters.

Land and water have long been viewed as highly sensitive political topics in this region. In both countries, there is an urgent need for improved management systems. The only way to achieve this will be to take an objective and informed look at how the existing systems have been engaging inputs from resource users, and where there are opportunities for improvement. Environmental scientists must drive this process, rather than continuing to take refuge in technical reports and avoiding to mention social and economic issues. Social scientists on the other hand, – especially those who are engaged in evaluating the economics of land and water management programmes could make more use of relevant environmental data in their evaluations.

In the northern Sahara, there has been a tendency amongst scientists seeking to speak with authority to brush over data gaps or remain silent about them. However, at this time, north African scientists have an unprecedented opportunity to begin to write about the difficulties faced over recent decades in integrating natural environmental and socio-economic scholarship to understand and address the regional experiences of

living with environmental change (see e.g. Serageldin 2011). It is time for them to evaluate the gaps in knowledge that have been allowed to persist over recent decades, and to fill them through their ongoing research.

In light of the grey areas between `traditional` cultivation knowledge, and conventionally recognized scientific knowledge and expertise in the northern Sahara, together with other factors described above, many of these recommendations for further research are region-specific. However, the technological and scientific advances associated with agroindustrial development, hydrogeological exploration and other economic activities observed in this region are also of wider interest in relation to global land and water management agendas.

### 8.3 Concluding remarks

North African development initiatives have long played a key role in the circum-Saharan regional trading economy, and the Nile Basin. North African technological expertise has reached most dryland areas of the world, very notably in fields such as remote sensing, irrigation management, agricultural development. International economic contributions from North Africa are also widely celebrated (see e.g. Serageldin 2011). And yet, interdisciplinary publications from the North-African research community addressing the global theme of environmental change and making their experiences available to the global research community have been lamentably few over recent years. As geopolitical, environmental, and social

constraints are realigning across this region, it is hoped that scientists might take their opportunity to speak out about what has been happening on the ground in their countries, and provide enlightened guidance to their new generation of global policy-makers.

Study results suggest that favourable new horizons are opening up for cultivators` innovation in the endorheic basin oases. Such environments have previously been viewed as disadvantaged by their marginal locations and dependence on resources that are scarce, saline and only renewable through human innovation. However, where it is recognized that there is no limit to human innovation, this becomes the key determining factor. To create viability in a global market environment requires cultivators to maintain their resource base, understand their comparative advantages in relation to other producers in other regions, and anticipate global market trends. National decision-makers need to consider whether global companies and international trade regimes are enabling cultivators to do this effectively. Research that informs this endeavour will contribute to the achievement of development objectives and support improved management of environmental change.

This research project was situated within the emerging literature on dryland systems and cultivators` knowledge, tracing the interaction of landscape and market through data from conventional and unconventional sources. Examining cultivators` experiences of living with environmental change suggests that the desiccated saline environment produces valuable commodities, wherever water is available. The fragile condition of the available resources, and their undervalued potential to bring

economic development or environmental destruction to these regions, require both cultivators and international market institutions to play a much greater role in ensuring national resource monitoring and management. Expanding the documentation of this knowledge, both locally and more widely, will be the lasting contribution of this DPhil research.

When deciding how to structure and manage the global trade in products from marginal dryland environments, the international community has the means and the opportunity to determine whether environmental monitoring and management systems are strengthened or weakened through the emerging regulatory regimes. Rather than ignoring these collective responsibilities, the global environmental community could choose to address them, whether through the existing international environmental agreements, or through the evolving trade regimes and voluntary export standards, or through the development of a more integrated global system for monitoring and managing the impacts of trade on the lucrative, fragile and resilient dryland systems.

Interdisciplinary observations presented in this thesis speak to new scientific horizons for discussion, engaging with the work of north African scientists from across a range of disciplines, and inviting them to consider opportunities for the scientific community across this region. The research process opened up a rich new world of scholarship and experience to the researcher. The thesis makes that experience available to others who may choose to read it. It also celebrates the changing endorheic environment in

the northern Sahara, its cultivators and its scientists – which and who fascinated the researcher, from beginning to end.

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# APPENDICES

**Appendix 1: Map of Study Areas in 1954** (U.S. Army Map Service 1954) Courtesy of the University of Texas Libraries, The University of Texas at Austin

**Figure A1.1: Overview of Study Areas as Mapped in 1954**

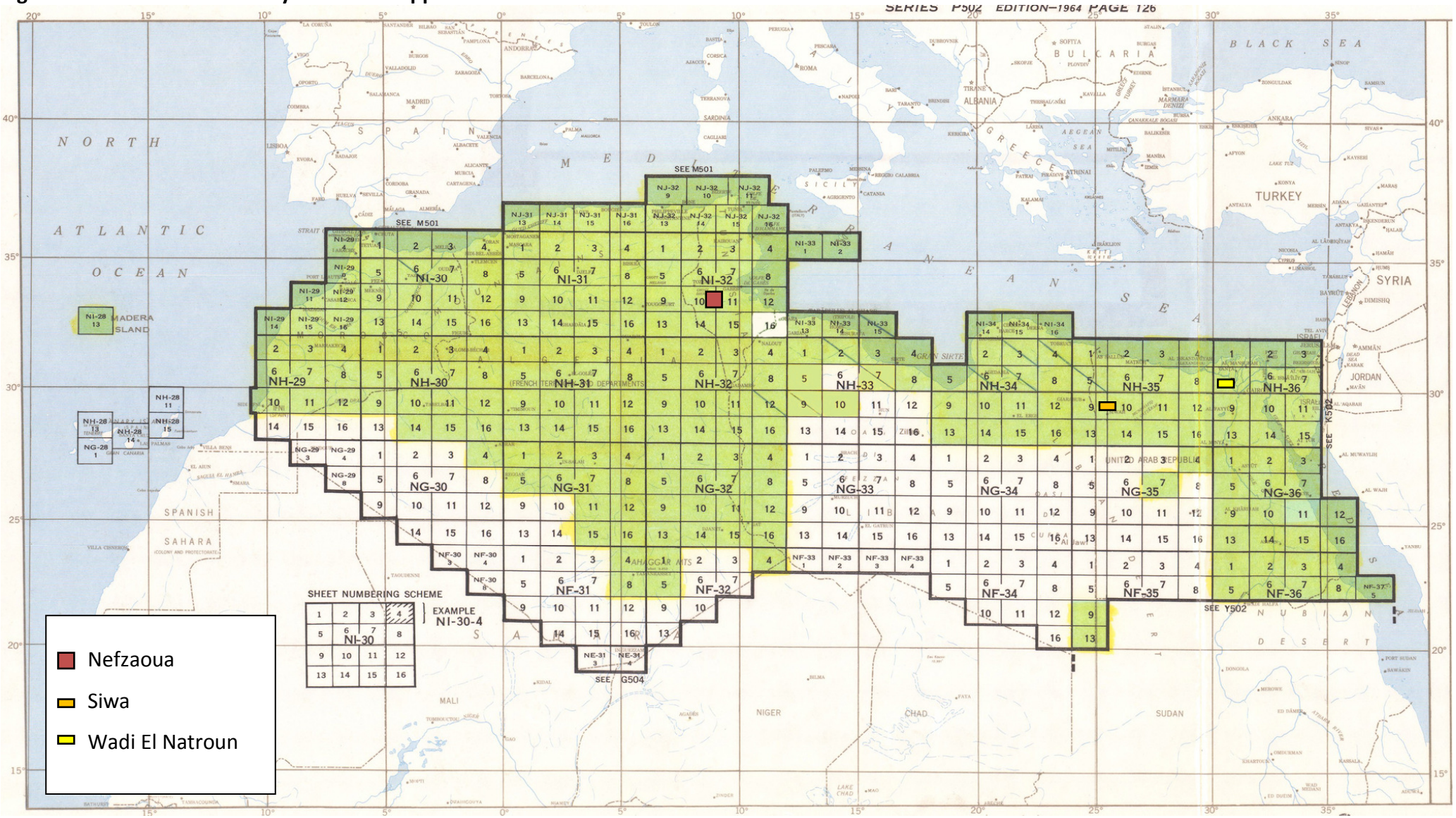


**Figure A1.2: Nefzaoua, Southern Tunisia, 1954**

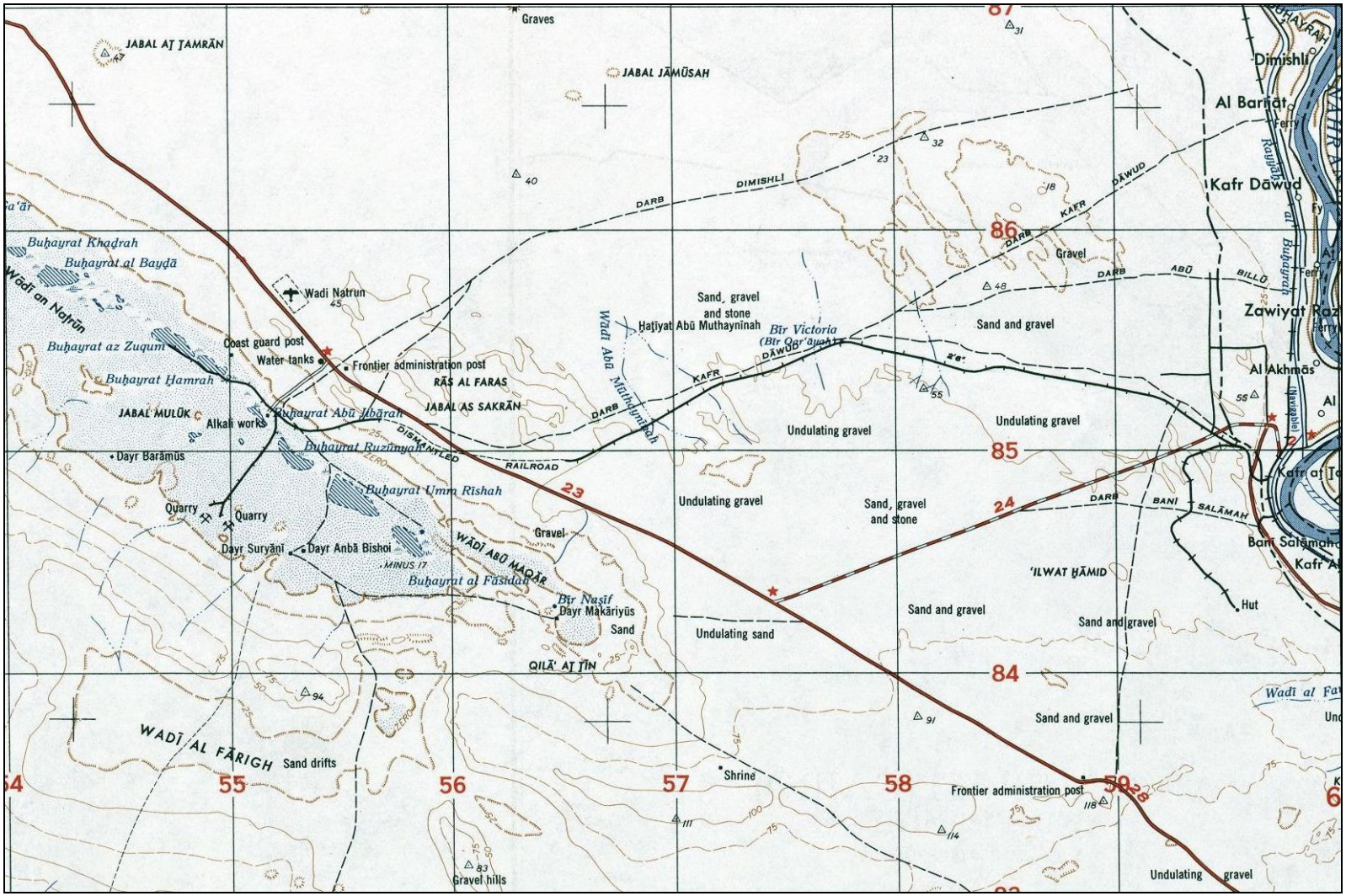


**Figure A1.3: Siwa, Western Desert, Egypt, 1954**




0km 10km 20km

**Figure A1.4: Wadi El Natroun, Western Desert, Egypt, 1954**



## Appendix 2: Rainfall in Study Areas from National Oceanic and Atmospheric Agency [26]

**Figure A2.1: Comparison of Trends in Annual Rainfall, 1995-2005 (sources: CRDA & NOAA)**

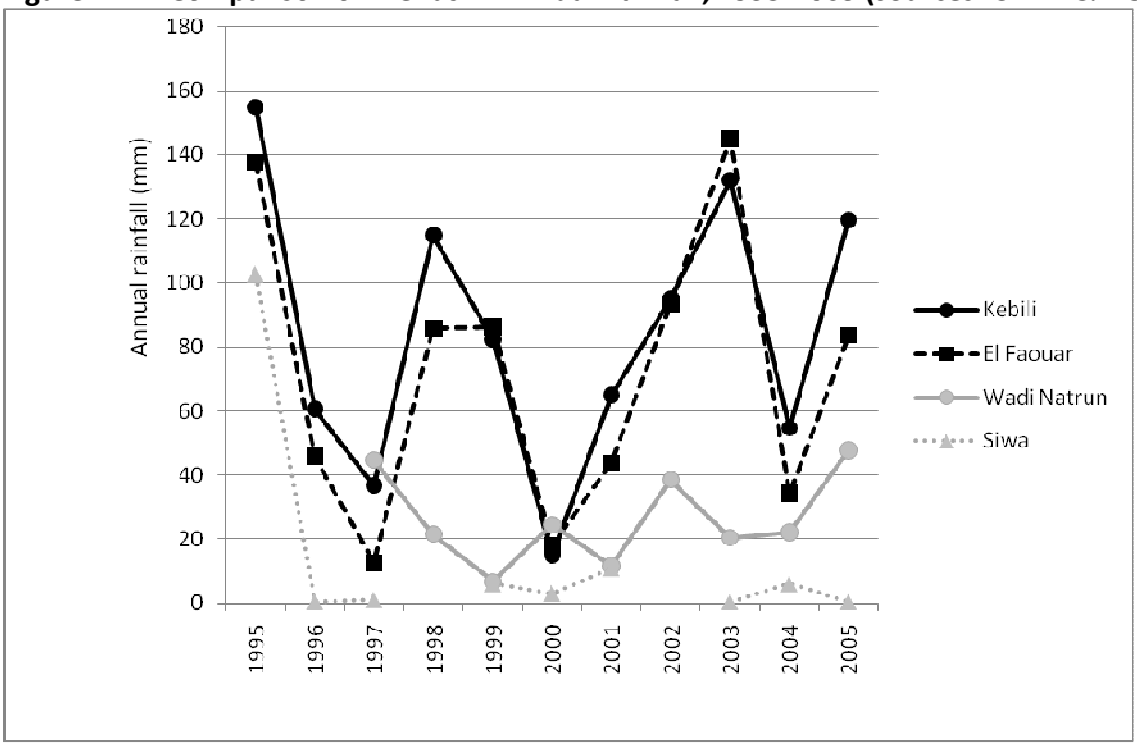
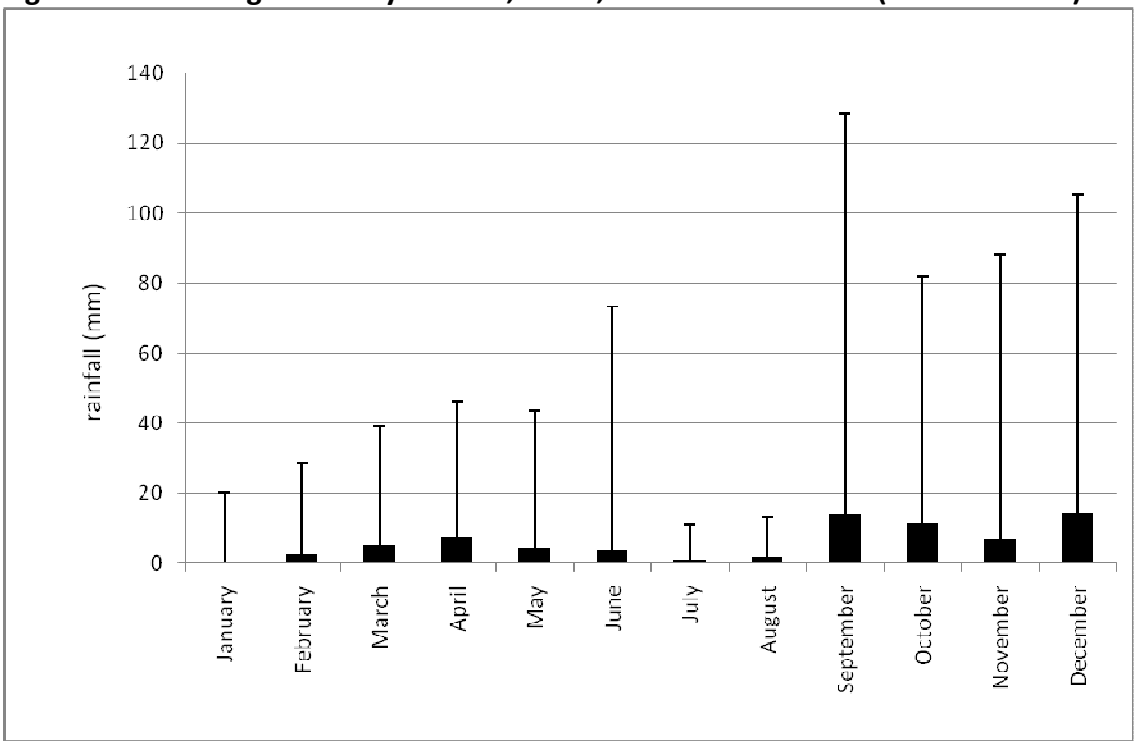


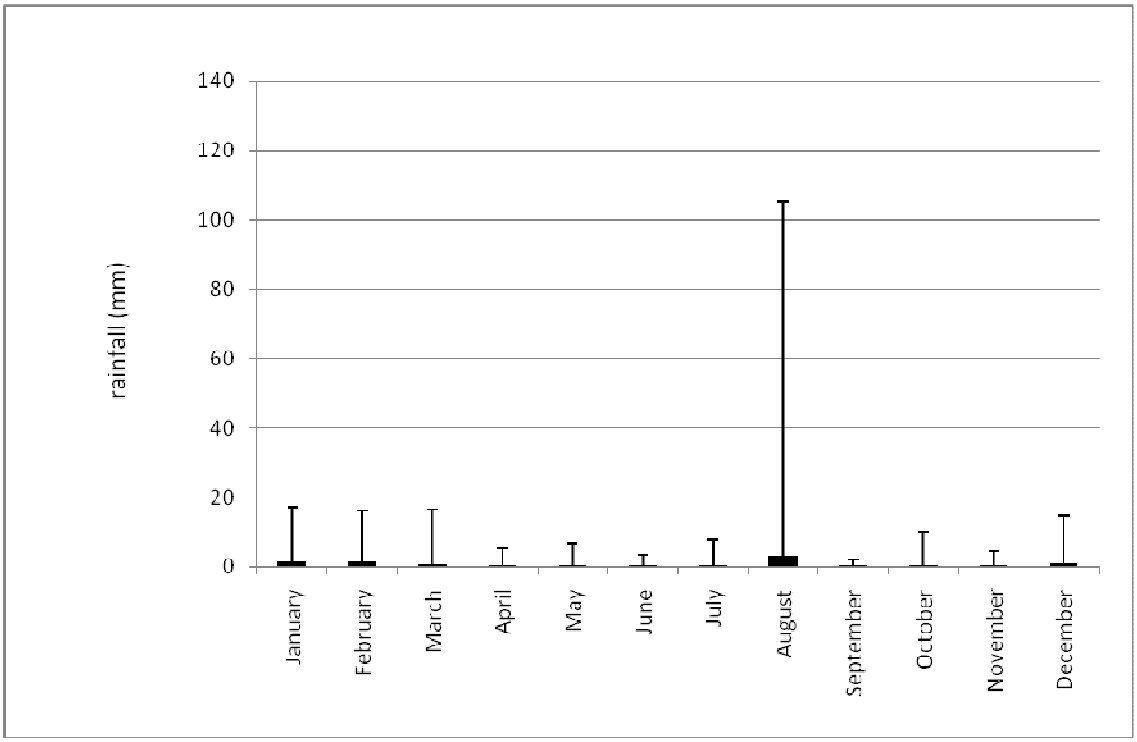

**Figure A2.2: Average Monthly Rainfall, Kebili, Tunisia 1997-2011* (source: NOAA)**




**(error bar showing max monthly rainfall over the same period)*

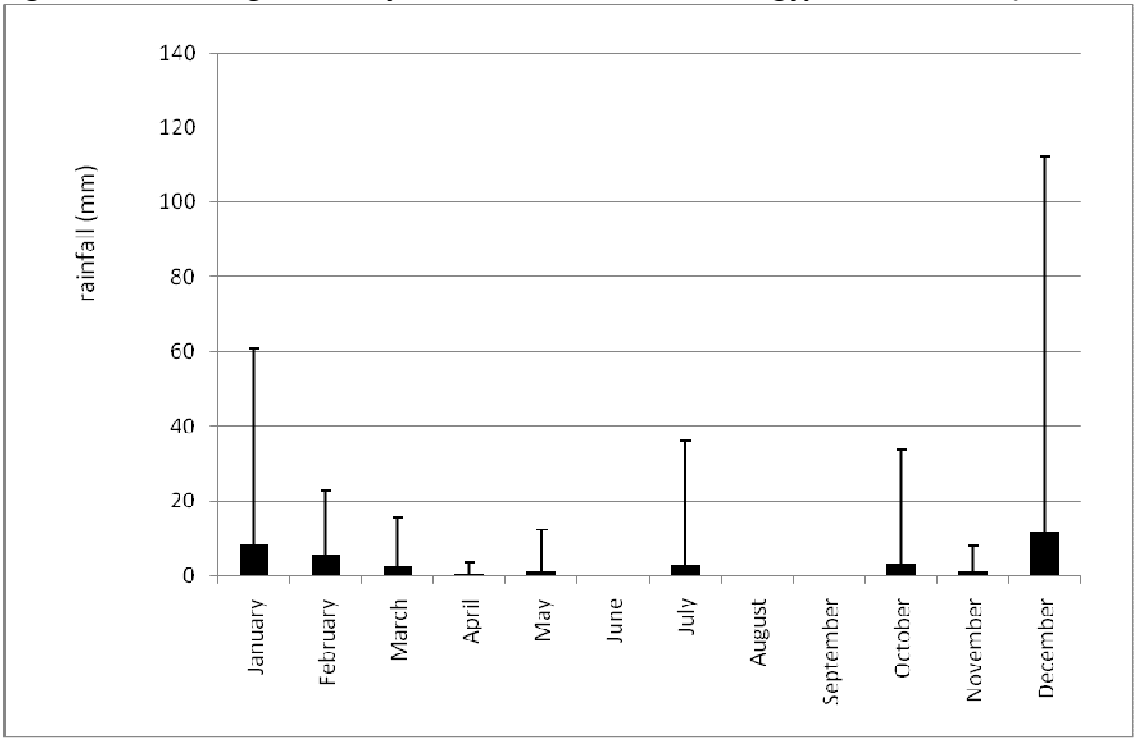
**Figure A2.3: Average Monthly Rainfall, Siwa, Egypt 1958-2011* (source: NOAA)**

[26] Daily ground surface datasets from NOAA: http://gis.ncdc.noaa.gov/map/gsod/




*(error bar showing max monthly rainfall over the same period)

**Figure A2.4: Average Monthly Rainfall, Wadi El Natroun, Egypt, 1996-2011* (source: NOAA)**




*(error bar showing max monthly rainfall over the same period)

## Appendix 3: Hydrogeology of Beni Salama Village: From 2009 fieldwork report

**Characterisation of aquifers**

The hydrogeological map of Wadi El Natroun identifies the following five main aquifers in the study area (RIGW 1990). The first three are shown on two W-E cross sections of the depression (***Figure A.3.1 and A.3.2)***. Between the lake, at the base of the depression and the Desert Road, the land surface slopes upward. Beneath the surface, the Pleistocene and Pliocene Aquifers are 110m below sea level. (***Figure A.3.2*** (from Abdel Mogheeth 2006, see also Ibrahim 2007 : p77). The Miocene Aquifer, lies beneath the Pleistocene and Pliocene. In order of depth from the surface, the five major aquifers in the study area, may be described as follows (after RIGW 1990):

*Pleistocene aquifer*

An unconfined aquifer, formed of sand and gravel with clay lenses (deltaic deposits). From 50-250m below sea level (RIGW 1990). It is 300m thick near the delta, 150 m at Wadi El Natroun and just a few metres near east of Wadi El Natroun ((Ahmed 1999b) . This aquifer is called the Nile Delta Aquifer because flow is east to west, bringing recharge from the Nile Delta (to the east). Estimates of annual recharge volumes vary from 41 cubic metres estimated during 1975 by Abdel Baki (1999a) to 160.3 million cubic metres per year estimated by Ahmed (1983), to 70 × 106 $m^3$/yr from seepage zones into small lakes, ponds and sabkhas estimated by Dawoud et al (2005). Recharge from the Nile waters is affected by changes in the irrigation and drainage activities in the Delta. Significant changes have been caused by engineering works such as the Rosetta Branch and the El Nasr Canal in the South. Transmissivity (T) and conductivity (K) are high. Water in this aquifer is 68.2% from Nile water and 31.8% paleowater in origin (Ahmed 1999a p169) – indicating connectivity and recharge occurring between this aquifer and underlying aquifers. Recharge from the Nile Waters includes seepage from the Rosetta branch to the North and the El Nasr canal, to the South.

*Pliocene aquifer*

Confined to semi-confined water bearing formations alternating sand and clay layers with gypsum and limestone (brackish water and marine facies). Wells of around 100m deep in Wadi El Natroun tap this aquifer. Shata 1955 recognized an upper series composed of porcellaneous limestone with flint and a lower series, composed of black shale alternating with argillaceous sandstone. Flow is east to west, with local flow paths north to south and southwest. This aquifer has lower transmissivity (T) and conductivity (K) than the Pleistocene. It receives downward flows from the Pleistocene Nile water and also upward flow of palaeowater 38.6% (Ahmed 1999b). The Pliocene aquifer is separated from the Miocene below by a clay layer. However, faults are present, enabling interconnection (Fekry and Salam 2002). The transmissivity is lower than that in both the Pleistocene above, and the Miocene below, at less than 500 $m^2$/day (Attia et al. 2005).

*Miocene aquifer*

This aquifer extends westward beneath the desert. It is known as the Moghra formation, and emerges at the Moghra oasis, to the West. It also outcrops on the surface in Wadi El Natroun and Wadi El Farigh, covering an area of approximately 50,000$km^2$. Thickness varies from 50-250m in the east (Wadi el Farigh) to about 800 m in the west (east of Quattara depression at Moghra). Transmissivity varies from 500 to 5.000 m2/day−1. (Dawoud et al. 2005). Recharge is achieved mainly though deep percolation from the Nile alluvium and groundwater flow across the common boundary of the Moghra and the Nile alluvium (Dawoud et al. 2005). The Miocene formation is connected to the Nubian Sandstone Aquifer System, although the flow between these aquifers is not well studied (El Tahlawi, Farrag and Ahmed 2008). Beneath Wadi El Natroun, these aquifers are separated by a basalt layer of oligocene rock (Idris and Nour 1990).

*Cretaceous/Eocene limestone aquifer*

This layer is underlying the Oligocene rocks. It has low to moderate productivity (Idris and Nour 1990). It contains a basalt layer separating the Miocene from the NSAS in the study area (RIGW 1990).

*Nubian Sandstone Aquifer System (NSAS)*

Although it is fresh elsewhere, beneath Wadi El Natroun, the NSAS is understood to be saline. This aquifer is not exploited in the study area but mixing with the upper layers has been identifed Ahmed 1999b). Recharge to the NSAS coming from Sudan is estimated at around an order of magnitude less than extraction. On a regional scale, the connections between the NSAS and the Miocene aquifer are not well understood.

**Figure A3.1: West-East Cross Section from the Depression to the Desert Road** (Ahmed 1999b: p53)

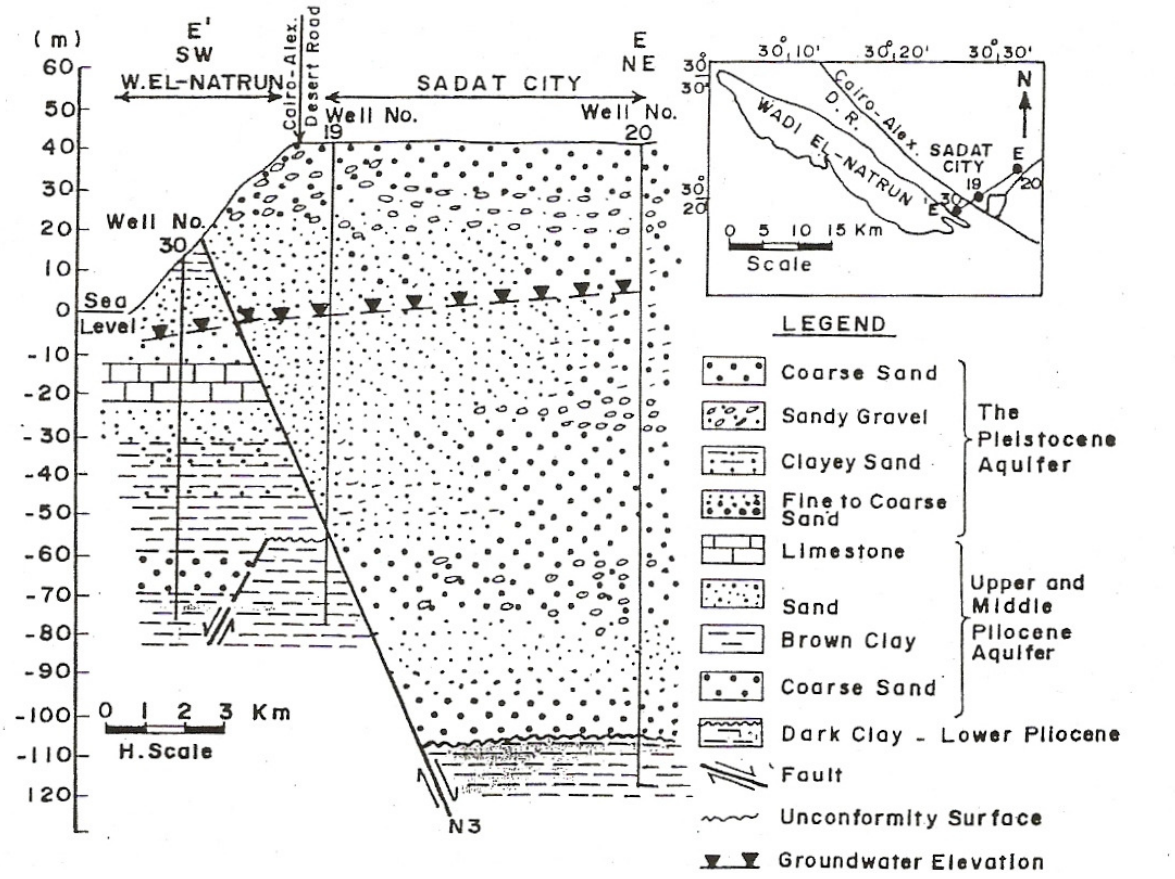
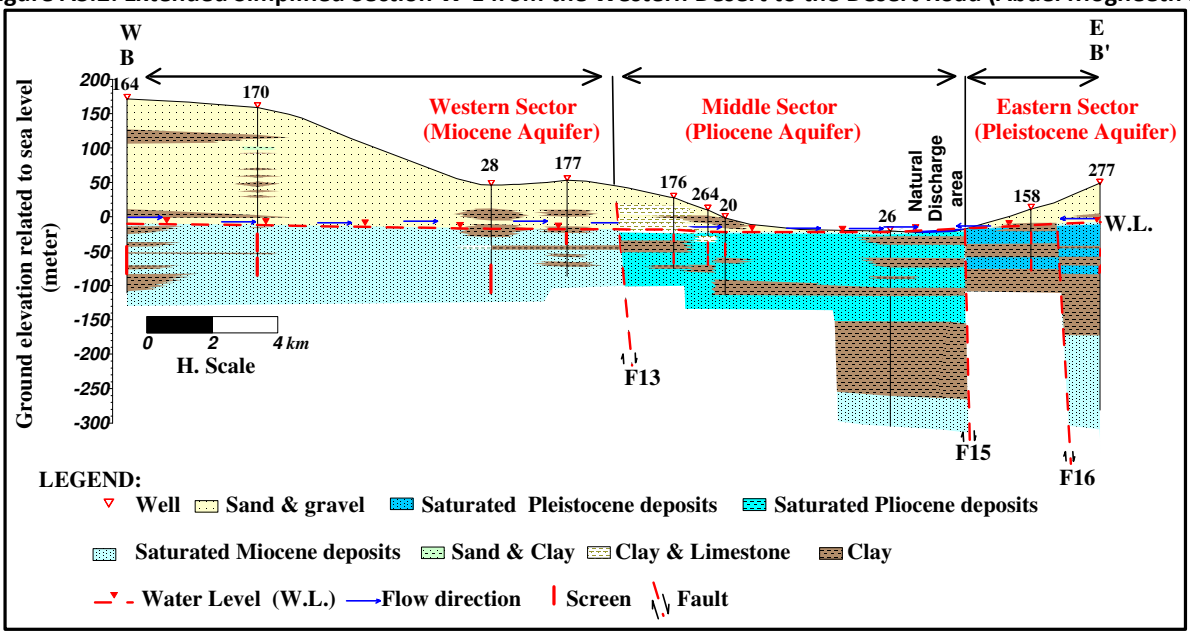



**Figure A3.2: Extended Simplified Section W-E from the Western Desert to the Desert Road (Abdel Mogheeth 2006)**



The 8km study area is divided into four quarters, each covering an area of 4x4km, to the North West, North East, South West and South East, as shown on the figure below. An additional 2km square to the East of the center of the 8 km study area is singled our for further attention, where the residential area of the village is located. This is highlighted in yellow on **Figure A.3.3.**

**Figure A3.3: Subdivision of 8kmx8km Study Area (image courtesy of Google Earth)**



## Well data in the village area

**Table A3.1: Location of Well Sampled in Previous Study (Ahmed 1999b)**

| Ahmed No. | Saluma No. | N | E | Total drilled depth | Depth to screen | Depth to water | Elevation | Water tabl msl | Aquifer |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 54 | 30 20 10 N | 30 25 24 E | 87m | 33.57 | 17.2 | 11 | -6.2 | Pliocene |

**Figure A3.4: Village Area: Profile of Well Published in Previous Studies (Ahmed 1999b, Saluma 1974)**

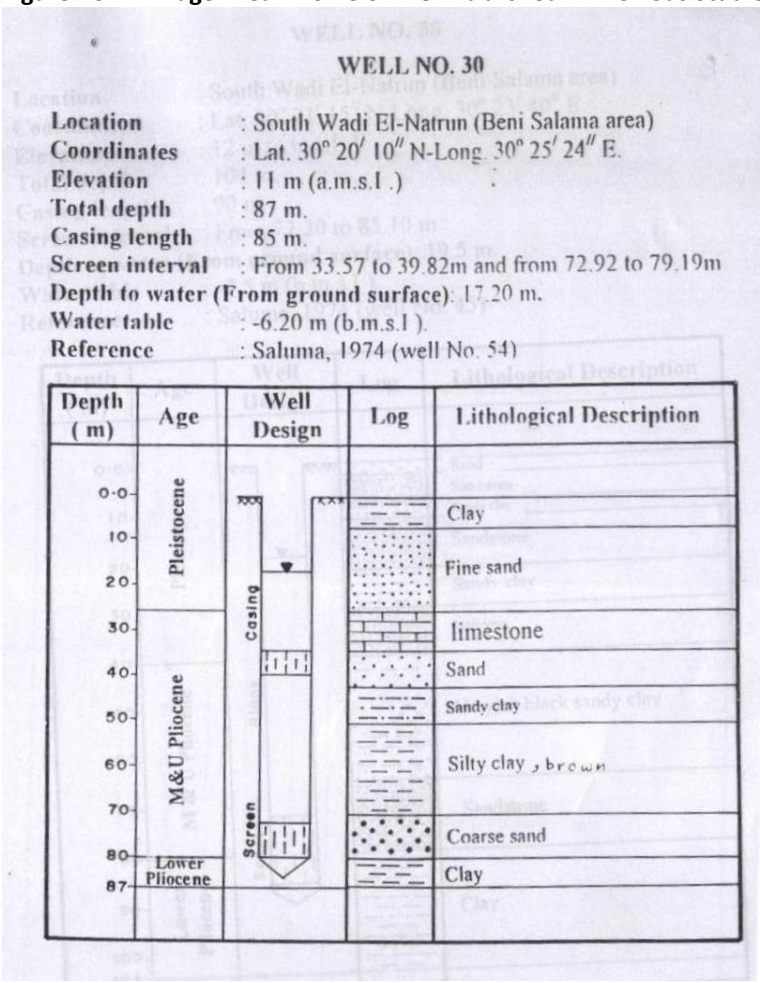


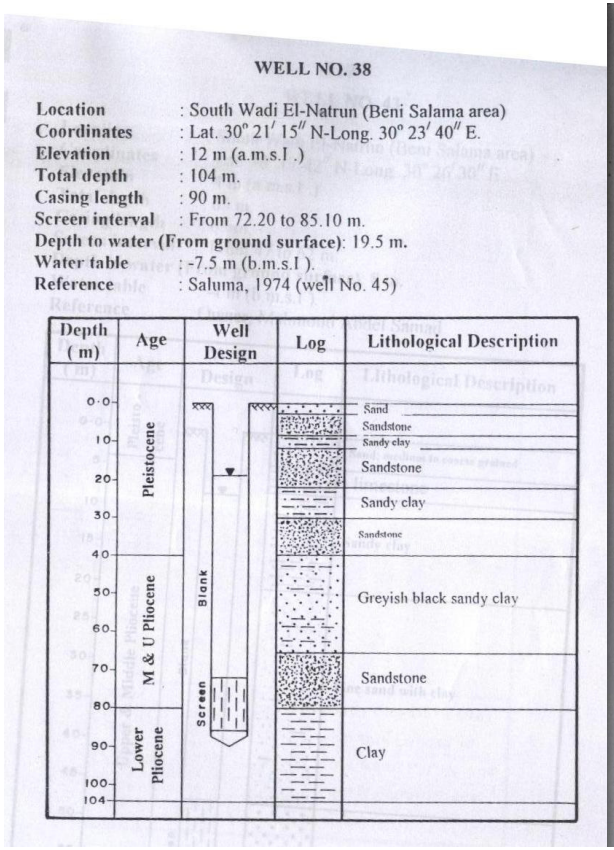
**Table A3.2: Wells in North West Area According to MWRI Well Permit Application Dossiers**

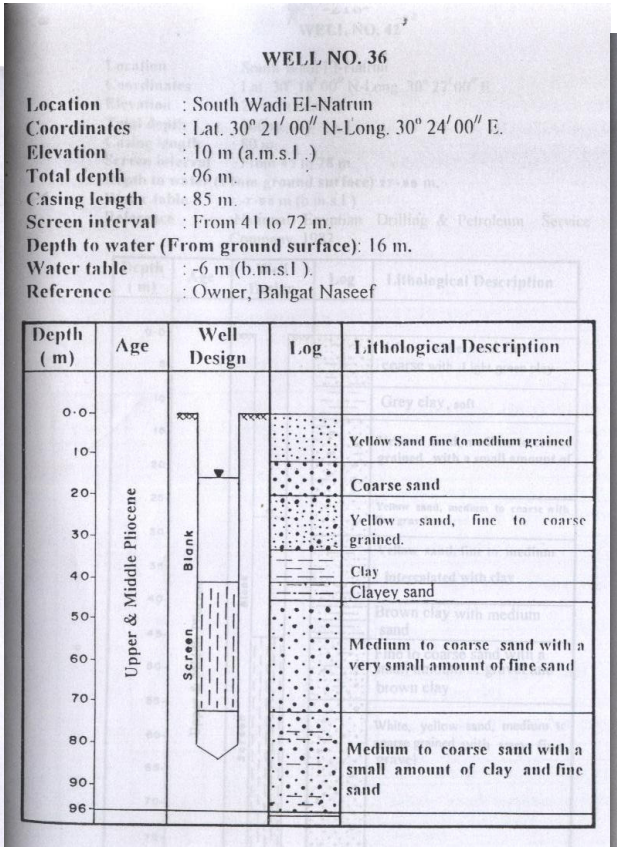
| type | Farm area (feddan) | code | salinity | Total depth of well (m) | capacity in bousa | length of pipe | length of filter | type of pump | well flow in $m^3$ |
|---|---|---|---|---|---|---|---|---|---|
| 20-100 feddan | 51 | 020 MWRI NW 01 | 500 | 92 | 10 | 67 | 25 | kabrari | 80 |
| | 30 | 020 MWRI NW 02 | 350 | 80 | 12 | 65 | 16 | local | 80 |
| 3-20 feddan | 4 | 003 MWRI NW 01 | 450 | 70 | 8 | 45 | 35 | johnson | 54 |
| | 7 | 003 MWRI NW 02 | 600 | 72 | 10 | 50 | 22 | local | 100 |

Table **A3.3: Published Data on Pliocene Wells in Previous Studies in North West Study Area (Ahmed 1999b, Saluma 1974, Awad 2002)**

| **No.** | **Study** | **Sampling date** | **N** | **E** | **Total drilled depth** | **Depth to screen** | **Elevation** | **Depth to water** | **Water table msl** |
|---|---|---|---|---|---|---|---|---|---|
| 8 | Ahmed & Saluma 51 | Not known | 30 20 48 N | 30 24 30 E | 100m | 28.3 | 10 | 16.4 | -6.4 |
| 28 | Ahmed | | 30 20 48 N | 30 24 30 E | 100m | 28.3 | 10 | 16.4 | -6.4 |
| 36 | Ahmed & Bahgat Naseef | | 30 21 00 N | 30 24 00 E | 96m | 41 | 10 | 16 | -6 |
| 38 | Ahmed & Saluma 45 | | 30 21 15 N | 30 23 40 E | 104m | 72.20 | 12 | 19.5 | -7.5 |
| 34 | Awad 34 | October 2002 | 30°21.103 | 30°23.306 | Not known | Not known | Not known | Not known | Not known |

**Figure A3.5: Profiles of Wells in North West Study Area (Ahmed 1999a)**



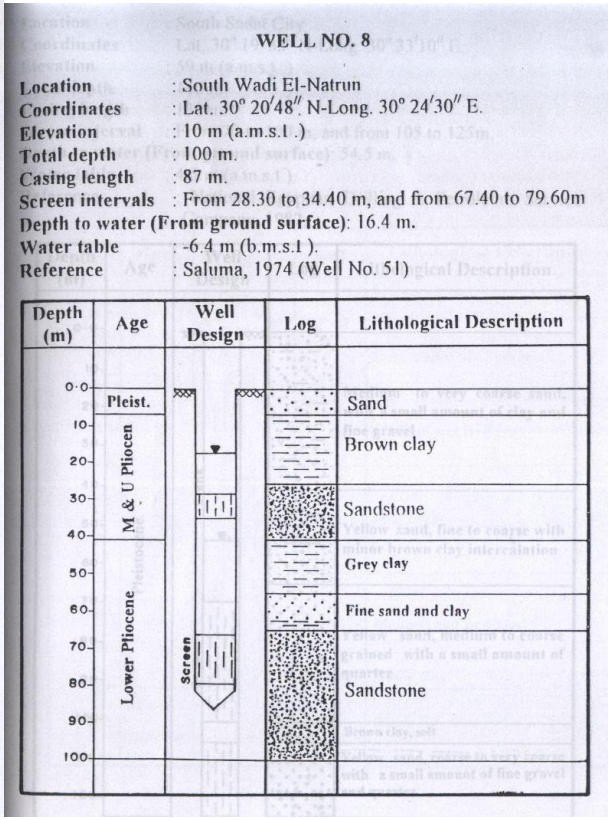



**Table A3.4: Previously Published Well Data in North East** Study Area (Ahmed 1999a)**

| Ahmed No. | Other studies No. | N | E | Total drilled depth | Depth to screen | Elevation | Depth to water | Water tabl msl |
|---|---|---|---|---|---|---|---|---|
| 9* | None | 30 21 00 N | 30 25 15 E | 62.5m | - | 28 | 30.2 | -2.2 |
| 29 | None | 30 20 48 N | 30 24 30 E | 60m | 38 | 10 | 16. | -6. |

*in Pleistocene

** Note: no well profile data has yet been obtained from this area.

**Table A3.5: Wells in North East Area According to MWRI Well Permit Application Dossiers**

| type | area total | cultivated area | dossier no | code | salinity | احداثيات_الـ بئر_N | احداثيات_الـ بئر_E | depth of well (m) | capacity in bousa | length of casing | length of filter | type of pump | well flow in $m^3$ | number of hours per day | total daily flow |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20-100 feddan | 28 | | 1600 | 020 MWRI NE 01 | 500 | 30 20 22.7 | 30 27 37.5 | 95 | 10 | 65 | 30 | كبراري | 300 | 0 | 0 |
| | 28 | | 1602 | 020 MWRI NE 02 | 600 | 30 19 53.3 | 30 27 30.0 | 88 | 10 | 65 | 23 | كبراري | 264 | | |
| | | | | 020 MWRI NE 03** | 500 | 30 19 03.1 | 30 32 21.7 | 190 | 10 | 130 | 60 | اعماق | 100 | 100 | 12 |
| | 83 | 83ف | 1081 | | 500 | 30 18 35.4 | 30 32 15.7 | 19 | 10 | 130 | 60 | اعماق | 100 | 12.0 | 1250 |
| | | 83ف | 1081 | | | | | | | | | | | | |

**in extended study area

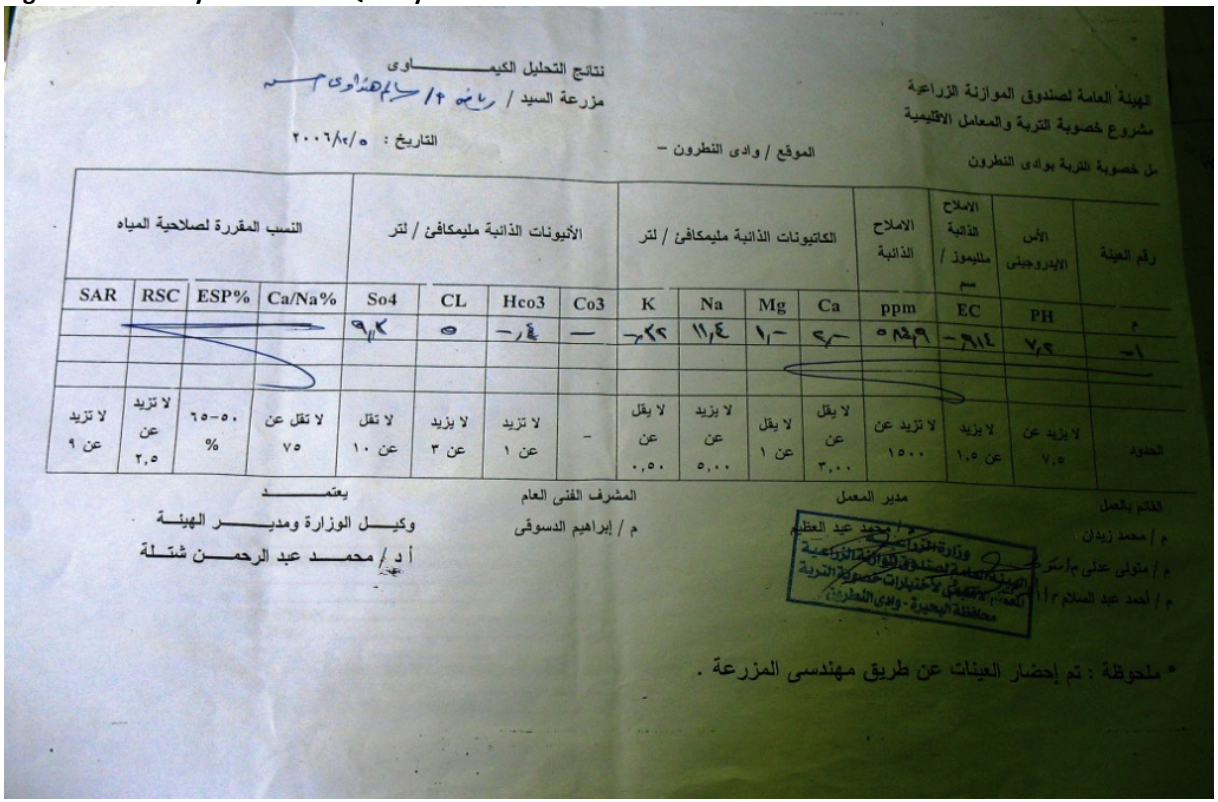
**Table A3.6: MWRI Database on Well Permit Applications in SE of Study Area**

| type | code | area total (f) | cultivated area | dossier no | salinity | احداثيات_ا لبئر_N | احداثيات_ا لبئر_E | depth of well (m) | capacity in bousa | length of pipes | length of filter | type of pump | well flow in $m^3$ | # hours per day | total daily flow |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1-3 feddan | 010 MWRI SE 01 | 3 | | 797 | 300 | 30 18 520 | 30 25 334 | 24 | 8 | 18 | 6 | local | 60 | | 0 |
| 3-20 feddan | 030 MWRI SE 01 | 15 | 15ف | 1859 | 500 | 30 18 55.1 | 30 27 30.0 | 60 | 10 | 40 | 20 | local | 50 | 1.5 | 90 |
| | 030 MWRI SE 01 | 17 | | 884 | 630 | 30 19 014 | 30 26 819 | 66 | 8 | 46 | 20 | local | 240 | | 0 |
| | 030 MWRI SE 02 | 17 | | 789 | 630 | 30 18 064 | 30 24 395 | 100 | 10 | 65 | 35 | local | 204 | | 0 |
| | 030 MWRI SE 03 | 18 | | 787 | 300 | 30 18 881 | 30 25 149 | 52 | 8 | 38 | 14 | local | 80 | | 0 |
| 20-100 feddan | 020 MWRI SE 01 | 58 | 55ف | 718 | 400 | 30 17 15.9 | 30 24 44.8 | 76 | 10 | 56 | 20 | local | 100 | 7 | 700 |

**Table A3.7: Listing of Pliocene Wells in Previous Studies in South East Study Area (Ahmed 1999a)**

| Ahmed No. | Other studies No. | N | E | Total drilled depth | Depth to screen | Elevation | Depth to water | Water tabl msl |
|---|---|---|---|---|---|---|---|---|
| 39 | none | 30 18 56 N | 30 24 56 E | - | - | -16 | flow | well |
| 40 | none | 30 18 35 N | 30 25 12 E | - | - | -13 | flow | well |
| 42 | National Egyptian Drilling and Petroleum Service Company | 30 18 00 N | 30 27 00 E | 100m | 45 | 20 | 28.10 | -8.10 |
| 43 | Owner Mahmoud Abdel Samad | 30 19 42 N | 30 26 30 E | 65m | 47 | 4 | 8 | -4 |

**Figure A3.6: Analysis of Water Quality on Farm in 2006**



الهيئة العامة لصندوق الموازنة الزراعية
مشروع خصوبة التربة والمعامل الاقليمية
معمل خصوبة التربة بوادى النطرون

نتائج التحليل الكيماوى
مزرعة السيد / رياض ابو الهداوى

الموقع / وادى النطرون –

التاريخ : ٢٠٠٦/٨/٥

| رقم العينة | الأس الايدروجينى | الاملاح الذائبة مليموز / سم | الاملاح الذائبة | الكاتيونات الذائبة مليمكافئ / لتر | | | | الأنيونات الذائبة مليمكافئ / لتر | | | | النسب المقررة لصلاحية المياه | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| م | PH | EC | ppm | Ca | Mg | Na | K | Co3 | Hco3 | CL | So4 | Ca/Na% | ESP% | RSC | SAR |
| ١- | ٧,٤ | ٢,١٤- | ٥٨٩ | ٤- | ١,- | ١١,٤ | ٠,٢٢- | — | ٤,- | ٥ | ٩,٢ | | | | |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| الحدود | لا يزيد عن ٧,٥ | لا يزيد عن ١,٥ | لا تزيد عن ١٥٠٠ | لا يقل عن ٣,٠٠ | لا يقل عن ١ | لا يزيد عن ٥,٠٠ | لا يقل عن ٠,٥٠ | – | لا تزيد عن ١ | لا يزيد عن ٣ | لا تقل عن ١٠ | لا تقل عن ٧٥ | ٦٥-٥٠ % | لا تزيد عن ٢,٥ | لا تزيد عن ٩ |

القائم بالعمل
م / محمد زيدان
م / متولى عدلى م/ اسكر
م / احمد عبد السلام م/

مدير المعمل
م / محمد عبد العظيم

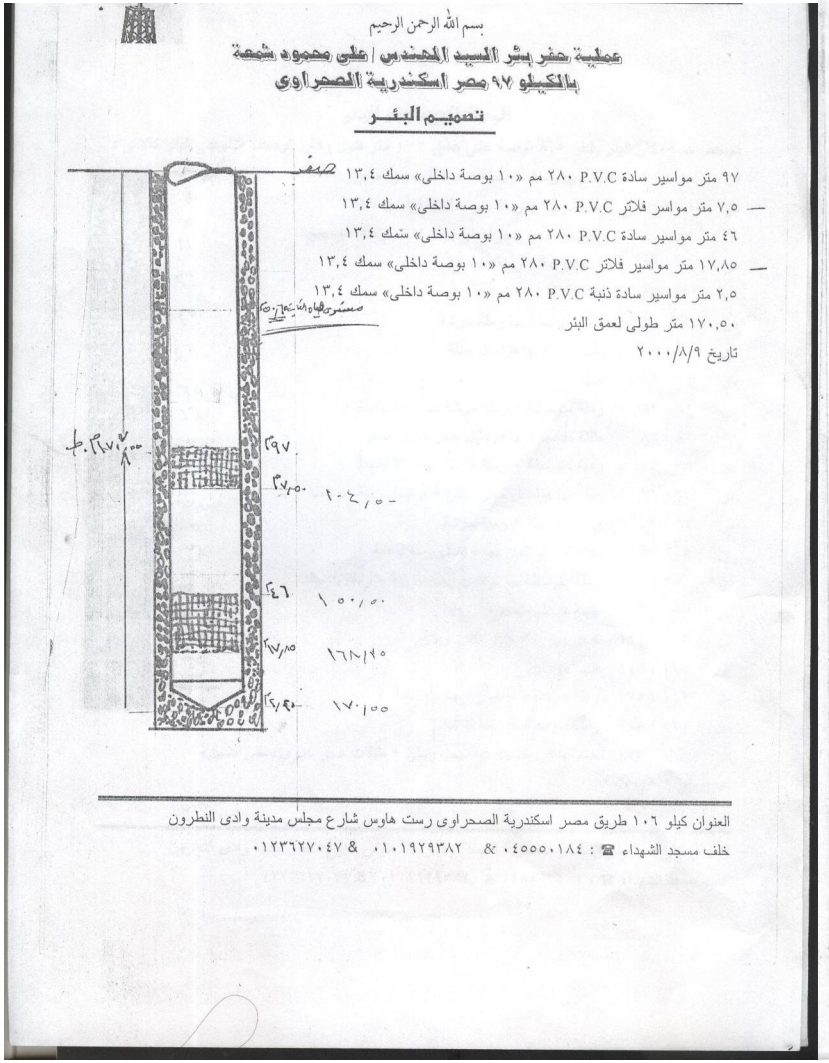
المشرف الفنى العام
م / إبراهيم الدسوقى

يعتمـــــد
وكيـــل الوزارة ومديـــر الهيئـــة
أ د / محمـــد عبد الرحمـــن شتـــلة

وزارة الزراعة
الهيئة العامة لصندوق الموازنة الزراعية
المعمل المعتمد لاختبارات خصوبة التربة
محافظة البحيرة - وادى النطرون

• ملحوظة : تم إحضار العينات عن طريق مهندسى المزرعة .

**Figure A3.7: Profile of a Well Provided By Cultivator**



بسم الله الرحمن الرحيم

عملية حفر بئر السيد المهندس / على محمود شعبة
بالكيلو ٩٧ مصر اسكندرية الصحراوى

تصميم البئـــر

٩٧ متر مواسير سادة P.V.C ٢٨٠ مم «١٠ بوصة داخلى» سمك ١٣,٤
٧,٥ متر مواسير فلاتر P.V.C ٢٨٠ مم «١٠ بوصة داخلى» سمك ١٣,٤
٤٦ متر مواسير سادة P.V.C ٢٨٠ مم «١٠ بوصة داخلى» سمك ١٣,٤
١٧,٨٥ متر مواسير فلاتر P.V.C ٢٨٠ مم «١٠ بوصة داخلى» سمك ١٣,٤
٢,٥ متر مواسير سادة ذنبة P.V.C ٢٨٠ مم «١٠ بوصة داخلى» سمك ١٣,٤
١٧٠,٥٠ متر طولى لعمق البئر
تاريخ ٢٠٠٠/٨/٩

العنوان كيلو ١٠٦ طريق مصر اسكندرية الصحراوى رست هاوس شارع مجلس مدينة وادى النطرون
خلف مسجد الشهداء ☎ : ٠٤٥٥٥٠١٨٤ & ٠١٠١٩٢٩٣٨٢ & ٠١٢٣٦٢٧٠٤٧



بسم الله الرحمن الرحيم

عملية حفر بئر السيد المهندس / على محمود شعبة
بالكيلو ٩٧ مصر اسكندرية الصحراوى

الوصف الجيولوجى للبئر

تم حفر جسة مكان البئر بقطر ٨,٥ بوصة حتى عمق ١٧٣ متر طول وكان الوصف الثلوجى للبئر كالاتى :

| | | | |
|---|---|---|---|
| من | ٠ : ٤ | طفلة بها رملة متوسطة + فواصل حجر اصفر | ٤ |
| من | ٤ : ٨ | رملة حرشة + رملة متوسطة بها فواصل طفلة | ٨ |
| من | ٨ : ١١ | حجر جيرى + حجر طفلى بها فواصل رملة متوسطة | ١١ |
| من | ١١ : ٢٦ | رملة حرشة + رملة متوسطة | ٢٦ |
| من | ٢٦ : ٣٩ | طفلة | ٢٩ |
| من | ٣٩ : ٤٩ | رملة متوسطة بها رملة حرشة | ٤٩ |
| من | ٤٩ : ٦١ | رملة ناعمة بها فواصل طفلة | ٦١ |
| من | ٦١ : ٦٦ | طفلة | ٦٦ |
| من | ٦٦ : ٨٣ | رملة متوسطة + رملة حرشة بها رملة ناعمة | ٨٣ |
| من | ٨٣ : ٨٥ | طفلة متحجرة بها فواصل حجر طفلى اصفر | ٨٥ |
| من | ٨٥ : ٩٣ | رملة متوسطة + رملة حرشة بها رملة ناعمة | ٩٣ |
| من | ٩٣ : ٩٦ | طفلة بها فواصل حجر طفلى + فواصل رملة متوسطة | ٩٦ |
| من | ٩٦ : ١٠٥ | رملة متوسطة + رملة حرشة | ١٠٥ |
| من | ١٠٥ : ١٠٩ | طينة سوداء اللون بها فواصل رملة ناعمة | ١٠٩ |
| من | ١٠٩ : ١١١ | رملة متوسطة بها فواصل رملة حرشة + رملة ناعمة | ١١١ |
| من | ١١١ : ١١٣ | طينة سوداء متحجرة | ١١٣ |
| من | ١١٣ : ١١٧ | حجر جيرى + حجر طفلى رمادى اللون | ١١٧ |
| من | ١١٧ : ١٤٩ | طينة سوداء | ١٤٩ |
| من | ١٤٩ : ١٦٥ | رملة حرشة + فواصل رملة متوسطة | ١٦٥ |
| من | ١٦٥ : ١٦٨ | رملة متوسطة + رملة ناعمة | ١٦٨ |
| من | ١٦٨ : ١٧٣ | حجر طفلى متداخل فيه حجر رملى + طبقات حجر جيرى يسمى «شيل» | ١٧٣ |

تحرير فى ٢٠٠٠/٨/٩

العنوان كيلو ١٠٦ طريق مصر اسكندرية الصحراوى رست هاوس شارع مجلس مدينة وادى النطرون
خلف مسجد الشهداء ☎ : ٠٤٥٥٥٠١٨٤ & ٠١٠١٩٢٩٣٨٢ & ٠١٢٣٦٢٧٠٤٧

**Table A3.8: MWRI Database on Well Permit Applications in SW of Study Area**

| | code | area total | dossier no | salinity | احداثيات_ا لبئر_N | احداثيات_ا لبئر_E | depth of well (m) | capacity in bousa | length of pipes | length of filter | type of pump | well flow in $m^3$ | permit status | cultivated area | number of hours per day | total daily flow |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20-100 feddan | 020 MWRI SW 01 | 22 | 4863 | 400 | 30 18 53.9 | 30 22 41.2 | 50 | 8 | 26 | 24 | محلى | 100 | مرخص | 22ف | 1.3 | 135 |
| | 020 MWRI SW 02 | 25 | 2482 | 600 | 30 17 30.1 | 30 23 43.7 | 70 | 10 | 50 | 20 | محلي | 100 | | | 0 | 0 |
| | 020 MWRI SW 03 | 50 | 1604 | 600 | 30 17 24.3 | 30 23 30.0 | 60 | 10 | 40 | 20 | كبراري | 480 | | | | 0 |

**Table A3.9: Location of Samples from South West Study Area Analysed in Previous Studies**

| Study & # | N | E | Other information |
|---|---|---|---|
| Awad 31 | 30°19.461 | 30°22.449 | Private Farm |
| Gad 169 | 30 17 40 N | 30 20 30 E | Well in Miocene Aquifer |

## Groundwater quality

Beni Salama is known for the good quality of its water. Public water supplies for the wider area of Wadi El Natroun are piped from this location, and a series of commercial water bottling factories are located close to the village. Information on water quality in the study area has been published in previous studies by Egyptian students (e.g. Ahmed 1999b, Awad 2002, Ibrahim 2007). In the tables below, published data on Total Dissolved Solids (TDS) in water samples from the study area is reviewed in comparison to available drinking water quality standards, including Egyptian standards for drinking and domestic uses (Higher Committee for Water, 1995), WHO guidelines and Ayers 1977 recommended water quality criteria for irrigation, as referred to by Ibrahim (2007). Overall, according to these data, the quality of water is better in the south of the study area.

**Table A3.10: Selected Standards for TDS**

| **Egyptian Standards** | **WHO (Mg/l)** | | **Ayers 1977 recommended water quality criteria for irrigation referred to by Ibrahim (2007)** | |
|---|---|---|---|---|
| 1200 | excellent | 0-300 | suitable | <480 |
| | good | 300-600 | marginal | 480-1920 |
| | fair | 600-900 | unsuitable | >1920 |
| | poor | 900-1200 | | |
| | unacceptable | 1200- | | |

Monitoring of groundwater quality is routinely carried out by government agencies responsible for health and irrigation, and also by the larger farms and water bottling companies in the study area. This information is not in the public domain. The local government in Wadi El Natroun voluntarily shared some analyses of public wells. This information was shared in confidence and cannot be included in this report. However, it has informed the investigations that are presented.

**Effects on groundwater caused by human activities**

A series of potential threats to groundwater resources have been observed in and around the study area of Beni Salama (see Salem 2008b):

**Falling water table**

Groundwater level depletion has been observed across Wadi El Natroun, affecting wetland and cultivated areas (Attia et al. 2005, 2007). Estimates of the degree of depletion over the period 1990-2002 reported in previous studies range between 1-12m (Ibrahim 2005, Abdel Mogheeth 2006). Long trends in groundwater depletion since 1960 were studied by Abdel Mogheeth et al (2006). These authors identified an acceleration of the rate of depletion during the most recent decade, accompanying the expansion of irrigated agriculture that occurred over this period, as described in the previous section.

According to Dawoud et al (2005), groundwater levels in the Wadi El Natroun area oscillate up and down due to a range of factors, of which groundwater extraction is only one. Other essential influences are:

- Level of water in the river Nile and its branches determined by climate and hydrology across the Nile Basin
- Method and frequency of irrigation in West Nile Delta (e.g. increasing use of drip irrigation).
- Construction of water infrastructure, e.g. canals to support horizontal and vertical agricultural extensions in the Western Delta.

**Table A3.11: Comparison of Published Analyses of Farm Water Samples to Standards**

| Location | sample | year | Total well depth (m) | Screen interval (m) | Aquifer | TDS ppm | WHO rating | Acceptable under Egyptian Drinking Water Standards | Suitabiility for irrigation |
|---|---|---|---|---|---|---|---|---|---|
| North above 0 contour | Ahmed 7 | 1998 | 105 | 45-60 | Pleistocene | 582.4 | good | yes | marginal |
| | Ahmed 9 | 1998 | - | - | Pleistocene | 595.2 | good | yes | marginal |
| North of lakes just above sea level (w-e) | Ahmed 28 | 1998 | - | - | Pliocene | 1798 | unacceptable | no | marginal |
| | Awad 135 | 2001 | - | - | | 416 | good | yes | suitable |
| | Ahmed 38 | 1998 | 104 | 72.20-85.10 | Pliocene | 774.4 | fair | yes | marginal |
| | Ahmed 36 | 1998 | 96 | 41-72 | Pliocene | 806.4 | fair | yes | |
| | Ahmed 8 | 1998 | 100 | 28.30-34.40 &67.40-79.60 | Pliocene | 460.8 | good | yes | suitable |
| | Ahmed 29 | 1998 | - | - | Pliocene | 1549 | unacceptable | no | marginal |
| | Ahmed 30 | 1998 | 87 | 33.57-39.82 & 72.92-79.19 | Pliocene | 972 | poor | yes | |
| North of lakes below sea level (w-e) | Ahmed 41 | 1998 | - | - | Pliocene | 371.2 | good | yes | suitable |
| | Ahmed 43 | 1998 | 65 | 47-62 | Pliocene | 377.6 | good | yes | suitable |
| | Ahmed 44 | 1998 | - | - | Pliocene | 371.2 | good | yes | suitable |
| South of lakes below sea level (w-e) | Awad 29 | 2001 | - | - | | 7680 | unacceptable | No | unsuitable |
| | Awad 31 | 2001 | - | - | | 2752.00 | unacceptable | No | unsuitable |
| | Ahmed 37 | 1998 | - | - | Pliocene | 780.8 | fair | yes | marginal |
| | 020 07 | 2006 | 102 | 24 | | 584,9 | good | Yes | marginal |
| | Ahmed 39 | 1998 | - | - | Pliocene | 371.2 | good | yes | suitable |
| | Ahmed 40 | 1998 | - | - | Pliocene | 371.2 | good | yes | suitable |
| | Ibrahim 168 | 2004 | - | - | Pliocene | 381.30 | good | Yes | suitable |
| | Ahmed 42 | 1998 | 100 | 45-78 | Pliocene | 396.8 | good | yes | suitable |
| South of 0 contour | Ibrahim 169 | 2004 | - | - | Miocene | | | yes | |
| | Ibrahim 170 | 2004 | - | - | Miocene | | | yes | |

Some attempts to model the effects of ongoing climatic changes and effects on the Nile have been published (see Conway 2004, Mohamed et al. 2005). This is important because the Nile provides one of the most important sources of recharge to the aquifer system of Wadi El Natroun, as described in the previous section. The other important source of recharge to the Nubian Sandstone Aquifer System and the Miocene Aquifer consists of palaeowater flowing beneath the Western Desert. Separate efforts to model this system have been published (CEDARE 2001, Attia 2002a, Robinson et al. 2007). The intersection of the different systems and their recharge processes at Wadi El Natroun has been the subject of a number of theses (Hamza et al. 1984, Ahmed 1999a, Ahmed 1999b). None of these has yet taken into account anticipated climatic and anthropogenic effects. Dawoud et al (2005) concluded that there was a need for a more detailed analysis with respect to the effect of irrigation improvement in the region in order to understand the effects on the water table in Wadi El Natroun.

There are no official published statistics on groundwater extraction by private farms. Periodical well inventories have been conducted by the Groundwater Research Institute (RIGW) in 1996 and 2002(Gaame 2005). The best available proxy for reliable figures on the number of wells remains the observation of the rapid expansion of the irrigated area, as described in the previous section of this report (Ibrahim 2005, Abdel Mogheeth 2006).

**Salinization**

Salinization threats have been observed in the study area for several decades. Abdel Salam et al (1972) identified this concern and reported readings of salinity in irrigation water on two farms receiving water from the same well, and a third nearby. A more recent study conducted some twenty years later included data on salinity in the same wells (Ahmed 1999b). Unfortunately, none of the sampling dates are recorded in either study in order to enable consideration of the possible effects of seasonal variations on the salinity levels. No discussion of the different results recorded for water from the same well was presented in the earlier study. One possible explanation of the difference in levels of salinity could be the effects of evaporation, concentrating the level of salts in the water. This effect of distance and possible evaporation must be borne in mind in the comparison of 1961 and 1967 readings of salinity in the irrigation water to the 1997 readings taken directly at the well. One of the 1997 well readings was lower than the level recorded three decades previously, while the other was higher. The data are too few to substantiate any solid conclusions concerning the long term trend in salinity **(Table A3.12)**.

**Table A3.12: Changes in Reported Salinity of Groundwater in the North of the Study Area 1961-97**

| **Well no** | | Farm name in 1972 | **Area Cultivated with Crops (feddan)** | | | **TDS (ppm)** | | | |
|---|---|---|---|---|---|---|---|---|---|
| GDDO/ Abd el Salam et al 1972 Saluma 1974 | Ahmed 1999 | | Citrus | Olives | Rotation of Beans and Sesame | 1961 | 1967 | 1971 | 1997 |
| 45 | 38 | No name given | 10 | 15 | 4 | 840 | 840 | 1190 | 774.4 |
| | | Um El Risha Farm | - | 27 | 50 | - | 613 | 840 | |
| 54 | 30 | No name given | 11 | 34 | 4 | 700 | 840 | 770 | 972 |

A series of past analyses of farm water quality was obtained from farms in the least developed southern part of the study area (A.3.13). Due to inconsistencies and gaps in the dating and logging of the locations of these previous samples, a more detailed analysis of the distribution and trends in past water quality results in the study area has not been attempted.

No further data on water quality in the study area could be obtained during the period of writing of this study, despite a request to the Egyptian Groundwater Research Institute (RIGW) because the electronic database in which the groundwater monitoring data is stored had broken down. In 2009, MWRI launched a new monitoring programme (**Table A3.14**).

**Table A3.13: Analysis of Well Water Samples in Previous Studies in South of Study Area**

| Sample location &source | pH | EC mohs/cm | TDS ppm | UNIT | CO3-- | CL | HCO3 | SO4 | TOTAL ANIONS | Na | K | Ca | Mg | TOTAL CATIONS | T. H ppm | SAR epm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SW 2001 | 7.87 | 4.30 | 2752.00 | Mg.L | | 677.78 | 442.49 | 685.62 | | 819.5 | 10 | 65.41 | 39.67 | 42.43 | | |
| Awad 31 | | Ds/m | Mg/L) | Meq/L | | 19.12 | 7.25 | 14.27 | | 35.65 | 0.26 | 3.26 | 3.26 | | | |
| | | | | % | | 47.04 | 17.84 | 35.12 | | 84.01 | 0.60 | 7.69 | 7.69 | | | |
| SE 2007 Ibrahim 168 | 8.9 | 610 | 381.30 | ppm | 39.00 | 51.50 | 210.00 | 8.00 | 6.36 | 122.00 | 5.00 | 4.24 | 6.45 | 6.17 | | 8.71 |
| | | | | epm | 1.30 | 1.45 | 3.44 | 0.17 | | 5.30 | 0.13 | 0.21 | 0.53 | | | |
| | | | | % | 20.44 | 22.83 | 54.11 | 2.62 | | 85.92 | 2.07 | 3.43 | 8.58 | | | |
| SE 2006 farmer | 7.2 | 0,914 | 584,9 | Mg.L | | | | | | | | | | | | |

**Table A3.14: Analysis of Well Water Samples by MWRI, 2009**

| | date of monitoring | Jan-09 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| well no | location | date drilled | hole depth (m) | casing depth (m) | Vol-ume | SWL (m) | TDS (ppm) | EC | N | E | area (feddan) |
| P3 | Behind Anba Bishoi | 26/10/2008 | 180 | 176 | | 63.2 | 800 | NA | | | NA |
| P6 | Behind Deir Baramus | 17/09/2008 | 185 | 185 | | 32.98 | 1766 | NA | 30°23'15.10"N | 30°13'58.60"E | NA |
| P10 | Wadi El Natroun Midaq Kahrabah | NA | 145 | 109 | | | TDS: 686.72 | 1.072 | 30°18'22.00"N | 30°18'31.00"E | 90 |
| P23 | El Wadi (road to Deir Baramus) | NA | 150 | 115 | 12 | | TDS: 2227.2 | 2.38 | 30°22'2.00"N | 30°14'20.00"E | 100 |
| P30 | Wadi El Natroun Electricity Road | NA | 125 | 80 | 10 | | TDS: 4691.2 | 7.22 | 30°19'39.00"N | 30°18'13.00"E | 20 |
| P31 | El Hamra Village, Wadi El Natroun | NA | 65 | 50 | 8 | | TDS: 1188.48 | 1.858 | 30°23'22.20"N | 30°17'56.00"E | 15 |
| P33 | Wadi El Natroun K98 | NA | 80 | 50 | 10 | | TDS: 2462.4 | 5.4 | 30°21'29.00"N | 30°23'43.00"E | |

**Appendix 4: Questionnaire, Western Desert, Egypt**

## Research project on the relationship between groundwater and human dependence on it

بحث مشترك بين جامعة اسكندرية و جامعة اكسفردرية و جامعة الأمم المتحدة

**A cooperative study by the University of Alexandria, the University of Oxford and the United Nations University**

**-الموقع**
**-ملكية الأرض والأستخدام**
**-الآبار**
**-استعمال المياة**
**-انتاج المحاصيل**
**-العاملين**
**-الأسرة**
**-الأنشطة الاقتصادية بالمنزل وعلاقتها بالمياه الجوفية**
**-مياة الشرب و الاستعمال في المنزل**
**-التغيرات المؤثرة على المياه الجوفية**

| | | |
|---|---|---|
| **CODE كود :** *00 00 XXXX 0000* | | |
| **DATE تاريخ :** | **TIME وقت :** | **INVESTIGATOR(S) باحث :** |

**1. LOCATION**
**الموقع**

| | |
|---|---|
| **1.1 Farm name : اسم المزراعة** | |

| | | |
|---|---|---|
| **1.2 Farm location موقف مزراعة : (UTM WGS84)** | X: | Y: |

| | |
|---|---|
| **1.3 Number of Parcels رقم حيازات :** | |

| | |
|---|---|
| **1.4 Total area (incl. all crops, fallow, grazing, unused land)**<br>**مساحة جملة الحيازات** | **فدان** (feddan) |

**1.5 Please mark your land(s) on map**
ضع علامة بالخريطة عن مكان الأرض

**2. LAND TENURE AND USE**
ملكية الأرض والأستخدام

## 2.9 ATTACH SKETCH OF EACH PLOT INCLUDING LOCATION OF WELLS

| **2.1 Plot ID**<br>**كود القطعة** | **2.2 Tenure**<br>**الحيازة** | **2.3 Size of plot** (feddan)<br>**حجم القطعة**<br>بالفدان | **2.4 Irrigated area** (feddan)<br>**المساحة المروية**<br>بالفدان | **2.5 Crop**<br>**المحصول**<br>Please list /note briefly | **2.6 Crop Use**<br>**استخدام المحصول**<br>Home consumption استهلاك منزلى<br>Local sale البيع المحلى<br>Export تصدير<br>Certified organic export شهادة تصدير عضوى بدون كيماويات | **2.7 Irrigation system**<br>**نظام الرى**<br>Drip, flood, sprinkler, rush, other (please specify)<br>(التنقيط - الغمر – الرش المحورى أخرى) - | **2.8 Drainage system**<br>**نظام الصرف** |
|---|---|---|---|---|---|---|---|
| 1 | | | | | | | |
| 2 | | | | | | | |
| 3 | | | | | | | |
| 4 | | | | | | | |
| 5 | | | | | | | |
| 6 | | | | | | | |
| 7 | | | | | | | |
| 8 | | | | | | | |
| 9 | | | | | | | |
| 10 | | | | | | | |
| 11 | | | | | | | |
| 12 | | | | | | | |
| 13 | | | | | | | |

***Please indicate other wells nearby if known, and distance***
***برجاء تحديد* وجود أى آبار مجاورة ومكانها بالمسافة.**

## 3. WELLS
## الآبار

| 3.1 Plot code (as above) كود القطعة الأرضية | 3.2 Well letter كود البئر | *3.3 Total depth* العمق بالمتر | *3.3 Depth to water(winter)* العمق بسطح المياه فى الشتاء بالمتر | 3.4 Depth to water (summer) العمق فى سطح المياه فى الصيف بالمتر | 3.5 Depth to screen العمق للمصفاه | 3.6 Distance to nearest well المساحة من البئر القريب | 3.7 Type of Pump - electric, diesel, other نوع المضخة كهرباء – ديزل أخرى | 3.8 Date dug تاريخ الحفر |
|---|---|---|---|---|---|---|---|---|
| | a | | | | | | | |
| | b | | | | | | | |
| | c | | | | | | | |
| | d | | | | | | | |
| | e | | | | | | | |
| | f | | | | | | | |
| | g | | | | | | | |
| | h | | | | | | | |
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## 4. WATER USE

## استعمال المياة

| 4.1 Well code<br>كود البئر | 4.2 Average water use summer<br>الأستخدام اليومى فى الصيف<br>$M^3$/hr x Hr/day or by bousa<br>متر3 / س × س / يوم | 4. 3 Average water use winter<br>متوسط الأستخدام اليومى فى الشتاء<br>$M^3$/hr x Hr/day or by bousa<br>متر3 / س × س / يوم | 4.4 Total yearly usage<br>الأستخدام السنوى<br>$M^3$/year<br>متر3 | 4.5 Salinity winter<br>الملوحة بالشتاء<br>ppm<br>(جزء فى المليون) | 4..6 Salinity summer<br>الملوحة بالصيف<br>ppm<br>(جزء فى المليون) | 4.7 Frequency of testing<br>تكرارية الأختبار | 4.8 Parameters tested<br>القياسات | 4.9 Attach results if available<br>(number attachments)<br>احداثيات البئر |
|---|---|---|---|---|---|---|---|---|
| a. | | | | | | | | |
| | | | | | | | | |
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## 5. CROP PRODUCTION
## انتاج المحاصيل

| 5.1 Part of household food supply grown on own land:<br>جزء من غذاء الأسرة ينمو بالأرض التى تمتلكها<br>Tick only one box ضع علامة على واحدة | None لا | ¼<br>ربع الغذاء | ½<br>نصف الغذاء | ¾<br>ثلاثة أربع الغذاء | Entire<br>الغذاء كلها |
|---|---|---|---|---|---|
| | | | | | |

| 5.2 Crops for household consumption<br>المحاصيل المستهلكة للمنزل | No. consumed/yr الكمية<br>المستهلكة كل عام | 5.3 Crops for sale<br>المحاصيل المباعة | No. sold/yr<br>عدد المباع فى العام |
|---|---|---|---|
| | | | |
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| 5.4 Livestock variety<br>نوع الثروة الحيوانية | Number<br>وعددها | Crops for livestock consumption<br>المحاصيل المستخدمة للثروة الحيوانية | No. consumed/yr<br>الكمية المستهلكة كل عام |
|---|---|---|---|
| | | | |
| | | | |
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| | | | |
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## 6. FARM WORKERS
## العاملين

**List all individuals present during the interview, followed by other workers on the farm**
**قائمة بكل الأفراد المتواجدين أثناء هذه المقابلة ثم العمال الآخرين العاملين بالحقل**

| No العدد | Name الأسم | Permanent Address العنوان المستديم | Telephone (if willing to be contacted) التليفون | Sex الجنس M=male F=female امراة - رجل | Age السن | Family member or employee عضو بالعائلة أو عامل | Presence during interview التواجد أثناء المقابلة |
|---|---|---|---|---|---|---|---|
| 1. | (Owner) المالك | | | | | | |
| 2. | | | | | | | |
| 3. | | | | | | | |
| 4. | | | | | | | |
| 5. | | | | | | | |
| 6. | | | | | | | |
| 7. | | | | | | | |
| 8. | | | | | | | |
| 9. | | | | | | | |
| 10. | | | | | | | |
| 11. | | | | | | | |
| 12. | | | | | | | |
| 13. | | | | | | | |

## 7. THE HOUSEHOLD (small farms only)
## الأسرة

| No<br>العدد | 7.1 Occupations العمل<br>(Start with the name of hh head) برجاء البدء برب الأسرة<br>Primary occupation (/class in school)<br>العمل الأساسى | Others<br>أخرى | 7.2 Sex<br>النوع<br>male or female<br>(رجل – أمراة) | 7.3 Age<br>السن | 7.4 Relation to hh head[1]<br>العلاقة برب الأسرة | 7.5 Presence during interview التواجد أثناء المقابلة |
|---|---|---|---|---|---|---|
| 1. | | | | | | |
| 2. | | | | | | |
| 3. | | | | | | |
| 4. | | | | | | |
| 5. | | | | | | |
| 6. | | | | | | |
| 7. | | | | | | |
| 8. | | | | | | |
| 9. | | | | | | |
| 10. | | | | | | |
| 11. | | | | | | |
| 12. | | | | | | |
| 13. | | | | | | |

[1]Relation to HH head:العلاقة برب الأسرة

HH= Household head *رب الأسرة*
W= Wife *الزوجة*
H= Husband *الزوج*
S=Son *البن*
D=Daughter *البنة*
F=Father *الأب*
M=Mother *الأم*
B=Brother *الأخ*
S=Sister *الأخت*

**7.6 Is the house next to the farm?**

**7.7 Length of household residence in the area فترة تواجد الأسرة بالمنطقة**

## 8. RELATION BETWEEN GROUNDWATER AND HOUSEHOLD ECONOMIC ACTIVITIES

| Sector<br>اقسام النشات الاقتسادية الرئسية بالاسرة | Description of employment<br>وصف الوظيفة | Relation to groundwater use<br>العلاقة بالمياه الجوفية | % total monthly household income<br>نسبة الدخل الشهرى للأسرة |
|---|---|---|---|
| a) Agriculture and fishing<br>الزراعة واستغلال الغابات وقطعة الاشجار وصيد الاسماك | | | |
| b) Mining<br>التعدين واستغلال المحاجر | | | |
| j) Processing or intermediate industries<br>الصناعات التحويلية | | | |
| d) Energy supply (electricity, gas, steam)<br>امدادات الطاقة (الكهرباء والغاز والبخار) | | | |
| h) Water supply, sewage network and waste management<br>الأمداد المائى وشبكات الصرف الصحى وإدارة معالجة النفايات | | | |
| w) Construction and development<br>الترشيد والبناء | | | |
| z) Retail and wholesale trade and repair of vehicles<br>تجارة الجملة والتجزئة والأصلاح لمركبات ذات المحركات النارية | | | |
| h) Transportation and storage<br>النقل والتخزين | | | |
| t) Hospitality<br>خدمات الغذاء والأقامة | | | |
| y) Communications<br>المعلومات والأتصالات | | | |
| k) Financial services and insurance<br>الوساطة المالية والتأمين | | | |
| l) Property and business<br>العقارات والأعمال | | | |
| m) Scientific activities and technical specialist<br>الأنشطة العلمية والتقنية المتخصصة | | | |
| n) Administrative activities and subsidies<br>الأنشطة الإدارية وخدمات الدعم | | | |
| s) Public offices, defence and social security?<br>الأدارة العامة والدفاع والضمان الأجتماعى | | | |
| a[c]) Education<br>التعليم | | | |
| f) Health and social services<br>الصحة والخدمات الأجتماعية | | | |
| So) Arts, recreation and entertainment activities<br>أنشطة الفنون والأبداع والتسلية | | | |
| q) Other services<br>أنشطة الخدمات الأخرى | | | |
| Sh) international organizations<br>المنظمات والهيئات الدولية والسفارات والقنصليات الأجنبية | | | |

**9. DRINKING AND DOMESTIC WATER**

مياة الشرب و الاستعمال في المنزل

**(interviewer please mark below): للباحث أن يضع علامة**

| | Yes no<br>نعم - لا | Frequency of use<br>تكرارية الأستخدام | Volume of water used per month if known<br>حجم المياه المستخدمة بالشهر | Cost per month<br>التكلفة الشهرية | Main source (tick one only)<br>المصدر الأساسى ( ضع علامة واحدة فقط) |
|---|---|---|---|---|---|
| Connected to public network in the house<br>**المنزل متصل بالشبكة العامة** | | | | | |
| In the building<br>**داخل المبنى** | | | | | |
| Outside the building<br>**خارج المبنى** | | | | | |
| Pump<br>**طلمبة** | | | | | |
| Well<br>**البئر** | | | | | |
| Purchase water from vendor<br>**شراء مياه معدنية** | | | | | |
| Other (please specify)<br>**أخرى( برجاء التحديد)**<br>..... | | | | | |

| | |
|---|---|
| **Total monthly household expenditures on water**<br>**جملة التكلفة الشهرية للمياه (جميع الأنواع)** | **EGY.....** |
| **Monthly expenditures on food**<br>التكلفة الشهرية للغذاء | **EGY.....** |
| **Total monthly income**<br>الدخل العام الشهرية | **EGY.....** |
| **Expenditures on water as % of total monthly expenditures on food**<br>جملة التكلفة الشهرية للمياه بالنسبة لالتكلفة الشهرية للغذاء (مثلا خمسة في المية لالمياة او. | **.....%** |
| **Monthly expenditures on food as proportion of total monthly income**<br>نسبة التكلفة الشهرية للغذاء بالنسبة للدخل العام | **.....%** |

## 10. CHANGES AFFECTING GROUNDWATER
## التغيرات المؤثرة على المياه الجوفية

| 10.1 Are the following observed in the area<br>هل تم مشاهدة الآتى: | Observed شوهدت<br>( yes/no/don't know نعم – لا - لا أعرف) | Could it indicate change in groundwater?<br>مدى الأشارة للتغير بالمياه الجوفية<br>( yes/no/don't know) (نعم – لا – لا أعرف) |
|---|---|---|
| Abandoned wells آبار مهجورة | | |
| Increased digging of new wells زيادة حفر آبار جديدة | | |
| Other alternative infrastructure (e.g. pumps) بناية تحتية بديلة (مواسير) | | |
| Reduced productivity of salt-sensitive crops<br>نقص الأنتاجية للمحاصيل الحساسة للملوحة | | |
| Abandoned land أراضى مهجورة | | |
| Waterborne diseases أمراض محمولة بالمياه | | |
| Kidney problems مشاكل بالكلى | | |
| Other (please indicate) أخرى برجاء التحديد | | |

### 10.2 In the future, do you believe your well(s) could be affected by: هل تعتقد أن البئر الذى تمتلكه سوف يتأثر فى المستقبل

| | There is no possibility<br>لا يوجد احتمال | Probability is small<br>احتمال ضئيل | Probability is high<br>احتمال مرتفع | Don't know<br>لا أعرف | Would not matter<br>لا يمثل مشكلة |
|---|---|---|---|---|---|
| Falling groundwater level<br>انخفاض مستوى المياه الجوفية | | | | | |
| Salinization<br>التملح | | | | | |
| Waterborne diseases<br>أمراض محمولة بالمياه | | | | | |
| Agrochemicals<br>كيماويات زراعية | | | | | |

### 10.3 Changing Salinity in Own Wells تغير الملوحة بالبئر الخاص بك

| Well البئر (number/ location) (العدد – الموقع) | Change التغير | Time period المدة الزمنية | Means of Observation وسيلة المشاهدة | Reason السبب |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

### 10.4 Changing Water Level in Own Wells تغير مستوى المياه بالبئر الخاص بك

| Well البئر (number/ location) (العدد – الموقع) | Change التغير | Time period المدة الزمنية | Means of Observation وسيلة المشاهدة | Reason السبب |
|---|---|---|---|---|
| | | | | |
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### 10.5 Other Changes in Water Quality in Own Wells تغيرات أخرى فى جودة مياه البئر

| Well البئر (number/ location) (العدد – الموقع) | Change التغير | Time period المدة الزمنية | Means of Observation وسيلة المشاهدة | Reason السبب |
|---|---|---|---|---|
| | | | | |
| | | | | |
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**Appendix 5: Questionnaire, Southern Tunisia**

# بحث عن

# ادارة التغيرات في المياه الجوفية و الاعتماد البشري عليها

| | | |
|---|---|---|
| **1. LOCATION** | ***/ LE LIEU*** | الموقع |
| **2. WELLS** | ***/ LES PUITS*** | الآبار |
| **3. CHANGES AFFECTING GROUNDWATER** | **/ LES CHANGEMENTS ET LES EFFETS SUR L'EAU** | التغيرات المؤثرة على المياه الجوفية |
| **4. WATER USE** | **/ L`UTILISATION DE L` EAU** | استعمال المياه |
| **5. CROP PRODUCTION** | ***/ LA PRODUCTION*** | انتاج المحاصيل |
| **6. HOUSEHOLD USE OF CROPS** | ***/ L`UTILISATION DES PRODUITS A LA MAISON*** | استعمال المحاصيل في البيت |
| **7. HOUSEHOLD BUDGET** | ***/ LE BUDGET DU MENAGE*** | ميزانيةالأسرة |
| **8. MEMBERS OF THE HOUSEHOLD** | ***/ LES MEMBRES DU MENAGE*** | افراد الأسرة |

**Participation in this survey is voluntary.** ***La participation à l'enquête est volontaire***
**The interviewee is free to withdraw at any time.** ***L'interviewé peut arrêter les questions selon son gré***

**All information provided will be stored anonymously, to be identifiable only by a code number:**
***Les réponses seront introduit dans une basse de données sous l`anonymat avec un numéro de code :***

**CODE الرمز:**

| | | |
|---|---|---|
| **DATE تاريخ الإستقصاء:** | **TIME** التوقيت : | **INVESTIGATOR(S)** الباحث : |
| | | |

## 1. LOCATION / LIEU

الموقع

| | | | |
|---|---|---|---|
| **1.6 اسم المستغل:**<br>**Name** | **(UTM WGS 84)**<br>X: | Y: | |
| **1.7 موقف المستغلة والمسافة من المنزل:**<br>**Plot location** | **المساحة المروية**<br>**Irrigated area** | **مساحة الكل**<br>**Total area** | **ملك من تاريخ**<br>**Date of ownership** |
| **1.8 موقف المستغلة و المسافة من المنزل:**<br>**Plot location** | **المساحة المروية**<br>**Irrigated area** | **مساحة الكل**<br>**Total area** | **ملك من تاريخ**<br>**Date of ownership** |
| **1.9 موقف المستغلة و المسافة من المنزل:**<br>**Plot location** | **المساحة المروية**<br>**Irrigated area** | **مساحة الكل**<br>**Total area** | **ملك من تاريخ**<br>**Date of ownership** |
| **1.10 موقف المستغلة و المسافة من المنزل:**<br>**Plot location** | **المساحة المروية**<br>**Irrigated area** | **مساحة الكل**<br>**Total area** | **ملك من تاريخ**<br>**Date of ownership** |
| **1.11 موقف المستغلة و المسافة من المنزل:**<br>**Plot location** | **المساحة المروية**<br>**Irrigated area** | **مساحة الكل**<br>**Total area** | **ملك من تاريخ**<br>**Date of ownership** |
| **1.12 موقف المستغلة و المسافة من المنزل:**<br>**Plot location** | **المساحة المروية**<br>**Irrigated area** | **مساحة الكل**<br>**Total area** | **ملك من تاريخ**<br>**Date of ownership** |
| **1.13 موقف المستغلة و المسافة من المنزل:**<br>**Total number of plots for household** | **Number** | **مساحة جملة الحيازات**<br>**Total area** | |

**1.14 Please mark your land(s) on map (to be inserted)**

ضع علامة بالخريطة عن مكان الأرض

**1.15 Please sketch the land and location of wells (including indication of other nearby wells if known)**

**برجاء رسم الاض و أى آبار مجاورة**

## 3. CHANGES AFFECTING GROUNDWATER / CHANGEMENTS ET EFFETS SUR L'EAU التغيرات المؤثرة على المياه الجوفية

| **Well** (number/ location) **البئر (العدد – الموقع)** | **Changing Salinity تغير الملوحة** | **Time period المدة الزمنية** | **Means of Observation وسيلة المعاينة** | **Reason السبب** |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |

| **Well** (number/ location) **البئر (العدد – الموقع)** | **Changing Water Level in Own Wells تغير مستوى المياه** | **Time period المدة الزمنية** | **Means of Observation وسيلة المعاينة** | **Reason السبب** |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |

| **Well** (number/ location) **البئر(العدد – الموقع)** | **Other Changes in Quality تغيرات أخرى فى جودة** | **Time period المدة الزمنية** | **Means of Observation وسيلة المعاينة** | **Reason السبب** |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |

| **3.2 In the future, do you believe your well(s) could be affected by: هل تعتقد أن البئر الذى تمتلكه سوف يتأثر فى المستقبل من:** | There is no possibility **لا يوجد احتمال** | Probability is small **احتمال ضئيل** | Probability is high **احتمال مرتفع** | Don't know **لا أعرف** | Would not matter **لا يمثل مشكلة** |
|---|---|---|---|---|---|
| Falling groundwater level **انخفاض مستوى المياه الجوفية** | | | | | |
| Salinization **التملح** | | | | | |
| Waterborne diseases **أمراض محمولة بالمياه** | | | | | |
| Agrochemicals **كيماويات زراعية** | | | | | |

| **3.3 Are the following observed in the area هل تم مشاهدة الآتى:** | **Observed شوهدت** ( yes/no/don't know) (نعم – لا – لا أعرف) | **Could it indicate change in groundwater? مدى الأشارة للتغير بالمياه الجوفية** ( yes/no/don't know) (نعم – لا – لا أعرف) |
|---|---|---|
| Abandoned wells **آبارمهملة** | | |
| Increased digging of new wells **زيادة حفر آبار** | | |
| Other alternative infrastructure (e.g. pumps) **بناية تحتية بديلة** | | |
| Reduced productivity of salt-sensitive crops **نقص الأنتاجية للمحاصيل الحساسة** | | |
| Abandoned land **أراضى رمهملة** | | |
| Waterborne diseases **أمراض محمولة** | | |
| Kidney problems **مشاكل الكلة** | | |
| Other (please indicate) **أخرى برجاء** | | |

## 4. WATER USE / L`UTILISATION DE L`EAU

## استعمال المياه

| 4.1 Well code رمز البئر | 4.2 Summer استخدام المياه فى الصيف | | | | 4. 3 Average daily water use winter استخدام المياه فى الشتاء | | | | 4.4 Total yearly usage الأستخدام السنوى |
|---|---|---|---|---|---|---|---|---|---|
| | Frequency of use المايةالدورة | Duration of use توقيت الاستعمال | Volume (m) كمية المياه | Water storage خزن المياه | Frequency of use المايةالدورة | Duration of use توقيت | Volume (m) كمية المياه | Water storage خزن المياه | |
| a | | | | | | | | | |
| b | | | | | | | | | |
| c | | | | | | | | | |
| d | | | | | | | | | |
| e | | | | | | | | | |
| f | | | | | | | | | |

| 4.2 Domestic water use مصدر مياه الشرب | Yes no نعم - لا | Frequency of use تكرارية الأستخدام | Volume of water used per month حجم المياه المستخدمة بالشهر | Cost per month التكلفة الشهرية | Main source (one only) المصدر الأساس |
|---|---|---|---|---|---|
| Connected to public network in the house المنزل متصل بشبكة | | | | | |
| In the building داخل المبنى | | | | | |
| Outside the building خارج المبنى | | | | | |
| Pump بئر مجهز بمضخة | | | | | |
| Well بئر إرتوازى | | | | | |
| Purchase water from vendor شراء مياه معدنية | | | | | |
| Other (please specify) ……..…… أخرى( برجاء التحديد) | | | | | |

| | |
|---|---|
| 4.3 Total monthly household expenditures on water (including GDA subscription) جملة التكلفة الشهرية للمياه | TND…… |
| GDA subscription | TND…… |
| Expenditures on water as % of total monthly income جملة التكلفة الشهرية للمياه بالنسبة للدخل العام الشهرى | ……% |

## 5. CROP PRODUCTION / LA PRODUCTION الإنتاج

| 5.1 Fruit trees الاشجار المثمرة | Les frutiers | Variety النوع | Number عدد الاصول | Irrigation system نظام الرى Drip, flood, sprinkler, other (please specify) (التنقيط - الغمر – الرش المحورى أخرى) - | Drainage system نظام الصرف Ciel ouvert enterree | Required inputs (chemicals, manure, labour) المستلزمات الفلاحية | Crop Use استخدام المحصول Home consumption استهلاك منزلى Local sale البيع المحلى Export تصدير Certified organic export شهادة تصدير عضوى بدون كيماويات | Market value الثمن في السوق |
|---|---|---|---|---|---|---|---|---|
| Bitter Orange النارنج | Bigaradier | | | | | | | |
| Lemon الليمون | Citron doux | | | | | | | |
| Citron الاترش | Cedrat | | | | | | | |
| Orange البرتقال | Oranger douce | | | | | | | |
| Tangerine-orange اليوسفى | Mandarinier | | | | | | | |
| Fig التين | Figuier | | | | | | | |
| Apple الثفاحة | Pommier | | | | | | | |
| Mango المنجا | Mangue | | | | | | | |
| Mulberry التوت | Mûrier | | | | | | | |
| Banana الموز | Bananier | | | | | | | |
| Olive الزيتون | Olivier | | | | | | | |
| Indian Fig / prickly pear التين الشوكى | Figuier de Barbarie | | | | | | | |
| Date Palm التمور | Dattier | | | | | | | |
| Apricot المشمش | Abricotier | | | | | | | |
| Plum العوينة | Prune | | | | | | | |
| Almond اللوز | Amandier | | | | | | | |
| Peach الخوخ | Pêcher | | | | | | | |
| Pomegranate الرمان | Grenadier | | | | | | | |
| Pear الاتغاص | Poirier | | | | | | | |
| Grape Vine عنب | Vigne | | | | | | | |
| Other اخرى | Autres | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
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| 5.2 Vegetables الخضروات Cultures maraicheres | Variety النوع | Number عدد الاصول | Irrigation system نظام الرى Drip, flood, sprinkler, other (please specify) (التنقيط - الغمر – الرش المحورى أخرى) - | Drainage system نظام الصرف Ciel ouvert enterree | Required inputs (chemicals, manure, labour) المستلزمات | Crop Use استخدام المحصول Home consumption استهلاك منزلى Local sale البيع المحلى Export تصدير Certified organic export شهادة تصدير عضوى بدون كيماويات | Market value الثمن في السوق |
|---|---|---|---|---|---|---|---|
| tomato طماطم | | | | | | | |
| beans فلفل بدري | | | | | | | |
| Seasonal beans فلفل فصلى | | | | | | | |
| Seasonal potato بطاطا فصلية | | | | | | | |
| بطاطا بدرية | | | | | | | |
| Other seasonal بطاطا آخر فصلية | | | | | | | |
| قنارية | | | | | | | |
| Green onions بصل أخضر | | | | | | | |
| Summer onions بصل صيفى | | | | | | | |
| garlic ثوم | | | | | | | |
| watermelon بطيخ | | | | | | | |
| melon دلاع | | | | | | | |
| Green beans فول أخضر | | | | | | | |
| جلبانة خضراء | | | | | | | |
| بسباس | | | | | | | |
| turnip لفت | | | | | | | |
| سفنارية | | | | | | | |
| Beet greens سلق | | | | | | | |
| parsley معدنوس | | | | | | | |
| كرافس | | | | | | | |
| Other خضروات أخرى | | | | | | | |
| Green barley شعير أخضر | | | | | | | |
| Summer fodder أعلاف صيفية | | | | | | | |
| Other seasonal أعلاف موسمية أخرى | | | | | | | |
| | | | | | | | |
| | | | | | | | |

## 6. HOUSEHOLD USE OF CROPS / *L`UTILISATION DES PRODUITS A LA MAISON* استعمال المحاصيل في البيت

| **6.1 Part of household food supply grown on own land:**<br>**جزء من غذاء الأسرة ينمو بالأرض التى تمتلكها**<br><br>Tick one box for each crop ضع علامة على واحدة لكل محصول | | **None لا** | ¼<br>**ربع الغذاء** | ½<br>**نصف الغذاء** | ¾<br>**ثلاثة أربع الغذاء** | **Entire**<br>**الغذاء كلها** |
|---|---|---|---|---|---|---|
| | **All crops** | | | | | |
| | **wheat** | | | | | |
| | **fodder** | | | | | |
| | **fruits** | | | | | |
| | **vegetables** | | | | | |
| | | | | | | |
| | | | | | | |

## 7. HOUSEHOLD BUDGET / *LE BUDGET DU MENAGE* ميزانيةالأسرة

**7.1 Monthly expenditures on food** التكلفة الشهرية للغذاء

| | item | cost | | subtotal |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| **TOTAL** | | | | **TND……..** |

**7.2 Other significant monthly expenditures** تكاليف شهرية اخرى

| | item | cost | | subtotal |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| **TOTAL** | | | | **TND……..** |

**7.3 Significant periodic household expenditures (festivals, weddings, travel, etc)** تكاليف اخرى غير شهرية

| description | frequency | Estimated amount | | Annual subtotal |
|---|---|---|---|---|
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | **TND……..** |

## 8. THE HOUSEHOLD / LES MEMBRES DU MENAGE

## افراد الأسرة

| | 8.1 Occupations العمل | | | 8.2 Sex النوع male or female (رجل – أمراة) | 8.3 Age السن | 8.4 Relation to hh head العلاقة برب الأسرة | 8.5 House of residence | 8.6 Presence during interview التواجد أثناء المقابلة |
|---|---|---|---|---|---|---|---|---|
| | Primary occupation (/class in school) العمل الأساسى | Others أخرى | Work in oasis العمل في الغابة | | | | | |
| Head of household رب | | | | | | | | |
| Spouse الزوجة | | | | | | | | |
| Son ابن | | | | | | | | |
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## Appendix 6: Cultivation patterns in Beni Salama: From 2009 fieldwork report

A series of cultivation types observed in the study area are presented according to their size, physical configuration and economic use of crops. In each of the cultivation types, the availability and salinity of irrigation water influences crop choices. Economic factors are also important in the choice of crops, and vary according to the cultivation type and purpose, whether for subsistence uses (gardens and small farms), local markets (small, medium and large farms) or export to the Gulf and European countries requiring environmental certification (largest farms).

The distribution of the cultivation types across the study area was mapped through field observation and the use of high resolution satellite images. The data collected during the field survey were compared to a database of well permits held by the Ministry of Water Resources and Irrigation (MWRI) which lists permitted extraction volumes for some wells.

**The typology of cultivation**

A typology of cultivation derived from the analyses referred to above is presented according to size of farm. This typology was developed at the outset of the study with advice from Dr Mustapha Bedier at the Department of Social Affairs at the Egyptian Ministry of Agriculture (**Table A6.1 and Figure A6.1)**. A similar typology was also used in a previous study in the area by Yehia (2004) with the exception of the group of the smallest farms identified in this study (< 3feddan), which may be referred to as gardens. Another farm survey conducted close to the study area (AFD 2008) differentiated between farms above or below fifty feddan in size, however this distinction was not employed in the present study.

**Table A6.1: Overview of Cultivation Types and General Characteristics**

| Farm size (feddan) | Use of produce | Most important crops | Chemical inputs | Most common irrigation methods | Type of pump |
|---|---|---|---|---|---|
| 1-3 | Home use | Datepalm, wheat, various fruits and vegetables | None except manure | flood | Diesel 3 bousa |
| 3-20 | Home use and local sale | Alfalfa, beans, mango | increasing | sprinkler flood and drip | Diesel 8-10 bousa * |
| 20-100 | Local sale | Peach, grapes, citrus fruits (vegetables esp. medium sized rented farms) | signficant | drip and sprinkler | diesel or electric 80-90$m^3$/hr |
| 100 + | Export or local sale | | Some certified organic | drip | Electric 110m/r |

1 feddan = 4200$m^2$ = 0.42ha = 0.0042k $m^2$

*based on MWRI database

The nature of ownership and relations to the households in the village of Beni Salama are quite differentiated amongst the different cultivation types, although gradations were observed. For example, some of the smaller farms still operate like large gardens, and some of the medium sized farms are simply sub-divided large farms. To a considerable extent, the differences between cultivation types determine the management options. Overall, the largest farms have the deepest wells and most drip irrigation systems. The survey findings regarding well types and pumping capacity were compared to the MWRI database of well permit applications. **Table A6.2** shows an overview of the different cultivation types in terms of the well depths, pumping and irrigation arrangements.

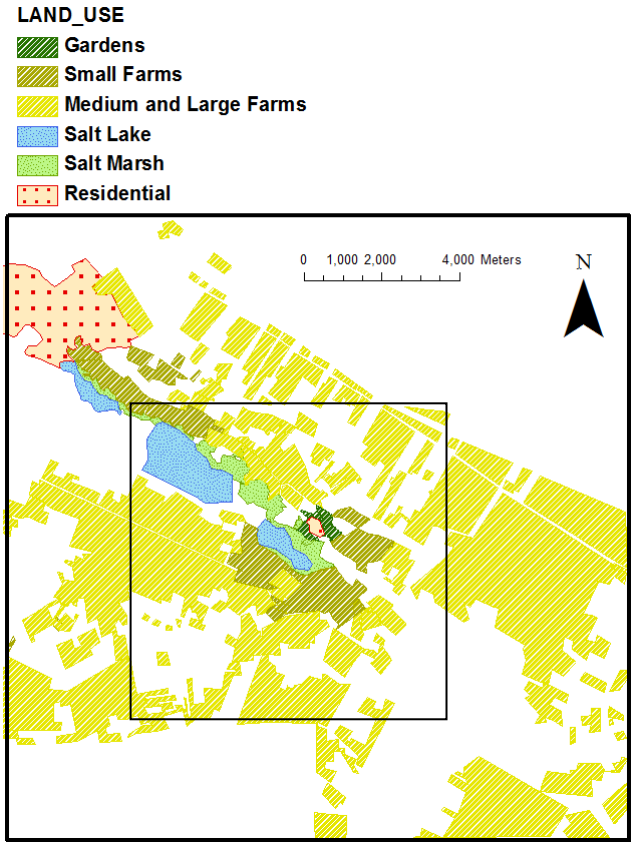
**Table A6.2: Summary Comparison of Farm Types and Groundwater Uses**

| Farm size (feddan) | Average size (feddan) | Average well depth | Average feddan/ well | Average distance to next farm well | Type of pump | Most common irrigation methods |
|---|---|---|---|---|---|---|
| 1-3 | 2 | 25 | 2 | 50 | Diesel 3 bousa 5 horse power | flood |
| 3-20 | 8 | 43 | 8 | 117 | Diesel 8-10 bousa * | sprinkler flood and drip |
| 20-100 | 50 | 114 | 50 | 433 | diesel or electric 80-90$m^3$/hr | drip and sprinkler |
| 100 + | 264 | 146 | 42 | 700 | Electric 110m/r | drip |

1 feddan = 4200$m^2$ = 0.42ha = 0.0042k $m^2$

*based on MWRI database

**Figure A6.1: Overview of Cultivation Types**




Farm management choices, such as mix of crops, well depths and styles of irrigation are influenced by local factors, including depth to the water table, soil type and salinity (**Tables A6.3-4)**. Other environmental factors affecting crop water requirements include:
-climate and growth stages of crops
-planting patterns
-soil conditions
-pests

The FAO has published a series of generic crop coefficients **(Table A6.3)** that may be multiplied by the reference evapotranspiration (ETo) to obtain the irrigation water requirement of a crop (ETc in mm) at each stage in the growth season: (ETc = Kc * ETo). Where intercropping is practiced, as is the case in traditional oasis cultivation, the generic coeeficients can be adjusted to allow for the effect of the canopy **(Table A6.4)**.

**Table A6.3: Crop Coefficients for Different Growing Stages of Selected Crops (FAO)**

| | Growing stage | | | |
|---|---|---|---|---|
| | **Initial** | **Dev** | **Mid** | **Late** |
| Bananas | 1.00 | 1.00 | 1.00 | 1.00 |
| Citrus | 0.75 | 0.75 | 0.75 | 0.75 |
| Fibres | 0.35 | 0.68 | 1.00 | 0.60 |
| Fodder | 0.40 | 0.70 | 1.00 | 0.90 |
| Fruit | 0.75 | 0.75 | 0.75 | 0.75 |
| Maize | 0.30 | 0.75 | 1.20 | 0.60 |
| Other cereals | 1.00 | 1.00 | 1.00 | 1.00 |
| Other root crops | 1.00 | 1.00 | 1.00 | 1.00 |
| Potatoes | 0.50 | 0.83 | 1.15 | 0.75 |
| Pulses | 0.40 | 0.78 | 1.15 | 0.55 |
| Sesame | 0.35 | 0.73 | 1.10 | 0.25 |
| Sugarcane | 1.00 | 1.00 | 1.00 | 1.00 |
| Sunflower | 0.35 | 0.73 | 1.10 | 0.35 |
| Vegetables | 0.60 | 0.85 | 1.10 | 0.90 |
| Wheat | 0.40 | 0.78 | 1.15 | 0.30 |

**Table A6.4: Adjustment of FAO Coefficients for Intercropping: Example: Citrus**

| | **Stages of Development** | | | | |
|---|---|---|---|---|---|
| **Crop characteristic** | **Initial** | **Crop Development** | **Mid-season** | **Late** | **Total** |
| Stage length, days | 60 | 90 | 120 | 95 | 365 |
| Depletion Coefficient, p | - | - | - | - | 0.5 |
| Root Depth, m | - | - | - | - | 1.2 |
| Crop Coefficient, Kc Citrus no ground cover | | | | | |
| 70 % canopy | 0.7 | >> | 0.65 | 0.70 | - |
| 50 % canopy | 0.65 | >> | 0.60 | 0.65 | - |
| 20 % canopy | 0.5 | >> | 0.45 | 0.55 | - |
| Crop Coefficient, Kc Citrus no ground cover | | | | | |
| 70 % canopy | 0.75 | >> | 0.70 | 0.70 | - |
| 50 % canopy | 0.80 | >> | 0.80 | 0.80 | - |
| 20 % canopy | 0.85 | >> | 0.85 | 0.85 | - |
| Yield Response Factor, Ky | - | - | - | - | 0.8-1.1 |

**Table A6.5: Characteristics of Crops Grown on Medium Sized Farms (**FAO 2002 and CRUESI 1967)

| Common name | Latin name | Local harvest period* | 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 | *Phoenix dactylifera* L. | October | 4.0 | 3.6 | T | 4 | 6.8 | 10.9 | 17.9 | 32 |
| olives | *Olea europaea* L. | Sept Oct | 4.0 | 3.6 | T | 4 | 6.8 | 10.9 | 17.9 | 32 |
| guava | *Psidium guajava* L. | Sept Nov | | | MT | 2.7 | 3.8 | 5.5 | 8.4 | 14 |
| fig | *Ficus carica* L. | | 4.7 | 9.8 | MT | | | | | |
| pomegranate | *Punica granatum* L. | | | | MT | 2.7 | 3.8 | 5.5 | 8.4 | 14 |
| grapes | *Vitis vinifera* L. | June July | | | MS | 2.7 | 3.8 | 5.5 | 8.4 | 14 |
| mangoes | *Mangifera indica* L. | July | 1.5 | 9.6 | MS | 1.5 | 2.5 | 4.1 | 6.7 | 12 |
| apricots | *Prunus armeniaca* L. | June | | | S | | | | | |
| pears | *Pyrus communis* L. | August | 1.6 | 24 | S | | | | | |
| peaches | *Prunus persica* (L.) Batsch | May June | | | S | | | | | |
| orange | *Citrus sinensis* (L.) Osbeck | | 1.7 | 21 | S | | | | | |
| alfalfa | *Medicago sativa* | | 1.3 | 13.1 | S | 1.7 | 2.3 | 3.3 | 4.8 | 8 |

* note: harvest periods based on local observation and AFD (2004).

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

**Cultivation Types, Crop Choices and Water Use**

**Subsistence Gardens: 1-3 feddan**

These very smallest farms may best be considered either farms or gardens. Most are located near to the houses of the owners in the residential area of the village. The ownership of the small pieces of land is mostly not formally registered but falls under the traditional system of *'wadaa yid'*. Some were located to the South East of the village. Gardens in the South east were a little larger in size and newer than the gardens in the village, most of which were over one hundred years old. In the South East, the land is formally owned.

Cultivators experiment with a wide range of different varieties of fruits in their gardens and a very wide range of fruit trees and vegetables were observed during the survey, as well as berseem and wheat (**Table A6.6)** . All gardens include *Phoenix dactylifera* L. (date palm). A *Tamarindus indica* L. (tamarind) tree in the village was found in one of the gardens in this category(**Figure A6.6:)**. *Ficus sycomorus* L. (bitter sycamore) **(Figure A6.4)**, *Zizyphus lotus* Lam. (jujube) (**Figure A6.5)**, *Morus alba* L. (mulberry), *Ficus carica* L. (fig), *Psidium guajava* L.(guava), *Olea europaea* L. (olive), *Punica granatum* L. (pomegranate) and *Vitis vinifera* L.(grapes) were also present. Citrus fruits, *Mangifera indica* L.(mango), *Prunus armeniaca* L. (apricots) and *Prunus persica* L. (peaches) appeared not to be so frequently cultivated in the gardens, although they are present on larger farms. Ground crops are planted beneath the fruit trees, enhancing water efficiency (**Table A6.4)**. Planting patterns of ground crops continually change with the seasons.

**Figure A6.2: Gardens in the Village**





The produce grown in the gardens is most often used by the cultivators' households, although sometimes it may be sold locally. Some gardens provide food for several households. All gardens surveyed were locally owned.

**Table A6.6: Garden Size and Crops**

| code | area | size | well | Fruit trees | Cereal and fodder | vegetables | irrigation |
|---|---|---|---|---|---|---|---|
| 001 03 | village | 1 | 35 | | alfalfa | onions | drip |
| 001 04 | village | 1.5 | 28 | Dates pomegranate, olives, guava | wheat | onions | flood |
| 001 05 | village | 1 | 25 | Dates, guava, zisiphus, jamiz | Wheat, alfalfa, corn | onions, peppers, jews mallow, eggplant | |
| 001 07 | village | 1.5 | none | Nothing growing yet | | | |
| 001 09 | south east | 1 | 25 | | alfalfa, wheat, corn, | corgettes, reham, mishwiz, fenugreek onions, beans, | |
| 001 10 | south east | 1.5 | 25 | Dates, tangerines, guava, grapes, olives, | corn, sugarcane | | Flood and |
| 001 11 | south east | 2 | 29 | dates, mulberry | wheat, alfalfa, corn | onions | |
| 001 12 | village | 2 | 24 | dates | wheat, corn, berseem, | green peppers, eggplant, onions, jews mallow, rocket, radish, | flood |
| 001 13 | village | 2 | 21 | dates | wheat, corn | onion, garlic, beans, rocket, radish | |
| 001 14 | south west | 2 | 20 | dates | white corn wheat, | onions, garlic, tomatoes, okra, jews mallow, peas | drip and flood |
| 001 15 | village | 2 | 16 | dates, Jamiz, olives | wheat, corn, alfalfa | Jews mallow, onions | flood |
| 001 16 | village | 2 | 21 | Dates, tamarind | Wheat, corn, alfalfa | onions | aprinkler |
| 001 17 | village | 2 | 22 | Dates, lemon, olives, grapes | corn, alfalfa | beans, watermelon | |
| 001 18 | South east | 3 | | | Corn alfalfa | | |

**Figure A6.3: Garden in the South East of Beni Salama**



**Figure A6.4: *Ficus sycomorus* L. (bitter sycamore)**



**Figure A6.5: *Zizyphus lotus* Lam. (jujube) tree in garden, Beni Salama Village**



**Figure A6.6: *Tamarindus indica* L. (tamarind) Tree in Beni Salama Village Garden**



The gardens are cared for by family members, including women, children and retired people. Family members who are employed elsewhere help in the gardens in their spare time. Vegetables and herbs grown in the gardens are used immediately by the families or dried in the kitchen. Wheat is ground either at home or in the town and used by the families. Chemicals are not applied in the gardens. Livestock are grazed, children play and family members of different ages work together in the gardens.

**Water Use in Gardens**

In order to assess water use in gardens, the following methods were used:
-survey of eighteen gardens
-interviews with a group of gardeners
-observation of water use in one garden in more detail through visits at different times of the day over a period of several months Apr-July, 2009

Gardens were observed to use mostly flood irrigation and natural drainage systems, although sprinklers are also present in some places. Each farm has a shallow well (ranging from 16-42m) (**Table A6.7)**. They operate with diesel pumps, mostly imported from India. It is common for the well to be sunk down into the ground in order to reduce the distance for pumping (**Figure A.6.7-8)**. The small pumps frequently require maintenance attention.

**Table A6.7: Calculation of Annual Water Use in Gardens Surveyed**

| Code | Type of pump | Horse power | Water/hr $m^3$ | Well diameter (inches) | Hrs/ day summer | Days/ month summer | Total summer | Hrs/day winter | Days/month winter | Total winter | Total annual |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 001 07 | diesel | | 60-90 | 3 | 6 | 4 | 8640 | 4 | 3 | 4320 | 12,960 |
| 001 09 | diesel | 10 | 20 | | 10 | 15 | 6000 | 4 | 4 | 1920 | 7920 |
| 001 10 | diesel | 5 | 30 | 3 | 3 | 10 | | 1 | 7 | | |
| 001 12 | diesel | | 40 | | | | | | | | |
| 001 15 | diiesel | 5 | | 3 | | | | | | | |
| 001 16 | diesel | | 30 | 6 | 4 | 15 | 1800 | 5 | 6 | 900 | 2700 |
| 001 17 | diesel | | | | 3 | 8 | 1200 | 3 | 4 | 600 | 1800 |

The garden wells can pump up to around 60$m^3$ per hour. In summer, the well may be used around four times per month for six hours to water one feddan. In winter, the well may be used around once every ten days. The following estimation of water use may therefore be made:

(summer: 4 times per month x 6hrs x 60$m^3$ x 6months)
+
(winter: 3 times per month x 4 hours x 60$m^3$ x 6months)
= 8640 + 4320 = 12,960 $m^3$/feddan/year (estimated for a 1 feddan garden)

**Figure A6.7: Wells in Gardens**



**Figure A6.8: Diesel Pumps in Beni Salama Gardens**





**Small farms: 3-20 feddan**

**Figure A6.9: *Medicago sativa* L. (alfalfa) and Fruit Trees on a Small Farm**



The small farms were located along the main roads to the west, east and south of Beni Salama village. Most belonged to local people, although several (in the South) were owned by people living in Cairo, and managed by a local person. The absent owners included a family who visited on the weekend. Another was an agricultural expert growing special varieties of mango to be showcased in exhibitions. An exotic weight-loss plant *(Babaz)* was also being experimented on this farm. Another small farm observed included a nursery growing seedlings for sale including ornamental plants not otherwise observed in the study.

Two of the small farms were on pieces of land from the local agricultural association. According to local people, this institution does not influence water management practices. Its role is understood to be limited to providing chemical inputs.

Some of the small farmers were local people who had retired from paid employment and owned their land. Some of the land was registered and included electric pumping systems. Paid labourers, including local people and workers from other areas were employed and had accommodation on some of the farms, while others relied on the labour of family members.

**Figure A6.10 Workers Harvesting Wheat on a Small Farm**



A range of crops was grown on these farms, including fruits, vegetables and alfalfa. Livestock, including camels, sheep, goats, cows, and poultry were also kept. Usually, part of the crop was for use by the farmers` households and animals, while the rest was for local sale. Popular crops for local sale included beans, wheat and mango. Dates, olives, strawberries and mandarines were also grown for local sale.

**Table A6.8: Small Farms Size, Crops and Irrigation**

| code | Size (f) | Well depth (m) | Fruit trees | Fodder and cereals | Vegetables | irrigation |
|---|---|---|---|---|---|---|
| 003 01 | 18 | 30 | date, olive, fig, guava, pomegranate | | seasonal vegetables | sprinkler, drip, flood |
| 003 02 | 7 | 2 wells, 40 m both | mulberry | alfalfa | | |
| 003 03 | 17 | 2 wells, 72 m and 35m | | wheat | peppers, beans, eggplant | drip and flood |
| 003 04 | 8 | 72 | mango, guava, dates | Alfalfa, wheat | | drip and flood |
| 003 06 | 8 | 30 and trench | dates | Wheat, alfalfa | | flood |
| 003 07 | 9 | 22 | mango, tangerine, pear, guava, lemon | | | |
| 003 08 | 6 | 67 | | hashish sudani, dora | wheat, onions, beans | |
| 003 10 | 5 | 40 | guava, fig, olive, teen bershoum | corn | okra, jews mallow, watermelon, cucumber, beans, onions, carrots, peas, garlic | drip and flood |
| 003 11 | 7 | 36 | dates | wheat, white corn | onion, garlic, beans, mulukhia, peas, rocket | flood |
| 003 12 | 5 | 40 | dates | Corn, alfalfa, wheat | beans baladi, onions, garlic, eggplant, peppers | drip |
| 003 13 | 5 | 40 | Dates, Jamiz,olive | Wheat, corn | beans, onions, garlic, peas, jews mallow, okra, eggplant, peppers | flood |
| 003 14 | 5 | trench | Dates, guava, olives, tangerine, orange, lemon, zaghloul and samani dates | wheat, alfalfa, corn | | flood |
| 003 15 | 5 | 45 | | wheat, corn | onions, beans baladi, eggplant, cucumber, watermelon, tomatoes | |
| 003 16 | 15 | 95 | dates, olives, fig bershoum, peaches, grapes | corn | okra | drip |
| 003 17 | 3.5 | 24 & 54 | Mango, pomegranate, babaz weight loss plant | | | |
| 003 18 | 4 | 24 & 78 | Datepalm, olive, mango | corn | eggplant, peppers capsicum, onions | |
| 003 19 | 3 | 42 | fruit trees around house | wheat, alfalfa | | drip and flood |

**Figure A6.10: *Mangifera indica* L. (mango) Seedlings on Small Farms**





Local farmers disagreed with the finding from a previous study by Yehia (2008) that small farming was not profitable, but underlined the importance of sound knowledge of agricultural practices and changing local environmental conditions in order to succeed.

**Water Use on Small Farms**

In order to gain an idea of water use on small farms, the following methods were used:
- survey of eighteen small farms
- more detailed interview on one farm (using electric pump)
- comparison to MWRI permits database

Eighteen small farms were surveyed in order to identify water use. The survey revealed that there was considerable variation in water use practices amongst the farmers within the typology. Small farms in Beni Salama may have either one or two wells ranging in depth from only a few meters up to seventy two meters deep in the case of the deepest wells identified through the survey in this farm type. Two small farms still had trenches tapping water near the surface instead of wells.

**Figure: A6.11: Trenches for Irrigation on Small Farms**





Irrigation methods included a wide range of combinations of flood, sprinkler and drip irrigation. In addition to seasonal variations in irrigation practices and timings, the irrigated area itself varied significantly between the seasons on these farms. For example, one farm had a total of 30 feddan, of which 15 was irrigated in winter and five or six in summer. The farmer said that this is because in summer the area is very hot and dry, and a lot of water is required to grow anything in the sandy soil. Irrigation methods are also

changing quickly and farmers are aware of the need to save water by using drip irrigation. On one farm visited, an overhead sprinkler system was in use to water mango seedlings growing in hothouses.

Use of pumping technologies is also changing on the small farms. Some farms had electric pumps, although most were still using diesel. The cost of electric pumping is cheaper than diesel (E.g. 4 kilos per hour at ½ LE per kilo on farm 003 03). However, in order to have an electric pump, the well must have a permit from the Ministry of Water Resources and the land should be registered formally.

The findings of the survey concerning the types and capacities of pumps in the study area were compared to the MWRI database of well permits. This database lists permits for wells on six small farms in the study area (**Table A6.9)**. The pumping capacities seemed higher than those surveyed, ranging from 8-10 bousa, while those surveyed ranged around 4-10 inches in diameter. Well flows listed in the database ranged from 50-240$m^3$ per hour, while an estimate of 60$m^3$ was commonly given during the survey. This difference could be due to wells of increased capacity being dug and registered. Only one of the well permits gave information concerning hours of pumping, indicating 1.5 hours of pumping permited per day. This is significantly lower than all of the estimates of pumping times recorded on other farms in the study area during the survey.

**Table A6.9: Wells on Small Farms in MWRI Database**

| size | code | type of pump | Capacity in bousa | well flow in $m^3$ | # of hours per day | Total daily flow |
|---|---|---|---|---|---|---|
| 3-20 | 003 MWRI SE 01 | local | 10 | 50 | 1.5 | 90 |
| | 003 MWRI SE 02 | local | 8 | 240 | | |
| | 003 MWRI SE 03 | local | 10 | 204 | | |
| | 003 MWRI SE 04 | local | 8 | 80 | | |
| | MWRI NW 01 003 | johnson | | 54 | | |
| | MWRI NW 02 003 | local | | 100 | | |

**Figure: A6.12: Wells on Small Farms Using Electric Pumps**



With farmers cultivating small farms, it was difficult to obtain general estimates of water usage in response to the survey questions on this issue. In some cases, the application of the same kind of calculation as used for the small gardens was pursued, where farms were configured somewhat similarly to gardens using flood irrigation and intercropping, but on a larger scale. On one such farm, 5 feddan was irrigated every other day in summer for two hours and every 3 days in winter, except for the part of the farm where wheat was grown which could be irrigated only every week for six hours in winter. Water use could therefore be calculated as follows:

(summer: 15 times per month x 2hrs x 60$m^3$ x 6months)
+

(winter: 10 times per month x 2 hours x 60$m^3$ x 6months)
+
(winter wheat: 4 times per month x 6 hours x 60$m^3$ x 6months)

= 10,800 + 7200 + 8640 = 26,640 $m^3$/5 feddan/year
5,328$m^3$/feddan/year

Due to the diversity of cultivation types and practices, the generalisation of the calculation is more problematic than for the gardens. Farmers using drip irrigation reported similar time patterns of water use to those using flood irrigation, e.g.:

(summer: 26 times per month x 5hrs x 4 bousa x 6 months)
+
(winter: 10 times per month x 2 hours x 4 bousa x 6 months)

= 51,600 $m^3$/5 feddan/year
= 10,320 $m^3$/feddan/year

If this is compared to the well listed in the MWRI database, assuming that the well is used to the maximum amount permited every day, an upper bound estimate of water use would be generated, as follows:

(all year round: 30 times per month x 1.5 hrs x 50$m^3$ x 12months)

= 27,000 $m^3$/15 feddan/year
= 1,800 $m^3$/feddan/year

**Large farms (>100 feddan) and medium-sized farms (20-100 feddan)**

These farms are developed as investments, usually owned by people from outside the village, and managed by agricultural engineers and workers either from Beni Salama or elsewhere. The largest farms in the study area include new farms along the Desert Road, and older farms established during the 1960s. Some of the medium sized farms were once parts of larger farms. The owners of the largest farms include overseas investors. Only one of the medium sized farm owners was interviewed in Beni Salama and another was visited in Cairo, where he runs another business. One of the large farm owners from Saudi Arabia was also interviewed while he was visiting his farm. On other farms, interviews were carried out with farm managers or employees. Workers providing labour and security are accommodated on the farms. The sample of large and medium sized farms is spread about the study area, quite far from the village.

The large and medium-sized farms are run according to an agro-industrial model of crop production, mostly for local sale, described in a previous study in the area by Yehia (2004). This production pattern is quite different from the family-oriented nature of labor and productivity of the small farms and gardens. One of the medium-sized farms was leased on a five year basis rather than owned. Another farm of 90 feddan had been cultivated by its owners with 30 feddan of grapes with the remainder rented out to other farmers. Rented farms are used for vegetable production, which is more profitable in the short term. The longest that any of the medium-sized farms surveyed had been in business was 10 years. Most had been around for considerably less than that length of time.

The major difference between the large and medium sized farms concerns the scale of operations, capital and management expertise available. The largest farms have access to alternative capital-intensive options to maximise the profitability of the resources and produce, such as plants for storage and post-harvest processing. They can also invest in alternatives to cultivation activities such as water bottling, land development, leisure facilities and construction of housing. Some of them have explored combinations of these activities alongside or instead of farming. The largest farms are managed by agricultural experts and employ consultants from various parts of Egypt. They produce crops of a high quality, including crops for export to Europe and the Gulf countries.

**Figure: A6.13: *Mangifera indica* L. (mangos) on a Medium Sized Farm**



**Figure: A6.14: *Vitis vinifera* L. (grapes)on a Medium Sized Farm**



A previous study carried out adjacent to the study area made a distinction between farms of less than 50 feddan oriented to domestic markets, and above this size which could be export-oriented (AFD 2008). In the present study, the line is drawn at 100 feddan, although many farms around this size were still not exporting. In most cases, crops are still sold locally to traders. Traders select those that they want to sell on. Particularly in recent years, export has been seen as a high risk market by farmers. There are a lot of requirements concerning the use of chemicals that are difficult for farmers to comply with. Some large farms that had produced crops for export in the past had decided not to continue doing so.

**Figure: A6.15: Intercropping *Phoenix dactylifera* L. (datepalm), Citrus and *Mangifera indica* L. (mango) on Older Large Farms in Beni Salama**




At the top end of the market, certification by the Global Good Agricultural Practices (GAP) programme and ISO enables export of organic produce to Europe. This process includes monthly analysis of water quality. The manager of one certified farm in Beni Salama was interviewed on a series of occasions during the field study period[27]. Sustainable farming practices such as intercropping to reduce evapotranspiration of ground crops have been in use on the older farms for many years. Even though *Phoenix dactylifera* L. (date palm) require longer to grow, and are not currently as profitable as the soft fruits, they have been retained and cultivated. The owners of these larger farms are in some cases able to take a more long term view of the farm investment and to secure contracts with suppliers for export. Crops that produce a faster return, such as onions and other fruit and vegetables are also grown on these farms (**Table A6.10)**.

**Figure: A6.16: Growing Grapes on Large Farms and Grapes with Other Crops on Small Farms in Beni Salama**




[27] Other farms certified by Global Gap in Beni Salama area: Kamel Ghonem, Ustaz Khalid Melegy (Desert Rd), Al Marmar (Desert Rd), Muhandis Mahmoud Al Ghandar, Muhandis Said Fethi, Al Beltagy (Desert Rd).

**Table A6.10: Large Farms 'Crops**

| code | area | Size (feddan) | wells number | feddan/ well | Well depth (m) | Fruit trees | Fodder and cereals | Vegetables |
|---|---|---|---|---|---|---|---|---|
| 100 | | 900 | ? | | 100 | | | |
| 100 02 | south east | 450 150 irrigated | 4 | 37.5 | 2 x 100, 150 & 85 | Date palm, peach, oranges, grapes, mango, lemon, olives, dates, | | canteloupe, tomato, onions |
| 100 | south | | 4 | | 85 x3 & | Date palm, mango, tangerine | | |
| 100 | north | 360 | | | 200m | Peach, apricot, guava, pear | | |
| 100 | north | 100 | ? | | 190m | grape, peach, apricot, orange | | |
| 100 | north | 105 | 3 | 35 | 3 wells | grapes and olives | | |
| 100 07 | north east | 105 | 2 | 52.5 | 2 well 180m- | olives, onions, grapes banati, sperio and ahmar, zaghloul | Alfalfa `hegazi` and `masri` , | |
| 100 | north | 125 | 3 | 41. 7 | three | orange, mango, grape, | | onions |
| **100 09** | | | | | | Mango, grapes | | Medicinal plants (fenugrec) |

For farms of this size, the choice of crops is an investment decision that involves analysis of the soil and water at the establishment of the farm to check the most suitable crop choices. Depending on the growing conditions, the most profitable crops for farms of this size are often grapes (particularly banati or sperio varieties) and peaches. Tangerines and mangos are also very frequently grown on this size of farm. Dates, beans, onions, alfalfa and wheat, which are the traditional crops grown on smaller farms and gardens in the study area are still present. None of the farms visited in Beni Salama reported growing bananas, although this is understood to be highly profitable in the area. Further analysis of the economics of farming in the study area according the agro-industrial model is presented by Yehia (2004), including the routine use of mineral and organic fertilisers, and the relatively low proportion of the operating costs that are associated with the provision of irrigation water. The mix of crops observed on the largest farms is relatively similar to those produced by the medium-sized farms, although some additional medicinal crops including *Trigonellafoenum graecum* L. (fenugreek) were also noted on one large farm.

**Water Use on Large and Medium Sized Farms**

In order to assess water use on medium and large farms, the following methods were used:
- survey of farm workers and managers on eighteen medium and large farms
- comparison to MWRI permits database on medium sized farms
- detailed interviews and observation on two large farms

Medium and large farms require at least one deep well per 50 feddan. Farms over fifty feddan have two wells. One farm of 24 feddan shared a deep well with another farm, however, the sharing of wells is unusual. Well depths range from 60-164 metres on medium sized farms and up to 200m on large farms. Around 50% of the medium sized farms and almost all of the largest farms surveyed had electric pumps. Where farms do not have their own generator, diesel wells are less vulnerable to power cuts. Those farms that have electric pumps also have water meters, but those still using diesel do not. Most of the medium and large farms are using drip irrigation for fruit and vegetable production.

The observation of well capacity through the survey was compared to the MWRI database, which contained information on wells on nine medium sized farms in the study area. The capacity of the wells listed in the permits database ranged from 8-12 bousa, which was higher than those observed during the field survey. The flow of the wells ranged from 80-480$m^3$ per hour. The permited pumping times, where listed, were considerably less than those reported in the survey –ie 1.3 and 1.6 hours per day only. The MWRI database contained no data on farms above 100feddan in size or on water use by water bottling factories located in the area.

**Figure: A6.17: Peaches on a Large Farm in Beni Salama**



**Table A6.11: Medium Sized Farms' Crops and Irrigation Types**

| code | location | Size (feddan) | Well depths (m) | Fruit trees | Fodder and cereals | Vegetables | Irrigation |
|---|---|---|---|---|---|---|---|
| 020 01 | north east | 70 | 200 | | | | drip |
| 020 03 | North west | 65 | 2 wells 100m and 150m | Peach, grapes, mango | fodder 9 feddan | | |
| 020 05 | north east | 60 | 2 wells 90m and 60m | none | none | Various e.g. canteloupe, tomatoes | |
| 020 06 | south east | 40 | 120 | orange, tangerine, peach, grapes, fig | berseem al hagazi, wheat, onions | beans | drip and sprinkler |
| 020 07 | south east | 39 | 102 | peach, grapes, mango, orange, dates | alfalfa, corn | beans | |
| 020 09 | south east | 50 | 70 | orange, tangerine, mango | | | Drip and 4 feddan sprinkler |
| **020 10** | north east | **50** | | Olives, oranges, mango | | | |
| **020 11** | north east | **90** | | grapes | | Various e.g. canteloupe, tomatoes | |

**Table A6.12: Details of Wells on Medium Sized Farms Listed in MWRI Database**

| code | type of pump | Capacity in bousa | well flow in $m^3$ | # of hours per day | Total daily flow |
|---|---|---|---|---|---|
| MWRI NW 01 020 | kabrari | 10 | 80 | | |
| MWRI NW 02 020 | local | 12 | 80 | 1.6 | 160 |
| MWRI NE 01 020 | kabrari | 10 | 300 | | |
| MWRI NE 02 020 | kabrari | 10 | 264 | | |
| MWRI NE 03 020 | | | | | |
| 020 MWRI SE 01 | local | 10 | 100 | | |
| 020 MWRI SW 01 | local | 8 | 100 | 1.3 | 135 |
| 020 MWRI SW 02 | local | 10 | 100 | | |
| 020 MWRI SW 03 | kabrari | 10 | 480 | | |

**Figure: A6.18: Well on Large Farm with Electric Pump and Meter**



During the survey, water use on medium and large farms was recorded in terms of hours of pumping. The results obtained are shown in **Tables A6.13 -14,** below.

On medium-sized farms, the wells pump all day in summer -ie around 8-12 hours x 80 $m^3$ of water in summer, and around 4 hours per day in winter. Annual water usage for the medium and large farms would therefore be somewhere in the region of:

(summer: 180x12x80) + (winter: 180x4x80) = 172800 + 57600
= 230,400 per 50 feddan per year
=11,520 per feddan per year

As shown in **Table A6.13** one medium-sized farm surveyed had a much lower water usage because it only grew grapes. Here, the well was pumped for half an hour in the morning and half an hour in the evening, only.

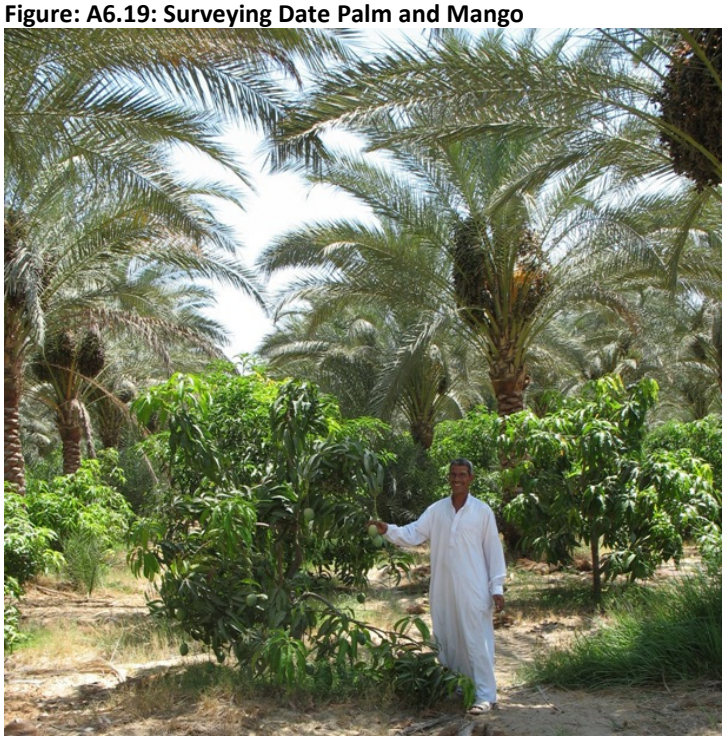
**Table A6.13: Water Requirements on Selected Medium Sized Farms**

| Name | Type of pump | Horse power | Water/hr $m^3$ | Bousa | Hrs/ day summer | Days/ month summer | Total summer | Hrs/day winter | Days/month winter |
|---|---|---|---|---|---|---|---|---|---|
| 020 11 | | | | | 1 | 30 | | | |
| 020 07 | diesel | | | 4 | 8 | 30 | | 2 | 10-15 |
| 020 06 | diesel | 4 engine | 90 | | 10 | 15 | | 4 | |
| 020 05 | | | | | 12 | | | | |
| 020 02 | | | | | 8 | | | 6 | |

Farm workers on large farms provided approximate estimates of daily water use in winter and summer on the largest farms as shown in **Table A6.15**, below. Large farm managers described the need for care not to over-pump wells because this would cause salinization.

A rough estimate of water usage on one large farm was in the order of 110$m^3$/hr from each well, pumping for 15-16 hours in summer = 1,650$m^3$/ day in summer = 180,000$m^3$/ yr
and in winter only 2 hours, 2 days per week = 12,320 $m^3$
= total 192,320$m^3$/yr per well
= if each well irrigates 50 feddan: 9,616 per feddan per year

**Figure: A6.19: Surveying Date Palm and Mango**



A more detailed exploration of the farm water requirements was made with the assistance of one of the farm employees, as follows:

The farm consists of three sections of 18 feddan planted with young datepalm and mango, 19 feddan planted older mango and tangerine and 32 feddan planted with datepalm and mango, each irrigated by a separate well.
The farm is planted in sections of 5 feddan.

One five feddan section of the 18 feddan area planted with datepalm and mango was surveyed to assess the number and spacing of trees. 600 mango trees (120 per feddan) and 330 datepalm (66 per feddan) were counted, totalling 930 trees in all.

The number of trees in the whole 18 feddan was calculated at approximately three times this amount, while in the 19 feddan area, there would be four times as many and in the thirty two feddan area there would be six times as many.

Daily water requirements were known to the farm employees, as follows:

| | |
|---|---|
| Datepalm | 80 litres per day |
| Mango | 60 litres per day or 80 for older trees |
| Tangerine | 40 litres per day |

It was agreed to estimate the total water requirements as follows:

**Table A6.14: Estimation of Water Requirements on a Large Farm in Beni Salama**

| | Feddan | # of trees | Water per tree (litres per day) | Total water requirement (litres per day) | Annual water requirement (litres per year) |
|---|---|---|---|---|---|
| 1 | 18 | 2,790 | 60 | 167,400 | 61,101,000 |
| 2 | 19 | 3,720 | 80 | 297,600 | 108,624,000 |
| 3 | 32 | 5,580 | 60 | 334,800 | 122,202,000 |
| **TOTAL** | **69** | **12,090** | | **799,800** | **291,927,000** |

= 291,927$m^3$ per 69 feddan = 4,231 $m^3$/feddan/year

Specific water requirements in litres per hour for other crops grown in the study area were reported by a number of the farm workers. One farm reported water requirements for peach at 4 litres per hour for two hours per day, and grapes 2 litres per hour for two hours per day. Water requirements for peaches and grapes vary with the growing season. They are controlled through the drip irrigation systems in terms of litres per hour for each plant.

**Figure: A6.20: *Citrus sinensis* (L.) Osbeck (orange) Saplings on a Large Farm**



**Figure A6.21: *Citrus sinensis* (L.) Osbeck (orange) Trees on a Large Farm**



**Cultivation Types, Crop Choices and Water Use: Conclusions**

The survey produced an estimate of the volume of water needed to irrigate a one feddan garden at around 12,926 $m^3$/feddan/year. The generation of comparable estimates of water needs on a per feddan basis for larger areas was more challenging. Estimates obtained through the survey ranged around 5,000-10,000 $m^3$/feddan/year for both smaller farms and also the medium-larger sized farms. The estimates are quite inexact, and generalization is also problematic. Where estimation was done on the basis of crop-water requirements rather than pumping times, lower estimates of water use were obtained.

Some exchange of knowledge and technologies for water management and irrigation could be observed taking place between the categories of large and small farms visited during the survey. Local peoples expertise also used to guide the medium and large farms, which are under their care. There was some reverse transfer of knowledge apparent. Increasing use of drip irrigation systems on the smaller farms is one very clear example. This appeared to be due to local peoples` employment on the large farms, observation of technologies there, and transfer to their own farms and gardens.

Some locally adapted crops that are grown in the small gardens, such as the *Ficus sycomorus* L. (bitter sycamore), *Zizyphus lotus* Lam. (jujube), *Morus alba* L. (mulberry), are not commercially attractive, and are absent from the larger farms.

The survey focused on the cultivation of conventional crops and was not constructed to identifiy non fruit-bearing trees and indigenous plants that do not require irrigation, although local peoples` use of them was observed to be considerable. In addition to the cultivated crops, during the field survey local cultivators voluntarily pointed out and named wild plants and animals in the reed beds and marshlands around the lakes. Wild plants, including unirrigatated date palm trees, rushes and grasses are used in the farms and gardens for fencing and building materials. Livestock are grazed on wild plants growing in the saltmarsh and halfa grasslands around the drainage lakes. Many species of wild plants are used as fodder for livestock. Wild flowers, such as Keff Maryam were encouraged for decoration in one of the gardens visited. Such plants are usually not watered and require little care because they are already well adapted to local conditions. A neighbour observed the semi domestication of this plant and took a cutting for his own garden. At the present time, although these plants are well adapted to local environmental conditions, they are also not commercially attractive.

The increasing popularity of organic produce, both in international markets and also with well-off consumers in Egypt demonstrates that the possibility exists to educate consumers to appreciate different qualities in their diet. There is considerable popular awareness and concern about the use of chemicals in Egypt, and the unsafe disposal of wastes. A very large organic farm located close to the study area employs local people and is popular amongst consumers from Cairo and Alexandria, as well as for export. There is also a growing interest within and outside Egypt in the medicinal uses of indigenous desert plants. In Beni Salama, local people pointed out with particular interest a field cultivated entirely with *Trigonellafoenum graecum* L. (fenugreck) for medicinal use. Although under current market conditions the cultivation of well-adapted desert plants is usually anticipated to be less profitable than farming strawberries and grapes, this is a matter of consumer taste and education. If consumers were aware of the availability and benefits of crops that are well-adapted to water scarce conditions, the market conditions could alter, particularly if efforts were made to raise public awareness of these issues.

Although elsewhere, groups of small farmers have formed collectives for the marketing and export of their produce, this was not observed in the study area. A collective farming project is proposed for development in an adjacent area where the construction of an irrigation canal is proposed, this project is oriented to the production of conventional irrigated export crops with tried and tested markets in Europe. In the following section of this report, the scope for collective organization amongst the small-scale cultivating households in Beni Salama is explored.

**Table A6.15: Water Requirements Estimated by Farm Employees on Large Farms**

| Code | Type of pump | Irrigated area | Estimated $M^3$/day summer | total summer | Estimated $M^3$/day winter | total winter | Total annual | $M^3$/feddan/day summer | $M^3$/feddan/day winter |
|---|---|---|---|---|---|---|---|---|---|
| 100 01 | | 900 | | | | | | 0 | |
| 100 02 | electric | 450 | | | | | | 0 | |
| 100 03 | diesel | | | | | | | | |
| 100 04 | 50-75 horse power or 80hp | 360 | Need 3000 litres per day don't know season | | | | | 0 | |
| 100 05 | electric | 100 | 3000 | 540000 | 1000 | 180000 | 720,000 | 30 | 10 |
| 100 06 | Electric | 105 | 2000 | 360000 | 500 | 90000 | 450,000 | 19 | 5 |
| 100 07 | Electric and diesel | 105 | 3000 | 540000 | 2000 | 360000 | 900,000 | 29 | 19 |
| 100 08 | electric | 125 | 3000 | 540000 | 500 | 90000 | 630,000 | 24 | 4 |

Farm managers advised that more precise calculation of water needs for tree crops would require consideration on the basis of the number of trees and individual water requirements. This was attempted on one farm, where a survey of trees was made. It was estimated that there were are around 5000 *Phoenix dactylifera* L. (date palm) trees, 6400 *Mangifera indica* L. (mango trees) and around 650 *Citrus reticulata* blanco (tangerine) on the farm. For each date palm tree, around $100m^3$ of water are needed per year. Therefore, $5,000,000m^3$ of water would be required for the date palm alone. The date palm are interplanted with mango, tangerine and other fruits.

## Appendix 7: Environmental Change in Beni Salama Village: From 2009 fieldwork report

Tables in this Appendix show observations concerning environmental changes reported during the survey in different parts of the study area, beginning with the area to the Northeast of the Lakes (above the dotted line in Figure A7.1) and the area to the Southwest (below the dotted line), and finally the village of Beni Salama itself.

**Figure A7.1: NW-SE Subdivision of the 8x8km Study Area along the Lakes**

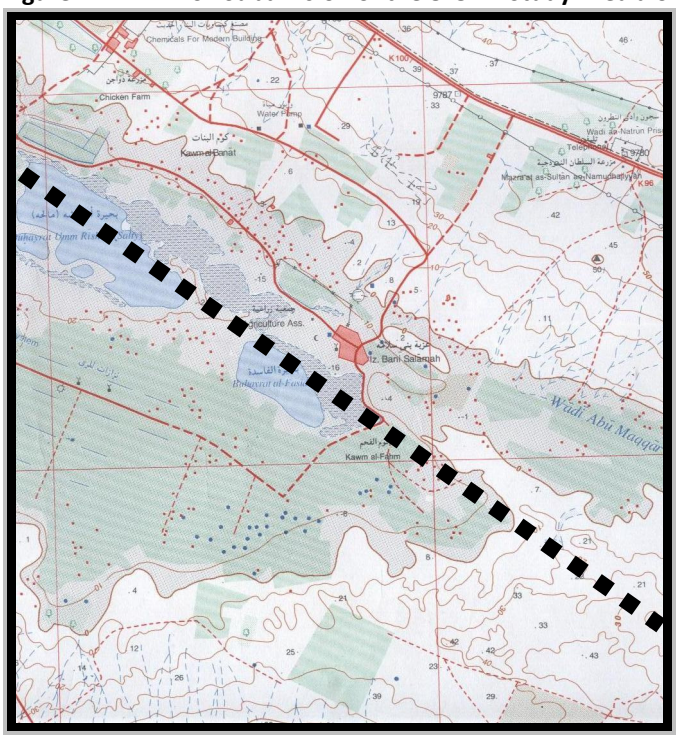



**Table A7.1: Changes in Wells North of the Lakes as Observed by Survey Respondents**

| Area | Farm size (feddan) | Total depth of well (s) (m) | Well age (years | Falling water table | Salinization | Other changes in quality |
|---|---|---|---|---|---|---|
| Along Desert Road | 360 | 140-200 | 14 | | | |
| | 100 | 200 | | N | | |
| | 105 | 190 | | Y | | N |
| | 105 | 150 -160 | | Y | | N |
| | 125 | 180-190 | 4-6 | Y | Y | N |
| | 70 | 200 | | | | N |
| | 50 | 120-170 | 2-15 | | Y | |
| | 80 | 160-195 | 3-13 | | Y | |
| | 750 | 89 | | | | |
| | 60 | 60-90 | 43 | N | N | |
| | 65 | 50- 100 | | N | N | |
| | ***Mean size:170*** | ***Mean depth: 147*** | ***Mean age:12 yrs*** | ***Observed: 50%*** | ***Observed: 60%*** | ***Observed: 0%*** |
| Along village road (below sea level) | 150 | 100-150 | | Y | N | N |
| | 15 | 95 | 2-6 | Y | Y | |
| | 5 | | | Y | Y | N |
| | 7 | | | | | |
| | 17 | 40 | | Y | N | N |
| | 6 | 67 | | Y | N | N |
| | 8 | 35-72 | 9 | Y | N | N |
| | 8 | 72 | 9 | | | |
| | 10 | 30 | | | | |
| | 5 | 42 | | | Y | |
| | ***Mode size:8*** | ***Mean depth: 75*** | ***Mean age:6.5yrs*** | ***Observed: 100%*** | ***Observed:57%*** | ***Observed: 0%*** |

**Table: A7.2: Changes in Wells South of the Lakes as Observed by Survey Respondents**

| Area | Farm size (feddan) | Total well depth (m) | Well age (years) | Falling water table | Salinization | Other changes in quality |
|---|---|---|---|---|---|---|
| South of Lake (below sea level) | 1.5 | No well yet | | | | |
| | 1 | 25 | 5 | | | |
| | 1.5 | 25 | 9 | | | |
| | 2 | 29 | 9 | N | N | N |
| | 3 | 40 | 1 | Y | | |
| | 2 | Trench 50m long | | | Y | |
| | 3.5 | 24 - 54 | 0-13 | Y | Y | |
| | 4 | 24 - 78 | 13 | Y | Y | |
| | 9 | 22 | | N | N | N |
| | 100 | 85-110 | 3-43 | Y | Y | N |
| | ***Mean size:13*** | ***Mean depth: 43m*** | ***Mean age:11yrs*** | ***Observed: 67%*** | ***Observed: 67%*** | ***Observed: 0%*** |
| further South (> sea level) | 30 | 120 | 7 | Y | N | N |
| | 39 | 102 | 3 | | N | |
| | 50 | 70 | | | | |
| | ***Mean size:40*** | ***Mean depth: 97m*** | ***Mean age:5*** | | ***Observed: 0%*** | ***Observed: 0%*** |

**Table A.7.3: Changes observed in wells in village**

| Area | Farm size (feddan) | Well age (years) | Total well depth (m) | Falling water table | Salinization | Other changes in quality |
|---|---|---|---|---|---|---|
| N of village | 2 | < 1 | 16 | Y | N | N |
| | 2 | 13 | 21 | Y | Y | |
| | 5 | | 40 | Y | N | N |
| | 1 | | 22 | Y | Y | Y |
| | 1 | | 35 | | | |
| W of village | 5 | | 24 | Y | Y | |
| | 2 | 9 | 24 | N | | |
| | 2 | | 21 | Y | Y | Y |
| | 2 | | 20 | | | |
| | 5 | | 36 | Y | N | N |
| E of village | 1.5 | < 1 | 28 | | | |
| | 1 | 19 | 25 | | Y | |
| | 5 | | 35 | N | Y | N |
| | ***Mean size: 2.7*** | ***Mean age: 8.6yrs*** | ***Mean depth:24m*** | ***Observed: 78%*** | ***Observed: 67%*** | ***Observed: 33%*** |

**Table A.7.4: Range of salinity values recorded in shallow wells operating in Beni Salama Village, 2009**

| EC dcms |
|---|
| 2.920 |
| 2.070 |
| 1.990 |
| 3.550 |
| 2.440 |
| 1.485 |
| 2.380 |
| 2.390 |
| 1.433 |
| 2.750 |
| 5.000 |
| 1.087 |

## Appendix 8: Comparison of Salinity Levels and Trends in Nefzaoua (Tunisia) and Siwa (Egypt)

**Figure A8.1: Comparison of Salinity Levels in Siwa and Nefzaoua Oases, 2002 (Based on Gad and Abdel-Baki 2002 in Siwa, compared with DGRE published data from Nefzaoua)**

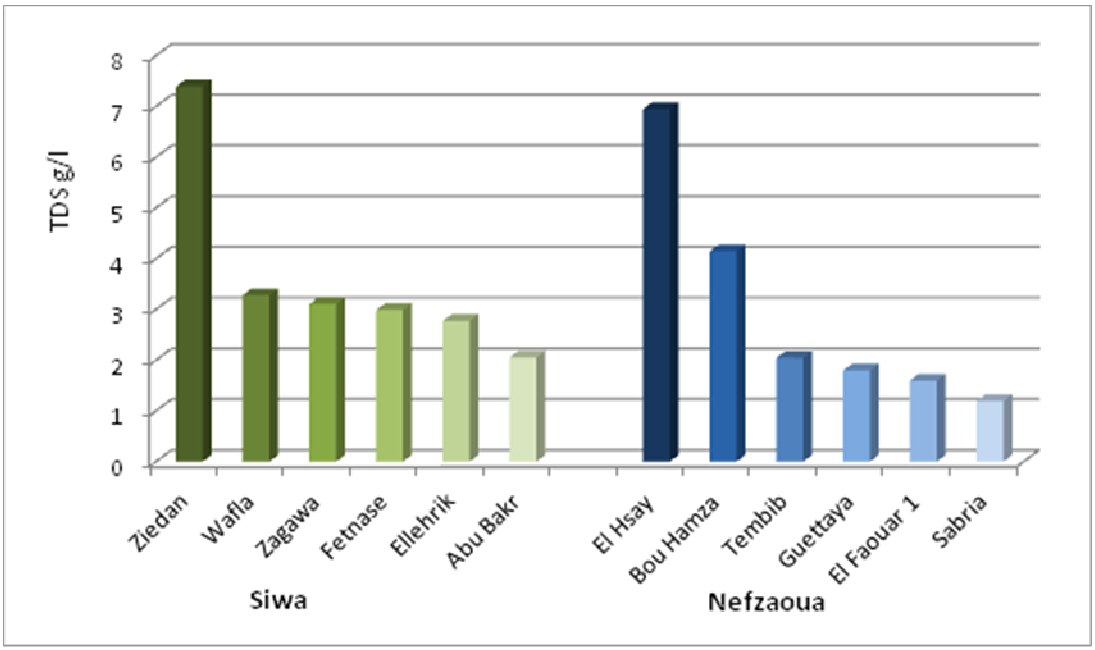



**Figure A8.2: Trend in Salinity in Nefzaoua Oases (DGRE 1979-2006)**

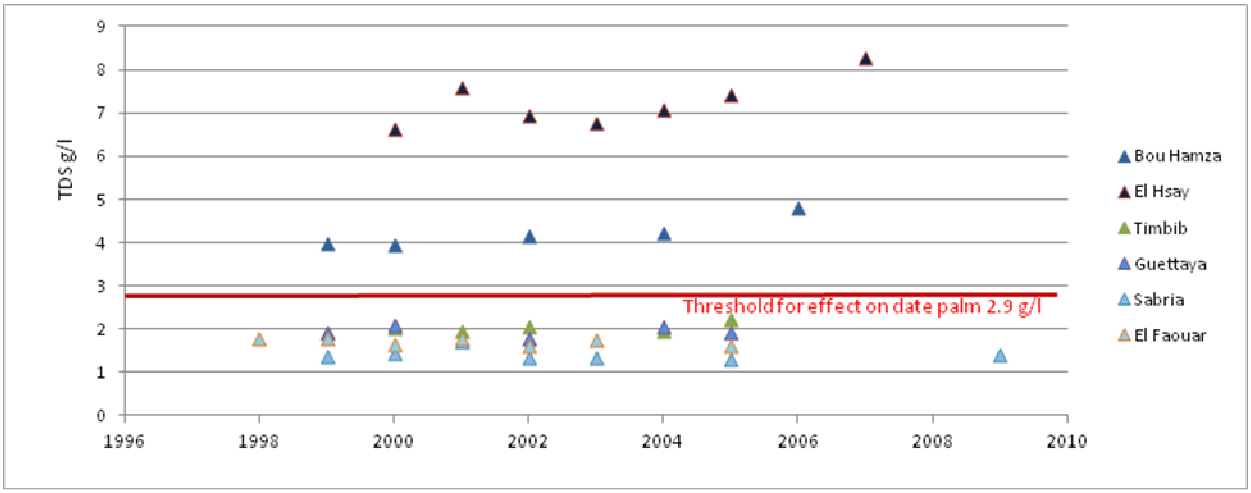


**Figure A8.3: Trends in Salinity in Western Siwa (after Anwar 2007)**

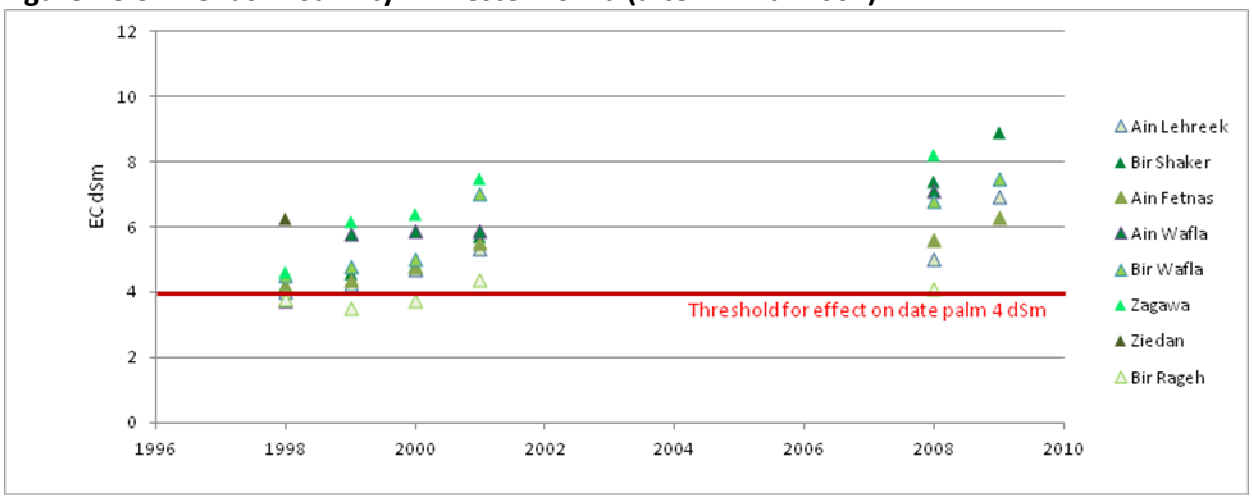



**Figure A8.4: Trends in Salinity in Central and Eastern Siwa (after Anwar 2007)**

