GROUNDWATER, ENVIRONMENTAL CHANGE AND CONSERVATION IN NORTH EGYPT

THE IMPACT OF ENVIRONMENTAL CHANGE AND WATER CONSERVATION ON DRYLAND GROUNDWATER RESOURCES IN NORTHERN EGYPT: MODELING AQUIFER RESPONSE USING SPARSE DATA

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TITLE:	The Impact of Environmental Change and Water Conservation on Dryland Groundwater Resources in Northern Egypt: Modeling Aquifer Response Using Sparse Data
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ABSTRACT

Groundwater depletion and quality degradation in many dryland environments is accelerating simultaneously with increasing demand for reliable groundwater resources. Groundwater resource sustainability is a particular significant challenge in dryland environments, as it is often the sole source of freshwater for a variety of competing uses. The area of Wadi El Naturn, located in the Egyptian Western Desert (northern Egypt), has been subject to significant groundwater degradation in both quality and quantity since approximately the 1990s, attributed primarily to agricultural development. In recent years, several local and regional initiatives have been proposed to increase the sustainability of groundwater resources in the Wadi El Natrun area, however they have yet to be evaluated with respect to their potential impact on groundwater itself. Information required to diagnose the drivers of groundwater quality degradation and aquifer depletion, and assess management options in dryland environments like Wadi El Natrun is frequently sparse. This thesis presents an approach for modeling the impacts of dryland environmental change on groundwater over time in the context of sparse data. A particular focus is placed on understanding the potential impacts of demand management, or conservation, strategies in the context of climate change.

The objective of this research was to generate a validated groundwater model using limited available information while sufficiently accounting for local drivers of non-stationarity, namely changes in surface water boundaries (Nile River), and land use which could impact groundwater recharge (irrigation return flow), and water demand (well abstraction) over time. Water use, hydrostratigraphic and groundwater flow data were collected from literature, monitoring records, satellite imagery and a survey of local landholders. MODFLOW-NWT was used to model the multi-layer aquifer system, and algorithms were developed in R to create statistical realizations of potential groundwater recharge, and well pumping at a monthly time-step from 1957 to 2011. Efforts were made to quantify the uncertainty in the conceptual model, data inputs, and observational records used for calibration. An ensemble of outputs from multiple simulations results were validated against monitoring records and demonstrated that the model was found to be reasonably capable of capturing the cumulative impact of environmental change with known level of uncertainty. A risk assessment approach was then used to assess the impact of various water resource management scenarios on groundwater sustainability in Wadi El Natrun, Egypt. Climate change was incorporated in each modeled scenario using an ensemble of the most recent future climate predictions from the Coupled Model Intercomparison Project (CMIP 5). Results demonstrate that demand management implemented through optimized irrigation and crop rotations has the potential to significantly reduce risk of groundwater depletion. Additionally, the influence of groundwater pumping was found to far outweigh that of climate change for the local area. Although there is high confidence that evapotranspiration in the area will increase due to climate change, the direct impact of this trend on groundwater will be negligible compared to the influence of abstraction. Water budget analysis also revealed that surface recharge in the area is negligible.

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THESIS STRUCTURE AND AUTHOR CONTRIBUTIONS

This thesis has been assembled in accordance with the McMaster University School of Graduate Studies' "GUIDE FOR THE PREPARATION OF MASTER'S AND DOCTORAL THESES" for a sandwich thesis. This thesis contains four chapters. Chapter 1 provides an overview of the main research theme and research objectives. Chapters 2 and 3 consist of manuscripts prepared for publication and document key methodologies and findings with respect to the modeling of environmental change, groundwater flow and the potential impacts of conservation on groundwater resources. The material in Chapters 2 and 3 was co-authored, and as such a brief description of the contributions made by this thesis author are detailed below. Chapter 4 presents overall conclusions on the findings and limitations of the research, along with recommendations for future work. Because the manuscripts in Chapters 2 and 3 references the same study area of Wadi El Natrun, there is some repetition in the type of information presented in the introductory sections and study area descriptions.

Chapter 2 Contributions

Title:	An Approach to Modeling Groundwater Impacts of Dryland Environmental Change Using Sparse Data
Authors:	Harris R. Switzman, Paulin Coulibaly, and Zafar Adeel
Submitted to:	*Groundwater*
Contributions:	H. R. Switzman designed and conducted the field program, including water user surveys, collected and reviewed in-country literature for groundwater model development, developed the well pumping and 1-D groundwater recharge models, created the remote sensing processing routines, conducted modeling and interpreted results; P. Coulibaly and Z. Adeel provided expert advice in the design of field data collection, modeling, analysis, and edited text written by H.R. Switzman.

Chapter 3 Contributions

Title: The Impacts of Climate Change and Water Conservation Measures on Groundwater Resources in Northern, Egypt: Is Sustainability Achievable?

Authors: Harris R. Switzman, Paulin Coulibaly, Zafar Adeel, Caroline King, Boshra Salem, and Mohamed Gad

Prepared for: *Water Resources Management*

Contributions: H. R. Switzman designed and conducted the field program for expanding the geographic coverage of water user information in Wadi El Natrun, created the geodatabase used for the risk assessment, bias-corrected and interpreted climate change projections from CMIP5, conducted the groundwater modeling of climate change and management scenarios, interpreted the results and wrote the manuscript text; P. Coulibaly and Z. Adeel provided expert advice in the design of field data collection, modeling, analysis, and edited text written by H. R. Switzman; B. Salem and M. Gad provided data used in the risk assessment geodatabase from previous fieldwork conducted from 2008 to 2010 and expert advice and support in the collection and interpretation of local information.

Copyright

Both Chapters 2 and 3 have yet to be submitted to the respective target journals and thus no copyright has been assigned to date.

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LIST OF ABBREVIATIONS

1D	One dimensional
3D	Three dimensional
ASCE	American Society of Civil Engineering
asl	Above sea level
ASTM	American Society for Testing and Materials
AVHRR	Advanced Very High Resolution Radiometer
CADR	Cairo-Alexandria Desert Road
CHD	Constant head package in MODFLOW
CMIP3	Coupled Model Inter-comparison Project 3
CMIP5	Coupled Model Inter-comparison Project 5
CSS	Composite scaled sensitivity
CWR	Crop water requirement
DRN	Drain package in MODFLOW
ET	Evapotranspiration
EVT	Evapotranspiration package in MODFLOW
f	Feddan
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Climate Model
GW	Groundwater
GWAHS-CS	United Nations Groundwater and Human Security Case Studies
GPS	Global Positioning System
HK	Hydraulic conductivity
HK_F	Hydraulic conductivity in faults
IWRM	Integrated Water Resource Management
L	Length dimension
MWRI	Egyptian Ministry of Water Resources and Irrigation
NCDC GSOD	National Climate Data Centre's Global Summary of the Day
NDVI	Naturalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NSAS	Nubian Sandstone Aquifer System
R^2	R-squared statistic
RCH	Deep recharge
RCP	Relative concentration pathway
RIGW	Research Institute on Groundwater
RSE	Standard error of the regression
SOSWR	Sum of squared weighted residuals
SD	Standard deviation

SS	Specific storage
SY	Specific yield
T	Time dimension
USGS	United States Geological Survey
VKCB	Vertical conductance

LIST OF SYMBOLS

a	Mean historical evapotranspiration for a given month of the year
A	Area of irrigation
b	y-axis intercept
B	Baseline scenario
c	Individual MODFLOW cell intersected by the receptor
C	Fraction of maximum seasonal water
C_D	Denominator constant for evapotranspiration reference equation
C_N	Numerator constant for evapotranspiration reference equation
d	Average flow
dpm	Days per month
D	Year in which scenario condition met
DR	Irrigation drain return flux
e_a	Actual vapour pressure
e_s	Saturation vapour pressure
E	Exposure
EFF	Water use efficiency
ET_{anom}	Evapotranspiration anomaly
ET_{ref}	Reference evapotranspiration
f	feddan
F	Total number of MODFLOW cells intersected by the given receptor
G	Soil heat flux
h	Set of hazards
H	Predicted hydraulic head at the end of the planning horizon
hpm	Hours per month
hpd_{alc}	Hours per day allocated by MWRI allocated
hpd_{sw}	Hours per day allocated for areas under surface water allocation
i	Month
IRR	Irrigation return flow
j	Pumping rate
J	Risk receptor
k	Model cell or well identifier
K_c	Crop coefficient

l	Downstream distance
L	Length
m	Day of month
M	Slope
n	Management scenario
N_{days}	Number of days in a given month
N_{obs}	Number of observations
NIR	Near-infrared portion of the electromagnetic spectrum
p	Season
P	Precipitation flux
q	Specific water flux
q_{alc}	MWRI water pumping allocations per unit of irrigated area
q_{DR}	Irrigation tile drain flux
q_{ET}	Evapotranspiration flux
q_{IRR}	Irrigation return flow
q_P	Precipitation flux
q_{RCH}	Recharge flux
q_S	Soil storage flux
$Q20$	Reduced pumping rate in the 20% water use reduction scenario
Q_{abs}	Groundwater abstraction rate
Q_{pump}	Groundwater pumping rate
r	Irrigation district
R	Risk score
R_N	Net radiation
RED	Visible red portion of the electromagnetic spectrum
rhs	Mean daily relative humidity
s	Sustainability
ΔS	Change in storage
S	Soil water storage
$scfWind$	Mean daily wind speed
t	Time
T	Temperature
$tasmax$	Maximum daily temperature

$tasmin$	Minimum daily temperature
u	Wind speed at crop height
u_2	Mean wind speed at elevation of 2 m above the ground surface
U	Conjunctive water use subscript
V	Vulnerability or susceptibility to the impact
w	Water level
W	Receptor
z	Hazard
Z	Threshold value for a given receptor
ϕ	Variability associated with external stresses such as evaporation, pumping, and drainage return
τ	Slope of the saturation vapour pressure-temperature curve
γ	Psychrometric constant

CHAPTER 1. INTRODUCTION

Groundwater is critical to both human wellbeing and ecosystem health in arid and semi-arid environments, as it often represents the primary source of freshwater in these environments (Trondalen 2009; Aeschbach-Hertig and Gleeson 2012). Groundwater is also an important input to agriculture globally, accounting for approximately 43% of worldwide irrigation consumption (Siebert et al. 2010; MacDonald et al. 2012; Aeschbach-Hertig and Gleeson 2012). Although groundwater has enabled commercially viable agriculture to develop in drylands, as population and food demand in these areas increase, so does demand for subterranean water (Scanlon et al. 2012). This increased demand is placing significant pressure on aquifers (Zhou et al. 2010; Wada et al. 2010), and frequently results in water quality and quantity degradation (Aeschbach-Hertig and Gleeson 2012; Foster and Chilton 2003). Although groundwater abstraction has been estimated to constitute approximately 10% of annual recharge globally, depletion of major aquifers is increasingly correlated with high rates of extraction, particularly in arid environments (Aeschbach-Hertig and Gleeson 2012). For example, in Egypt, Libya and Saudi Arabia, groundwater abstraction exceeds the total availability of annual renewable groundwater resources by between 300 and 900 % (Giordano 2009). These levels of abstraction are by definition unsustainable, having important implications for other aspects of human security, namely food supply and agricultural production. Unsustainable groundwater abstraction, also termed groundwater overdraft, and has been cited as one of the top three risks to global food security by the UN's Food and Agriculture Association (Moench, et al. 2003).

Many programs and policies have been implemented in dryland environments to concurrently improve the sustainability of groundwater use and manage the risks of its degradation. These initiatives include demand management incentives, irrigation equipment retrofits, the optimization of irrigation scheduling, and other allocation schemes. While balancing multiple human needs and ecosystem requirements for high quality freshwater is a fundamental goal of dryland groundwater management, the historical tendency has been for individuals to abstract groundwater at will, without regard for the cumulative impact of such actions (Shiferaw et al. 2008; Whitfield and Reed 2012). Examples of collective groundwater management, in which users develop and adhere to basin-scale allocation schemes are rare (Whitfield and Reed 2012), and where successful require robust governance and high levels of water user participation (Mukherji and Shah 2005). Communal groundwater distribution systems, such as Qannat, Aflaj, or piped-water networks, are good examples of shared groundwater sources, however regimes dominated by private wells are seldom communally governed (Blomquist et al. 2001). This is the case for aquifers exploited in many dryland environments around the globe (Hammani et al. 2009; Green et al. 2011; King and Salem 2012). One such example is the Egyptian Western Desert, where groundwater has been relied upon as the dominant source of irrigation water for dryland agricultural development programs (Baietti et al. 2005).

Egypt's population is currently estimated at approximately 82 million and is rapidly growing (El-Din 2013). Most of this population is concentrated in and around the Nile Delta in the northern portion of the country between Alexandria and Cairo, occupying between 4 and 6 % of Egypt's total land base (El-Din 2013; African Development Bank 2009; Antipolis 2011). While Egypt's economy is relatively diversified, agriculture represents over 30% of the country's overall GDP and over 35% of employment, largely because of the need to supply growing domestic markets (African Development Bank 2009; ARECMEEAA 2010). The Nile river supplies over 95% of the country's freshwater, making recent international negotiations over allocations throughout the river Nile Basin an important domestic and international political issue for Egypt (Antipolis 2011). Given that agriculture constitutes over 81% of Egypt's total water consumption, water issues are an important element of overall human security for Egypt (Ministry of Water Resources and Irrigation 2005). Although groundwater only constitutes 3% of the country's total water consumption, in areas like the Western Desert it is the dominant portion of irrigation supply and will become an increasingly important source of water as pressures on the Nile increase both domestically and internationally (El-Din 2013; Booij et al. 2011). Throughout Egypt, groundwater is also used conjunctively with surface water, for example in the areas fringing the Nile Delta (Attia et al. 2007).

Groundwater abstraction in the Egyptian Western Desert has been driven by several policies to expand the area of reclaimed desert land and is projected to increase in the future. By 2017, the Egyptian Ministry of Water Resources and Irrigation's (MWRI) National Water Resources Plan (NWRP) aims to expand the area of cultivated land by an additional 3.4 million hectares (Ministry of Water Resources and Irrigation 2005). In the NWRP, much of this reclamation is dependant upon private investors using groundwater for irrigation. This is the case in the Wadi El Natrun depression and surrounding areas of Wadi El Farigh and Sadat City.

The high level of groundwater use and certain land management practices in the agricultural area of Wadi El Natrun area has resulted in the degradation of groundwater quality and quantity. Primary concerns among users are salinization, pollution from wastewater ponding and declining water levels (King and Salem 2012; Salem et al. 2010; Ibrahim 2005; Fattah 2011). These problems have raised questions about the sustainability and potential risks of the current water use regime on local water, food and economic security in the area, particularly as climate change is projected to add additional pressures to water demand (Attia et al. 2007; Ganzori 2013). Groundwater-dependent agriculture is a significant aspect of the local socio-economic fabric in Wadi El Natrun, providing over 60% of jobs (King and Salem, 2013). The range of crops cultivated in Wadi El Natrun is diverse and agricultural products are used for domestic consumption, sold at local markets and increasingly for export both within Egypt and abroad (King and Salem, 2013).

The impacts of climate change on both the supply and demand sides of water resource management is also becoming increasingly important globally (Ganzori 2013; Green et al. 2011; Ali et al. 2012; Pasini et al. 2012). Changes in local climate influence the overall water budget of an area, and alter the timing and magnitude of demand, especially for agriculture (Corbeels 2012; Eid et al. 2006). In North Africa specifically, recent studies have shown that changes in the climate regime are already apparent (ARECMEEAA 2010). For the area of Wadi El Natrun, reference evapotranspiration is projected to increased by more than 9% by 2025 (Candela et al. 2012), while changes in precipitation are projected to be nil (Terink et al. 2013). Groundwater levels have also been shown to respond both directly to changes in climate change in areas with pronounced groundwater-surface water interactions (Green et al. 2011), and indirectly through changes in water use. One impact in particular is the influence of sea level rise on coastal aquifers (Sayed Frihy et al. 2009; El-Nahry and Doluschitz 2009). Surface water bodies, such as the Nile River in Egypt, are also predicted to become stressed due to climate change. Anticipated stresses include increased variability in flow rates due to changes in seasonal trends, greater frequency and intensity of extreme precipitation events in upstream watersheds, and heightened evaporation (Booij et al. 2011).

Given the complex set of environmental and anthropogenic issues pertaining to groundwater management, information on the state of the regional groundwater system is required for the scoping and implementation of management initiatives. Groundwater modeling is often used for the analysis of groundwater management options. The aim of this thesis was to develop a groundwater modeling system capable of assessing the impacts of various groundwater management schemes in the Wadi El Natrun depression. Regional groundwater models that contain the Wadi El Natrun area have been created previously, however they have not been validated under transient conditions (Molla et al. 2005; Dawoud et al. 2005; Diab et al. 2002; Ammar 2010; Mohamed and Hua 2010). These previous models did also not incorporate all the three main aquifers in the area, or account for the cumulative impact of land development over time. Because of the gaps in the existing models, the model developed for the current study has been validated under transient conditions, account for the three aquifers, and assessed the cumulative impacts of the local land development on groundwater.

1.1. Research Objectives and Outputs

The main objective of this research is to understand the extent to which water conservation might improve the sustainability of groundwater resources in the context of environmental change in Wadi El Natrun, Egypt. Achieving this objective required developing a modeling system that accurately represents local hydrogeological and water use conditions with a known level of confidence. Because the nature of this work required forecasting, it was also necessary to develop a mathematical model capable of simulating groundwater conditions under a variety of scenarios. Finally, it was necessary to develop a set of future water conservation scenarios that could realistically be implemented in the local area and contribute to the development of effective policies. These scenarios were run using climate change projections in order to capture the effect of this important phenomenon. It should be noted that water quality issues related to groundwater salinization, microbial contamination and emerging contaminants of concern are important aspects of groundwater management in Wadi El Natrun, however it was beyond the scope of this thesis to assess these risks in detail. Several research questions and methodologies were developed to meet these objectives, as follows:

1. *What are the historical trends in land-use, water use and hydrology in Wadi El Naturn, and how have they influenced groundwater levels and flow regimes?* The hypothesis underpinning this research question is that land, water use and hydrologic processes influence groundwater levels in the study area. Prior to this research, there had been little to no physical modeling of the area to understand these dynamics in a transient way. Chapter 2 of this thesis present an approach for modeling the impacts of changing land and water use of local groundwater. Conducing this modeling required developing a 3-dimensional characterization of the subsurface using existing geologic information (i.e., borehole records, cross sections, and geophysical analysis). It was also necessary to develop a statistical model for distributing surface recharge and groundwater pumping rates across the model domain in both space and time dimensions. This required conducting water user surveys in the field, reviewing historical records and interpreting satellite imagery.
2. *Given the sparse data available to assess trends in historical land use, groundwater levels, and other hydrologic variables, what is the uncertainty of the resulting hydrogeologic model?* The required data available for use in this modeling exercise were sparse and associated with significant uncertainty, especially the model calibration data. Chapter 2 presents an approach to conducting transient groundwater modeling using sparse data that enables the results to be framed with respect to the overall accuracy of the model.

3. *What are the projected impacts of climate change in Wadi El Natrun?* Chapter 3 presents an approach for incorporating climate change into the assessment of water conservation scenarios on groundwater resources. An ensemble of the most recent CMIP5 climate models was used and individual models were downscaled locally using bias correction.
4. *Given local technology, stakeholder interest, capacity, and environmental conditions in Wadi El Natrun, what are some realistic groundwater conservation and land use management scenarios that could reduce risk to groundwater depletion?* Water conservation and land use management scenarios were developed using an socio-ecological framework, building on work already completed as part of the United Nations' Groundwater and Human Security Case Studies project. Developing and evaluating these scenarios required consulting with local water users, but also creating a geodatabase to incorporate all the necessary information. Details on scenario development and evaluation are presented in Chapter 3.

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CHAPTER 2. AN APPROACH TO MODELING GROUNDWATER IMPACTS OF DRYLAND ENVIRONMENTAL CHANGE USING SPARSE DATA

ABSTRACT

Often, information available to diagnose the drivers of groundwater depletion and assess management options in drylands is sparse. This paper presents an approach for modeling the impacts of dryland environmental change on groundwater using sparse data. This method was applied to Wadi El Natrun, northern Egypt, where agricultural development relying exclusively on groundwater has been aggressive since the 1960s, resulting in local groundwater depletion and quality degradation. The objective of this research was to generate a validated transient groundwater model using limited available information, while sufficiently accounting for drivers of non-stationarity, namely changes in surface water boundaries (Nile River), and land use which could impact irrigation-driven groundwater recharge, and water demand. Water use, hydrostratigraphic and groundwater flow data were collected from literature, monitoring records and a survey of local landholders. Remote sensing data (LANDSAT and AVHRR) were used to drive changes in the spatial distribution of well pumping and surface recharge over time using a novel set of statistically-based algorithms developed in R. An ensemble of recharge and well pumping outputs were then used as boundary conditions in a 3D groundwater flow model (MODFLOW-NWT) of the local multi-layer aquifer system to simulate head changes. Results were validated against monitoring records, and various performance tests demonstrated that the model was capable of simulating cumulative impact of environmental change with known level of uncertainty despite the sparse data available for model development. Water budget analysis revealed that significant aquifer storage depletion has occurred as the extent agricultural land expanded since the 1960s.

2.1. Introduction

Groundwater is critical to both human wellbeing and ecosystem health in arid and semi-arid environments, as it often represents the primary source of freshwater (Trondalen 2009; Aeschbach-Hertig and Gleeson 2012). Groundwater is also an important input in agriculture, accounting for approximately 43% of global irrigation water consumption (Siebert et al. 2010; MacDonald et al. 2012; Aeschbach-Hertig and Gleeson 2012). Agriculture in dryland environments is rapidly increasing in its reliance on groundwater for irrigation (Zhou et al. 2010; Wada et al. 2010; Voss et al. 2013). The heavy reliance on groundwater for dryland agriculture is often attributed to causing local water over-extraction and quantity degradation (Aeschbach-Hertig and Gleeson 2012; Foster and Chilton 2003).

Many programs and policies have been implemented in dryland environments to concurrently improve the sustainability of groundwater use and manage the risks of its degradation, including demand management incentives, irrigation equipment retrofits, the optimization of irrigation scheduling, and other allocation schemes (Mukherji and Shah 2005). Information on the state of the regional groundwater system is required for the scoping and implementation of such initiatives, and groundwater modeling is often used for the analysis of management options.

In many dryland environments, particularly in developing nations (Easton et al. 2011), the data used to develop groundwater models for resource management policies and programs can often be sparse and/or of unknown quality. Water resource agencies operating in these contexts may also be constrained by financial, technical or human resource capacity to undertake rigorous modeling exercises. In a recent synthesis of groundwater knowledge in developing nations, the United Nations concluded that there is a definite trend of groundwater models being unconvincingly validated or incompletely conceptualized in the developing nations (Tujchneider and van der Gun 2012). Yet, as global environmental change becomes an increasingly important factor affecting water use and hydrology, groundwater models capable of capturing these dynamics will be of greater value (Green et al. 2011).

In the context of this paper, the term environmental change will refer to natural and human induced stresses on the landscape and natural resources. Drivers of environmental change include global climate warming, land development, and the associated ecological transformations, all of which lead to variance in the hydrologic regime.

The typical approach to modeling the impact of environmental change on groundwater has been to develop, calibrate and validate a 3D or quasi-3D finite element or finite difference groundwater model, and run it under plausible scenarios of change by adjusting stress factors (Holman et al. 2012; Green et al. 2011; Goderniaux et al. 2009; Liggett and Allen 2009). Such models should be capable of capturing groundwater flow dynamics in response to several possible sources of natural and anthropogenic stresses present in a study area, such as surface recharge, groundwater abstraction, changes in barometric pressure, and the magnitude and direction of exchanges with surface water (Brouyere et al. 2003; Bakker et al. 2008; Scibek et al. 2007). Another key requirement for modeling the non-stationary impacts of environmental change on groundwater is that models should be able to simulate the cumulative effects of these stresses (Holman et al. 2012; Milly et al. 2008; Perkins and Sophocleous 1999). Successfully modeling environmental change requires sufficient data to support the calibration of the model over a range of conditions, which typically means having evidence of these changes in the historical groundwater record and being able to replicate them using a model.

The current methods for conducting this kind of calibration rely on having a well calibrated and validated groundwater model, or multiple plausible models that can run these scenarios using a multi-model approach (Rojas et al. 2010; Ye et al. 2010). Bakker et al. (2008) have suggested that time series and momentum analysis can be used to discern the relative importance of different stresses in a groundwater system, and calibrate a model accordingly. This approach relies however, on an abundance of high resolution time series data for both the stresses and groundwater heads (Bakker et al. 2008). A more commonly used approach in groundwater modeling is trial and error calibration, for which there exist many examples of models being calibrated iteratively to different temporal conditions with the objective of minimizing residuals across the model domain (Dawoud et al. 2005; Chenini and Ben Mammou 2010; Xie and Cui 2011).

In circumstances where there is a high level of uncertainty regarding the hydrology, hydrostratigraphy or other model inputs, multi-model approaches are suggested (Ye et al. 2010; Poeter and Anderson 2005; Singh et al. 2010; Rojas et al. 2010). Monte-Carlo stochastic methods and multi-criteria optimization algorithms can then be used to select the optimal model from an array of possible models (Tartakovsky 2013; Zhou and Li 2011). Multi-model approaches have become typical in climate change impact assessments (Green et al. 2011; Brouyere et al. 2003; Holman 2005; Scibek et al. 2007; Holman et al. 2012; Goderniaux et al. 2009), however they typically use an average monthly time-step over a single year, rather than modeling long-term cumulative changes. Additionally, within the body of literature on multi-model studies, the authors are not aware of any studies that have demonstrated this approach to modeling a real-world situation over historical long-term, transient, and non-stationary conditions.

Another approach to modeling the impacts of environmental change on groundwater is through the use of integrated or coupled groundwater-surface water models. The general process is to feed scenarios into the land-surface or climate-driven aspects of the hydrologic model, which influence the groundwater processes such as recharge, surface water interactions or water use. Numerous codes and a few examples exist for such studies focusing on groundwater impacts specifically, including hydrogeosphere (Goderniaux et al. 2009), Mike-SHE (Liggett and Allen 2009), GS-FLOW (AquaResource 2011), SWAT-MODFLOW (Kim et al. 2008; Chung et al. 2010; Perkins and Sophocleous 1999; Sophocleous 2000), and SWANCATCH (Holman 2005). Others have used or developed GIS-based approaches for distributing recharge across groundwater model domains (Candela et al. 2012; Chenini and Ben Mammou 2010), or used existing 1D methods, such as the HELP model (Liggett and Allen 2009). Certain model codes, such as SWAT and MODFLOW's FMP module are designed to model the effects of changing agricultural land and water use on hydrologic processes, with the latter focused on groundwater specifically. These aforementioned modeling approaches are data-intensive however, requiring data for calibration and validation of both surface water and groundwater routines, along with details of water usage over time. There are numerous advantages to using integrated or coupled groundwater-surface water models, namely the ability to more realistically model all physical processes (Kim et al. 2008). When the available data are insufficient to conceptualize the physical system, the use of a more sophisticated and complex method (e.g., an integrated model) is not practical. Increased complexity can elevate a model's uncertainty (Rojas et al. 2010; Zhou and Li 2011; Hill 1998).

The objective of this paper is to present an approach for modeling the impacts of long-term environmental change on groundwater in a dryland environment. The approach is applied to the area of Wadi El Natrun, located in the Egyptian Western Desert. Given that significant environmental changes that have taken place in this area, any attempt to model the groundwater system without considering the non-stationarity of these stresses would represent an incomplete conceptualization of the system. Since the 1960s, there have been incremental yet significant cumulative changes in the hydrogeological variables of recharge and pumping that need to be accounted for in any groundwater model to be used for policy planning in this area. Given this non-stationarity, it is necessary to use a long-term calibration and validation simulation period to reliably validate this groundwater model. Additionally, the approach presented in this paper was developed to accommodate sparse data availability. Assuming that this approach could be transferred to other dryland environments with similar data constraints, an emphasis was placed on using open source and publically available code and datasets.

2.2. Study Area

Egypt’s Western Desert is a local representation of the global trend of increased reliance and stress on groundwater due to agricultural land development in dryland environments. The study site presented in this paper, Wadi El Natrun, is an endorheic depression at the eastern boundary of the Egyptian Western Desert, located adjacent to the Cairo-Alexandria Desert Road (CADR) between Cairo and Alexandria (Figure 1).

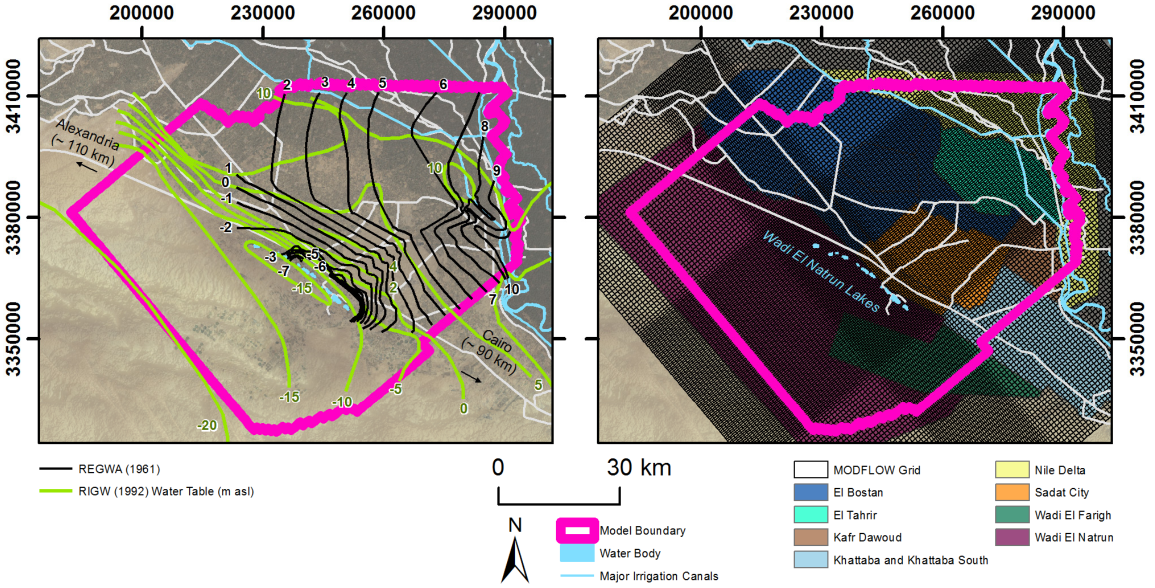


Figure 1. Map of study area with historic water levels from RIGW (1992) and REGWA (1961) (left) and model grid with delineations of the different irrigation districts (right).

Since the late 1980s, the study area has experienced a significant degradation of groundwater quality and quantity due to the over-exploitation of local and regional aquifers, and contaminating land-use practices (e.g., wastewater ponding, waste disposal, and agrochemical application) (King and Salem 2012; Salem et al. 2010; Masoud and Atwia 2010; Awad 2002). Wadi El Natrun's aquifers provide local communities with a reliable source of domestic water while supporting an extensive landscape of agro-ecosystems developed under the Egyptian government’s desert reclamation program (Abdel-Hamid et al. 2010). Eleven saline lakes are located at the base of the depression, and represent a regional groundwater discharge zone. Groundwater flows toward the depression from both the Nile Delta in the east and the Western Desert in west (USAID 1998; Attia et al. 2007; Salem et al. 2010; Research Institute on Groundwater 1992).

Excessive groundwater pumping for irrigation has led to the development of more localized flow fields, although few recent studies have quantified these (Masoud and Atwia 2010; El-Sheikh 2000). The lakes and fringing wetlands are also significant habitats to the area's wildlife (Taher 1999; Geirnaert 1992), and salt is harvested for commercial purposes (Shortland 2004).

Desert reclamation using groundwater began in Wadi El Natrun around 1985 (Baietti et al. 2005), although irrigation using the Nile River canal system in tandem with groundwater has occurred since the 1950s (Sabbah and Metwally 1996). Local groundwater extraction rates increased significantly around 1990. By the year 2000, total groundwater abstraction is estimated to have increased by approximately 87% in Wadi El Natrun relative to the 1990 levels, and 700% to 2000% in Wadi Farigh (located approximately 35 km to south of Wadi El Natrun) (Baietti et al. 2005). Salinization of groundwater has increased significantly over time as a result of the increased abstraction (Fattah 2011; Attia et al. 2007; Masoud and Atwia 2010).

Regional groundwater models that contain the Wadi El Natrun area have been created previously, however they have not been validated under transient conditions (Molla et al. 2005; Dawoud et al. 2005; Diab et al. 2002; Ammar 2010; Mohamed and Hua 2010). These previous models did not incorporate all the three main aquifers in the area, or account for the cumulative impact of land development over time. Because of the gaps in the existing models, the model developed for the current study has been validated under transient conditions, account for the three aquifers, and assessed the cumulative impacts of the local land development on groundwater.

2.2.1. Hydrology and Hydrogeology

The hydrogeologic setting of Wadi El Natrun is complex (Figure 2), and there is uncertainty regarding the precise flow regime and hydraulic connections between aquifers (Salem et al. 2010). General consensus is that the area is underlain by four main aquifers (Awad 2002; Ibrahim 2005; Ibrahim 2007; Salem et al. 2010; El-Fayoumi 1964; Ammar 2010; Zaghloul et al. 1999; Geirnaert 1992; Kashef 1983; Research Institute on Groundwater 1990; Research Institute on Groundwater 1992), of which three are currently being exploited (Attia et al. 2007; Salem et al. 2010; King and Salem 2012). From deepest to shallowest, these aquifers are known based on their geologic ages, as the Miocene, Pliocene and Pleistocene aquifers (Salem et al. 2010; Zaghloul et al. 1999). The Nubian Sandstone Aquifer System (NSAS) is the fourth aquifer present in Wadi El Natrun, and is a deep trans-boundary aquifer system. The NSAS underlies, and is theorized to recharge, the Miocene aquifer in Wadi El Natrun across a deep fracture system (King and Salem 2012; Murray 1952; Geirnaert 1992; Ahmed 1999; El-Sheikh 2000). The geology of the area is largely sedimentary in character, comprised of unconsolidated sands, sandstone, limestone, mudstones, clays and shale (Shata 1982; Geirnaert 1992; Ammar 2010).

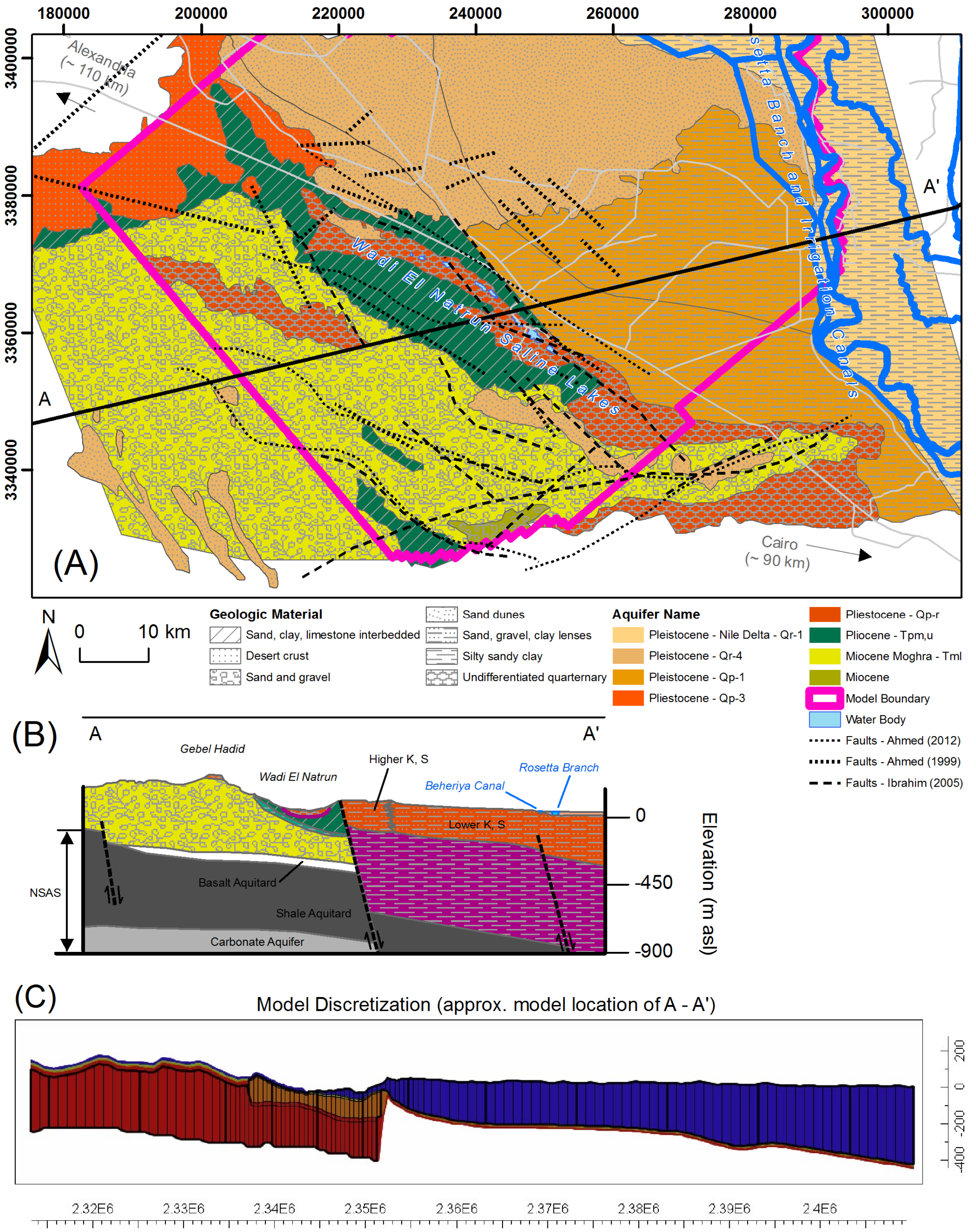


Figure 2. (a) spatial extent of aquifers in the study area (adapted from MWRI, 1992); (b) composite geologic cross section, based on multiple sources (MWRI, 1992a,b; Ahmed, 1999; El Shiehk, 2000); (c) discretized cross section on ModelMuse (approximate location of A to A')

The Pleistocene Aquifer extends from the Nile Delta in the east to a major fault oriented northwest-southeast, located parallel to the CADR (Research Institute on Groundwater

1990; Research Institute on Groundwater 1992; Ibrahim 2005). This fault is theorized to hydraulically connect the otherwise isolated Pleistocene aquifer to the Pliocene aquifer below (Ibrahim 2005; Hamza et al. 1984). The flow in the Pleistocene Aquifer is under free conditions, originating at the Nile River's Rosetta Branch from river seepage and irrigation return flow (El-Fayoumi 1964; Molla et al. 2005; Awad 2002; Attia et al. 2007). Groundwater flows west toward Wadi El Natrun where it discharges in the saline lakes at the base of the depression (El-Fayoumi 1964; Molla et al. 2005; Awad 2002; Attia et al. 2007). An isotopic study by Ahmed (1999) demonstrated that approximately 68% of the water in the aquifer originates from the Nile Delta sources, with the remaining 32% being of meteoric origin. Depth to the water table ranges from just below grade in the Nile Delta to 40 m below grade on the slopes of the Wadi El Natrun depression (Zaghloul 1999). The aquifer is composed of lagoonal, deltaic, and alluvial sands and gravels with some interbedded clay (Zaghloul 1999; El-Sheikh 2000; Awad 2002; Ibrahim 2005), and is capped at the surface by a thick layer of fractured Nile Delta clay (Warner et al. 1984). The aquifer thickness ranges from up to 300 m in the east to less than 50 m in the base of the Wadi El Natrun depression (El-Sheikh 2000; Ibrahim 2005; Salem et al. 2010). The storage capacity, transmissivity, and hydraulic conductivity of the Pleistocene Aquifer are high (Research Institute on Groundwater 1992) (Table 1).

Below the Pleistocene Aquifer is a thick layer of Pliocene-era clay, approximately 200 m in thickness (Ibrahim 2005; Ahmed 1999). This clay layer acts as barrier to vertical flow between the Pleistocene and Pliocene Aquifers, except in areas where tectonic faulting has created preferential flow paths and hydraulic connections (El-Sheikh 2000; Hamza et al. 1984; Shata 1982; Geirnaert 1992). The geologic horizon below the Pliocene-era aquitard constitutes the Pliocene aquifer, which has complex material properties as it is comprised two spatially discontinuous water-bearing members known as the El Mulk, and Beni Salama members (Masoud and Atwia 2010; Kashouty and Sabbagh 2011).

Table 1. Summary of aquifer parameters

Source	Saturated Thickness (m)	Storativity (unitless)	Transmissivity ($m^2\ d^{-1}$)	Hydraulic Conductivity ($m\ d^{-1}$)
Pleistocene Aquifer				
Dawoud et al. (2005)	200 to 680	0.1 to 0.01	1.0 to 7.0 $\times 10^5$	50 to 150
El-Shazly et al. (1975)	-	-	-	77.76
General Petroleum Company (GPC) (1978)	3,900	3.9×10^{-3}	2,600	26
Ibrahim (2000)	-	-	3,034	-
Pavlov (1962)	-	-	-	15.38
Saad (1962)	3,950	3.95×10^{-3}	1,292	52.98
Molla et al. (2005)	-	-	-	30 to 100
Abdel-Baki (1983)	-	6.92×10^{-3} to 4.33×10^{-2}	4,130 to 5,927	-
Warner et al. (1984)	-	[a]0.001 to 1.1 [a,b]3.0×10^{-5} to 4.9×10^{-3}	-	-
Pliocene Aquifer				
Ibrahim (2005)	-	-	1240	-
Mostafa (1993)	-	7×10^{-3}	943	47
Research Institute on Groundwater (1990)	-	1.7×10^{-3}	500	9.8
Kashouty and Sabbagh (2011)	500 to 1,000	1.8×10^{-4}	-	9.8 to 47
Saad (2012)	1,350 to 7,500	7.5×10^{-3}	95 to 1,181	38.9
Miocene Aquifer				
Ibrahim (2005)	55.97 to 4,600		0 to 5,001	2.8 to 36.4
Mostafa (1993)	-	1.2×10^{-4}	1,951	-
Geirnaert (1992)	-	-	-	20

[a] refers to vertical hydraulic conductivity
[b] refers to the clay cap layer at the surface of the Pleistocene aquifer

The El Mulk member is comprised of interbedded layers of sand, clay, and limestone (Masoud and Atwia 2010; Kashouty and Sabbagh 2011; King 2011). It is separated from the lower Beni Salama member by a clay layer of variable thickness and spatial extent. The Beni Salama member is composed of sand, sandstone, gypsum and fractured shale; materials that contribute to the natural salinity of the groundwater in the area (Rashed and Rashed 1991). Due to the presence of interbedded clays and shale, the Pliocene Aquifer has a lower overall storage capacity and transmissivity than the other aquifers in the area (see Table 1) (Research Institute on Groundwater 1990). The Pliocene Aquifer's thickness ranges from 150 to 300 m thick (Masoud and Atwia 2010; King 2011; Ibrahim 2005). The Pliocene Aquifer is theorized to be recharged by the Pleistocene Aquifer across the northwest-southeast trending fault at the eastern extent of Wadi El Natrun (Salem et al. 2010). Faulting and fractures within the thin clay layer that separate the Pliocene and underlying Miocene Aquifer also provide conduits for deep meteoric water under pressure to recharge the Pliocene aquifer from below (El-Sheikh 2000).

The Miocene Aquifer has a much larger spatial extent than the Pliocene and Pleistocene Aquifers. It extends to Upper Egypt in the south, and as far west as the Qattara depression (Zaghloul et al. 1999; Ibrahim 2005), and is part of the deep transboundary NSAS. The main water-bearing unit in the Miocene aquifer in Wadi El Natrun is known as the Moghra formation. The Moghra formation is comprised of sand and sandstone, and is separated from the lower units of the NSAS by basalt and shale. It is regarded to have a moderate to high storage capacity and transmissivity (Table 1) (Ibrahim 2005; Geirnaert 1992; Research Institute on Groundwater 1992).

Based on an analysis of NOAA's National Climate Data Centre (NCDC) Global Summary of the Day dataset from 1996 to 2012 for the Wadi El Natrun station the area receives an average of 31.5 mm of total precipitation annually, and has a total reference evapotranspiration of 1515 mm. This corresponds to an aridity index of 0.021, classifying the area as hyper-arid (United Nations Environment Programme 1992). The NCDC time series revealed that precipitation occurs predominantly during January, February and December distributed on an average of 2 wet days in each of those months. Daily precipitation records also demonstrate that rare extreme rainstorms have occurred in the past, with daily 30 mm events having an approximate return period of 5 years. While such storms are rare, they have resulted in local temporary flooding conditions in parts of Wadi El Natrun (Awad 2002).

Time series of monthly groundwater levels from pre-development monitoring data (1956 to 1960) demonstrate that ambient seasonal groundwater fluctuations range between approximately 0.5 m to 4 m, with peak levels occurring from September through March, and minimum levels occurring from March to August, and oscillations being greater in the area closer to the Nile River (Figure 3b).

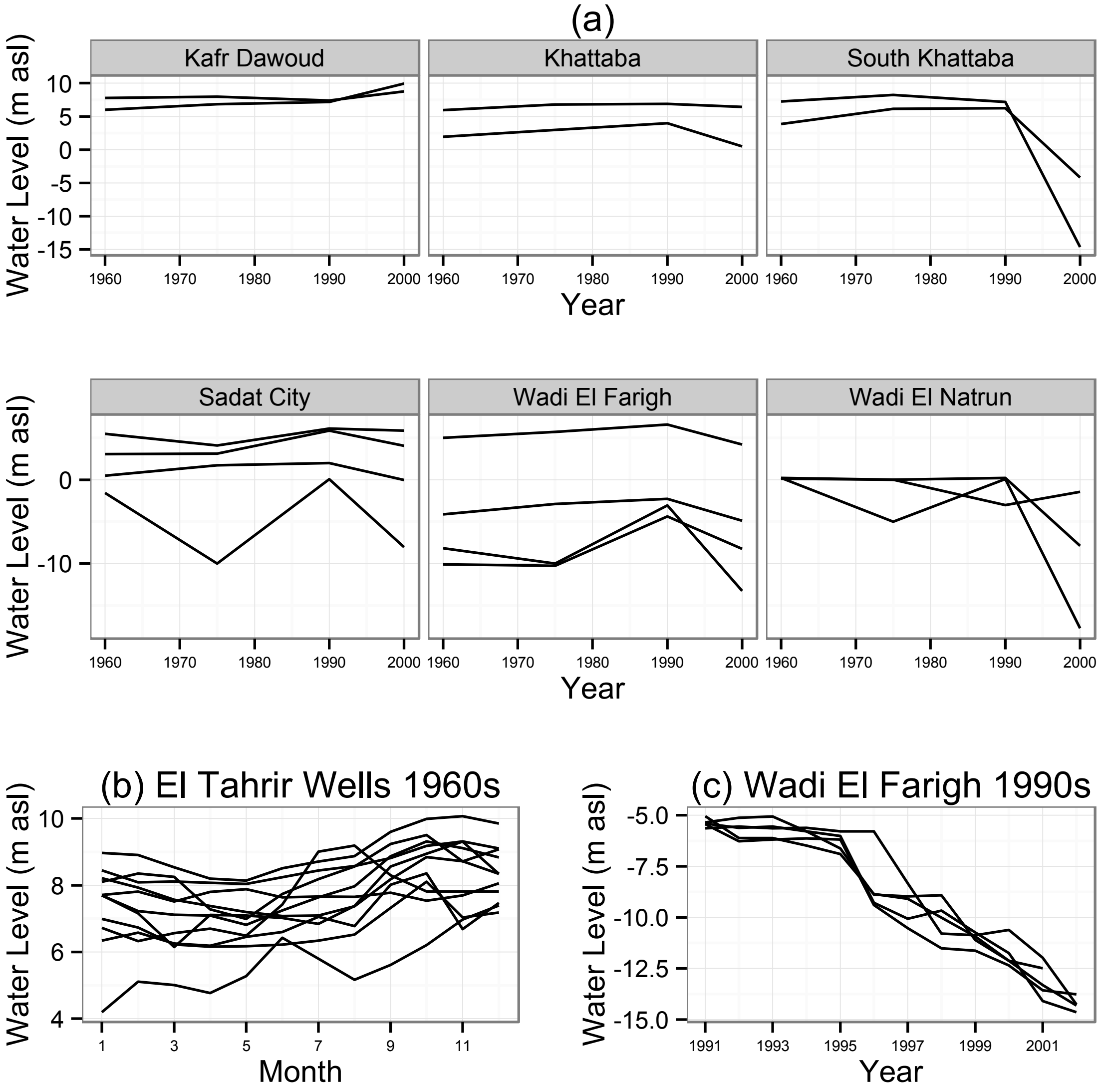


Figure 3. (a) long term trends in groundwater levels at different irrigation zones in the study area (Baietti et al. 2005); (b) pre-development seasonal groundwater fluctuations for wells located adjacent to the Nile River in the El Tahrir irrigation district (REGWA 1962), and (c) yearly groundwater declines in Wadi El Farigh (Ibrahim 2005)

Of note is the fact that these data are from a time prior to the regulation of the Nile River. Only one recent study presents data on seasonal groundwater level fluctuations in Wadi El Natrun, in which water levels were monitored for the period of March and September 1998, and January and May 1999 for 86 wells (El-Sheikh 2000). Fluctuations of the same magnitude as the 1956 to 1961 dynamic equilibrium data were observed in El-Sheikh (2000), with the average range of fluctuations over the monitoring timeframe being 0.13 m (standard deviation of 0.31 m). When outliers of 2.35 m and 1.05 m were removed from this dataset, the average seasonal difference was 0.10 m (standard deviation of 0.16 m), thereby confirming that seasonal fluctuations are small. Previous hydrogeochemical and isotope tracer studies have identified a relationship between groundwater levels and irrigation return flow from the Nile Delta and surface water irrigated sectors of the Western Desert, located to the east of Wadi El Natrun (Hazzaa et al. 1965; Awad 1997; Ahmed et al. 2010; Sharaky et al. 2007; Warner et al. 1984; El-Fayoumi 1964). Surface recharge is a principle factor controlling the natural seasonal oscillation of groundwater levels in the study area, principally through seepage from the Nile River's Rosetta Branch, the irrigation canal network in the El Bustan and El Tahrir areas, and irrigation return flow. The magnitudes and timing of recharge due to the latter two factors are closely interdependent.

There is a significant inter-annual long-term trend of the groundwater levels across the entire study area declining by approximately 1 m per year. Since the 1990s, this inter-annual trend is of a greater magnitude than the aforementioned seasonal trends (Figure 3). This phenomenon has been independently documented in several locations within the study area through both groundwater monitoring data and interviews with water users (Ibrahim 2005; Research Institute on Groundwater 1992; Masoud and Atwia 2010; Baietti et al. 2005; King and Salem 2012; Salem et al. 2010). The decline is primarily attributed to the cumulative impact of the increased groundwater abstraction over time. A core objective of this research was to develop a model capable of replicating this cumulative trend.

2.3. Model Development

2.3.1. Groundwater Flow Model

MODFLOW-NWT was used to simulate groundwater flow in the three main aquifers of the Wadi El Natrun area using a quasi-3D model. The software ModelMuse was used to pre-process data and generate input files. A single hydrostratigraphic model was created based on an inventory of borehole records, geologic cross-sections, and interpretations of the study area collected from previous research (Ibrahim 2005; Ibrahim 2007; Warner et al. 1984; El-Sheikh 2000; Kashouty and Sabbagh 2011; Sharaky et al. 2007; Awad 2002; Zaghloul et al. 1999; Ammar 2010; Ahmed 1999). Based on this information, a conceptual model of the impacts of environmental change on groundwater was developed (Figure 4).

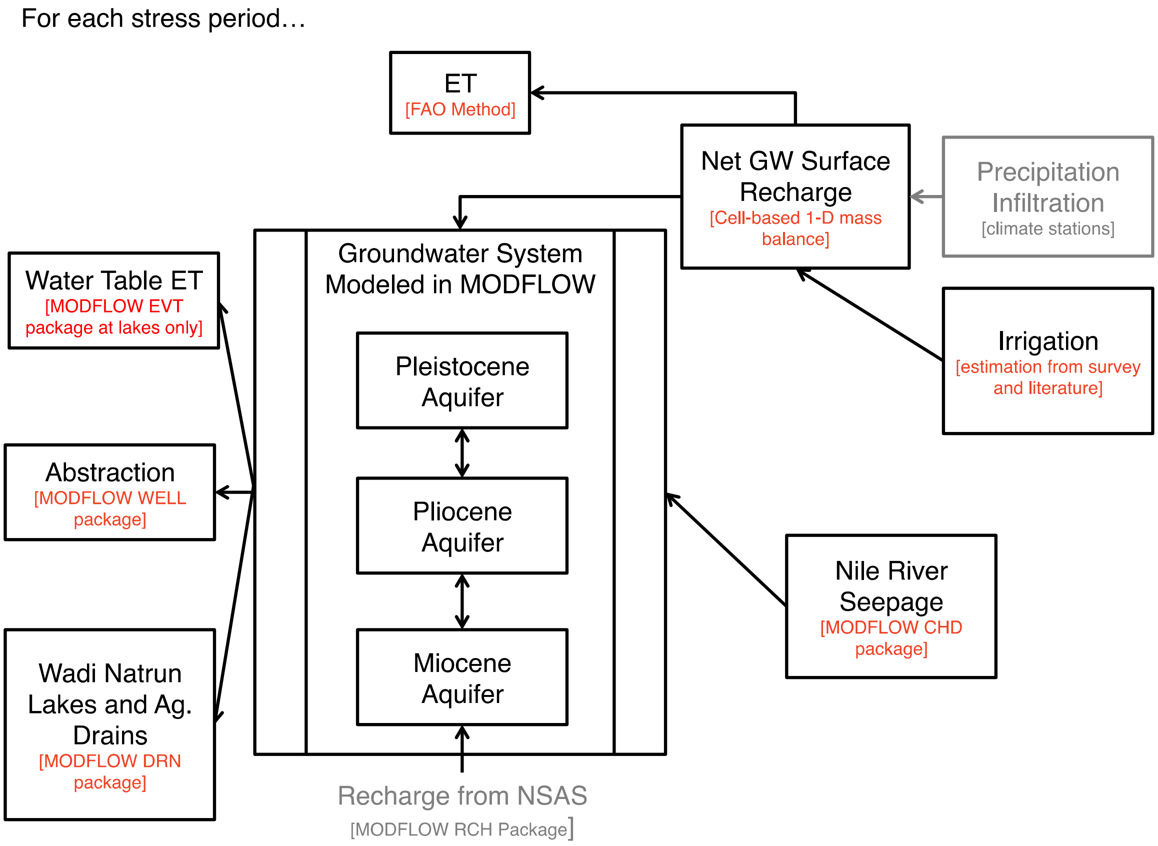


Figure 4. Schematic representation of model components. Grey text denotes processes that were assumed to be negligible and were thus excluded from the model system.

Statistical, geographic, and remote sensing functions were used in R to generate a model for computing ensembles of spatially distributed groundwater recharge and well pumping rates. The model was designed to run at a monthly time-step from 1957 through 2011, resulting in 660 MODFLOW stress periods for which well pumping, recharge and boundary condition changed.

The geographic domain of the model was set to extend west from the Nile River’s Rosetta branch in the east to a constant head boundary approximately 40 km west of the Wadi El Natrun depression (Figure 1). The northern and southern boundaries of the model were coded as no-flow boundaries. This decision was based on an analysis of historical water levels, which demonstrated that flow in these areas is from northeast to southwest (Figure 1). Given that the three aquifers are spatially discontinuous across the model domain, model cells were set as inactive in areas where the aquifers do not exist. The aquifer extents were mapped from the Hydrogeologic Map of Egypt, and other available borehole records and cross sections (Figure 5) (Research Institute on Groundwater 1992; Research Institute on Groundwater 1990; Geirnaert 1992; Ibrahim 2005; Ibrahim 2007; Sharaky et al. 2007; Zaghloul et al. 1999; El-Sheikh 2000).

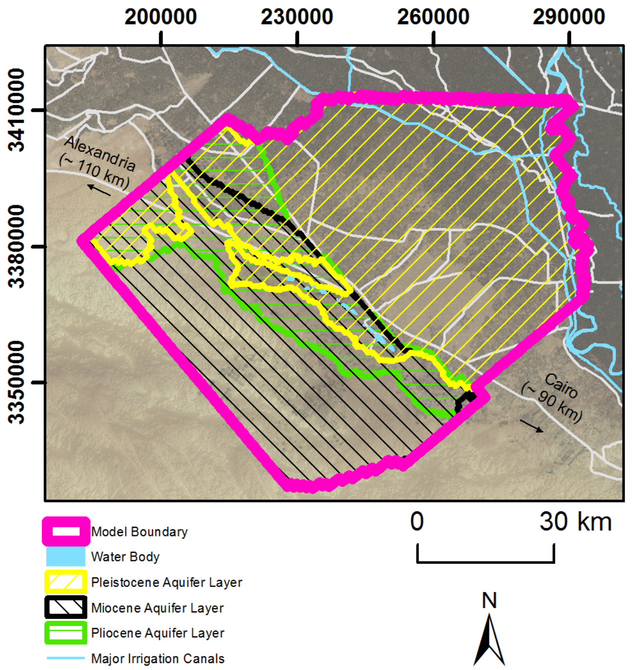


Figure 5. Aquifer extents within the model.

The western constant head boundary was modeled as an assumed constant water level of -20 m above sea level (asl) as reported in the Hydrogeologic Map of Egypt, which is based on monitoring data from the early 1990s (Research Institute on Groundwater 1992). This boundary was deemed distant enough from any agricultural development to be influenced by well pumping. Moreover, it represents the unconfined portion of Miocene Aquifer, which is recharged from below and is relatively unexploited in the Wadi El Natrun depression. The Nile River was used as a constant head boundary in the east, and was set to fluctuate during every stress period. This fluctuation assumes that the groundwater levels in the aquifer adjacent to the Nile River fluctuated in accordance with surface water levels, as was observed in monitoring data from the 1960s (REGWA 1962).

Several assumptions were made in order to balance the need for computational stability, model parsimony, and accuracy. Firstly, because precipitation in the study area is minimal in comparison to evapotranspiration, it was assumed to be negligible and was therefore removed from the computation of net groundwater surface recharge. This assumption was based on the fact that the amount of precipitation falling during daily events is small enough that percolation through the soil profile to the water table would contribute only negligibly to overall surface recharge on a monthly scale. Additionally, although extreme precipitation has led to flash flooding in the past, because of the rarity of such events, their impact on cumulative monthly water budget was also assumed to be negligible. The second major assumption was that water table evapotranspiration in most of the study area was negligible due to the depth of the water table below grade. The exception was the area around the saline lakes, where the water table is close to the surface and oasis vegetation is present (King and Salem 2012). Fluxes of water out of the groundwater system were instead modeled by modeling the lakes as drains features and calibrating the drain's hydraulic resistance. The basis for this assumption is that the depth of the water table is typically greater than 4 m below grade, and previous studies have demonstrated that ground-surface temperature only affects flux rates in the top 0.3 m of desert soils (Scanlon and Milly 1994). Additionally, root-zone depths in the study area are typically less than 2 m (Abbott and Quosy 1996; Sabbah and Metwally 1996; Abdel-Hamid et al. 2010), representing a depth below grade less than the water table.

The lakes present at the base of the Wadi El Natrun depression were modeled as drain features in MODFLOW. Taher (1999) describe the lakebeds of the saline lakes of Wadi El Natrun as consisting of sand, with some salt encrustation and microbial mats. Initial values of lakebed leakance were therefore set to 40 m d^{-1}, similar to the local sand with interbedded clay. This value was ultimately adjusted during model calibration.

Evaporation is also an important process, directly controlling the lake levels, with recent estimates of annual evaporative flux from the lakes being 7.0×10^7 m^3 (Dawoud et al. 2005). The balance between evaporation and groundwater discharging into the lakes via seeps and springs is the biggest determinant on their levels (Attia et al. 2007; Taher 1999). Thus, as evaporative potential and groundwater heads fluctuate seasonally, so do the lake levels (Taher 1999; Awad 2002). Taher (1999) observed that water is present all year at the three main lakes in the centre of the depression (i.e., Lakes Hamra, Beida, and Khadra). These water levels are at their annual maxima between December and March, and significantly lower in summer months causing some of the lakes to subdivide (Taher 1999; Awad 2002). The lakes can have depths between 0.5 and 2 m during their peak water level, indicating that groundwater fluctuations in Wadi El Natrun may be of a similar magnitude.

Much of the agricultural land reclaimed with surface water is outfitted with a network of tile drains installed after the mid-1970s through several irrigation improvement projects (Attia et al. 2007; Oosterbaan 1999). The drainage system was installed to remove excess water from soils that inhibit plant growth (Farag et al. 2008; Allam et al. 2007). Water table mounding has been consistently identified as a problem for agriculture in the area due its effect on soil water quality and drowning of plant roots (Kashef 1983; Warner et al. 1984). Drainage water is either returned to main irrigation canals or the Nile branch itself (Sabbah and Metwally 1997). Drain conductance in MODFLOW was set during the calibration process.

2.3.2. *Nile Water Level Model*

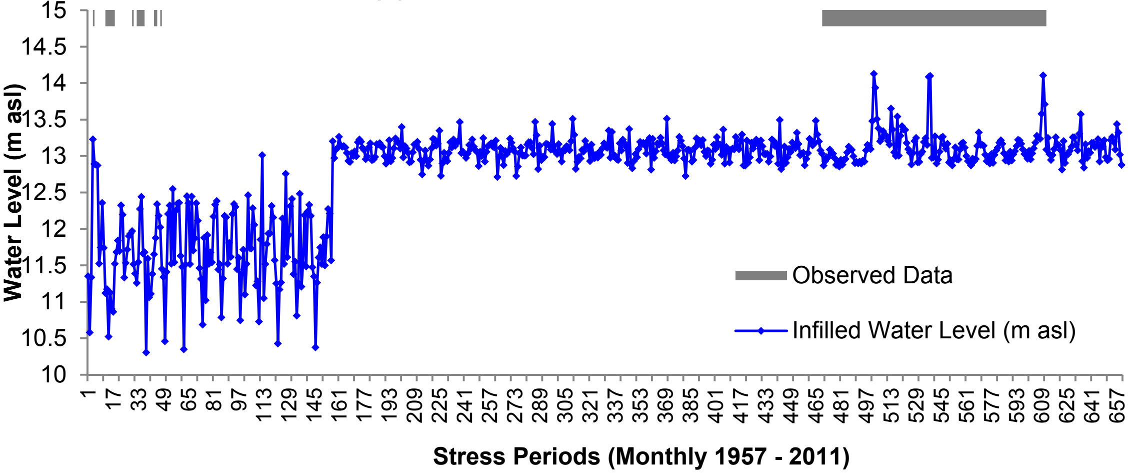
Water levels in the Nile River Rosetta branch are influenced by three factors: (i) inflow from the main upstream branch of the river, which is regulated by the MWRI; (ii) return flows from the drainage canal system; and, (iii) abstraction for irrigation. Water level data along the reach that acted as the constant head boundary was of limited availability, therefore infilling was necessary to create a full time series for use in MODFLOW. Short-term gaps of one month were infilled using a two-month moving average. Water levels for missing months, $w(t)$, were infilled using a statistical model based on the central tendency of the monthly average flow, $d(i)$, which changes based on the monthly demand for irrigation. Variability associated with external stresses such as evaporation, pumping, and drainage return was assessed using an added factor, $\Phi(i)$ (Eq. 1).

$$w(t) = d(i) + \phi(i) \tag{1}$$

Similar to the approach presented in Bakker et al. (2008), in this case, $d(i)$ and $\Phi(i)$ were the monthly mean and standard deviation, respectively. This model assumes that the water levels for each month are normally distributed. This assumption was confirmed with an exploratory analysis. The resulting hydrograph demonstrates that it was possible to replicate seasonal variability with the infilling model (Figure 6a), with no detectable non-stationarity with respect to time for each of the two time periods (Figure 6b and 6c). Residuals demonstrate a bias toward under-predicting higher water levels and over predicting lower ones (Figure 6c and 6d).

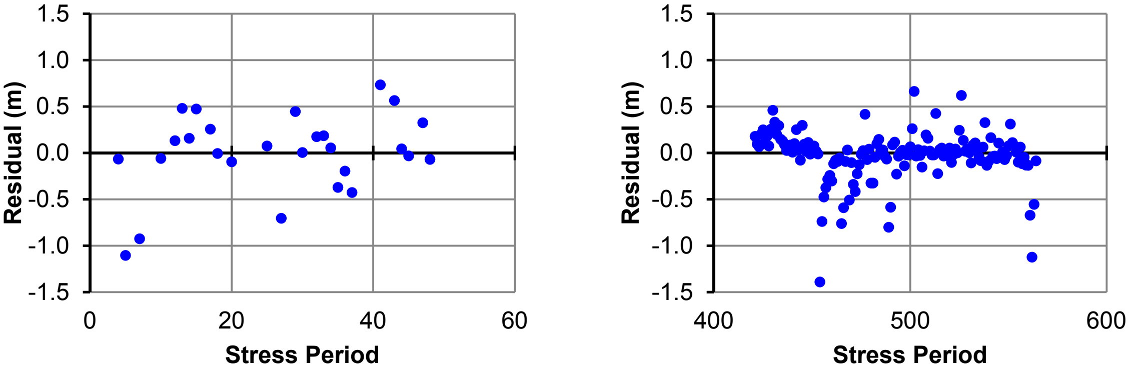
Prior to the construction of the Aswan High Dam in 1968, the flows in the Nile River were seasonally variable, with most irrigation occurring in the spring and summer months during the flooding period (Ramly 2009). The presence of the Aswan Dam has resulted in a more regular flow regime in the Nile River. This change in flow regime was accounted for by developing two separate models of $w(t)$, using separate monthly data from pre- and post-1970. The results demonstrate that this assumption produced a sudden water level increase between the pre- and post-1970 periods (Figure 6a).

(a) Final Infilled Water Levels



(b) Residual for Years < 1970

(c) Residual for Years > 1970



(d) Residual for Years < 1970

(e) Residual for Years > 1970

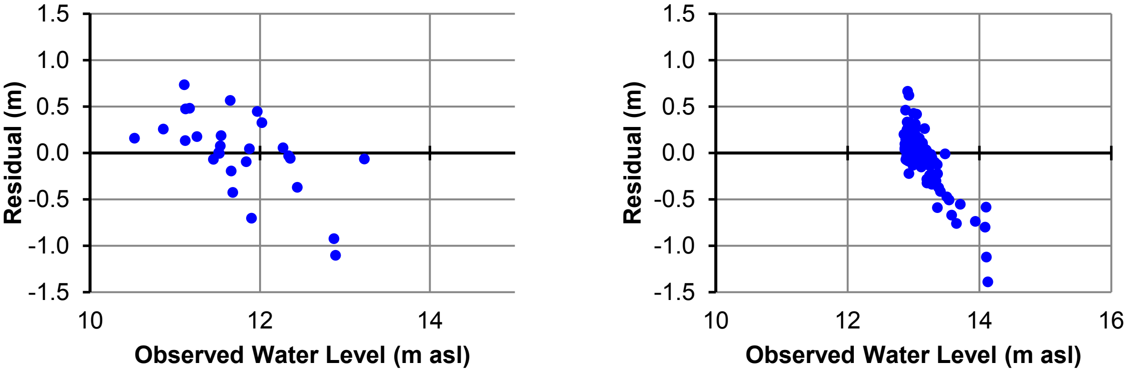


Figure 6. (a) Infilled hydrograph of water levels at the inflow to the Nile Rosetta Branch, (b - c) residuals over time and with respect to observed water levels, and (d – e) residuals with respect to observed water levels for the two distinct time periods.

A linear function relating downstream distance, *l*, to water levels at the inflow of the Rosetta branch, *w(t)*, was developed through regression analysis of data available from a previous river hydraulic model presented in Ismail (2008). This allowed for monthly water level changes to be distributed along the constant head boundary (Eq. 2 and Figure 7).

$$w(t,l) = -0.737l + w(t) \tag{2}$$

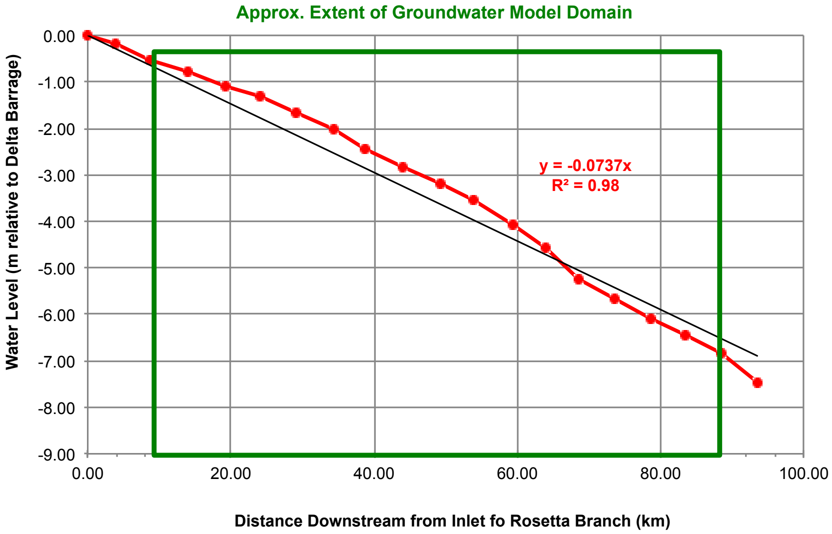


Figure 7. Regression of relationship between distance downstream from the inflow to the Rosetta branch with respect to water levels (Ismail, 2008).

2.3.3. Groundwater Pumping and Surface Recharge Model

The Naturalized Difference Vegetation Index (NDVI), computed from remote sensing imagery, was used as the primary source of information for quantifying changes in the extent of agricultural land use, and thus groundwater pumping and potential recharge over time (Eq. 3).

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{3}$$

NIR is the near-infrared band of the sensor and RED is the visible red band (Fan et al. 2008). Imagery for the area was available from 1972 until present from the various Landsat sensors. Raw Landsat images were acquired from the USGS and processed first by radiometrically correcting them to account for changes in the Landsat sensors over time following the procedure outlined in Chander et al. (2009). These images represent instantaneous measurements of the intensity of vegetation cover over the area and can be used to observe both seasonal and long-term changes in vegetation growth and land cover (Jang et al. 2009). A time series of scenes for the study area was compiled by first selecting images with a cloud cover of less than 10%. From this subset, images were selected at quarterly intervals for the months of January, April, July and October to represent seasonal dynamics. If images were not available for these months, the search was widened to include adjacent months.

There was a large gap in the Landsat record from 1991 to 1998 that was filled with maximum 10-day NDVI, processed by the European Space Agency with data from National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) sensor. Like the Landsat imagery, quarterly images were selected to fill the gap between 1991 and 1998. The Landsat and AVHRR sensors both measure NIR and RED bands, however the latter is at a resolution of 1000 m, while the former ranges from 30 to 60 m depending on the sensor. For each image, and area of land representing undeveloped desert was identified and its maximum NDVI value was set as the threshold for identifying agricultural land. Any NDVI above the threshold was considered to be agricultural land. The histogram and actual image for each time-step was inspected manually to determine if the background was being subtracted correctly. In some instances, high reflectivity of desert soil or problems with the sensor added erroneously high NDVI values to the dataset. Scenes with significant residuals were removed from the time series. Eighty-one images were ultimately available to construct the time series of land use change over time. Given that each of the 660 stress periods did not all have a unique image scene, the most temporally proximate historical NDVI dataset was chosen as representing the land-cover for that stress period.

Cultivation is commonly divided into two distinct growing seasons of summer and winter in the study area, and irrigation demand varies accordingly (Allam et al. 2007) . Some farmers also cultivate a third crop during the autumn, and many fruit trees require water applications all year (Allam et al. 2007). The monthly magnitude of irrigation water applied to crop areas was assumed to vary spatially based on the type of source water used for irrigation (i.e., groundwater, surface water or conjunctive), and the efficiency of the irrigation technology used in each area (i.e., drip, flood, or sprinkler) (Figure 1b). For instance traditional flood irrigation practices are still used in the area adjacent to the Nile and by smaller farmers across the study area. These flood irrigation practice influences groundwater levels through excess infiltration, and require a large volume of water to be pumped from the source (Warner et al. 1991; Salem et al. 2010; King and Salem 2012). Drip and sprinkler irrigation systems designed to reduce water usage and losses to groundwater have been developed in the Western Desert's reclaimed areas (Allam et al. 2007; Baietti et al. 2005).

Irrigation technologies used, water usage requirements and corresponding surface water allocations are generally associated with the time-period when the land was reclaimed for agriculture (Sabbah and Metwally 1997; Oosterbaan 1999). Groundwater permits are also issued, but can only be monitored for users running electrically-powered wells. Many users have diesel-powered wells that may not be registered with the MWRI (King and Salem 2012). The capacity of the MWRI to enforce groundwater permits is weak, and many users reportedly exceed their allocations (King and Salem 2012). Groundwater well locations and pumping rates, Q_{pump}, were available from a 2009 inventory of well permits and farm surveys conducted by the MWRI (Figure 8).

A survey was conducted with 38 local farmers was for the current research. This survey provided information on the water use practices, was used to validate the accuracy of the MWRI dataset, and determine the number of groundwater pumping and irrigation hours at the 38 farms. The location of wells in the MWRI dataset matched that from the survey in about a 60% of cases. The locations of wells provided by the MWRI were also cross-verified with a 2006 version of the same survey, and demonstrated that the location of the wells was consistent between the datasets about 80% of the time. The groundwater user survey provided information on monthly irrigation schedules, which was used to develop a statistical distribution of groundwater pumping hours, hpm, which fluctuated according to the season, p, and month, i. Monthly pumping hours were randomly extracted from this density function and multiplied by the pumping rate in the well record, j, to yield a total monthly pumping rate, Q_{abs} (Eq. 4).

$$Q_{abs}(i,p,j) = Q_{pump}(j) \times hpm(i,p,U) \tag{4}$$

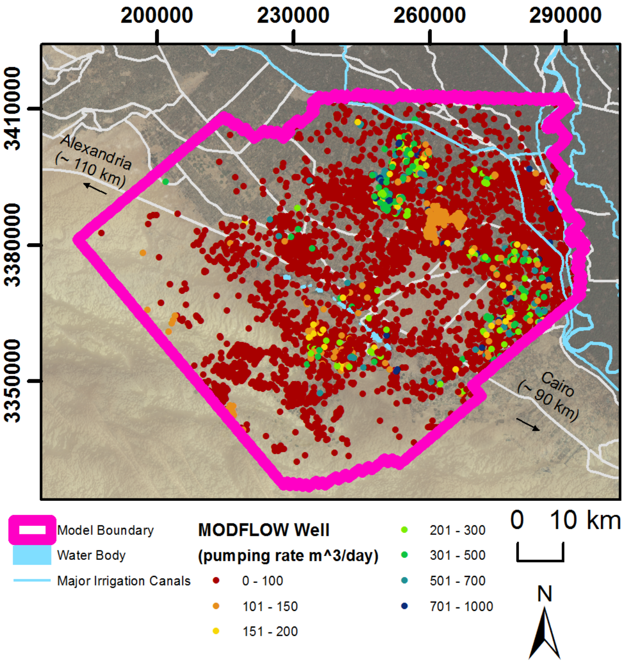


Figure 8. Locations of wells in the MWRI (2009) study.

Given that well pumping rates are fixed, farmers adjust the amount of water applied by changing the number of hours crops are irrigated per month. The total monthly hours a pump is run is a function of the daily irrigation hours, $hpd(i,p,U)$, the number of days per month irrigation occurs, $dpm(i,p,U)$, and whether groundwater is used for full irrigation or conjunctively with surface water, U. Both of these variables fluctuate on a seasonal basis, and there is some monthly variability within each season. During the groundwater user surveys, many users could only specify variations in their water use for irrigation on a seasonal basis. Monthly variations within the seasons were applied using a factor of the fraction of maximum seasonal water use required for each month, $C(i,U)$, based on data from Baietti el al. (2009) and Ismail (2007) for the West Delta Irrigation Improvement Project (Figure 9).

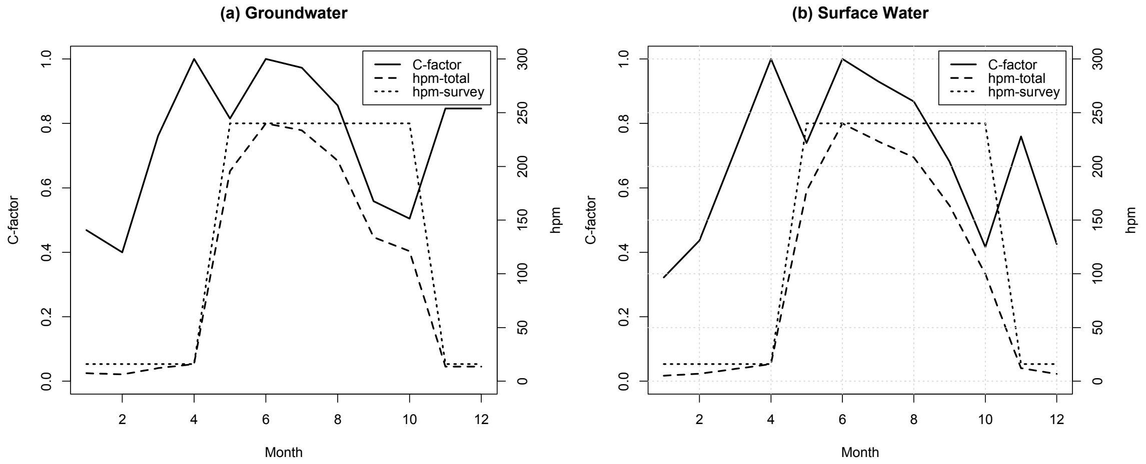


Figure 9. Monthly trends of C-factor, hours per month from survey results, and final model input for (a) the groundwater-irrigated areas, and (b) the surface water irrigated areas.

$$hpm(i,p,U) = dpm(p,U) \times hpd(p,U) \times C(i,U) \tag{5}$$

In areas irrigated with Nile surface water, groundwater is used conjunctively to augment irrigation water supply when the canal system is undergoing maintenance, or when crop water requirements cannot be met. The MWRI manages the flow to each branch of the canal network, and water user associations distribute quantities to users at the farm-scale based on periodic negotiations at the district-level (Oosterbaan 1999; Farag et al. 2008). The exact water volumes released are determined using 10-day demand periods based on demand estimates for each irrigation district. The 10-day demand periods are determined using models of predicted demand computed at the beginning of each calendar year (Farag et al. 2008; Allam et al. 2007; Oosterbaan 1999). Users are provided canal water on a schedule of either seven days on, seven days off, or three rotations of five days (Allam et al. 2007). Based on this system, over the course of one month, each farm is estimated to receive irrigation water for half of the month. Both crop irrigation and flows in the primary and secondary canals are significantly reduced or halted during the months of January and February each year for canal maintenance (Warner et al. 1991).

For areas using groundwater only, the number of days per month for each season were selected randomly from an empirical distribution (i.e., histogram) of data from the farm survey results and the farm survey conducted by King and Salem (2012) (Figure 9). In areas conducting conjunctive water use, it was assumed that the number of days per month a farmer can irrigate was fixed, given that flows to the canal system are controlled by the MWRI, and water is only available when activated by the MWRI. The conjunctive groundwater requirement was expressed by the difference between MWRI allocated amount of pumping hours per day, hpd_{alc}, and actual surface water availability, hpd_{sw} (Eq. 6).

$$hpd(p, U) = hpd_{alc}(p) - hpd_{sw}(p), \qquad U = conjunctive \tag{6}$$

Based on data and irrigation rules established in the mid-1990s, the pumping rates from primary and secondary irrigation canals in the El Bustan and El Tahrir areas were 2.25 and 2.00 m^3 hr^{-1} $feddan^{-1}$, respectively (Sabbah and Metwally 1996). The irrigation systems are constructed with the assumption of being 70% and 75% efficient in the El Bustan and El Tahrir areas, respectively, and scheduled to operate for 15 hours per day (hpd_{alc} = 15 in both seasons) (Sabbah and Metwally 1996). In practice, however, irrigation systems can only operate for between 8 and 11 hours per day due to electrical failures at pumping stations and canal water shortages (Sabbah and Metwally 1996). This difference between both the planned and actual daily operating hours is assumed to represent the groundwater requirement. Given the uncertainty in the actual number of hours of operation for each pump, wells located in conjunctive-use areas were randomly assigned an integer value from a uniform distribution between eight and 11 hours. Wells located in areas relying exclusively on groundwater were randomly selected from the empirical distribution from the farm survey results, and data presented in King and Salem (2012) (Figure 10). Finally, because information was not available on the age or installation date of each well, it was activated in the model during the earliest stress period when that cell was mapped as agricultural land according to the NDVI time series (Figure 11).

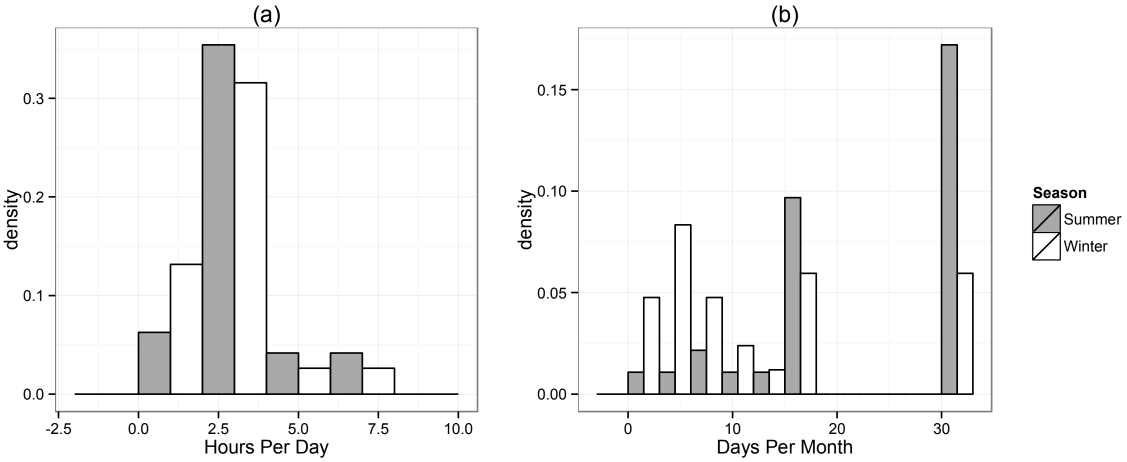


Figure 10. Empirical density distributions used to compute the variables (a) *dpm* and (b) *hpd* for groundwater-irrigated areas in the summer and winter months.

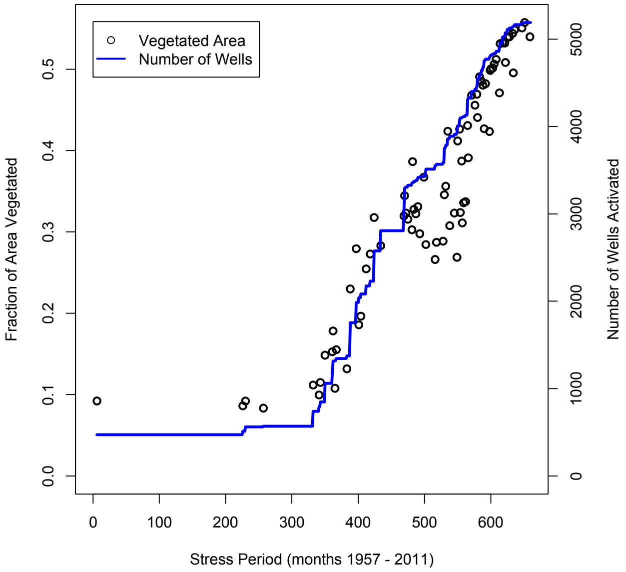


Figure 11. Graph of number of wells activated over time compared to the percent of vegetated area mapped according to the NDVI algorithms. Each point represents an NDVI image used.

Monthly groundwater recharge maps were developed for each stress period using a 1-D mass balance approach where groundwater recharge was assumed to be governed by the following relationship (Eq. 7):

$$q_{RCH}(i) = q_P(i) + q_{IRR}(i) + q_S(i) - q_{ET}(i) - q_{DR}(i) \tag{7}$$

where q is the specific water flux for each stress period in each MODFLOW cell in dimensions of L T^{-1} and the positive direction denotes groundwater recharge. The subscript *RCH* denotes the recharge flux, *P* is the precipitation flux, *IRR* is the irrigation return flow, *DR* is the flux to installed irrigation tile drains, *ET* is the evapotranspiration flux, and *S* is the soil storage flux. This mass balance was computed on a daily scale and then multiplied by the number of irrigation days per month. The mass balance assumes that recharge is primarily the result of excess irrigation water percolation, which occurs when crops are watered daily (Scanlon and Milly 1994; Chung et al. 2010; Abbott and Quosy 1996). As mentioned previously, the precipitation flux is also assumed to be negligible given the hyper-arid character of the study area. Moreover, because the soil in study area is comprised of easily drained desert sand with high hydraulic conductivities and daily evapotranspiration fluxes, changes in soil moisture would only be observed on the sub-daily or hourly scales (Scanlon and Milly 1994). As a result, *S* was also considered negligible on the monthly scale. Finally, subsurface drainage was modeled using the drain package in MODFLOW. The mass balance can therefore be simplified by eliminating the variables q_P, q_{DR} and q_S (Eq. 8).

$$q_{RCH}(i,p,U) = [q_{IRR}(i,p,U) - q_{ET}(i)] \times dpm(p,U) \tag{8}$$

q_{IRR} was computed in using the same statistical distribution-based algorithm, as were the well pumping rates. The additional factor of water use efficiency, *EFF*, was added to the model to adjust q_{IRR} by the amount of water actually reaching the ground. This factor assumes that for drip and sprinkler irrigation, some of the water pumped from the source is lost due to system leakage between the source and the field. For areas under flood irrigation, *EFF* represents the factor by which farmers over-irrigate to leach salinity from soil (Roest 1999). The hourly water allocations per irrigated area, q_{alc}, were computed by determining the ratio of the well pumping rate, Q_{pump}, to the number of feddans irrigated with each well, A_f (Eq. 9).

$$q_{alc} = \frac{Q_{pump}}{A_f} \tag{9}$$

The variables A_f and Q_{pump} were randomly selected from density distributions fitted to the MWRI well inventory data and the area of land irrigated per pump, as determined from the farm survey (Figure 12).

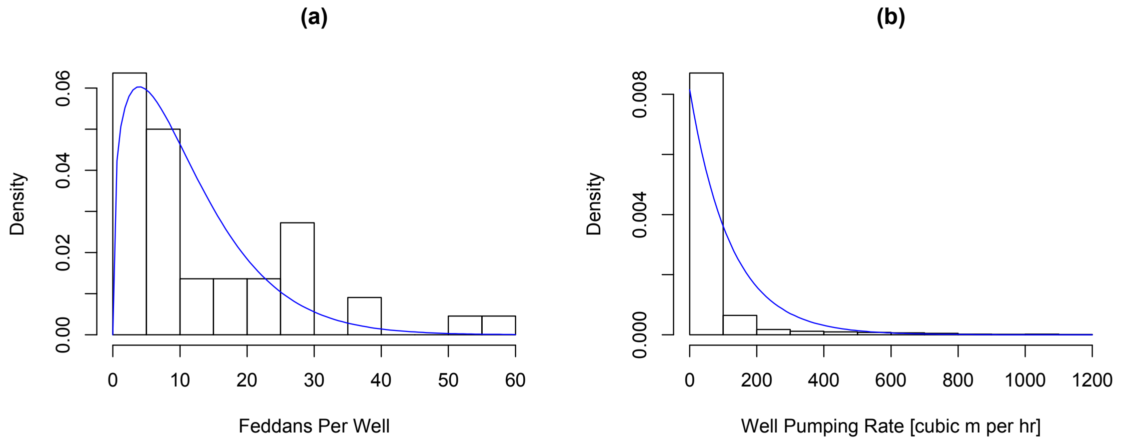


Figure 12. Density distributions fitted (blue line) to the empirical distributions (bars) of (a) the area irrigated per well (A_f) and (b) well pumping rates (Q_{pump}).

For areas irrigated with groundwater, A was fitted to an exponential distribution of values between 20 and 60 feddans, and Q_{pump} was fitted to a Weibull distribution of values between 20 and 1200 m^3. These represent distribution ranges, from which outliers were removed. For areas irrigated with surface water, q_{alc} was selected randomly from a uniform distribution between 2 and 4, representing ranges within which the MWRI allocates surface water (Sabbah and Metwally 1997). Values of *EFF* were available from a comprehensive inventory of irrigation systems collected in the late-1990s for various irrigation districts, *r* (Sabbah and Metwally 1997). Exploratory analysis indicated that the efficiencies were normally distributed for each irrigation district, thereby allowing the value for each cell to be randomly selected from a Gaussian distribution fitted to each district (Figure 12).

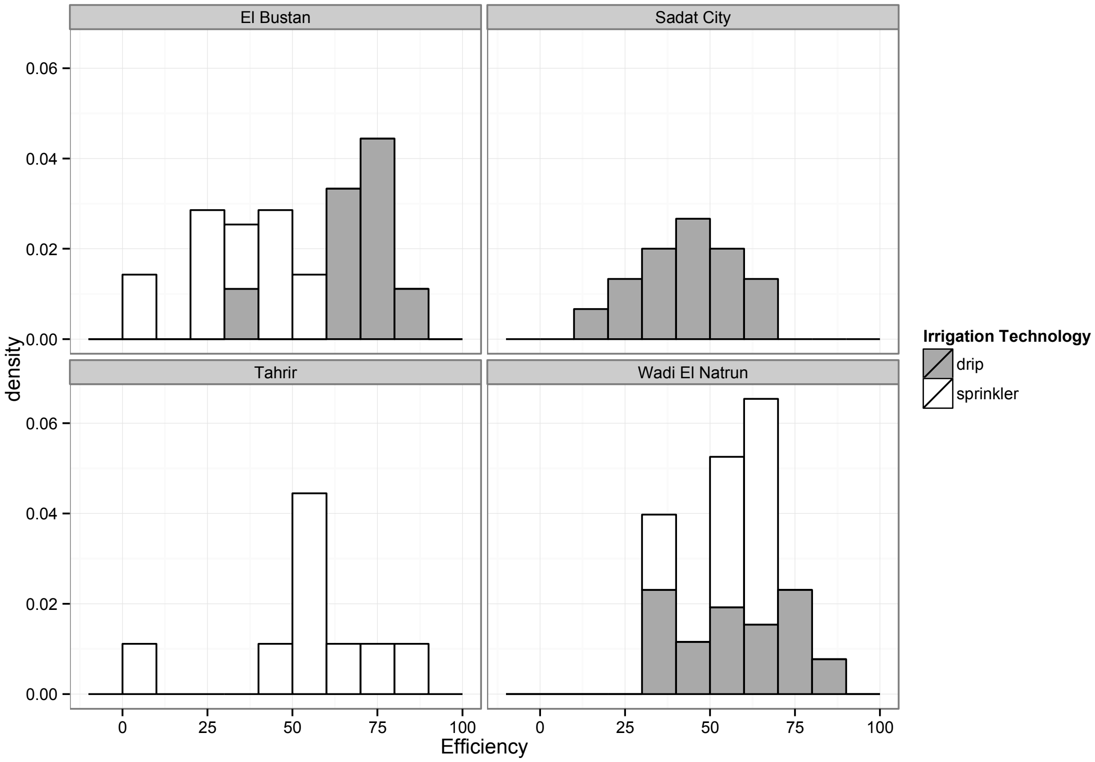


Figure 13. Irrigation efficiencies for the various irrigation districts by technology type (after Sabbah et al., 1997)

$$q_{IRR}(i,p,u,r) = q_{alc}(u) \times EFF(r) \times hpd(p,u) \times C(i,u) \times 4200\ m^2 \qquad (10)$$

Average daily evapotranspiration for each month, $q_{ET}(i)$, was computed for each cell, *k,* using the standard crop-water requirement formula of the product of the reference evapotranspiration, ET_{ref}, and derived crop coefficients, K_c, recommended by the FAO (Allen et al. 1998). Because only the vegetated portion of each MODFLOW cell is subject to evapotranspiration, the K_c value incorporates the effect of the vegetated surface on reference evapotranspiration (Allen et al. 1998) (Eq. 11).

$$q_{ET}(i,k) = \frac{K_c(i,k)}{N_{days}} \sum_{m=1}^{N_{days}} [ET_{ref}(m)] \qquad (11)$$

where m is the day of the month and N_{days} is the number of days in the month in question. Reference evapotranspiration was computed using the daily formula of the American Society of Civil Engineering (ASCE) Standard (Tasumi et al. 2005), requiring inputs of temperature, T, wind speed, u_2, vapour pressure deficit, e_s-e_a, net radiation, R_N, soil heat flux density, G, and the psychrometric constant, γ. The parameters τ (slope of the saturation vapour pressure-temperature curve), C_D (denominator constant for evapotranspiration reference equation) and C_N (numerator constant for evapotranspiration reference equation) are derived constants (Eq. 12).

$$ET_{ref}(m) = \frac{0.408\tau(R_N - G)\gamma \frac{C_N}{273 + T} u_2(e_s - e_a)}{\tau + \gamma(1 + C_D u_2)} \tag{12}$$

The climate variables needed to compute reference evapotranspiration on a daily scale were acquired form the NOAA's Global Summary of the Day website (http://www7.ncdc.noaa.gov/CDO/cdoselect.cmd?datasetabbv=GSOD&countryabbv=&georegionabbv=). Climate data was available for three stations in the model domain, although only two stations had enough data record to make them viable for time series for computing ET_{ref}. The Wadi El Natrun station had records from 1996 to present, and the Cairo Airport had records from the 1950s onward, although the data contained a significant gap between 1967 and 1972. Given that it had the longer period of record, the Cairo Airport station was used as the primary station for computing ET_{ref}. Infilling was completed by first by using a 9-day centred moving average, and if gaps remained, linear regression was used to transfer values from the Wadi El Natrun Station on a monthly basis. Finally, for the long-term gap, a Gaussian distribution was used to assign a random value, based on monthly average and standard deviations of the long-term Cairo time series.

Maps of crop coefficients, K_c, were produced by calculating the ratio of the monthly reference evapotranspiration to actual evapotranspiration available on a monthly time interval from the MODIS Global Evapotranspiration Project (MOD16). The MOD16 dataset of estimated actual evapotranspiration was available from 2003 onward, thus representing a limited period within the overall temporal domain of the model. Exploratory analysis was conducted to fit a linear model relating values of $NDVI$ and K_c for each MOD16 cell (Equation 13). These linear functions were produced on a seasonal basis, and were used to assign K_c values to each raster cell for each stress period based on the $NDVI$ value (Figure 13). Loose relationships existed between the variables allowing for the creation of linear equations for each season, with the parameters of b and M being adjusted accordingly (Eq. 13 and Table 2). January, April, July and October were selected to represent the seasons of winter, spring, summer and autumn, respectively.

$$K_c = M(NDVI) - b \tag{13}$$

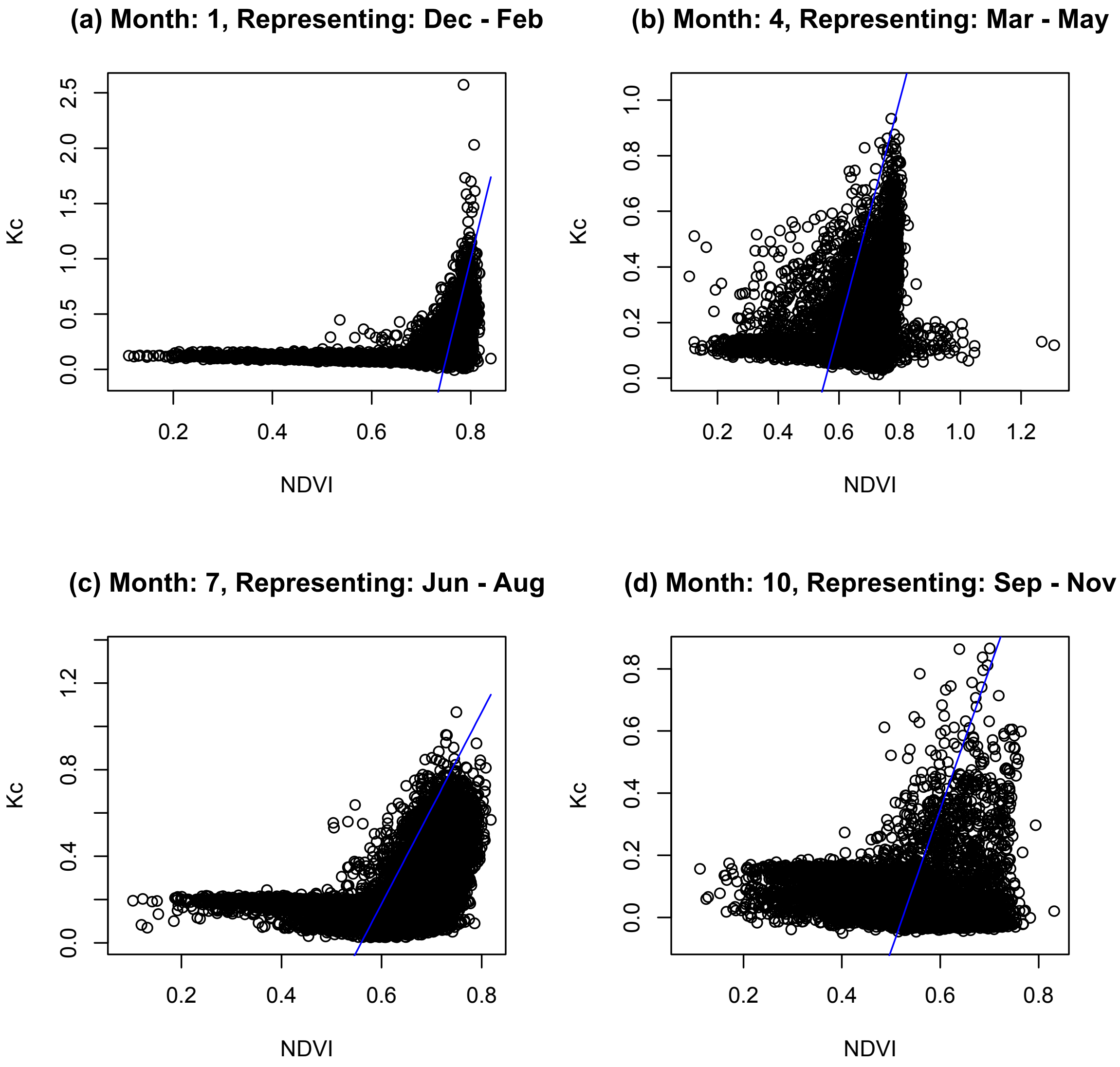


Figure 14. Graphs of the relationship between *NDVI* and K_c for the study area for months of (a) January, (b) April, (c) July, and (d) October. Blue lines represent the linear relationship used to distribute values of K_c spatially in the model.

Table 2. Parameters for the monthly linear model of the relationship between *NDVI* and K_c

Season	Month Analysed	Number of Images	*M*	*b*
Winter (Dec – Feb)	Jan (1)	2	18.22	13.58
Spring (Mar – May)	Apr (4)	2	4.10	2.28
Summer (Jun – Aug)	Jul (7)	3	4.43	2.47
Autumn (Sep – Nov)	Oct (10)	3	4.53	2.37

The recharge computed in using the aforementioned model represents potential recharge (Figure 15), assuming that all excess water percolates through the unsaturated zone to the water table. In reality however, because the depth of the water table below the ground surface is significant, it is possible that not all excess irrigation water percolates through the unsaturated zone to the water table. Similar assumptions have been made in previous studies of groundwater recharge in semi-arid environments, recognizing that under these conditions recharge is assumed to be over-estimated (Liggett and Allen 2009; Risser 2011). In the context of the current study, in which the analysis is long-term and cumulative, it is better to take a conservative approach and over-estimate recharge. To determine the potential impact of this assumption, a sensitivity analysis of the model parameters was performed.

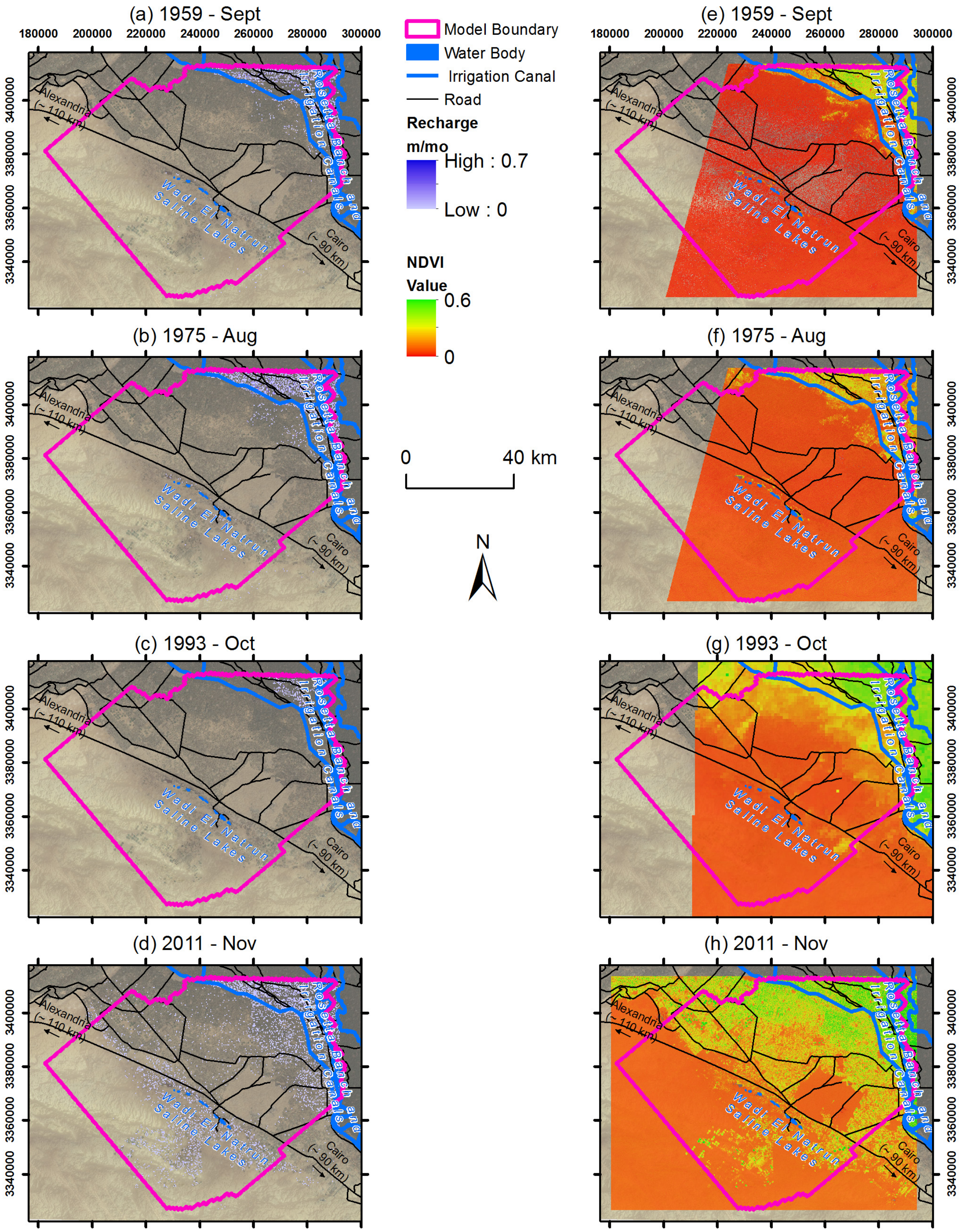


Figure 15. Maps of groundwater recharge (a-d) and NDVI (e-h)

2.4. Model Calibration Results and Uncertainty

Model calibration was completed following guidelines presented in Poeter et al. (2005), Hill (1998), (ASTM 2010) and (ASTM 2008). The model grid, vertical conductance, drain conductance, and hydraulic conductivities were initially calibrated in the steady-state model to observational data representing the average conditions from 1958 through 1960. The observational dataset used in steady-state calibration consisted of average annual water levels for the saline lakes in the Wadi El Natrun depression reported in El-Fayoumi (1964), and average groundwater levels for the Pleistocene Aquifer reported by REGWA (1962) and (Baietti et al. 2005) for the period of 1958 to 1961. These data represent the earliest available estimates of groundwater levels when the study area is regarded to be under little to no transient influence of pumping (El-Fayoumi 1964). These hydraulic parameters, along with additional transient parameters of specific storage and specific yield, were further calibrated for the transient model.

The transient calibration dataset consisted of 632 observations from 157 monitoring points collected between the years 1957 and 2011. It should be noted that much of the available calibration dataset was temporally imprecise, with only the year of measurement being specified. A separate observational dataset consisting of 347 observation points spanning 1992 to 2008 was used to validate the model's ability to simulate transient conditions. For this validation dataset, 347 observations were used, some of which were extracted from interpolated water level contour maps. Like the transient calibration dataset, the validation observation time reference for many records was imprecise.

For any particular groundwater system, there are an infinite number of possible conceptualizations that could be used to in a model to produce the result vector (Hill 1998; Poeter et al. 2005; Rojas et al. 2010). This non-uniqueness ultimately leads to uncertainty in the model results. Overall model error can also arise from uncertainty in the parameterization of hydraulic properties and processes (Ye et al. 2010; Singh et al. 2010; Poeter and Anderson 2005). Any method for either model selection or parameter calibration works by comparing, and attempting to reduce, the difference between the predicted and the observed vectors (e.g., hydraulic head) (Hill 1998). In cases where observational data are limited or imprecise, uncertainty within the observation records also increases overall model error (Ye et al. 2010).

For the current study, model input uncertainty was determined using multiple model runs in an ensemble approach, where each combination recharge and well pumping rate inputs represented an equally plausible realization. One multi-model approach is to compare various individual combinations of input variables or conceptual models and use performance criteria to select the optimal model with the best performance (Tartakovsky 2013; Poeter and Anderson 2005; Ye et al. 2010; Chung et al. 2010). Model selection criteria, such as the AIC, AICc, BIC, KIC, or Nash-Sutcliffe, can be used to select the best-fitted model from the set. It is also possible to frame the results from multiple plausible model runs using an ensemble, which can be use to characterize uncertainty in terms of a probability, or range or confidence (Rojas et al. 2010). Given the high degree of uncertainty associated with using sparse data, an ensemble approach was used in this study because the authors felt that all model realizations were equally plausible. The overall residual standard error of the regression (RSE) for the ensemble of realizations was used to frame this uncertainty.

Uncertainty with respect to the input variables in the recharge and well pumping models was characterized by producing five different realizations of recharge parameters and three realizations of the well pumping inputs and running them in combination with one another, to yield a total of 15 groundwater model runs, or realizations. Multiple realizations of well pumping and recharge were needed to adequately transfer the uncertainty embedded in the density distributions used to parameterize water use, groundwater pumping, and surface recharge to the groundwater model.

Uncertainty with respect to the observational dataset was quantified by weighting each record on a 5-point scale, based on the standard deviation for points with multiple measurements within a given stress period (Poeter and Anderson 2005; Faunt et al. 2010). The highest weights of 3, 4, and 5 were assigned to standard deviation ranges of 0.1 to 1, 0.01 to 0.09, and less than 0.09, respectively. For observations with a single measurement, weights were assigned as 2 for observed points, and 1 for records extracted from contours. Residual analysis is presented for both the weighted and unweighted residuals (Figure 17). Incorporating observation weights into the parameter estimation process also provided a means of ensuring that model parameters are not over-fitted to the observations (Rojas et al. 2010). In the transient model, 146 observations had multiple records within a stress period, allowing for variances to be calculated. For the remaining 506 transient observations with no variance, and a weight of either 1 or 2 was assigned, as described above. Twenty of the 145 observations in the steady state model had variance information.

Parameter uncertainty was addressed during calibration and sensitivity analysis and maximum likelihood estimation to optimize sensitive parameters, as implemented in the program UCODE (Poeter et al. 2005). The composite scaled sensitivity (CSS) was used to compare the sensitivity of the model parameters with respect to reproducing the observational dataset. The sum of squared weighted residuals (SOSWR) was divided by the number of observations to quantify overall model fit, with a value of 1 indicating perfect model fit (Faunt et al. 2010). Summary statistics of the residuals are also presented to quantify the absolute error of the model, including the residual mean, median, standard deviation and RSE.

Eleven of 32 parameters in the steady state model and 9 of 49 parameters in the transient model were deemed sensitive based on their CSS values (Figure 16). Eleven sets of parameters were determined to be highly correlated, and therefore the parameter with the higher CSS was calibrated.

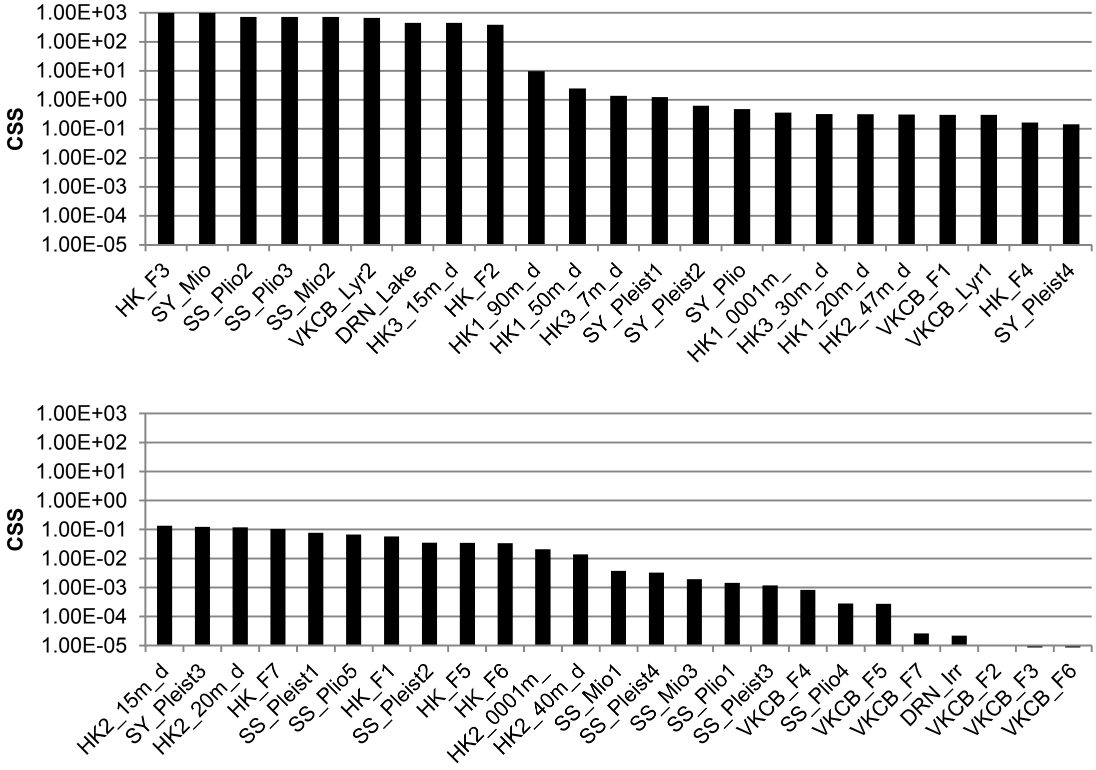


Figure 16. Composite-scaled sensitivity (CSS) for parameters in the transient model. The suffix HK denotes hydraulic conductivity, HK_F is for faults, VKCB represents vertical conductance, SY is specific yield, SS is specific storage, RCH denotes deep recharge, and DRN is drain conductance.

The average model Residual Standard Error (RSE) was 3.75 m and the standard deviation of the RSE was 0.10 m, indicating that model accuracy was within a reasonable range (Table 3), especially given the large spatial, vertical and temporal scales of the model domain and the sparse data available for model development and calibration. The average $SOSWR / N_{obs}$ was also reasonable, with ensemble average and standard deviation values of 3.49 m and 0.1 m, respectively. The low ensemble standard deviation for each model performance statistic and narrow range among the ensemble realizations suggests that uncertainty with respect to the well-pumping and recharge models was low (Table 3). As a percent of the each model performance statistic mean, the standard deviations were all between 0 and 2 %. Based on these values in comparison to the absolute model residual values, conceptual model uncertainty and parameterization was more significant, although still within a reasonable range, given the context of sparse data.

The mean and median absolute residual values were an average of -3.57 m and -3.99 m, respectively and the ensemble standard deviation for this statistic was an average of 4.88 m (Table 3). The overall fit of the model can be expressed by the R^2 value, which was 0.79 for all model runs further confirming that the model is acceptable for high-level analysis of management scenarios and that well pumping and recharge uncertainty was low compared to that of the conceptual model. The overall range of model residuals was within approximately ± 30 m, however a visual examination of the residuals demonstrate that the majority of the residuals were clustered randomly around 0, with the higher values representing outliers (Figure 17). When the residuals are broken down by aquifer (Figure 17), it is apparent that these outliers pertain to observations in the Pliocene and Pleistocene aquifers. The remaining residuals for those aquifers tend to cluster randomly around 0. The Miocene Aquifer residuals also plot tightly around 0 with no outliers, indicating that the model fit for this aquifer is also acceptable.

Table 3. Transient model ensemble performance statistics

	SOSWR	SOSWR / N_{obs}	RSE	R^2	RESIDUALS				
					MEAN	MEDIAN	SD	MAX	MIN
Ensemble Mean	7954	3.49	3.75	0.79	-3.57	-3.99	4.88	27.83	-28.02
Ensemble Standard Deviation (absolute)	45	0.01	0.01	0.00	0.03	0.01	0.02	0.54	0.18
Ensemble Standard Deviation (as % of mean)	1%	0%	0%	0%	1%	0%	0%	2%	1%
Ensemble Minimum	7894	3.48	3.73	0.79	-3.54	-3.98	4.86	26.94	-27.84
Ensemble Maximum	8006	3.50	3.76	0.79	-3.60	-4.00	4.90	28.15	-28.30

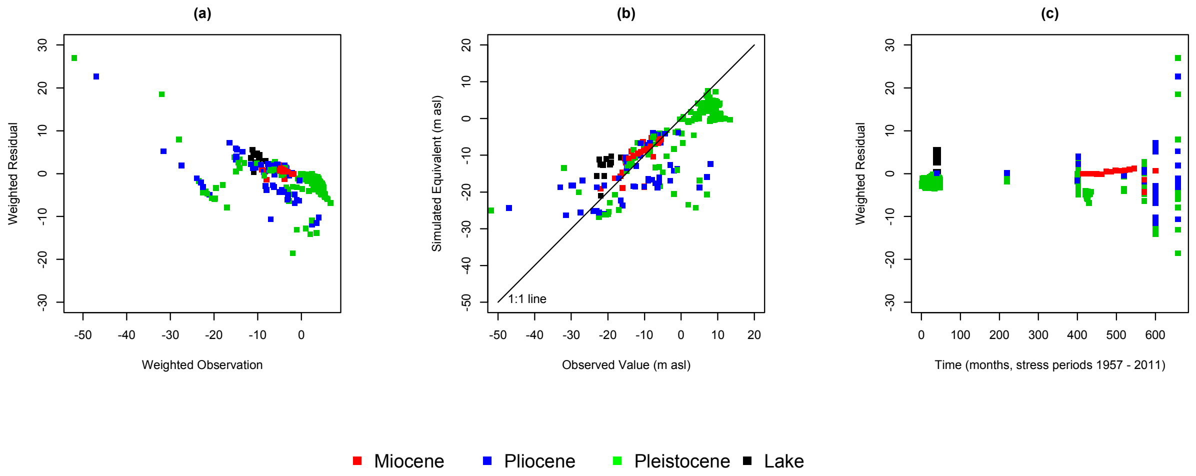


Figure 17. Residuals plots for the transient model showing (a) weighted residuals with respect to observations, (b) regressions of the unweighted residuals, and (c) weighted residuals with respect to time for the model realization with the lowest error.

The final calibration of both the steady state and transient models demonstrated that there was some spatial variability in bias statistics, with results being slightly over-estimated for observations at the saline lakes (Figure 18). A closer examination of hydraulic gradient in that area showed an upward flow pattern however, which is consistent with the expected flow regime in that area. When these residuals are considered in combination with the others for the Pleistocene Aquifer, which is the top model layer in that area, they add to the randomness of the residual distribution for that layer. It is possible that this over-estimation is an artefact of error in the lake level observations.

With respect to time, the residuals tend to cluster around 0, remaining within ± 10 m, with the exception of outliers present in the latter stress periods. A comparison of the simulated result to a separate validation dataset for the three model runs with the lowest RSE demonstrates that the model was reasonable capable of reproducing the overall flow pattern in the study area during later stress periods (i.e., the validation dataset covered 1992 - 2008). The $SOSWR / N_{obs}$ for this dataset was however slightly higher, with an average value of 7.76. The mean, standard deviation and median residuals were -2.71 m, 7.29 m, and -1.70 m, respectively. This higher error in the later stress periods of the model is consistent with the same trend in the calibration dataset (Figure 17c).

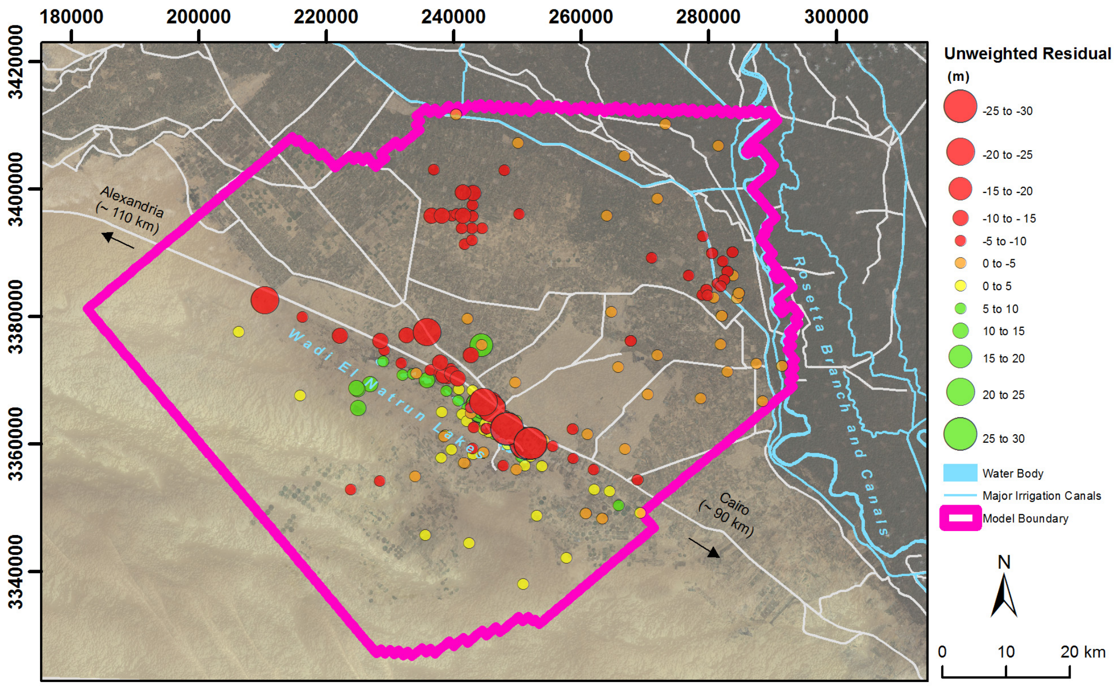


Figure 18. Unweighted spatial residuals for the model run with the lowest error

Error in the steady state model, which is subsequently propagated to the transient model, is attributed primarily to the uncertainty in the conceptualization of the hydrogeologic system. Hydraulic and storage parameter conductivity zone were delineated based on the materials described in RIGW (1992), however no information was available on how this map was derived. Sensitivity analysis demonstrated that these parameters were more sensitive than recharge. Although the extent of the aquifer boundaries were verified against borehole records and cross sections, few measurements of hydraulic parameters were available to reliably delineate precise zones. Instead trial and error and parameter estimation was used to arrive at values within a reasonable range compared to results of localized pumping tests presented in. The presence of regional groundwater recharge to the Miocene aquifer from below, in addition to the precise location of faults and fractures and their role on controlling vertical flow are also sources of conceptual model uncertainty.

2.5. Groundwater Impacts of Environmental Change

A key objective of this research was to develop a model capable of simulating groundwater responses to environmental change using sparse data in a dryland environment. A comparison of the model results to observed long-term temporal trends at several locations across the study area demonstrates that the model was reasonably capable of replicating the observed trend in the key location of the study area, Wadi El Natrun (Figure 19).

The observed long-term declines in hydraulic head at El Khattaba, Wadi El Natrun, and Wadi El Farigh were replicated in the model quite well, with the observed data falling within the uncertainty bounds (Figures 19a, 19d, and 19f). These areas represent 100% use of groundwater for irrigation. Slight increases in head over time were also matched in Kafr Dawoud and the Pliocene Aquifer at Wadi El Farigh (Figures 19b and 19e). The sharp decline in heads within the Miocene Aquifer at Wadi El Farigh was also matched, although the magnitude of the water levels was over-estimated in the model (Figure 19f). The reason for the apparent conflict between the results of declining groundwater levels in the Miocene Aquifer compared to increases in the Pliocene Aquifer in the Wadi El Farigh area can be attributed to the effect of recharge being applied to the upper of these layers, while the majority of pumping is in the Miocene aquifer.

Based on graphical inspection of the model results, and model statistics documented in Table 3, it can be determined that the recharge and well pumping ensembles produced relatively little variation compared to the observed data. It should be noted however, that the observations presented in Figure 19 (which correspond to those in Figure 3) are representative of few data points over long intervening intervals.

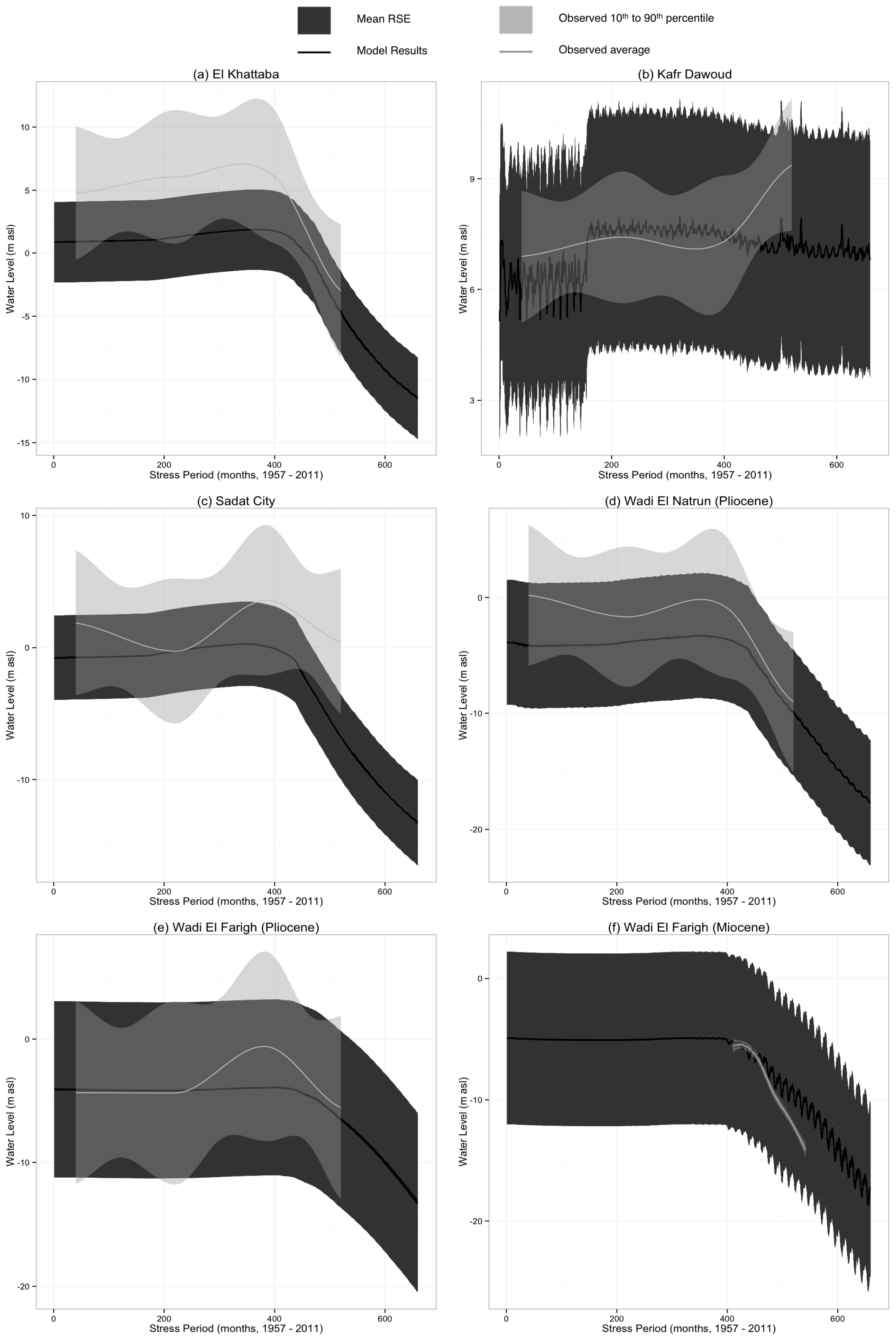


Figure 19. Comparison of model results (black lines ± interpolated RSE value) to long term average at several locations across the model domain (grey line ± 10th and 90th percentiles for the observed data). These panels correspond the same locations presented in Figure 3.

In addition to head drawdown within the three aquifers, another important impact of environmental change is the resulting change in regional flow patterns. Several water level contour maps were available for the study period, although they did not all cover the entire study area. Of particular interest were piezometric surfaces from 1992 and 2006 presented in Masoud and Atwia (2009) (Figure 20). These surfaces were created by measuring the exact same wells in both years. A similar spatial comparison can be made between REGWA (1962) and RIGW (1992), although these two studies did not monitor the same set of wells (Figure 20). A noticeable change in the flow field between the 1960s and 1990s was the migration of higher water tables toward the area of El Tahrir immediately west of the Rosetta branch in during the later years (Figures 20a and 20b). This migration of the flow field was observed in the model results and can be attributed to increased levels in the Nile River between during the intervening period, and greater amounts of surface water return flow from conjunctive irrigation as the area became cultivated. A trend of declining water levels, and an easterly migration of the flow field in the base of the Wadi El Natrun depression was evident in the contours from Masoud and Atwia (2008). While groundwater declines were evident in this same area in the model results, the easterly migration was less apparent.

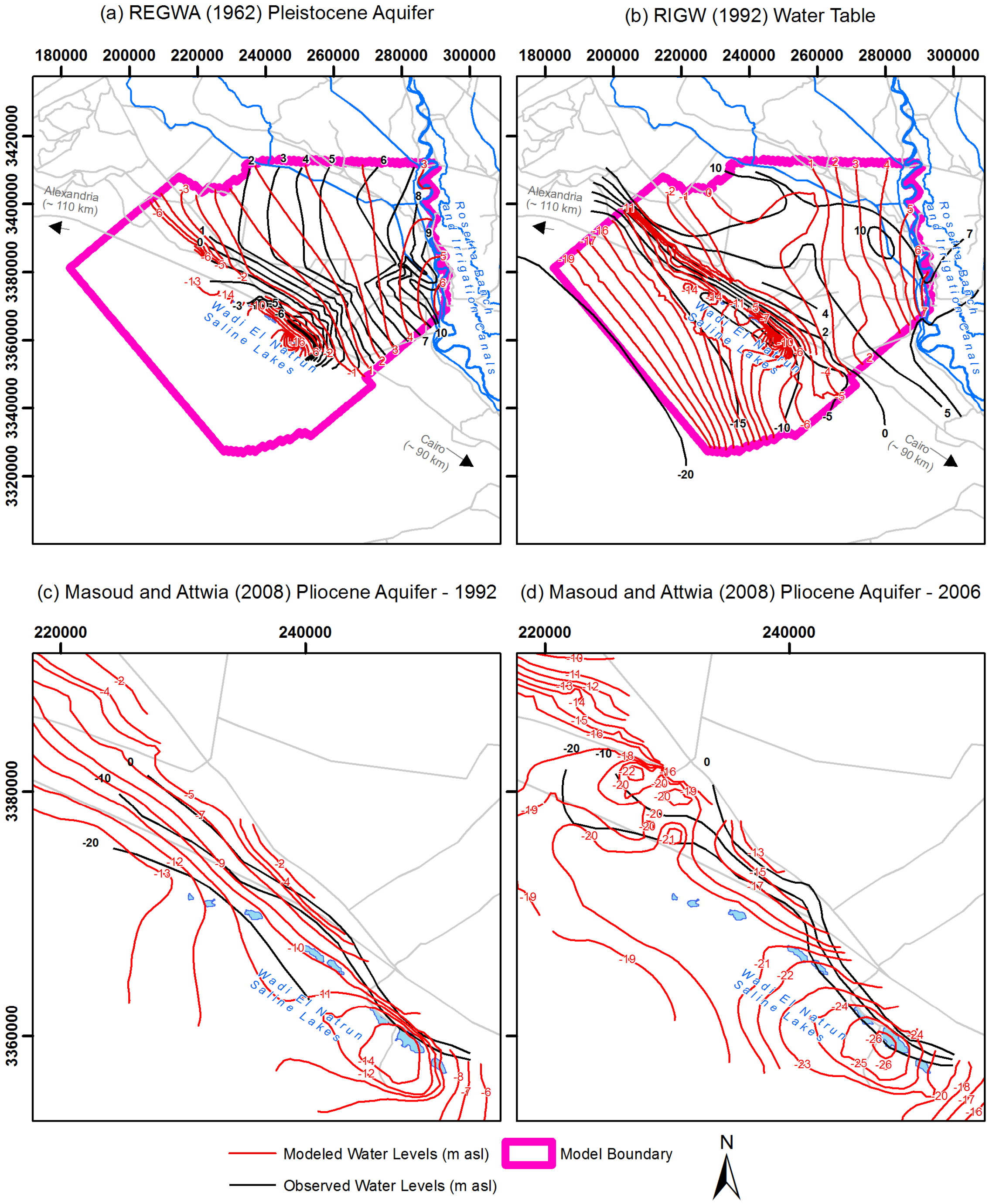


Figure 20. Maps comparing the flow fields from the transient model and water level contours interpreted from field data in previous studies.

Water budget analysis indicates that cumulatively since 1950, the groundwater system is in a deficit of more than 270 billion m^3 (Table 4), suggesting that the water use regime that has developed over time is unsustainable. This finding aligns with the evidence of declining groundwater levels reported by water users and shown in monitoring records throughout the study area. It is also consistent with findings for the broader Western Delta area presented in Dawoud (2005). Based on the breakdown of the inputs and outputs of the water budget presented in Table 4, the accumulated depletion can be directly attributed to increased groundwater abstraction. Prior to 1990, the annual water budget was positive, however between 1975 and 1990 well abstraction increases as a total proportion of the water budget, and continues to grow through the 2000s.

It should be noted that assumptions were made regarding the aquifer being tapped for each well and further work should be done to validate the number of wells tapping each aquifer and the extent to which each being depleted. Additionally, the current model assumes that the Miocene aquifer is recharge from below by the NSAS, and this contributes to the high overall recharge in the water budget. This assumption was also made by Dawoud et al. (2005). Nonetheless, these two factors will influence the accuracy of water budget analysis. Based on the ratio of the range of the model residuals (~ 60 m) to the total thickness of the model (~ 400 m), the accuracy of the water budget is estimated at 15%.

Table 4. Computed water budget for the study area.

Water Budget Component (million m^3)		Annual: 1960	1975	1990	2005	2011	Cumulative: 1957-2011
In	**CONSTANT HEAD**	355	331	588	1640	2091	498419
	RECHARGE	477	537	577	574	565	343312
	TOTAL	831	867	1165	2214	2656	841731
Out	**CONSTANT HEAD**	529	445	372	138	42	241490
	WELLS	71	68	1283	3279	3517	747075
	DRAINS	175	175	172	83	48	98181
	ET	50	50	50	47	37	32235
	TOTAL	825	739	1878	3547	3645	1118981
Net	**TOTAL IN - TOTAL OUT**	6	129	-713	-1333	-989	-277250

2.6. Discussion

Previous studies on the uncertainty in groundwater models has focused on addressing confidence in the conceptual model, and have implemented various multi-model approaches to quantify this uncertainty (Rojas et al. 2010; Ye et al. 2010). In these approaches, each model relies on a different assumption about the hydrostratigraphy or hydrologic processes, and it has been found that conceptual model uncertainty is typically the greatest source of potential error (Ye et al. 2010). In the current study, the conceptual model that was developed relied on information about the groundwater system presented in many previous studies of the local environment. There was little to no disagreement among these studies about the number, depth, spatial extent, and thickness of the aquifers in the study area system. That being said, the main confining layers are discontinuous and inadequate information was available on this aspect of the model.

Additionally, the range of possible values for the hydraulic parameters and their possible combinations is essentially infinite, and information on their spatial extent was also difficult to validate in the literature. One aspect of uncertainty in the current study's conceptual model is due to the fact that many of the conceptual models of the study area's groundwater system rely on a relatively small number of original datasets. As a result, any biases present in the original datasets may be reproduced and propagated throughout the literature. While it would be possible to further parameterize the model in the current study, it is the opinion of the authors that doing so would be based on inadequate information about the subsurface and hydrologic processes. It is desirable to increase a model's accuracy, however the current model was developed in consideration of the "rule of parsimony" by recognizing the limitations of the available information (Poeter and Anderson 2005; Y. Zhou and Li 2011).

Based on the water budget of the study area, the quantity of groundwater abstracted by wells does not exceed recharge until the 1990s (Table 2). This excessive groundwater use is leading to the degradation of the resource itself and increasing irrigation water salinity as fossil water is extracted from storage (Tweed et al. 2011; Qadir et al. 2008). Other studies of groundwater degradation in dryland environments have produced similar findings (Ó Dochartaigh et al. 2010; Foster and Chilton 2003; Collins and Bolin 2007; Green et al. 2011). This points to the need to continually strive to increase the spatial resolution of environmental modeling approach to better understand the local system and formulate effective management strategies to match. For instance, it is evident in the water budget analysis that the current positive balance was not present during the mid-20th century, and this may be due to the fact that the gradual increase in groundwater pumping at that time outpaced recharge from surface water development. It might also be due to inadequate conceptualization of the boundaries, hydrologic processes or parameters in the model. At the scale being modelled however, it is reasonable to expect that groundwater impacts will vary across the model domain.

Satellite imagery was a critical data source for the modeling of the incremental increase in groundwater pumping in the study area. Remote sensing provided a critical source of information for filling gaps in records of land development and water use. In this study, a relatively simple model was used to develop recharge maps based on satellite imagery using NDVI and the MOD16 evapotranspiration dataset. Quantitative methods, such as SEBAL (Senay et al. 2007; Senay, Budde, and Verdin 2011) and METRIC (R. G. Allen, Tasumi, and Trezza 2007), are able to estimate local evapotranspiration more precisely, and can be used to determine the amount of water being applied by irrigation in dryland environments. These quantitative methods require calibration of model parameters however, which rely on local water use and soil moisture field data (Allen et al. 2007). Because these field data were not available in sufficient spatial or temporal resolution in the study area of Wadi El Natrun, the more precise quantitative methods for determining evapotranspiration were not used in the current study.

The AVHRR and Landsat imagery used in this study had different spatial resolutions, thereby representing a potential limitation in the remote sensing analytical approach. The AVHRR imagery has a resolution of 1000 m grid cells, while Landsat imagery resolution ranges from 30 to 90 m. This discrepancy may have contributed to an over-estimation of the incremental addition of wells or groundwater recharge at the time-steps when the remote sensing time series switched from Landsat imagery to AVHRR. While it would have been preferable to have access to a continuous record of Landsat imagery at higher spatial resolution, it was necessary to use the AVHRR data for infilling to ensure a continuous time series for use in the model. Similarly, infilling in the Nile River hydrograph, such as during the 1970 to 1990 time period, adds some uncertainty to the model results.

There is some debate in the literature as to the appropriate method for computing evapotranspiration in dryland environments, given that standard evapotranspiration methods rely on the assumption that soil moisture will not be depleted below field capacity (Scanlon and Milly 1994). Nonetheless, in more recent comparisons by (Abdelhadi et al. 2000) and (Zhou et al. 2006), it was evident that the Penman-Montieth method for computing reference evapotranspiration, adjusted by crop coefficients, still represents an accurate method for deriving crop coefficients.

The use of statistical distributions to randomly extract values for the variables in both the recharge and well pumping model provided a solid statistical basis for the creation of an ensemble of groundwater pumping and recharge inputs. Even so, the fact that in irrigated areas, both the amount of irrigation and groundwater pumping are ultimately a function of human decision-making means that there is an inherent element of uncertainty in modeling these processes. Without a large and continuous record of water use, it is difficult to accurately determine the timing and magnitude of both groundwater recharge and pumping at high spatial and temporal resolution. Additionally, the current model assumes that all wells in a given area are “turned-on” for periods after they had been agriculturally developed. This assumption is limited by the fact that wells are often installed up to one to two years prior to crop planting, and some plants (e.g. trees) can take an additional three years to mature. As a result, wells under these conditions would have not been “turned-on” immediately upon agricultural development. Additionally, deeper wells are often installed to cope with groundwater degradation due to deepening water levels or increasing salinity. Sometimes, farming is abandoned altogether (Salem et al. 2010; King and Salem 2012). Based on the available information, it was not possible to know the actual date of individual well installation, the precise depth or whether wells were ultimately abandoned.

Finally, given the extensive agricultural development in the area to the south of the current model’s extent, it is possible that the groundwater divide has shifted over time. Collecting and analysing monitoring data from the area to the south, in tandem with further modeling of the area, could verify the validity of this assumption.

2.7. Concluding Remarks

Numerical groundwater modeling has and will continue to be a crucial tool in the development of policies on land and water usage, particularly in dryland environments where groundwater is the dominant source of freshwater. The ability of groundwater models to represent a range of possible conditions over time and with a known level of confidence have made them an important tool for evaluating water and land use policy options (Srinivasan et al. 2010; Dennis 2007; Attia et al. 2007; Dawoud et al. 2005; AquaResource 2011). The objective of this study was to present an approach to modeling the cumulative impacts of environmental change on groundwater resources in the context of sparse data.

Because of the inherent uncertainty in any modelling exercise, let alone one informed by sparse data, it is incumbent upon the modeller to adequately quantify and communicate the error and limitations of the model. Tucjchneder's (2012) review of groundwater modeling research from developing countries suggested that this aspect of modeling could be overlooked due to a lack of local resources, including a lack of access to data and restricted technical capacity. The approach presented in this study provides a parsimonious and low-cost method for developing a validated long-term transient groundwater model using sparse data. An emphasis was placed on using open-source and publically available datasets from the study area of Wadi El Natrun, with a view to ensure the approach is transferable to other dryland environments with limited groundwater data.

The groundwater flow, recharge, and well pumping models developed in the current study could be improved by using alternative conceptual models of the groundwater system and accessing more accurate information on local water use and groundwater head fluctuations. Datasets on groundwater conditions and use, and hydrology have become both politically and economically valuable in Wadi El Natrun (Salem et al. 2010). This indirectly indicates the significance of the area's scarce water resources and land use practices. Greater investments by the government and communities in monitoring and assessment can help better understand the divers of change in local groundwater resources.

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CHAPTER 3. THE IMPACTS OF CLIMATE CHANGE AND WATER CONSERVATION MEASURES ON GROUNDWATER RESOURCES IN NORTHERN, EGYPT: IS SUSTAINABILITY ACHIEVABLE?

ABSTRACT

Sustainable management of groundwater resources is a significant challenge in dryland environments, as it is often the sole source of freshwater for a variety of competing uses. The area of Wadi El Naturn, located in the Egyptian Western Desert, has been subject to significant groundwater degradation in both quality and quantity since approximately the 1990s, attributed primarily to agricultural development. In recent years, several local and regional initiatives have been proposed to increase the sustainability of groundwater resources in the Wadi El Natrun area, however they have yet to be evaluated with respect to their potential impact on groundwater itself. Simultaneously, there are also proposals to increase the extent of arable land in the Wadi El Natrun area, and thus the demand for freshwater. This study uses a risk-based approach to assess the impact of various water resource management scenarios on groundwater sustainability in Wadi El Natrun, Egypt. A particular focus is given to understanding potential impacts of demand management strategies in the context of climate change. Current water use practices, vulnerabilities and the feasibility of on-farm management practices were inventoried through semi-structured interviews with farmers and villagers in the area, and a literature review. Groundwater modeling was conducted to evaluate the potential impact of the different scenarios on groundwater levels. Climate change was incorporated in each modeled scenario using an ensemble of the most recent future climate predictions from the Coupled Model Inter-comparison Project (CMIP 5). Results demonstrate that demand management implemented through optimized irrigation and crop rotations has the potential to significantly reduce risk of groundwater depletion. Additionally, the influence of baseline groundwater pumping far outweighs that of climate change for the local area.

3.1. Introduction

Groundwater has been key to global agricultural development, particularly in dryland environments. Approximately 43% of global irrigation consumption is from groundwater (Siebert et al. 2010; MacDonald et al. 2012; Aeschbach-Hertig and Gleeson 2012), and its demand is rising as population and food demand increase (Wada et al. 2010). Drylands represent a unique challenge in groundwater management due to their heavy reliance on subterranean water for freshwater, increasing desertification, lack of natural recharge, and the strong reliance of livelihoods on arid agriculture (Whitfield and Reed 2012). Balancing multiple human needs and ecosystem flow requirements of high quality freshwater is a fundamental goal of dryland groundwater management, however, the tendency in these environments has been for individual users to abstract groundwater at will, often without regard for the cumulative impact of such actions (Shiferaw et al. 2008; Whitfield and Reed 2012).

Examples of collective groundwater management, in which users develop and adhere to basin-scale allocation schemes are rare (Whitfield and Reed 2012), and require robust governance and high levels of water user participation (Mukherji and Shah 2005). Communal groundwater distribution systems, such as Qannat or piped-water networks, are good examples of shared groundwater sources, however regimes dominated by private wells are seldom communally governed (Blomquist et al. 2001). This is the case for aquifers exploited in dryland environments around the globe (Hammani et al. 2009; Green et al. 2011), including the Egyptian Western Desert (King and Salem 2012).

Agriculture constitutes over 81% of Egypt’s total water consumption, and although groundwater only constitutes 3% of the country’s total water consumption, in certain regions it constitutes the dominant portion of irrigation water (El-Din 2013). This is the case in the Egyptian Western Desert, where groundwater is used extensively for irrigation, and exclusively in the Wadi El Natrun depression and surrounding areas of Wadi El Farigh and Sadat City. It is also used conjunctively with surface water in the areas to the east and north of Wadi El Natrun (Attia et al. 2007). In the Egyptian Western Desert, groundwater abstraction has been driven by several policies to expand the area of desert-reclaimed land in the area. By 2017, the Egyptian Ministry of Water Resources and Irrigation's (MWRI) National Water Resources Plan (NWRP) intends to expand the area of cultivated land by an additional 3.4 million hectares (Ministry of Water Resources and Irrigation 2005). In the NWRP, much of this reclamation is dependant upon private investors using groundwater for irrigation.

The high level of groundwater use and certain land management practices in the agricultural area of Wadi El Natrun areas has resulted in the degradation of groundwater quality and quantity. Primary concerns among users are salinization, pollution from wastewater ponding and declining water levels (King and Salem 2012; Salem et al. 2010; Ibrahim 2005; Fattah 2011). These problems have raised questions about the sustainability and potential risks of the current water use regime on local water, food and economic security in the area, particularly as climate change is projected to add additional pressures on water demand through reduced precipitation and greater potential evapotranspiration (Attia et al. 2007; Ganzori 2013).

Several policies and management measures have been suggested to improve the sustainability of agricultural water use in the area. These include piped water from the Nile River, wastewater reuse, artificial aquifer recharge, desalination, and conservation through economic instruments and other programs (Arabi 2012; Attia et al. 2007; El-Din 2013; Ganzori 2013). Alterative livelihoods, crop diversification and more robust enforcement of water allocation agreements have also been proposed as potential conservation measures (King and Salem 2013; Salem et al. 2010). Recent work has also focused on the potential of such measures to offset the economic costs of groundwater degradation (King and Salem 2013).

The impacts of climate change on both the supply and demand sides of water resource management are also becoming increasingly important to consider, especially in dryland environments like the Egyptian Western Desert (Ganzori 2013). Changes in local climate influence local water budgets and affect the timing and magnitude of demand, particularly for agriculture (Corbeels 2012; Eid et al. 2006). Recent studies in North Africa have shown that climate changes are already apparent (ARECMEEAA 2010). In the Wadi El Natrun area, climate change is likely to increase reference evapotranspiration by more than 9% by 2025, however precipitation patterns are not expected to change

(Terink et al. 2013). Groundwater levels have also been shown to respond both directly to changes in climate in areas with pronounced groundwater-surface water interactions (Green et al. 2011), and indirectly through changes in water use (Candela et al. 2012). One impact of concern is the influence of sea level rise on coastal aquifers (Sayed Frihy et al. 2009; El-Nahry and Doluschitz 2009). Furthermore, flows and water quality of surface water bodies such as the Nile River in Egypt, are predicted become increasingly variable and exposed to extreme weather due to climate change (Booij et al. 2011).

Climate change adaptation is an increasingly important aspect of water resource management and adds to the complexity associated with prioritizing and choosing evidence-based management strategies. With respect to Wadi El Natrun, much of the information required for implementing sustainable and adaptive groundwater management strategies exists, however, there has been no estimate of the potential impact of climate change on groundwater sustainability. For instance, there is a significant body of knowledge on crop suitability based on local soil conditions (Abdel-Hamid et al. 2010; Abdel Kawy 2011). An assessment of sustainable groundwater yield and availability at different locations and aquifers throughout the area, and the importance of different drivers of degradation, is currently lacking. Additionally, there is no current assessment of the impact of climate change on local groundwater resources, and none for Egypt using the newly released CMIP5 climate change scenarios. The objective of this paper is to fill these gaps by assessing the impact of water conservation measures on the sustainability groundwater resources in Wadi El Natrun. An emphasis is placed on understanding the potential impact of conservation in the context of climate change, to understand the extent to which it provides resilience against groundwater degradation for local water users. The analysis of conservation presented in this study is intended to inform an adaptive (or in some cases transformative) approach to groundwater management, in which conservation represents a “no-regrets” strategy to address risks (Kabat et al. 2009). Although water quality is a significant concern in Wadi El Natrun, and forms an important part of ay water sustainability analysis, a detailed assessment of water quality was not feasible within the scope of this study, but is recommended in future work.

Several conceptual frameworks have evolved to quantify the sustainability of water resource management regimes. A particularly relevant framework when assessing conservation is water footprinting, or virtual water. This method has been developed to account for the total volume of water required to produce a good and assimilate associated local water pollution (Mekonnen and Hoekstra 2010). Management strategies that often emerge from water footprint analysis pertain to allocation of scarce water resources to the highest value use (not necessarily economic value). The concept of water security provides a broader framework for understanding the trade offs in water resource management and is being increasingly used as a decision support framework to assist in the prioritization and selection of water management measures based on multiple criteria (UNU-INWEH 2013; Cook and Bakker 2012; Dunn et al. 2012). Integrated Water Resource Management also provides a framework for assessing the potency of various management schemes with respect to their total impact on water resources, although its has been applied largely in the context of trans-boundary management (Kennedy et al. 2009).

Within the domain of groundwater management, several concepts have been posited to evaluate the sustainability of allocation, well pumping and management schemes, including safe yield or drawdown, and water budgets (Zhou 2009). There is still debate within the groundwater community on the appropriate definition of sustainable, or safe well yield (Zhou 2009), however the importance of understanding both overall water budgets and local effects is increasingly recognized. This study aims to contribute to this dialogue by building upon previous sustainability risk assessments and providing an example of the application to a dryland environment where groundwater use can be considered de-facto “unsustainable” as suggested by Kalf and Wooley (2005).

3.2. Study Site Description

Wadi El Natrun is an endorheic depression, located at the eastern boundary of the Egyptian Western desert, just west of the Cairo-Alexandria Desert Road (CADR) approximately 90 km north of Cairo (Figure 21). The area is classified as hyper-arid, receiving approximately 35 mm of precipitation per year and over 1500 mm of evapotranspiration (Switzman et al. 2013). Despite these environmental conditions, Wadi Natrun supports an extensive agricultural sector that is increasing in both spatial extent and economic value (Salem, Gad, and King 2010).

The area of Wadi El Natrun has a population of approximately 72,000 living in approximately 18,000 households concentrated in approximately 7 small villages (King 2011). Agriculture and related sectors are the most important economic sectors in Wadi El Natrun, supporting over 60 % of the jobs and providing important sources food for domestic consumption locally, nationally and increasingly for export (King and Salem 2013). Much of the remaining employment is in support of industry associated with the harvesting of salt from Wadi El Natrun's saline lake, mining and construction (King and Salem 2013).

Freshwater supplies, critical to dryland irrigated agriculture in Wadi El Natrun, are sourced entirely through groundwater from three main aquifers. From deepest to shallowest, the exploited aquifers are known as the Miocene, Pliocene and Pleistocene aquifers. The Nubian Sandstone Aquifer (NSAS) is a deep trans-boundary aquifer system that underlays, and is theorized to recharge the Miocene aquifer in Wadi El-Natrun across a deep transverse fault (Geirnaert 1992; Zaghloul 1999; El-Sheikh 2000). The hydrogeologic setting in the Wadi El Natrun area is complex, and there is still significant uncertainty as to the precise flow regime and hydraulic connections between the aquifers. Nonetheless, multiple studies have observed both local and regional groundwater flow to be concentrated toward the base of the valley where it discharges to eleven saline lakes (Ibrahim 2005; Ibrahim 2007; Research Institute on Groundwater 1992; Sharaky et al. 2007; Masoud and Atwia 2010). These saline lakes support a range of important desert wetland ecosystems and shorebird populations (Awad 2002), and also provide an important source of grazing area for local shepherds (Salem 2010). These lakes are also used for salt harvesting, and are a local tourist attraction (Shortland 2004).

The Pliocene aquifer is local in extent, covers the entire Wadi El Natrun area, and is discontinuously covered by Quaternary deposits of the Pleistocene Aquifer. As a result, the Pliocene aquifer is considered to be partially confined (Masoud and Atwia 2010). The Pleistocene aquifer is much larger in spatial extent, extending east to the Nile Delta, where it receives lateral recharge from the river and vertical recharge from excess irrigation water (Dawoud et al. 2005; Mohamed and Hua 2010). At its western extent, a reverse fault oriented parallel to the CADR truncates the Pleistocene aquifer and groundwater flows across this fault to recharge the Pliocene aquifer laterally (Ibrahim 2007; Geirnaert 1992). The Miocene aquifer is regional in scale, extending several hundred kilometers to the southwest to the Qattara Depression (Dawoud et al. 2005). It is unconfined to the west of Wadi El Natrun, but is covered completely by the Pliocene aquifer within the valley. The Pliocene aquifer is theorized to be recharged from below by the Miocene aquifer across a leaky aquitard composed of clay and shale.

In addition to completely supporting irrigation in the Wadi El Natrun depression, the aquifer system described above is also used for conjunctive irrigation in the areas to the east and north of Wadi El Natrun (Attia et al. 2007). Surface water for this conjunctive use is supplied from the Nile Rosetta branch and associated irrigation and drainage canal network. The Rosetta Branch is located 25 km to the east of Wadi El Natrun and irrigation and drainage canal network borders the eastern boundary of the depression.

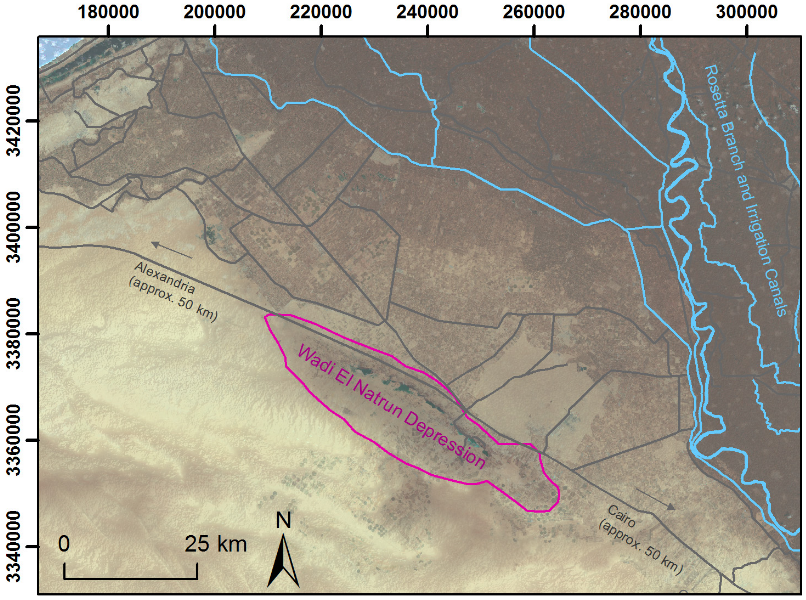

Figure 21. Map of study area highlighting the Wadi El Natrun depression

The extent of agricultural land, and thus groundwater abstraction in Wadi El Natrun, has increased significantly over time (Dawoud et al. 2005; Baietti et al. 2005), placing significant pressure on both the quality and availability of freshwater. Previous modeling and monitoring suggest that in some areas of Wadi El Natrun, groundwater levels have declined by between 10 m and 20 m between 1990 to 2000 (Ibrahim 2005; Baietti et al. 2005; Salem et al. 2010). Declining groundwater levels have also been accompanied with increased salinization of groundwater and contamination due to land use practices (Abdelkhalek 2013).

A 2009 inventory by the MWRI indicated that there were approximately 1,050 wells in use in the Wadi El Natrun depression alone, at an average spacing of 3 wells per kilometer. Another 4,200 wells are located in the surrounding area. These values likely underestimate the true inventory of wells, however, as they are based on well permits, and many well users operate without permits (Salem et al. 2010). A recent survey by Salem et al. (2011) demonstrates that well spacing is much denser, at up to one well per 50 m on small farms. A key conclusion from several modeling studies (Switzman et al. 2013; Dawoud et al. 2005; Diab et al. 2002; El-Din 2013) is that the overall groundwater budget for the area is positive or neutral, despite evidence of significant degradation in local areas in and around Wadi El Natrun.

To better understand the exposure of different populations in Wadi El Natrun to groundwater degradation, Salem et al. (2011) suggested a typology, based primarily on farm size for categorizing farms in Wadi El Natrun. Within this framework, it was concluded that investors were typically identified as owning large farms, with production serving export or cash-cropping markets. These larger farms have multiple deeper wells and exhibit greater resilience to groundwater degradation compared to smaller land-holders, whose farms are used primarily used for domestic consumption and typically rely on a single, shallower well for both irrigation and domestic uses (King 2011; King and Salem 2012). Medium-sized farms typically display attributes of the smaller farms, however the extent of land cultivated is typically greater and irrigation technology may be more sophisticated (King and Salem 2012). Wells on medium farms are typically shallow and the crops grown are a combination of local staples and export commodities. Given the relationship between farm size, well depth and coping capacity, the large farms are typically located in areas where water tables are deeper, on the slopes of the Wadi El

Natrun depression. In contrast, smaller farms are typically concentrated in several villages near the saline lakes.

3.3. Methodology

3.3.1. Sustainability and Groundwater Risk

This study uses a risk-based approach to assess the potential for water conservation measures to increase the sustainability of groundwater resources in the Wadi El Natrun depression. A core implication of the term "sustainability" is the need to understand near term and long term impact (Gleeson et al. 2010), and as such, the risk analysis in this paper is forward-looking. Notions of socio-cultural, economic, environmental and intergenerational equity are also embedded in the current use of the term sustainability (Kalf and Woolley 2005). The implication of these definitions is that a sustainability analysis needs to consider future impacts with respect to a range of socio-economic, cultural groups, and ecosystems that interact with a common resource. In the case of the current study, the common resource being considered is groundwater.

With respect to groundwater specifically, there has been some ambiguity as to the appropriate definition of "sustainable yield" or "drawdown". A review by Kalf and Woolley (2005) provides several principles for assessing groundwater sustainability, namely that under conditions with minimal natural recharge, groundwater abstraction is essentially an exercise of mining. This is particularly pertinent to Wadi El Natrun, where there is effectively no natural surface recharge, and there is no scientific consensus on sources of deep groundwater recharge. Kalf and Woolley (2005) suggest "sustainable yield implies that the… groundwater entity water balance reaches equilibrium at some time" (p. 311). Given that this scenario is highly unlikely in many dryland environments like Wadi El Natrun and would essentially require all abstraction to cease, alternative indicators, such as water quality or ecological flow requirements can be used as a basis for assessing sustainability (Kalf and Woolley 2005). Additionally, it is arguable that "sustainability" itself is not an achievable target in environments like Wadi El Natrun. Instead, interventions could focus on minimizing risk associated with exposure or vulnerability to groundwater hazards through adaptive management, such as gradually shifting crop patterns, or transformative approaches such as completely transforming local livelihoods out of agriculture. These approaches are often used in climate change adaptation planning (Park et al. 2012; Klerkx et al. 2010; Burton et al. 2004). This is the approach adopted in this study.

Previous studies in Wadi El Natrun have shown that exposure to groundwater degradation is variable within the local area, despite modeling showing that water balances for the overall area are net positive or neutral over time (Switzman et al. 2013; Dawoud et al. 2005; Mohamed and Hua 2010; Masoud and Atwia 2010). These localized effects have been further confirmed through field surveys and water user questionnaires, demonstrating that different populations have varying vulnerabilities to groundwater degradation (Salem et al. 2010; King and Salem 2012; Ahmed et al. 2010). This implies a need to understand the potential impacts of any management or technological intervention relative to these different populations and geographic locations in Wadi El Natrun.

Risks related to groundwater degradation are a function of both the ability of a particular social population or ecosystem to cope with groundwater degradation, or vulnerability, and their relative exposure to the unsustainable groundwater conditions (King and Salem 2012; Salem et al. 2010). Additionally, the natural ecosystems in Wadi El Natrun (i.e., saline lakes and wetlands) are presumed to have different exposures and vulnerabilities to groundwater degradation in comparison to the human populations (Salem et al. 2010).

The need to predict groundwater conditions resulting from different management scenarios necessitates the use of modeling. Model results are inherently uncertain and it is often beneficial for decision makers to incorporate this information into the analysis of trade-offs and impacts of potential management options, particularly adaptive ones (Burton et al. 2004). Risk-based approaches have the advantage of incorporating the uncertainty of predictive modeling into an analysis framework, and are therefore becoming increasingly used in both groundwater management and climate change adaptation scenario evaluation (Tartakovsky 2013; Green et al. 2011; Lereboullet et al. 2013; Byer and Yeomans 2007). It should be noted that risk can be determined using a range of different qualitative and quantitative methods, depending on the decision maker's needs, but in all cases the analyst is required to make judgement calls on the selection of indicators and assignment of scores to the various components of risk (exposure and vulnerability) (Burton et al. 2004). Because risk scores can be adjusted and re-calculated over time, they are a useful aspect of the monitoring and evaluation aspect of adaptive management (Lamhauge et al. 2013).

In general, risk is defined as the likelihood of encountering a certain outcome, usually a hazard or system failure (Tartakovsky 2013; Beck et al. 2012). The specific hazard can be defined as a set of conditions associated with a defined system to which a given group, or "receptors", is exposed and vulnerable. Throughout this paper, the term "receptor" will be used to refer to either social groups or ecosystem elements that have different vulnerabilities or exposures to groundwater degradation.

Risk can be used to understand the relative impact of alternative groundwater management scenarios by comparing the ability of each to change the exposure of different receptors to degradation relative to a baseline condition. Several protocols and standards exist for conducting risk assessments, however the general approach among them is similar (Tartakovsky 2013; Pasini et al. 2012; Beck et al. 2012; Bolster et al. 2009). The following key steps were used in this study:

1. Identification of hazards and associated impacts relative to groundwater degradation from literature and a local water user questionnaire;
2. Determination of the vulnerability of different groups and receptors (e.g. wells, ecosystems) to the impacts of groundwater degradation by building upon work of Salem et al. (2010);
3. Identification of impact exposure indicators using literature and water user questionnaire;
4. Risk analysis of different receptors for each management scenario (Tartakovsky 2013); and,
5. Risk reduction comparison among the management scenarios.

For each receptor, *J*, a risk score, R, with respect to hazard, z, can be calculated by multiplying the exposure, E, of that receptor to the hazard by their relative vulnerability or susceptibility to the impacts, V (Eq. 14) (Pasini et al. 2012). It should be acknowledged that this definition of risk arises from natural hazards literature, as compared to traditional definitions expressed in probabilistic risk analysis (Burton et al. 2004)

$$R_{J,z} = E_{J,z,n} \times V_{J,z} \tag{14}$$

A similar approach has been implemented specifically related to groundwater risks associated with climate change in (Pasini et al. 2012). This work demonstrated that a risk assessment approach was effective at identifying the impact of managed artificial recharge on groundwater irrigation risk with respect to specific areas and crops. Given that sustainability is not a viable management target in Wadi El Natrun, the concept of "risk reduction" with respect to groundwater depletion and degradation will be employed. The overall risk reduction, *s*, of a given management scenario in Wadi El Natrun, *n*, can be defined with Eq. 15:

$$s_n = \sum_{z=1}^{W} \sum_{J=1}^{h} R_{J,z,B} - R_{J,z,n} \tag{15}$$

where *B* is the baseline scenario to which the management scenario, n, can be compared, *W* is the total number of receptors in a given analysis group and *h* is the set of defined hazards.

3.3.2. Groundwater Hazard and Risk Indicator Identification

An essential component of risk analysis is the selection of appropriate indicators to represent both the exposure and vulnerabilities relevant to given hazards and impact receptors in the assessment framework (Lamhauge et al. 2013). In the context of groundwater management, risks can pertain to a variety of receptor classes, including specific wells, aquifers and surface water bodies under the influence of groundwater, or societal groups reliant on groundwater.

For the current study, relevant groundwater hazards, the impacts to different receptors and the vulnerability of different groups was elucidated in a 2008 field survey conducted by Salem et al. (2010) as part of the United Nations' Groundwater and Human Security Case Studies (GWAHS-CS) project. This field survey was conducted at the farms of the village of Beni Salama (see Figure 22) and was complemented by an extensive literature review of groundwater conditions in the area (Salem et al. 2010). This work provided a base of information on the types of groundwater degradation hazards relevant to different classes of receptors. In order to augment the spatial extent of the GWAHS-CS information, additional fieldwork was completed between September and November of 2011.

Information from both the GWAHS-CS 2008 and 2011 field surveys was combined in a geodatabase for the development of an indictor framework with which groundwater risk was assessed relative to different receptor classes. This geodatabase provided a mechanism for linking field survey data to the location and spatial extent of each farm. Five main types of records are present within the geodatabase (Figure 22):

1. Farms represented as polygons bounded by their areal extent where water user questionnaires were completed;
2. Wells and drainage ponds located on farms, represented by points elucidated from water user questionnaires;
3. Wells representing private urban wells where water user questionnaires were completed;
4. Polygons representing areas with multiple drinking water sources or points representing individual drinking water sources; and,
5. Polygons representing ecosystem receptors.

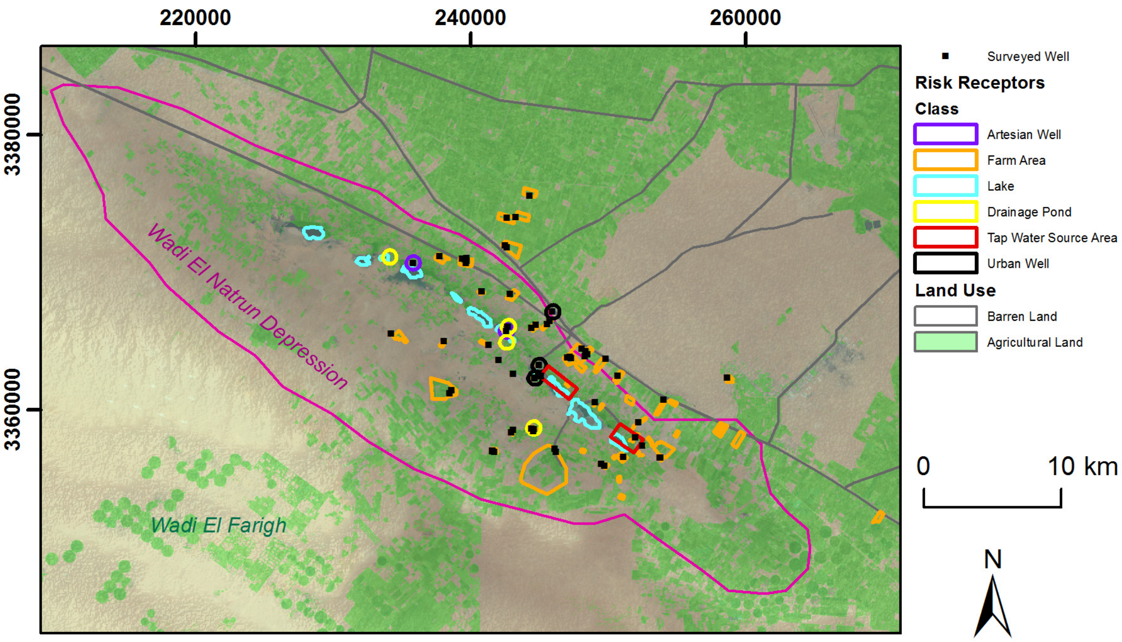

Figure 22. Map of the study area showing sample sites for the Salem et al. (2010) and the 2011 surveys.

Salem et al. (2010) and King and Salem (2012) provide detailed information about the methodology used during the 2008 GWAHS-CS survey, which included a water user questionnaire pertaining to water use, crop rotations, groundwater-related hazards, and groundwater degradation coping strategies.

The 2011 field survey also had a water user questionnaire, which was similar to the 2008 GWAHS-CS questionnaire. After an initial set of questions was developed and piloted with local informants, the 2011 questionnaire was adapted to capture the necessary data from the water users. The 2011 questionnaire focused on water use and irrigation timing, well conditions (i.e., water quality and groundwater levels), water user grievances and management priorities. In addition to the questionnaire, groundwater levels and basic water quality parameters (i.e., pH, salinity, temperature and microbial contamination) were measured at any accessible wells, end-point taps, and ponds at the time of the field survey. Water user questionnaires were not conducted at public water sources, however data on the water levels and flows were collected.

Forty-five water user questionnaires from the 2011 field survey and 29 from the 2008 GWAHS-CS field survey were included in the analysis, the majority of which were farms with one or more wells (Table 5). The 2011 field survey sites were randomly selected, and participation was voluntary. Efforts were made to ensure broad geographic coverage while ensuring that farms of different sizes were represented within Wadi El Natrun based on the typology presented in Salem et al. (2010). Coordinates of the wells or water receptor at each survey site were collected using a handheld GPS, and satellite imagery was used to plot the boundaries of each farm in the geodatabase. Questionnaire results were transcribed into the geodatabase, and the responses were coded based on categorical similarities and congruence with the 2008 GWAHS-CS coding scheme. It should be noted that it was not always feasible to visit every well at each survey site, therefore location(s) were inferred from the satellite imagery by identifying structures that resembled pumping houses. Furthermore, because exact well locations were not available from the 2008 GWAHS-CS survey, the approximate coordinates of the farms visited were used in the current study. The geodatabase database was then augmented with the data collected by Salem et al. (2010) in the 2008 GWAHS-CS survey, however only records with geographic coordinates were included. King and Salem (2012) estimated that there are approximately 2,000 farms in the Wadi El Natrun area, therefore the geodatabase has an approximately 3.7% coverage rate.

The groundwater in the villages of Beni Salama and Kafr Dawoud is considered to be of very good quality and as a result, there are multiple public drinking water wells and sources for piped networks in these villages (Abdelkhalek 2013; Salem et al. 2010). The precise location of these wells was unknown, so the larger areas associated with these villages were included in the geodatabase to represent key drinking water sources. Similarly, ecosystem receptors were primarily included based on descriptions in the literature, while their spatial extent was interpreted from Landsat satellite imagery.

Table 5. Breakdown of water survey sites in the geodatabase. Unless otherwise specified, records are from the 2011 Survey.

Survey Site Type	Number Questionnaires Completed	Groundwater Risk Receptor Type	Number Records In Geodatabase
Farm	41 (source: 2011 Survey) 29 (source: GWAHS-CS)	Wells (source: 2011 Survey) Wells (source: GWAHS-CS)	61 65
		Drainage Pond	3
Public Water Source	NA	Artesian Well	2
		Tap Water Source Area	2
Urban Water Source	4	Wells	4
Ecosystem	NA	Saline lakes and wetlands	11
Total	**74**		**148**

3.4. Hazard Exposure through Groundwater Modeling

The coupled irrigation-groundwater model for the Wadi El Natrun area presented in Switzman et al. (2013) was used to simulate groundwater levels under different management and climate change scenarios at a monthly interval from 2012 through 2062. This represents a 50-year planning horizon. The resulting outputs of water levels and storage were used as a basis for determining relative exposure of different receptors to groundwater degradation. Given that the model's uncertainty was quantified previously in Switzman et al. (2013), it was possible to use this information to compare risk reduction under the various scenarios.

The Switzman et al. (2013) model is a 3-D finite difference groundwater flow model implemented in MODFLOW-NWT that is driven by well pumping and surface recharge scenarios developed using statistical relationships in the computer program R. The relevant water use and irrigation efficiency routines in the 1-D recharge and well pumping models in Switzman et al. (2013) were adjusted to account for the changes required by each management scenario. Further details on the specific modifications are presented in Section 3.5. Within the Wadi El Natrun area, this model has an accuracy of approximately 4 m (RSE), however the overall spatial-temporal fit of the model can be regarded as being acceptable for the type of management comparison in this study. The model was able to successfully reproduce historical trends in groundwater heads across the domain in both space and time (Switzman et al., 2013).

3.4.1. Climate Change Projections

Given the importance of climate to both the supply and demand sides of water resource systems (Milly et al. 2008; Green et al. 2011), significant efforts were made to incorporate climate change into the risk analysis in this study. Current best practices related to the use of climate change data in hydrologic modeling suggests that it is advisable to use an ensemble of scenarios to capture a range of possible climate futures (Green et al. 2011; Teutschbein and Seibert 2012). The scenarios employed in this study were from the Coupled Model Inter-comparison Project (CMIP) 5, which represents the most recent projections of climate change (Taylor et al. 2012). Recent evaluations of these scenarios suggest that the CMIP5 models perform with similar or higher levels of accuracy with respect to the key variable of atmospheric temperature compared to projections from the previous CMIP3 experiment, and have the advantage of projecting climate changes at a higher spatial resolution (Yao et al. 2013; Watanabe et al. 2012). Additionally, preliminary research comparing results from CMIP5 and CMIP3 suggest that the range of models employed in each of these studies perform with similar biases (Terink et al. 2013; Watanabe et al. 2012).

This is the first study the authors are aware of that has employed CMIP5 data in a hydrogeologic and irrigation impact assessment of climate change. To date, no studies using CMIP5 data have been published in Egypt. A recent climate change impact assessments on Egypt’s water resources relied upon the CMIP3 projections (El-Din 2013; Ganzori 2013).

In comparison with the previous climate change data from CMIP3, CMIP5 employs scenarios called ‘relative concentration pathways’ (RCPs) to force the global climate models using greenhouse gas concentrations as the primary driver (Taylor et al. 2012). These scenarios are considered as a more accurate reflection of potential climate change mitigation policies than the CMIP3 data (Taylor et al. 2012). Current trends in global climate change indicate that there is likely to be a higher degree of climate change, which is represented by the RCP8.5 scenario (Watanabe et al. 2012). As a result, the scenarios of RCP4.5 and RCP8.5 were chosen as they represent moderate and high degrees of global climate change, respectively (Taylor et al. 2012).

Evapotranspiration is the dominant climate variable influencing both water supply and demand in the Wadi El Natrun area (Ganzori 2013). For each climate change scenario, the raw Global Climate Model (GCM) variables of mean daily relative humidity, *rhs,* maximum daily temperature, *tasmax*, minimum daily temperature, *tasmin*, and mean daily wind speed, *sfcWind*, were use in the ASCE Standard Reference Evapotranspiration Equation (i.e., modified Penman-Monteith equation) to compute daily reference evapotranspiration, ET_{ref}. The other parameters in the equation were kept the same for the baseline period. This yielded a total of twelve time series of raw climate change scenarios of ET_{ref} for the GCM cell at the location of Cairo Airport weather station. Each realization within the ensemble was then separately bias-corrected to the infilled Cairo station baseline time-series using the procedure in (Watanabe et al. 2012).

Six global climate models were employed in this study (Figure 23). At the time of this research, some of the required variables (*rhs*, *sfcWind*) were not available for all models included in CMIP5 for both of the climate change scenarios (i.e., RCP4.5 and RCP8.5). Nonetheless, the models selected do represent a reasonable range of predictions for air temperature in the CMIP3 scenarios of high climate change (i.e., scenario A1 from CMIP3) (Figure 23). Additionally, as it was beyond the scope of this paper to do a comprehensive comparison of climate change projections for the study area a set of scenarios that captured a range of potential future climates was selected.

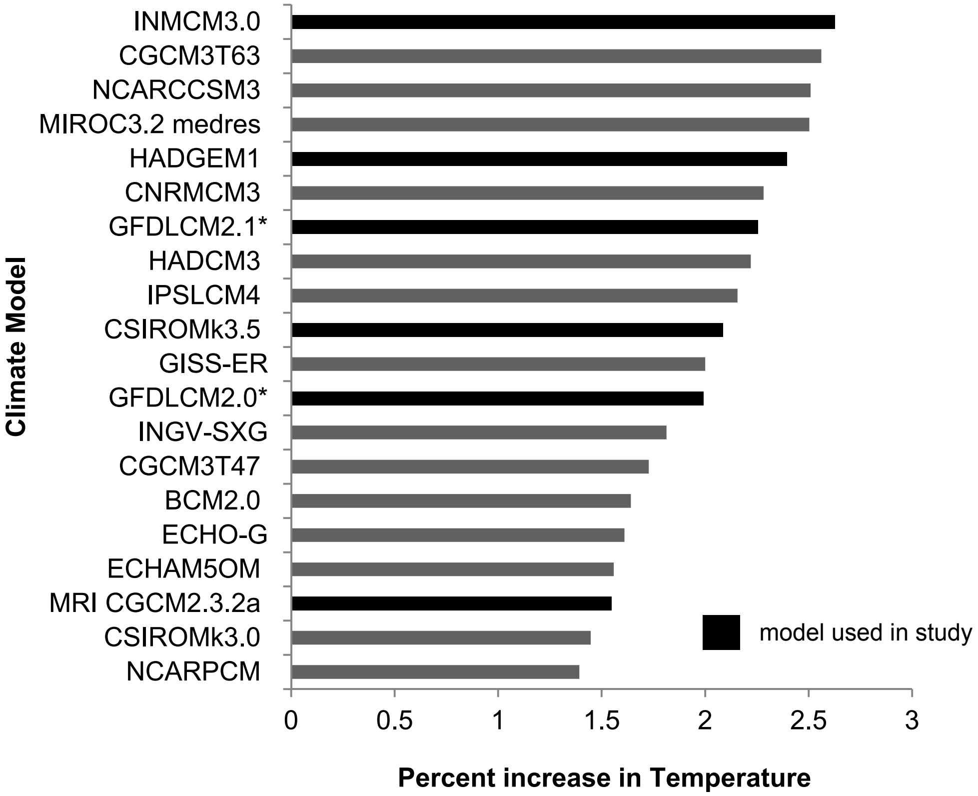

Figure 23. Projection of average percent temperature increases from baseline for the period of 2040 to 2070 for the CMIP3 A1 scenario. *The GFDL ESM model was used in the current study instead of CM2.0 and 2.1

3.5. Local Risk Indicators for Wadi El Natrun

3.5.1. Groundwater Hazards

The concept of socio-ecological vulnerability (King and Salem 2012; Lereboullet et al. 2013) was used as the basis for developing local indicators of groundwater-related risk, with respect to both the exposure and vulnerability components of the risk equation for Wadi El Natrun (Eq. 14). Within this framework, the level of vulnerability of a population group or individual to a given hazard can be derived through either direct or indirect relationships to that hazard (Collins and Bolin 2007). Indirect hazards can be understood as the impact of a hazard on an intermediary receptor, such as an ecosystem that provides goods and services to the group or individual whose vulnerability is being assessed (Hamouda et al. 2009). The vulnerability of different groups to the hazard of groundwater degradation is dependant upon their relative socio-cultural, economic, and environmental contexts; factors that contribute to their overall ability to cope with, and rebound, with a given hazard failure (King and Salem 2012).

The GWAHS-CS and the 2011 questionnaires demonstrated that the dominant concerns among water users are salinization and the sustainability of supplies for agriculture (Figure 24). Irrigation system and well malfunctions, along with water supply contamination, were also identified by water users as concerns, but to a far lesser extent. The field survey indicated, however, that the main ecological elements that were vulnerable to groundwater degradation were wetland habitats and livestock grazing adjacent to the saline lakes (King and Salem 2012; Salem et al. 2010), both requiring a minimum water table level to be sustained (Awad 2002). These environments provide multiple ecosystem services, such as provisioning of natural resources (salt, grazing land and fibres), food chain support, and water quality regulation (Salem et al. 2010).

Seventy percent of the 2011 questionnaire respondents indicated that their farm wells were also being used for drinking and domestic water. The towns of Beni Salama and Kafr Dawoud, located in at the base of the Wadi El Natrun depression, are also the locations of drinking water wells for local piped water networks. In addition, there are several active bottled water operations located in these towns. Given the importance of reliable and high quality drinking water for human security, declines in groundwater levels and contamination of these sources represent critical impacts of groundwater degradation in Wadi El Natrun.

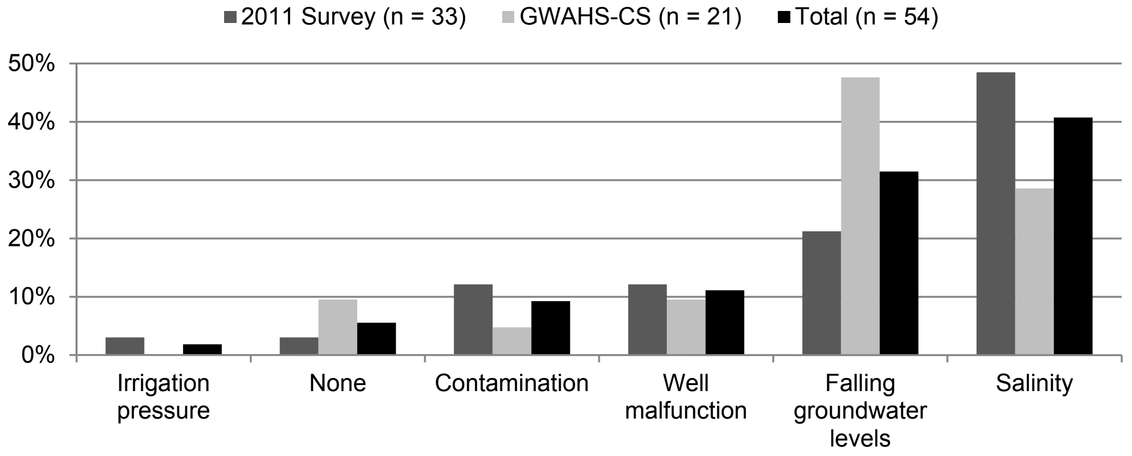

Figure 24. Priority concerns of groundwater users, as reported in the 2008 and 2011 questionnaires.

3.5.2. Vulnerability Indicators and Classes

Based on the analysis presented in Section 3.5.1, the major groundwater vulnerabilities in Wadi El Natrun are associated with falling groundwater levels, increased salinization, and irrigation system malfunctions (i.e., well malfunctions and loss of irrigation pressure). Surface contamination is also an important risk to consider for drinking water sources (Abdelkhalek 2013). Each of these hazards has a different relationship to the receptor classes present in Wadi El Natrun. The receptor classes present in Wadi El Naturn included pubic drinking water sources (artesian wells, tap water source zones), farms (garden, small, medium and large -sized), urban water wells, ecosystems (saline lakes and wetlands) and drainage areas. Table 6 presents a summary of the specific vulnerabilities assigned to each receptor class, based on the hazards to which it is sensitive. A numerical scale of 1 to 3 was used to assign vulnerability scores to each receptor, with values of 1 representing “low”, 2 representing “moderate”, and 3 representing “high” vulnerability.

Table 6. Relationships between receptor classes and groundwater degradation hazards and summary of vulnerability scores, *V*.

Hazard, *z* Receptor, *J*		Falling Water Levels, Salinization, and Irrigation / Well System Failure	Surface Contamination
Drinking Water Sources	Artesian Well	High (3)	Moderate (2)
	Tap Water Source Areas	Moderate (2)	Moderate (2)
Farm	Large	Low (1)	Low (1)
	Medium	Moderate (2)	Moderate (2)
	Small	High (3)	High (3)
	Garden	High (3)	High (3)
Urban Water Source (Wells)		High (3)	High (3)
Ecosystems (Saline lakes and wetlands)		High (3)	Low (1)
Drainage ponds		High (3)	Moderate (2)

King and Salem (2012) and Salem et al. (2010) have suggested that small farms and gardens are more vulnerable to the identified hazards than medium and large farms. Furthermore, Abdelkhalek (2013) used the DRASTIC method to assess intrinsic vulnerability to surface contamination based on geographic location within the Wadi El Natrun area. The results indicated that smaller farms, which are located at the base of the depression, had the highest levels of surface contamination vulnerability, while larger farms were located where vulnerabilities were lower (Abdelkhalek, 2013; Salem et al. 2010). As a result, the Salem et al. (2010) farm typology was used as the basis for assigning surface contamination vulnerability based on the their location in Wadi El Naturn (Table 6). It should be noted that the DRASTIC methodology represent a theoretical vulnerability, based purely on the physical characteristics of the environment (Aller et al. 1987), and other factors such as land-use and waste handling would need to be understood to translate this into real risk. That being said, contaminating land-use practices, such as human and agricultural wastewater ponding, as well as the presence of buried wastewater trenches are widespread across the farms and urban areas in Wadi El Natrun (King and Salem 2012).

The artesian public drinking water sources are also vulnerable to contamination, falling water levels and salinization. These sources are untreated, yet heavily relied upon by as sources of drinking water (Salem et al. 2010). A loss of groundwater head or increased salinization at the artesian wells jeopardizes their viability as drinking water sources. As a result, the public drinking water wells were therefore assigning “high” vulnerability score despite being located in an area of the DRASTIC map rated as moderately vulnerable to contamination.

The water supply wells associated with the local piped water networks and the bottle water plants is treated, therefore were considered to be less vulnerable than the artesian wells to the hazards of groundwater degradation. Furthermore, the owners of these systems are well capitalized, able to install larger pumps or drill deeper wells to cope with degradation scenarios, as other users have in the local area (King and Salem, 2013).

The urban water users exhibited similar characteristics to small farms and gardens, as wells were shallow – between 28 m and 51 m in depth. The vulnerability of local business to well failures, losses of hydraulic head or salinization were assumed to be relatively high given the capital cost associated with drilling new wells and/or installing treatment systems. Additionally, urban water users were determined to be highly susceptible to surface contamination because numerous wastewater ponds and dumping areas are present in the area.

Saline lake and wetland ecosystems were determined to be highly vulnerable to the impacts associated with declines in hydraulic head given that discharging groundwater is the main source of water for the flora and fauna that inhabit these environments. Nevertheless, their vulnerability to surface contamination was rated as “low” since the ecosystems provide water quality regulating services (Awad 2002).

3.5.3. Exposure Indicators and Classes

While vulnerability to groundwater degradation is relative to the receptor in question, exposure is based on the physical state of groundwater resources and how that contributes to the hazards of concern for the given receptor. Declines in water levels in Wadi El Natrun have been closely tied to increased salinization of groundwater (El-Hady et al. 2012; Zammouri et al. 2007; Fattah 2011). Additionally, losses in irrigation pressure and costs associated with replacing or repairing of wells are associated with losses in hydraulic potential in wells. This suggests that groundwater levels provide a useful indicator of exposure to the multiple groundwater degradation hazards identified in Section 4.2, namely salinization, loss in irrigation pressure and water availability. Kalf and Woolley (2005) suggest however, that water levels alone may be poor indicators of groundwater depletion or sustainability because they may not capture the physical process that actually produce degraded groundwater. That process is typically aquifer storage depletion (Van Camp et al. 2010; Zhou 2009; Kalf and Woolley 2005). Continuous water level declines (Freeze and Cherry 1979) and salinization (Zammouri et al. 2007; Sharaky et al. 2007) are the result of drawdowns in aquifer storage. Following the guidance of Kalf and Woolley (2005), changes in storage at a 50 year planning time horizon from 2012 were used as the basis for computing exposure scores for each of the well receptors (Eq. 16).

$$E_{J,z} = \frac{\sum_{c=1}^{f}(\Delta S_{c,J})}{F} \quad \{\Delta S | \Delta S > 0\} \tag{16}$$

ΔS represents the cumulative change in storage from 2012 to 2062 for the specific risk receptor, *J*, *F* is the total number of MODFLOW cells intersected by the given receptor, and *c* is an individual MODFLOW cell intersected by the receptor.

Hazards associated with well and irrigation system failure are a function of water levels inside the well, regardless of whether those levels might recover or reach equilibrium at some point. In order for current pump installations to be viable, the water level inside the well must be, at a minimum, above the pump lift rating. Likewise, the lake and wetland ecosystems require a certain water table level to be sustained, and this was used as the basis for computing exposure scores for this class of receptor. Water levels are also important for drainage ponds, which are used to harvest salt, and drain water-logged soils, and require the water table to remain above the pond's bottom in order to be effective. Hazards associated with potentiometric and water table levels impacts can be expressed by comparing observed or predicted groundwater levels with a given threshold at which groundwater levels become problems for those particular receptors (Eq. 17).

$$E_{J,z} = \frac{\sum_{c=1}^{f}(H_{c,J} - Z)}{F} \quad \{(H_{c,J} - Z) | (H_{c,J} - Z) > 0\} \tag{17}$$

where H is the predicted hydraulic head at the end of the planning horizon (i.e., 2062) and Z is the threshold value for a given receptor.

Based on an analysis in Kalf and Woolley (2005), these water level indicators do not reflect sustainability with respect to groundwater resources specifically, but "production facility sustainability" or impacts to ecological flows. Once these threshold water levels are reached, it is assumed that the receptor experiences damages with irreversible or severe impacts. Thus, as the threshold value approaches, exposure to the hazard increases. The thresholds were defined by determining the point at which water levels become unsustainable according to the criteria in Table 7.

All exposure scores were normalized to a 3-point scale using linear regression. The minimum and maximum values for each exposure indicator were assigned values of 1 and 3, respectively, and all values in between were assigned using the fitted linear model. Any score with a value outside the allowable minimum range for the given indicator was assigned a normalized score of 0.5, denoting negligible risk.

Table 7. Indicators for given receptors and hazards.

Hazard, z / Receptor, J	Water availability	Salinization	Water level declines	Surface Contamination
Farm or Drinking Water Well Area	*Groundwater storage*	*Groundwater storage*	*Decline > 90% of well depth, assuming pump rating is to within 10% of the bottom of the well*	*Increase in water table level > 5 m or > 20 m below grade compared to 2012 levels*
Artesian Well			*Decline in head < ground surface*	
Saline lake and wetland	*Expressed as water level decline*	NA	*Decline of > 5 m in head compared to long-term average level*	NA
Drainage pond	*Expressed as water level decline*	NA	*Decline of > 2 m in head compared to 2010 level reached*	NA

3.6. Management Scenario Development

One base case and three management scenarios were developed to compare the relative impact of water conservation measures on groundwater degradation risk. It was assumed that the spatial extent of both irrigated land and wells remained consistent with the geographic distribution of these factors at the end of the modeling period in Switzman et al. (2013) for the year 2011 (Figure 25) baseline scenario. These scenarios are summarized in Table 8.

Table 8. Summary of future management scenarios

Scenario	Water Use Calculation	Climate Change
Baseline	Same as historical	ETref anomaly applied for each combination of RCP (4.5 & 8.5) x ensemble uncertainty (mean±stdev)
20% reduction	Uniform 20% reduction in GW areas	
Optimal use	Drought/salt tolerant crop water req.'s	

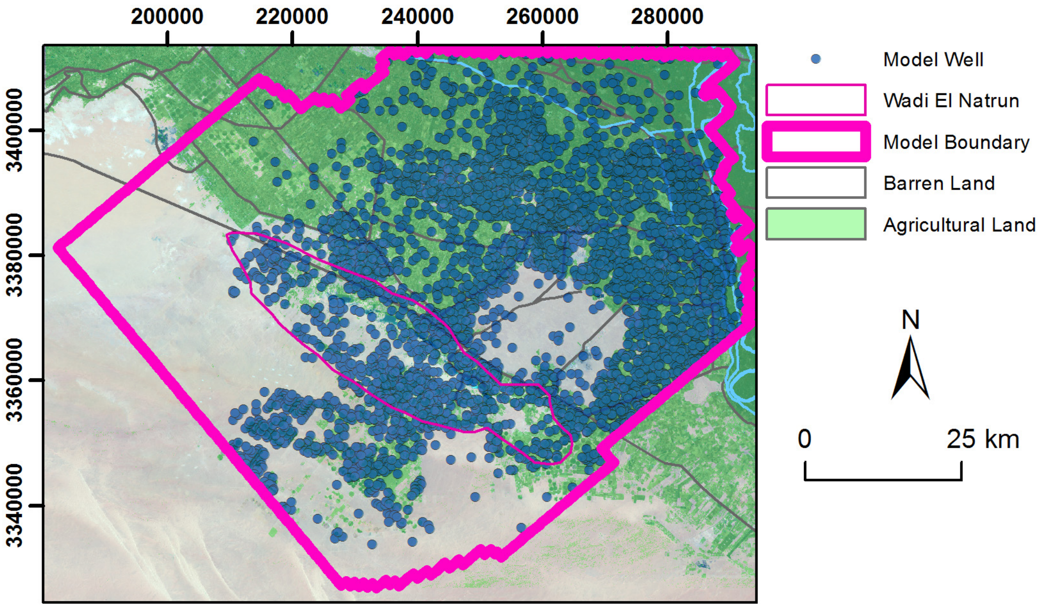

Figure 25. Location of pumping wells and the spatial extent of agricultural land used in management scenarios.

Each management scenario was run in combination with each of the climate change scenarios. The GCM ensemble for each climate change scenario was expressed its mean, and one standard deviation on either side of the mean. Climate change was incorporated through the variable of evapotranspiration, which influences 1-D surface recharge.

3.6.1. Scenario 1: Status Quo

This scenario is designed to elucidate the impact of the status quo (i.e., no changes in irrigation practices) in the Wadi El Natrun depression on groundwater degradation risk in the context of climate change. From a resilience or climate change adaptation perspective, this scenario represents a non-adaptive response to both climate change and groundwater degradation. This scenario is also used a baseline to compare the other two management scenarios using the risk-reduction principle (Eq. 15). Implementing this scenario required no changes to the mathematical routines employed in the well-pumping and recharge models described in Switzman et al. (2013).

3.6.2. Scenario 2: 20% Conservation Target

The purpose of this scenario is to understand the overall potential for water conservation measures to reduce groundwater degradation risk. Conservation targets are typically adopted as an overall policy objective for a specific area, while multiple possible technologies and measures are employed to reduce groundwater usage. Water conservation targets are identified in several of Egypt's climate change adaptation and overall strategic water management policies and guidelines (ARECMEEAA 2005; El-Din 2013). Additionally, several recent project proposals specific to the Egyptian Western Desert have posited that water conservation will be essential to the sustainability of the agricultural and water resource systems in this area (Attia et al. 2007). Egypt's NWRP and Climate Change Adaptation plans do not provide any specific conservation targets, therefore a target of 20% reduction from 2012 consumption by 2022 was used (Eq. 18). In the absence of any definitive Egyptian policy objective, 20% was selected as it was recently cited in the *The Stockholm Statement to the 2012 United Nations Conference on Sustainable Development in Rio de Janeiro (Rio+20 Summit)* as a key target. Specifically, the statement suggests that by 2020, signatories should aim for a "20% increase in total food supply-chain efficiency… [and] 20% increase in water efficiency in agriculture" (http://www.worldwaterweek.org/documents/WWW_PDF/2011/2011-Stockholm-Statement.pdf). It was assumed that in Wadi El Natrun, some water users would achieve this target immediately, while others would take up to the 10 years (i.e., from 2012 to 2022). As such, the time at which each well and MODFLOW recharge cell would reach the 20% reduction target was assigned randomly. It was also assumed that water use decreases to the 20% target occurred linearly over time.

$$Q20_{k,t} = Q_{k,t} \times \frac{(1-0.2)}{D_k} t \quad \{D \mid D \in \mathbb{Z}, 0 < D < 10 < t\} \tag{18}$$

Where *Q20* is the reduced pumping rate for the location, *k* (well or recharge cell), at time, *t* which is defined as the number of years since the initiation of the management scenario relative to the year in which that location achieves the full 20% reduction, *D*.

3.6.3. Scenario 3: Optimized Water Use

This scenario was intended to provide insight into the potential impacts of optimized irrigation water use in groundwater-dependent areas of Wadi El Natrun. Information from the water user questionnaires suggests that the average seasonal groundwater irrigation use is approximately 15 mm and 35 mm per 10 day period in the winter and summer, respectively (Figure 26). These values are in the high range of the crop water requirements for a selected set of commonly grown in Wadi El Natrun (Table 8). Additionally, the 15 mm and 35 mm estimates likely represent conservative figures of water use. Other analyses have also suggested that some prevailing cropping patterns are water-intensive and sensitive to salinity (King and Salem 2013). This heightened sensitivity to salinity has resulted in water users increasing irrigation in order to cope with the harmful effects of saline water (Baietti et al. 2005; Salem et al. 2010). The saline nature of both soil and water in the Wadi El Natrun area, in combination with declining water levels, suggest that drought and salt tolerant crops would provide a measure of resilience for producers, with respect to both groundwater degradation and economic risks of agriculture (Qadir et al. 2008; Khan et al. 2009). By optimizing irrigation system efficiency and growing drought and salt tolerant crops, it is hypothesized that farmers could improve resilience to groundwater degradation by requiring less crop irrigation while maintaining market-viable agriculture.

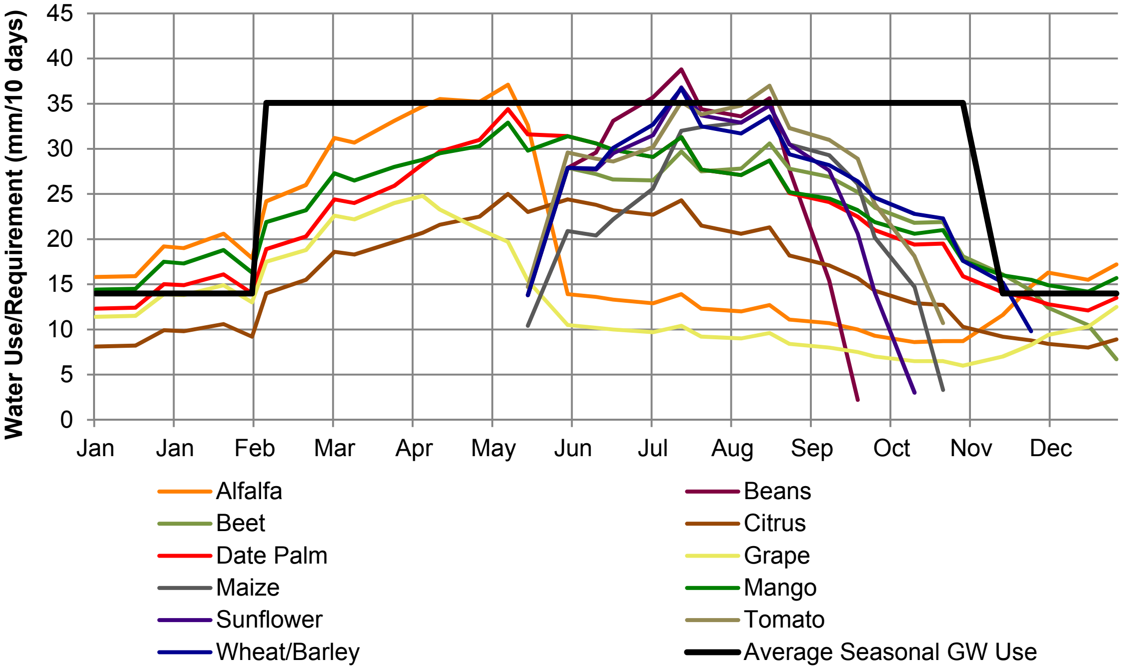

Figure 26. Crop water requirements for selected crops and seasonal groundwater use in Wadi El Natrun. Crop water requirements were computed using CropWat 8.0. Wadi El Natrun sessional use was estimated from survey results.

Water Footprinting has a similar hypothesis, suggesting that the sustainability of water resources in a given basin can be improved by cultivating crops in locations where the total water used and polluted in production is minimized (Mekonnen and Hoekstra 2010). Trade mechanisms then allow water-intense commodities grown elsewhere to be distributed to water-scarce regions where demand for these products is higher (El-Sadek 2009; Tartakovsky 2013). A host of behavioural and socio-economic factors need to be considered if such a water footprint or trade-based scheme were to be considered.

Crop suitability based on the local soil characteristics, already deployed technology, farmer preference and capacity, and market factors have been mapped for the Wadi El Naturn area (Abdel-Hamid et al. 2010; Abdel Kawy 2011). Table 9 provides a summary of the dominant crops grown in Wadi El Natrun, and those assessed for local suitability in previously published studies. Certain varieties of these crop types are deemed salt and drought tolerant, thereby representing more viable options for more dryland farming (Khan et al. 2009).

Table 9. Dominant crops and varieties assessed for soil suitability in Wadi El Natrun

Source	Cropping Patterns
Abdel Kawy (2011)	**Soil Suitability-Assessed Crops:** Beans*, Clover*, Maize*, Onion, Potato, Sugar Beet*, Sunflower*, Tomato, Wheat*
Abdel-Hamid et al. (2010)	**Soil Suitability-Assessed Crops:** Alfalfa*, Barley*, Fodder Beet*, Grapes*, Wheat*
2011 Water user survey	**Most Important Crops (small farms):** Clover*, Corn*, Date Palm*, Garlic, Wheat* **Most Important Crops (medium and large farms):** Beans*, Citrus, Grapes*, Mango*, Olive*, Pear, Tomato, Wheat*
Salem et al. (2010) GWAHS-CS survey	**Most Important Crops (small farms):** Date Palm*, Wheat*, Various Fruit and Vegetable Varieties **Most Important Crops (medium and large farms):** Alfalfa*, Beans*, Citrus*, Grapes*, Mango*, Peach, Vegetables

* Certain varieties considered drought and salt tolerant (Qadir et al. 2008; Saidi et al. 2009; Allen et al. 1998)

Soil capability maps presented in Abdel Kawy (2011), Abdel Hamid (2010) and Veenenbos et al. (1963) were used to spatially distribute crop-water requirements over the study area. For areas where the different maps overlapped, Abdel Kawy (2011) zones were given priority, followed by Abdel Hamid (2010). The soil classes in Veenenbos et al. (1963) were used to distribute crop water requirements (CWRs) in areas outside the extent of the latter two studies (Figure 27).

The monthly MODFLOW pumping rates were assigned as the CWR for the optimal set of crops for that cell. It was further assumed that the irrigation systems are 90% efficient (Baietti et al. 2005). Each well was randomly assigned a service area of 30 to 45 feddans from a uniform distribution. Cropwat 8.0 (http://www.fao.org/nr/water/infores_databases_cropwat.html) was used to calculate monthly CWRs for the five different cropping systems mapped for the groundwater use (Table 10 and Figure 27). Cropwat 8.0 requires inputs of rainfall, meteorological variables to calculate monthly reference evapotranspiration, soil moisture and rooting properties, and crop response variables. These variables were assigned based on a literature review, and are summarized in Table 11.

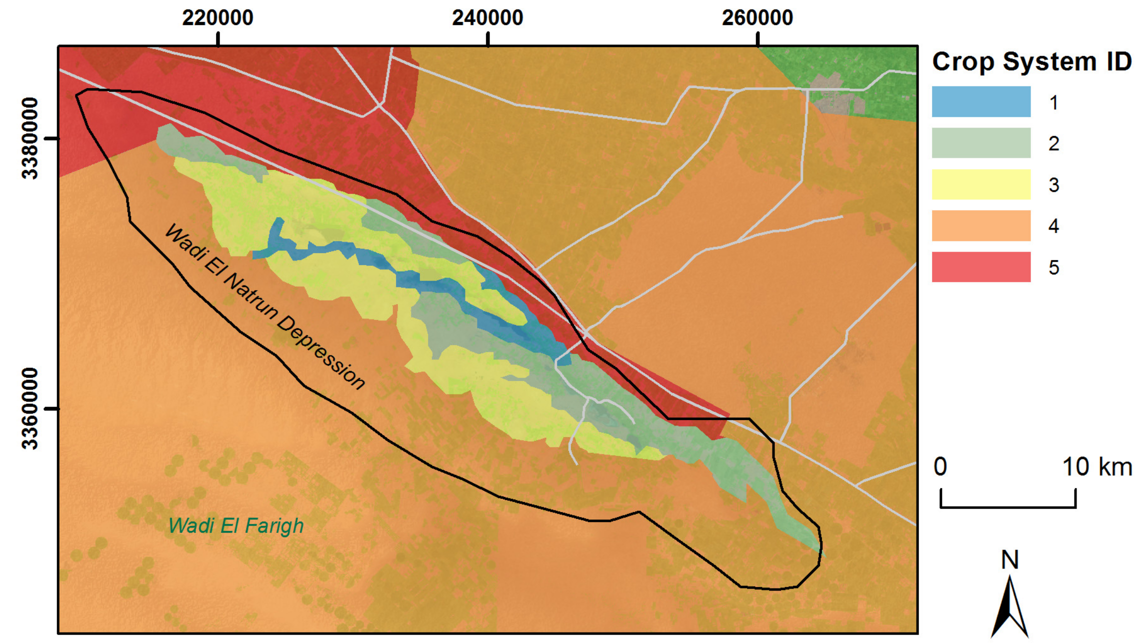

Figure 27. Map of crop systems used for the optimal water use scenario.

Table 10. Crop patterns implemented in Cropwat 8.0 Each crop pattern was applied to optimal soil zones in the model.

Crop Pattern	Crops	Percent Area	Planting Month	Harvest Month
1 – based on Abdel-Kawy (2011)	Beet	100	June	January
2 – based on Abdel-Kawy (2011)	Groundnut	25	March	July
	Potato	25	October	February
	Sunflower	25	May	September
	Tomato	25	May	September
3 – based on Abdel-Kawy (2011)	Alfalfa	25	October	September
	Barley	25	June	December
	Beans	25	June	October
	Maize	25	June	October
4 – Salt and drought tolerant crops grown on large farms (assumes tolerant varieties)	Citrus	20	N/A	March
	Mango	20		March
	Date Palm	20		October
	Grapes	20		June
	Sunflower	20	May	September
5 – based on Abdel Hamid (2010)	Grapes	60	N/A	June
	Alfalfa	10	October	September
	Beet	10	June	January
	Barley	20	June	December

Table 11. Additional Cropwat 8.0 input assumptions

Cropwat 8.0 Module	Variable	Value and Assumptions	
Soil	Total available soil moisture (mm m^{-1})	120 (Eid et al. 2006)	
	Maximum rain infiltration rate (mm day^{-1})	300 – maximum allowable in CROPWAT (El-Sheikh 2000)	
	Maximum rooting depth (cm)	500 - maximum allowable in CROPWAT (Abdel-Hamid et al. 2010)	
	Initial soil moisture depletion (%)	100 – assumes that soil is fully depleted in an arid environment with well-drained sandy soil (Kashouty and Sabbagh 2011)	
Rain	Effective rainfall (mm)	0 – no rainfall considered	
Climate / ET_{ref}	Weather station data	Monthly normal (1970 – 2010) Cairo Airport in-filled data (Switzman et al., 2013)	
Crop	K_c and development stage length (L_d) in days:	$\boldsymbol{K_c}$ (Initial, Mid, Late)	$\boldsymbol{L_d}$ (Initial, Dev., Mid, Late)
	Alfalfa	0.40, 1.15, 0.95	150, 30, 150, 35
	Barley	0.80, 1.10, 0.95	20, 25, 90, 40
	Beans	0.80, 1.15, 0.25	15, 25, 50, 20
	Citrus	0.70, 0.60, 0.70	60, 90, 120, 95
	Grapes	0.30, 0.85, 0.45	150, 50, 125, 40
	Groundnut	0.40, 1.15, 0.60	25, 35, 45, 25
	Date Palm	0.90, 0.95, 0.90	140, 30, 150, 45
	Maize	0.60, 1.15, 0.60	25, 40, 45, 30
	Mango	0.90, 1.10, 0.90	90, 90, 90, 95
	Potato	0.80, 1.15, 0.75	25, 30, 30, 20
	Sunflower	0.80, 1.15, 0.35	25, 35, 45, 25
	Tomato	0.85, 1.20, 0.65	30, 40, 45, 30
		Based on values calibrated to local conditions for local agricultural extension office and Cropwat 8.0 default values	

Climate change was assumed to influence crop water requirements and therefore monthly pumping rates. This was incorporated into the well pumping model by multiplying the computed CWR by the ET anomaly, ET_{anom}, representing the percent change relative to the historical period on a monthly basis (Eq. 19).

$$ET_{anom} = \frac{ET_{ref}(i)}{ET_{ref}(a)} \tag{19}$$

Where ET_{ref} is the reference evapotranspiration of the month, i, and a is the historical mean value for the month of the year.

3.7. Results and Discussion

3.7.1. Climate Change Impacts and Baseline Risk

Climate projections for northern Egypt from CMIP3 have estimated increases in ET_{ref} of between 7% and 9% by 2050 (Terink et al. 2013). The same study predicted no change in precipitation within the same time horizon (Terink et al. 2013). Both water and heat stress associated with climate change are projected to significantly impact crop productivity, with yields for staple crops of wheat, beans, rice and maize estimated to decrease by between 11% and 28% by 2050 (El-Din 2013). These climate stressors have direct implications on agricultural groundwater use. Irrigation requirements are expected to increase as evapotranspiration and crop heat stress rise (Candela et al. 2012). Increases in population in Egypt and Wadi El Natrun are also likely to be major drivers of both increased water demand for domestic and agricultural uses.

Figure 28 presents the bias-corrected monthly ET_{ref} for the GCM cell that contains both the Cairo Airport weather station and Wadi El Natrun. On average, increases in evapotranspiration are expected in each month for the period of 2052 to 2072 (i.e., the period in which 2062 is the midpoint). January, August and November are the only months when certain models for the RCP 4.5 scenario predict slight decreases in ET_{ref}. All models predict ET_{ref} increases for the RCP 8.5 scenario. The average annual increase in ET_{ref} in the RCP 4.5 and RCP 8.5 scenarios is 4.27% and 7.78%, respectively.

Within Wadi El Natrun's water resource system, these increases in ET_{ref} are anticipated to represent a need for more irrigation water should the current crop and irrigation practices be continued. The increases in ET_{ref} can be also expected to translate into greater demand for groundwater, particularly during the months of February, May, September and October when changes in ET_{ref} were the greatest and uncertainty in the model predictions were the lowest.

Climate change may have a doubly reinforcing impact on water demand, as increasing evapotranspiration will lead to more rapid soil salinization. It appears difficult to predict the increase in water demand associated with increased soil salinization, given that this is a behaviourally driven adaptation based on farmer responses. Soil salinization has been considered in the optimal use scenario, however the baseline scenario assumes that the irrigation practices employed for the historical period remain the same. Thus, within the modeling framework, climate change influenced only the mass balance in the 1D recharge model.

Climate change is expected to influence the amount of surface recharge associated with the deep percolation of excess irrigation water. Given that ET_{ref} is a key variable in the recharge model implemented in this study, changes in this variable are likely to influence the amount of water available for deep groundwater recharge. The other possible direct impact of climate change would be water table, which is also expected to be negligible due to the depth of the water table. The exception is the base of Wadi El Natrun, where the saline lakes are recharged by groundwater and the water table is within a few meters of the ground surface.

Groundwater model results demonstrate that there was no significant difference in any of the risk indicators among the climate change scenarios. The corollary is that the influence of baseline groundwater pumping far outweighs that of climate change. That being said, the ecosystems associated with groundwater discharge zones at the base of Wadi El Natrun will be subjected to higher levels of ET_{ref} and can thus be expected dry more rapidly in summer months.

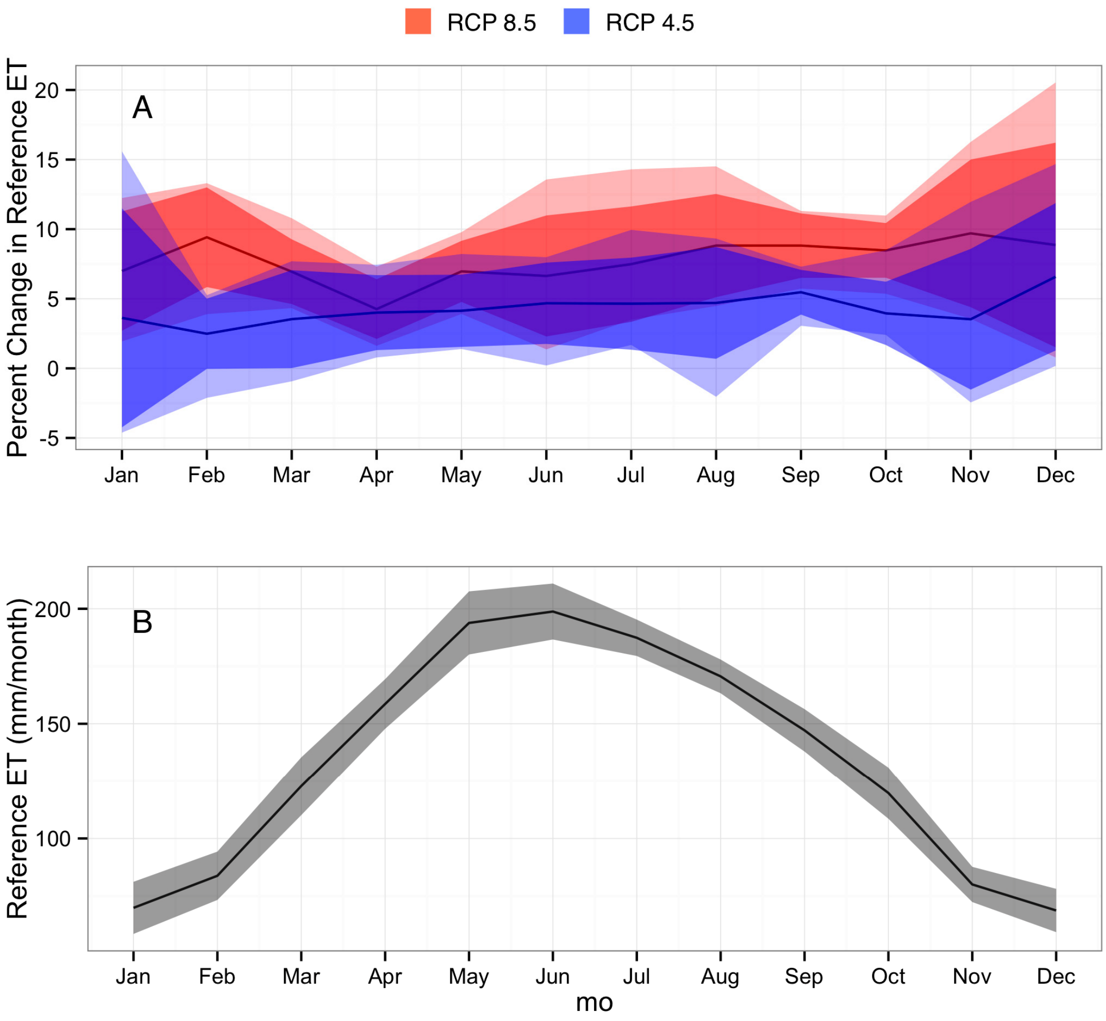

Figure 28. (A) Projected changes in ET_{ref} for the period of 2052 to 2072 (i.e., average centered around 2062) for both climate change scenarios. Least transparent section denotes the minimum and maximum for the ensemble, moderately opaque denotes the standard deviation, and lines represent the average. (B) Monthly ET_{ref} for the baseline period (1957 – 2011). Shaded grey area denotes the standard deviation.

3.8. Management Scenarios and Risk Reduction

It is evident an analysis of the results of the well pumping routine for the two management scenarios, that significant water savings result in both cases (Figure 29). It is striking to note however that by the end of the analysis period to 2062, the optimal use scenario would have saved an average of 72% more water than the 20% reduction policy. This has significant implications for the implementation of conservation policy, namely that efforts targeting specific commodity incentives, such as Water Footprinting, would have a far more significant impact compared to simply achieving an arbitrary demand reduction target. Additionally, the optimal use scenario provides greater savings in the months when the greatest amount of irrigation is needed and when climate change is expected to exert the greatest influence (i.e., May through September). During this period, an optimal use scenario would decrease water use by 14% more compared to the 20% reduction scenario. Even greater waters savings would be expected if more water conservative and salt tolerant crops were to be used, such as olives, pomegranate, loofa, and other improved varieties (Qadir et al. 2008; Khan et al. 2009).

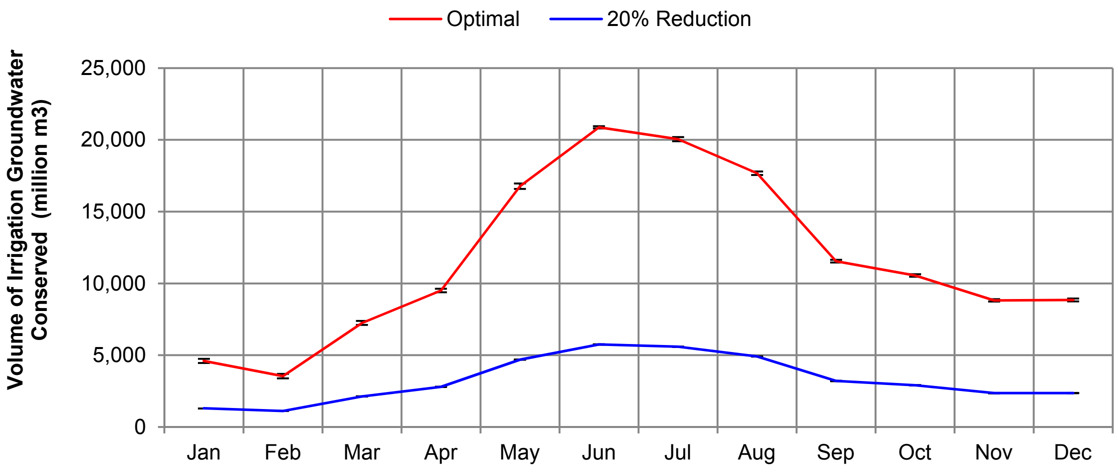

Figure 29. Monthly total water savings for the period of 2012 to 2062 (average of all climate change scenarios) for each management scenario. Error bars represent the variance among all climate change scenarios.

A comparison of the normalized exposure scores for the different classes of risk receptors confirms the hypothesis that different water user populations and ecosystems are variably exposed to groundwater degradation (Figure 30). In particular, Figure 30 confirms the farm typology presented in Salem et al. (2010) and King and Salem (2012), which states that smaller farms are more exposed to falling groundwater levels than larger farms. Figure 30A demonstrates that the gardens and small farms all had exposure scores greater than 2 and the large farms had scores of less than 2. The sample size for each category is not large enough to determine if this relationship is statistically significant, however Figure 30A shows that there is no overlap in the error bars among these risk receptors, indicating a strong likelihood that this relationship stands. This is likely the case because smaller-scale farms rely more heavily on shallower groundwater sources. This same relationship was less obvious for the storage indicator (Figure 30B); likely because of the difference in the way the storage and water levels indictors were defined. The water level indicator was defined by assessing predicted heads relative to a threshold as an absolute value. For any given location, as that threshold is approached, exposure scores would increase. In cases where the overall drawdown in two separate locations is the same, that with the absolute water level closer to the threshold would show a higher exposure. The storage indicator was defined as a change in time, which means that unique characteristics of a given risk receptor are not as influential in the exposure scores as the cumulative impact to aquifer storage. For this indicator, the exposure is a relative to the initial condition at each receptor.

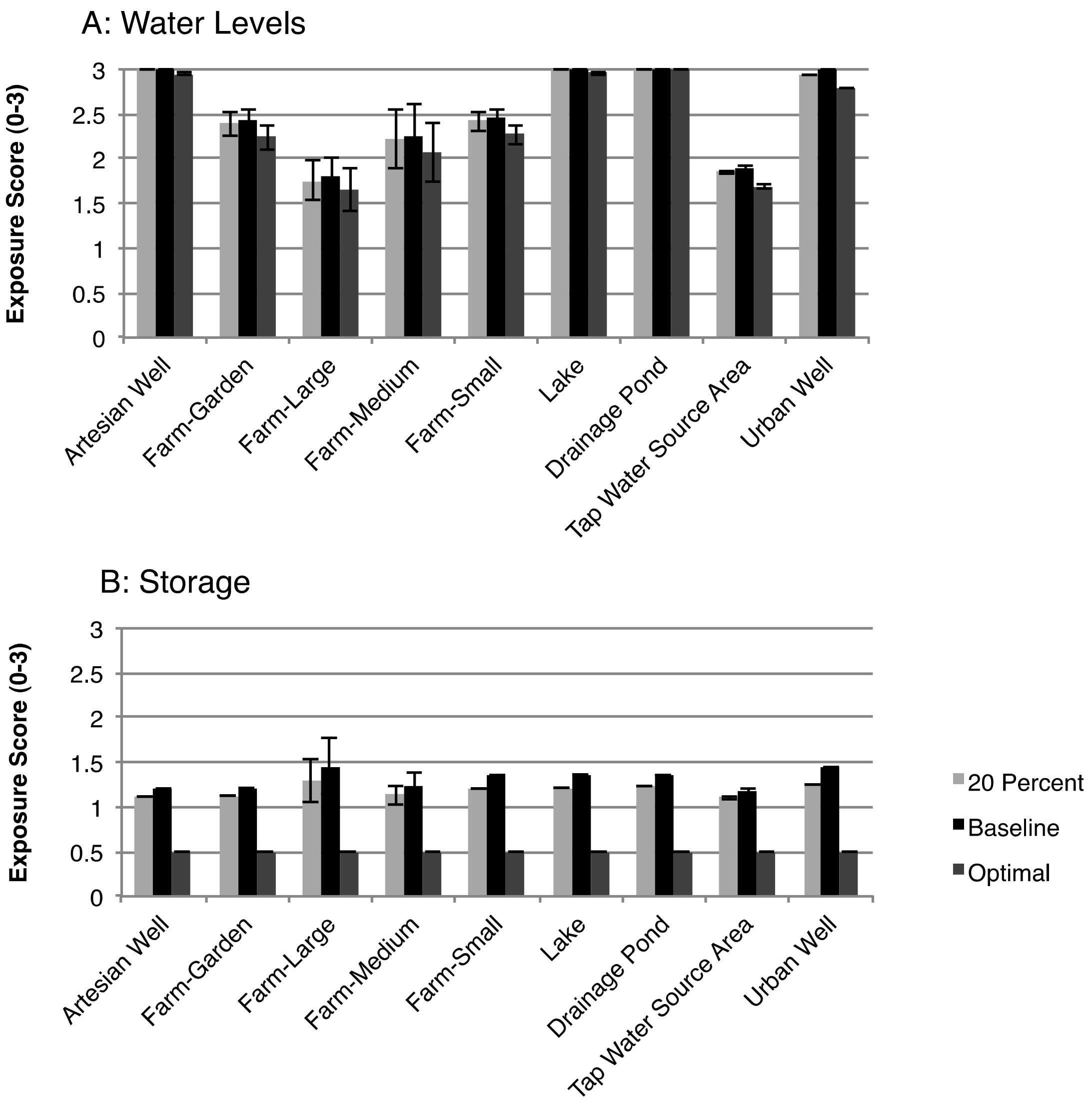

Figure 30. Normalized hazard exposure scores for the different classes of risk receptors and model aquifers for the indicators of (A) water levels and (B) groundwater storage. Error bars represent the standard deviation of the normalized risk score for the category for all climate change scenarios.

It is apparent from Figure 30B that the optimal water use scenario is projected to provide a significant reduction in exposure to groundwater degradation compared to the 20% reduction target scenario. Further analysis of risk reduction for each of the two water conservation scenarios suggests that the optimal use scheme provides much significant benefits across all risk receptor classes (Figure 31). The risk reduction provided by the optimal use scenario is of greatest benefit to those water user and ecological systems with the greatest vulnerability to groundwater degradation. This indicates that such a policy would increase groundwater resource sustainability by reducing impacts to the aquifer, but also by ensuring that the benefits are equitably distributed to those at the greatest risk of degradation.

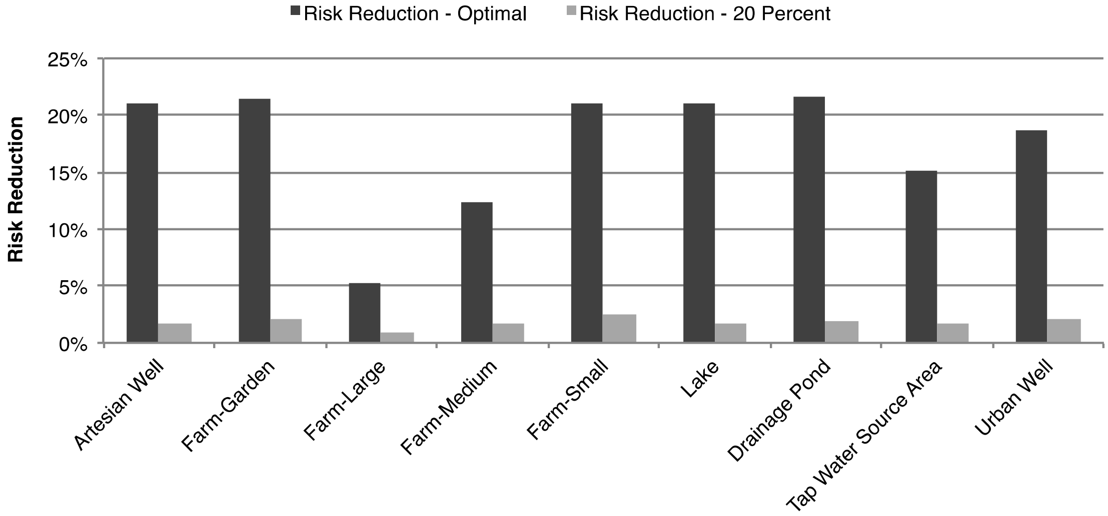

Figure 31. Comparison of risk reduction between the 20% reduction and optimal use scenarios for the storage indicator

Although it was not explicitly part of the indicator framework, it is useful to examine the impact of the management scenarios on groundwater level drawdown from 2012 to 2062, as this is an expression of the impact to both groundwater storage and individual users over the management period. Specifically, changes in rates of drawdown and the point at a drawdown curve flattens out can be used to identify when an aquifer reaches equilibrium (Zhou 2009). Figure 32 presents a hydrograph for the area around Kafr Dawoud at the base of Wadi El Natrun. It is evident from this figure that under both the baseline and 20% reduction scenarios, water levels continuously decline over time, not reaching equilibrium at any point during the simulation period. The hydrograph is for the Pleistocene aquifer layer and shows a steady decline in water levels from approximately 1990 onward for the baseline scenario. This, along with the trends observed in the other management scenarios, was common throughout the study area. The bottom of the Pleistocene aquifer at this location is at -52.92 m asl and it is clear that the trend is toward drying this entire MODFLOW cell completely, with water levels dropping to within 85% of the bottom of the cell by this time. In this case, the reason the curve appears to approach equilibrium, following a logarithmic curve, is due to the algorithm employed in the MODFLOW well package to smoothly transition the cell to a dry state when heads drop below 50 percent of the cell's thickness (Harbaugh 2005). Similar trends are observed in the Miocene aquifer, however in this aquifer the depth of the cell is a -354 m als, so the exponential trend could be the water level approaching equilibrium (Figure 33). The simulation period was not long enough to determine this definitively. These hydrographs also reinforce the finding that the optimal use scenario provides the greatest risk reduction with respect to groundwater degradation. It should be noted that these differences between the optimal use and 20 percent reduction scenario were well above the uncertainty bounds of the groundwater model (i.e., between 3 and 12 m). In many parts of the study area, the difference between the baseline and 20 percent scenario were within the uncertainty bounds of the groundwater model.

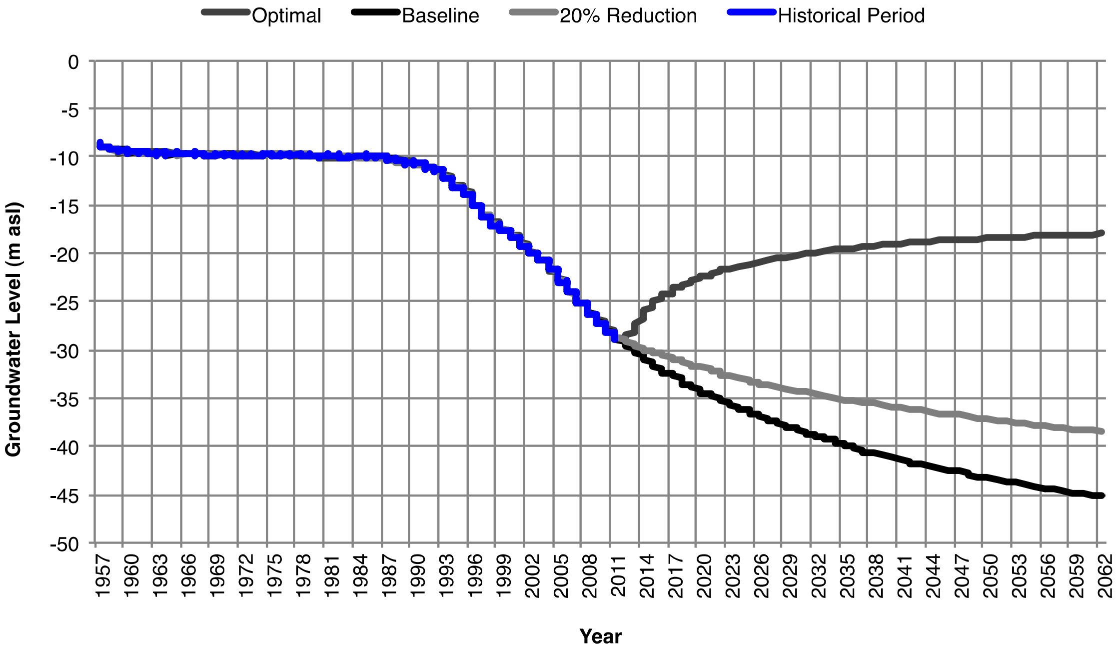

Figure 32. Example hydrograph of model results for the three management scenarios for the area around Kafr Dawoud in the Pleistocene aquifer at the base of Wadi El Natrun.

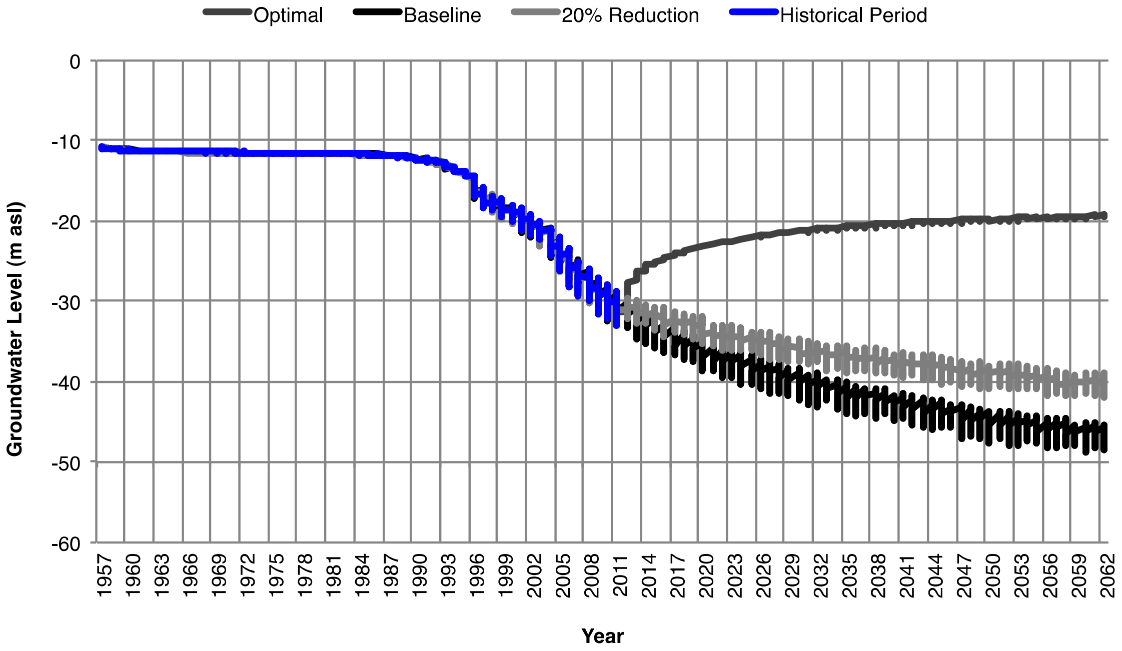

Figure 33. Example hydrograph of model results for the three management scenarios for the area on the western slopes of Wadi El Natrun for the Miocene aquifer

The increase in hydraulic head associated with the optimal use scenario poses a potential increase in risk to surface contamination. It should be noted however, that this risk is a result of the influence of water levels on the DRASTIC calculation, for which "depth to water table" is the most heavily weighted factor in the work of Abdelkhalek (2013). By the year 2062, groundwater levels will have risen by up to 20 m in many parts of Wadi El Natrun. Based on the DRASTIC analysis conducted in Abdelkhalek (2013), this would increase the intrinsic aquifer vulnerability by influencing the "depth to water table" risk factor. Essentially, the score for this DRASTIC risk factor would increase. Based on this analysis, surface contamination risk under the optimal use scenario would by an average of 44% higher than the baseline and 20% reduction scenarios. The average risk score for both of these other two scenarios is calculated to be 0.5 with it would be approximately 2 for optimal use scenario. It should be noted that any surface contamination risk is mitigated by the fact that there is minimal surface recharge in most of the Wadi El Natrun area.

3.9. CONCLUDING REMARKS

This was the first study the authors are aware of that has attempted to model the impacts of various management and climate change scenarios in Wadi El Natrun. The results presented in Section 6 demonstrate that important trade-offs need to be considered when planning for sustainable groundwater management in this area. This is particularly the case due to the various different kinds of groundwater hazards present in the area.

Although the optimal water use scenario provided the greatest risk reduction with respect to groundwater degradation, results were less clear for the water level exposure indicator, and surface contamination risk actually increased. There is also uncertainty associated with all climate model projections (Taylor et al. 2012). Despite quantifying the uncertainty of current projections of ET_{ref}, the greatest unknown is how farmers and ecosystems will cope with changes, as has been consistent with other studies (Conroy et al. 2011).

The modeling presented in this study demonstrated that the impacts of groundwater abstraction and agricultural development outweigh the impacts of climate change on the local groundwater system. That being said, if groundwater levels continue to decline, the ecosystems, local communities and agricultural sector relying on groundwater will have decreased access to the only reliable source of freshwater in the area. This poses a significant risk to the resilience of local ecosystems and farm systems by reducing their capacity to cope with the projected increases in ET_{ref} associated with climate change. Therefore, from a climate change adaptation and sustainability standpoint, programs that increase the capacity of local water users to conserve freshwater should be emphasized. The risk analysis presented in this paper also highlighted the fact that the most water-conserving strategy (i.e., the optimal use scenario) provided the greatest risk reduction to the most vulnerable populations in Wadi El Natrun. This suggests that the implementation of such a strategy would sufficiently address the socio-economic equity aspect of sustainability. Steady declines in groundwater levels and depletion of storage are observed for the baseline and 20% reduction, indicating that the system is not likely to reach equilibrium under the current groundwater pumping regime. Instead, significant adaptive or transformative management is needed to achieve significant risk reduction.

This has significant implications for the implementation of conservation policy, namely that efforts targeting specific commodity incentives using approaches like Water Footprinting would have a far more significant impact compared to simply achieving an arbitrary demand reduction target.

There has been significant debate among hydrogeologists as to the appropriate definition of "groundwater sustainability". Although recent reviews of this issue have posited key principles that have been applied in the current study, the analysis of risk demonstrates that definitions of sustainability continue to require subjective interpretation, especially to be applied in specific local contexts. Sustainability in its purest definition is simply not an achievable target in Wadi El Natrun, given the hydrologic regime of little to no natural recharge. In this context risk reduction through adaptive or transformative management is the next best alternative.

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CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Overall Conclusions

Agricultural land reclamation using groundwater resources has had a profound impact on the hydrogeology, ecosystem health, and overall human security of Wadi El Natrun. Since groundwater development in the accelerated in the area in the 1990s, groundwater levels have declined by up to 20 m, reaching a drawdown rate of almost 1 m year^{-1}. The research presented in this thesis demonstrated that these declines are the result of a groundwater over-abstraction in a hydrogeological setting that is by nature highly susceptible to storage and water level decline due to a lack of natural recharge. This makes sustainability an almost unachievable target, should groundwater be exclusively relied upon in the area. Groundwater degradation risk reduction supported by adaptive or transformative management represents a more realistic target. A key aim was to assess the potential impact of water conservation in the context of climate change. This required developing an understanding of the local groundwater system, its influences and vulnerabilities of local ecosystems and populations to various elements of degradation. Several conclusions can be drawn from this work, as follows:

1. Groundwater sustainability in Wadi El Natrun goes beyond the technical concepts of aquifer storage and safe yield, and extends to socio-ecological and intergenerational equity. Previous work in Wadi El Natrun posited a typology for understanding groundwater vulnerability using a socio-ecological approach (Salem et al. 2010). The research in this thesis demonstrated that this typology, based on farm size, indeed holds true with respect to exposure to groundwater degradation risk. Fieldwork to expand the spatial coverage of information gathered in the first phase of the GWAHS-CS project further confirmed that the dominant groundwater issues of concern in Wadi El Natrun are falling water levels and salinization.
2. A scenario of optimized water use, based on both increasing irrigation system efficiency and crop rotations, provides substantial risk reduction compared with establishing and meeting a 20% conservation target with respect to overall

groundwater degradation. The optimized scenario is also based on implementing measures that are locally relevant to the environmental, cultural and economic contexts of Wadi El Natrun. Although it provides the greatest level of risk reduction, the optimal use scenario also increases risk with respect to surface contamination by increasing the water table level. This means that any targeted conservation strategy must also incorporate measures to reduce the likelihood to surface contamination. Steady declines in groundwater levels and depletion of storage are observed for the baseline and 20% reduction, indicating that the system is not likely to reach equilibrium under the current groundwater pumping regime. Instead adaptive or transformative management is needed to achieve significant risk reduction. This has significant implications for the implementation of conservation policy, namely that efforts targeting specific commodity incentives using approaches like Water Footprinting would have a far greater impact compared to simply achieving an arbitrary demand reduction target.

3. Climate change analysis demonstrates that reference evapotranspiration is likely to increase by between approximately 4 and 8 percent by the 2060s. The direct influence of climate change on groundwater resources was significantly less than that exerted by pumping. The implication is that the most vulnerable ecosystems and populations will be subject to groundwater degradation while climate change adds pressure for additional water to support farm and ecological systems. The uncertainty related to how populations and ecosystems will adapt to climate change in Wadi El Natrun is substantial and represents an important limitation of the research presented in this thesis. Nonetheless, the influence of climate change itself appears be less important on groundwater degradation then that of abstraction.
4. An important objective of this research was to elucidate historical trends in groundwater and surface water flow regimes, water use and their relationships within the over hydrologic system. Groundwater levels across the study area have been declining, primarily in the Pliocene and Pleistocene aquifers in the Wadi El Natrun depression as the extent of agricultural land-use has increased, with the greatest declines beginning in the 1990s. This has been strongly linked to

degradation of water quality, salinity in particular, although the geochemical processes associated with these trends are highly complex and uncertain. Groundwater levels in the Miocene aquifer have also declined, but to a lesser extent. Groundwater adjacent to the Nile's Rosetta branch has declined far less than in the Wadi El Natrun depression. This is partly because there is less abstraction in this area, but also because surface recharge and infiltration from the Nile itself are greater than elsewhere. This is the primary connection between the groundwater and surface water systems. Although surface water irrigation and drainage canals are present throughout much of the study area, recent government projects to line them with concrete have lessened the extent to which primary and secondary canals would contribute to groundwater recharge through seepage. Excess irrigation water on individual farm canals and fields represents the major source of surface water recharge to the local groundwater system.

4.2. Contributions

The research presented in this thesis built on previous work conducted as part of the UN's GWAHS-CS project. The previous GWAHS-CS work, documented in Salem et al. (2010), identified several possible ideas for sustainable groundwater management that could realistically be implemented in Wadi El Natrun. Resulting from that work, a need was identified to model the potential impacts of these management ideas on the actual groundwater resources in Wadi El Natrun. Filling this gap was the principle objective of this research.

Although several prior groundwater models have been created for Wadi El Naturn, none of them incorporated the three main aquifers or have been validated under transient conditions. Additionally, previous models of the area have made general assumptions about the spatio-temporal distribution of well pumping and groundwater recharge. The research in this thesis resulted in a fully calibrated and validated 3-D groundwater model, along with statistical routines for modeling groundwater recharge and pumping rates over time. A key benefit is that this model can be used to understand dynamic influences on the groundwater system.

Within the broader field of hydrogeology, this work contributes to the body of research pertaining to the use of sparse data in modeling. It is anticipated that the approach presented can be used to build additional modeling capacity in other dryland environments, where data are sparse. Despite the sparseness of the data available for groundwater model calibration and validation, it was possible to create a 3-D transient groundwater and quantify its uncertainty.

This is also the first research the author is aware of that has made use of the most recent climate change projects in CMIP5 for Egypt and the first that has looked at climate change in Wadi El Natrun specifically. Additionally, there are few examples in the literature of bias-correction approaches for directly downscaling reference evapotranspiration.

4.3. Recommendations

1. It is important to share and validate the findings of this study with local water users in Wadi El Natrun prior to designing and implementing any strategy aimed at water conservation. There is substantial local knowledge among water users on effective ways of treating saline water and growing crops with minimal water that can be leveraged. That being said, there is also a desperate need to better enable the sharing of that knowledge on the successes, barriers and lessons in water conservation. Additionally, economic measures such as virtual water trading, aided by water footprint analysis, can be undertaken to benefit both economic development and water conservation simultaneously. Water sharing systems, such as communal wells and local water user associations could be developed to enhance the governance of local groundwater. Because all these potential measures require direct participation, it is essential to ensure any management approach is implemented in close collaboration with local water users. It should be noted that all survey respondents were asked if they were interested in attending a planning workshop or meeting on communal groundwater management and a majority of them responded in the affirmative. This underscores the need to invest in initiatives that help the local community fully

leverage their capacity for adaptive and/or transformative management in the face of environmental risks.

2. Preliminary data were collected as part of the fieldwork undertaken for this thesis to assess water quality related to biological and chemical parameters. The results of these analyses were extremely valuable to local water users and could aid them in implementing on-farm management measures that leverage the full range of soil, water quality and water quantity conditions on their farms. It is recommended that water quality sampling work continue and that results be disseminated to farmers. Further more, it would be of greater benefit to continuously sample the same locations to develop a temporal record of water quality changes. This could be linked to capacity building efforts and initiatives aimed at more communal water management. There is significant uncertainty with respect to the linkages between degradation in water quality and quantity and current data are inadequate for properly analysing spatio-temporal trends to understand the physics. This is especially the case with respect to salinization of groundwater.
3. Additional work should be done to assess the impact of climate change and better understand how local populations and ecosystems can adapt to the risks. This can involve the incorporation of additional GCMs in a modeling exercise, but it is also important to use other downscaling methods to derive projections with greater spatial resolution.
4. The groundwater model created for this thesis would benefit significantly from local grid refinement and incorporating additional information on the hydrogeological system. Specifically, it is recommended that additional work be completed to understand the role of potential deep groundwater recharging local aquifers across complex fault systems present in Wadi El Natrun.

APPENDICES

A. Farm Survey and Recording Sheet

SURVEY PERMISSION:
1. We are students doing research about how the groundwater affects farm productivity.
2. We are hoping to understand the problems of declining water tables and water quality in Wadi Natrun.
3. We would like to ask you some questions about the farm, the water in Wadi Natrun and make some tests of the water and well.
4. The result of our work will be an estimation of the available water for irrigation in Wadi Natrun.
5. We are very interested to learn from you about how you manage your farm, and deal with some of the problems related to farm productivity and water facing Wadi Natrun.
6. We hope the expertise you teach us can be used to provide other farmers and managers with information to help resolve the water and farm production issues here.
7. We will be taking the information you tell to make a scientific report.
8. We will provide you with a small report about your farm in a few weeks, and a more detailed assessment of the water in Wadi Natrun later on.
9. We will not release your name or the name of the farm in any of these reports, but the location may appear on certain maps of the whole Wadi Natrun area.
10. Would it be okay with you if we ask you some questions about your farm, and take some water quality and water table measurements at your wells?
11. We can stop the survey at any time and erase the answers if you want.

أذن عمل استبيان:
1. نحن طلاب نقوم ببحث عن المياه الجوفية وتأثيرها على انتاجية المزراع.
2. احنا نأمل أننا نفهم مشاكل نقص المياه وجودتها في وادي النطرون.
3. نحن نود نسألك بعض الأسئلة عن المزرعة وعن المياه، ونعمل بعض الاختبارات على مياه البير.
4. نتيجة عملنا ستكون قياس لنسبة المياه المتاحة للري في وادي النطرون.
5. نحن مهتمون جدا لنتعلم منك كيف تنظم مزرعتك، وكيف تتعامل مع المشاكل اللي تواجهك التي تتعلق بالانتاجية والمياة في وادي 6. النطرون. نحن نأمل أن الخبرات اللي
حتعلمها لينا ممكن تساعد مزارعين اخرين ومسئولين في حل مشكلة المياه والانتاجية.
7. نحن سنأخذ هذه المعلومات علشان نعملك تقرير علمي.
8. نحن سنعطيك هذا التقرير في عشرة أيام، وتقييم بالتفصيل بعدين عن المياه في وادي النطرون.
9. نحن لن ننشر أسمك أو أسم مزرعتك في أي تقرير، لكن موقع المزرعة ممكن يظهر على خريطة وادي النطرون كله.
10. هل يوجد مشكلة لو سألناك بعض الاسئلة وبعدين أخدنا عينات المياه وقسنا وش المياه في البير عندك؟
11. نحن ممكن أن نوقف الاستبيان في اي وقت ونسمح كل الاجابات اذا اردت ذلك.

التاريخ / الوقت Date / Time	GPS GPS Waypoint	أذن عمل استبيان: Permission to do survey provided ☐	أسم المزرعة ؟ 1. What is the name of the farm?	ها كام سنة 2. How old is this farm?	عندك كام فدان؟ 3. How many Feddans is your farm?	ك كام بير في المزرعة 4. How many wells are on your farm?
صيل اللي 5. What crops do you grow?	رع كل محصول كام 6. How many Feddans are grown for each crop?	كل م 7. In which month is crop each planted / harvested?	سد أد ايه من كل 9. How much of each crop is harvested?	محصول؟ تنق 10. What method of irrigation do you use for each crop – drip, flood or sprinkler?	في الاسبو 11. How many times a week do you irrigte each crop in the summer and in the winter?	سول كام 11. How many hours do you irrigate each crop each time?
بير Well ID	ر البير على 13. How deep is each well?	المياه على 14. What is the water depth in each well?	خلال 15. Does this water depth change during the year? If so, how and when?	كل بير اد 16. How old is each well?	البير؟ 17. What do you think about the water in the well, is it good, is it bad, how does it taste?	خلال الس 18. Does the water changes during the year? If so, how and when?

وي ب 18. Do you have concerns or problems about the water you use for irrigation, drinking or domestic use?	ترت المحاصيل دي علشان تزرعها ولم تختار 19. Why have you chosen to grow the specific crops you do?	عمله في ال 21. What future plans do you have for your farm?	قل أو مشاكل من انتاجية 19. Do you have any concerns or problems about the productivity of your farm?

هناك اجتماع عن المياه وانتاجية المزارع في وادي النطرون، تحب

22 .Would you be interested in attending a meeting about the water and farm productivity issues in Wadi Natrun? ☐

B. Survey Question IDs

UniqueQID	Question	HasCropType
1	Number of wells	No
2	Type of pump	No
3	What crops do you grow?	Yes
4	How many feddans per crop?	Yes
5	What the total area of your farm? (Feddan)	No
6	How often do you irrigate your farm in the winter? (times/week)	Yes
7	How often do you irrigate your farm in the summer? (times/week)	Yes
8	For how long do you irrigate your crops each time, on average in the winter? (hrs)	Yes
9	For how long do you irrigate your crops each time, on average in the summer? (hrs)	Yes
10	What irrigation method do you use for each crop?	Yes
11	What month do you plant each crop?	Yes
12	What month do you harvest each crop?	Yes
13	How much of each crop is harvested per Feddan, on average?	Yes
14	Why do you grow the specific crops you do?	No
15	What challenges do you have growing crops?	No
16	What water-related challenges do you see for the area?	No
17	What goals do you have for your farm?	No
18	Please explain your irrigation schedule/method.	No

C. Crop Types by Survey Respondant

UniqueQID	RespondantID	CropNumber	Response	CropArea_Feddans
3	F1	1	grasses	80
3	F1	2	potato	
3	F1	3	tomato	
3	F10	1	grapes	
3	F10	2	guava	
3	F10	3	lemon	
3	F10	4	orange	
3	F11	1	eggplant	
3	F11	2	onion	
3	F12	1	garlic	1
3	F12	2	wheat	1.5
3	F15	1	guava	65
3	F15	2	olive	50
3	F15	3	pear	20
3	F15	4	grasses	10
3	F18	1	wheat	
3	F18	2	watercress	
3	F18	3	clover	
3	F19	1	apple	8
3	F19	1	mango	8
3	F19	2	grapes	7
3	F19	3	wheat	5
3	F19	4	beans	5
3	F20	1	clover	4
3	F20	2	mango	4
3	F20	3	mango	4
3	F20	4	corn	4
3	F20	5	beans	4
3	F20	6	tomato	4
3	F20	7	kroomb	4
3	F20	8	pepper	4
3	F21	1	orange	6
3	F21	2	mango	6
3	F21	3	pear	6
3	F21	4	tomato	6
3	F21	5	beans	6
3	F21	6	eggplant	6
3	F21	7	onion	6
3	F21	8	cantaloupe	6
3	F21	9	cucumber	6
3	F21	10	wheat	1
3	F22	1	clover	0.75
3	F22	2	beans	0.75
3	F22	3	pepper	0.75
3	F22	4	garlic	0.75
3	F23	1	corn	
3	F23	2	clover	
3	F23	3	wheat	
3	F25	1	mango	20
3	F25	2	orange	30
3	F25	3	wheat	
3	F25	4	clover	
3	F27	1	grapes	
3	F27	2	mango	
3	F27	3	orange	
3	F28	1	date palm	
3	F28	2	lemon	1.5
3	F28	3	mango	6.5
3	F28	4	arabic 1	3
3	F28	5	arabic 2	1
3	F29	1	wheat	0.75
3	F29	2	clover	0.75
3	F29	3	date palm	
3	F30	1	clover	0.75
3	F30	2	wheat	0.75
3	F31	3	date palm	50
3	F31	1	orange	
3	F31	2	grapes	30

UniqueQID	RespondantID	CropNumber	Response	CropArea_Feddans
3	F31	3	olive	50
3	F31	4	mango	60
3	F32	1	wheat	8
3	F32	2	onion	7
3	F32	3	corn	6
3	F32	4	clover	5
3	F34	1	mango	12
3	F35	1	corn	1
3	F35	2	clover	1
3	F35	3	date palm	0.5
3	F36	1	olive	80
3	F36	2	loofa	2
3	F37	1	mango	75
3	F37	2	date palm	75
3	F38	1	orange	7
3	F38	2	mandarin	3
3	F38	3	lemon	2
3	F38	4	onion	2
3	F38	5	eggplant	5
3	F38	6	pepper	2
3	F38	7	grapes	4
3	F38	8	corn	1
3	F38	9	beans	5
3	F38	10	beets	5
3	F39	1	cantaloupe	20
3	F39	2	watermelon	20
3	F39	3	tomato	1
3	F40	1	apricot	20
3	F40	2	grapes	40
3	F40	3	pear	20
3	F40	4	orange	25
3	F41	1	olive	40
3	F41	2	pasture	20
3	F44	1	pomegranate	25
3	F44	2	olive	28
3	F44	3	beet	6
3	F5	1	orange	7
3	F5	2	mandarin	7
3	F5	3	mango	5
3	F5	4	peanuts	1
3	F5	5	beans	1
3	F50	1	mango	31
3	F54	1	pear	40
3	F56	2	pasture	
3	F56	1	corn	
3	F56	2	wheat	
3	F56	3	beans	
3	F8	1	bananas	6
3	F8	2	orange	20
3	F8	3	orange	20
3	F8	4	orange	20

D. Survey Results

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
31	1	4	Farm-20		
36	1	1	Farm-28		
9	1	1	Farm-34		
6	1	1	Farm-26		
27	1	4	Farm-17		
13	1	1	Farm-3		
11	1	2	Farm-1		
12	1	1	Farm-2		
14	1	1	Farm-4		
15	1	1	Farm-5		
17	1	2	Farm-7		
18	1	3	Farm-8		
20	1	1	Farm-10		
22	1	2	Farm-12		
23	1	2	Farm-13		
34	1	1	Farm-23		
29	1	2	Farm-19		
33	1	1	Farm-22		
4	1	1	Farm-24		
5	1	1	Farm-25		
35	1	5	Farm-27		
37	1	2	Farm-29		
38	1	1	Farm-30		
1	1	1	Farm-31		
7	1	2	Farm-33		
10	1	1	Farm-35		
21	1	3	Farm-11		
28	1	1	Farm-18		
19	1	1	Farm-9		
2	1	1	Farm-32		
16	1	3	Farm-6		
30	1	1	U2		
47	2	electric	Farm-34		
44	2	diesel	Farm-26		
65	2	electric	Farm-17		
51	2	electric	Farm-3		
49	2	electric	Farm-1		
50	2	electric	Farm-2		
52	2	electric	Farm-4		
53	2	electric	Farm-5		
55	2	electric	Farm-7		
56	2	electric	Farm-8		
58	2	electric	Farm-10		
61	2	electric	Farm-13		
72	2	electric	Farm-23		
62	2	electric	Farm-14		
67	2	electric	Farm-19		
71	2	electric	Farm-22		
42	2	diesel	Farm-24	0.45 m3/min	
43	2	electric	Farm-25		
75	2	diesel	Farm-29	80 m3/hr flow rate	
76	2	electric	Farm-30		
45	2	electric	Farm-33		
48	2	electric	Farm-35	40 hp; 80 kw generator; 4.7 bar pressure	
59	2	electric	Farm-11		
66	2	electric	Farm-18		
63	2	electric	#N/A		
64	2	electric	#N/A		
70	2	electric	#N/A		
57	2	electric	Farm-9	115 m3/hr	
54	2	electric	Farm-6		
68	2	electric	U2		
411	3	grasses	Farm-20		1
449	3	potato	Farm-20		2
487	3	tomato	Farm-20		3
416	3	grapes	Farm-28		1
454	3	guava	Farm-28		2
492	3	lemon	Farm-28		3
530	3	orange	Farm-28		4
389	3	eggplant	Farm-34	white variety; 36 bags sent	1

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
				to mkt	
427	3	onion	Farm-34	has the highest production	2
386	3	garlic	Farm-26		1
424	3	wheat	Farm-26		2
521	3	grasses	Farm-17		4
407	3	guava	Farm-17		1
445	3	olive	Farm-17		2
483	3	pear	Farm-17		3
469	3	clover	Farm-3		3
431	3	watercress	Farm-3		2
393	3	wheat	Farm-3		1
5207	3	apple	Farm-1		1
505	3	beans	Farm-1		4
429	3	grapes	Farm-1		2
391	3	mango	Farm-1		1
467	3	wheat	Farm-1		3
544	3	beans	Farm-2	hereti variety	5
392	3	clover	Farm-2		1
506	3	corn	Farm-2		4
620	3	kroomb	Farm-2		7
430	3	mango	Farm-2		2
468	3	mango	Farm-2		3
658	3	pepper	Farm-2		8
582	3	tomato	Farm-2		6
546	3	beans	Farm-4		5
660	3	cantaloupe	Farm-4		8
698	3	cucumber	Farm-4		9
584	3	eggplant	Farm-4		6
432	3	mango	Farm-4		2
622	3	onion	Farm-4		7
394	3	orange	Farm-4		1
470	3	pear	Farm-4		3
508	3	tomato	Farm-4		4
736	3	wheat	Farm-4		10
433	3	beans	Farm-5		2
395	3	clover	Farm-5		1
509	3	garlic	Farm-5		4
471	3	pepper	Farm-5		3
435	3	clover	Farm-7		2
397	3	corn	Farm-7		1
473	3	wheat	Farm-7	reported as "grains"	3
512	3	clover	Farm-8		4
398	3	mango	Farm-8		1
436	3	orange	Farm-8		2
474	3	wheat	Farm-8		3
400	3	grapes	Farm-10		1
438	3	mango	Farm-10		2
476	3	orange	Farm-10		3
516	3	arabic 1	Farm-12		4
554	3	arabic 2	Farm-12		5
402	3	date palm	Farm-12	inter-cropped	1
440	3	lemon	Farm-12		2
478	3	mango	Farm-12		3
441	3	clover	Farm-13		2
479	3	date palm	Farm-13	5 trees	3
403	3	wheat	Farm-13		1
414	3	clover	Farm-23		1
452	3	wheat	Farm-23		2
5208	3	date palm	Farm-14		3
442	3	grapes	Farm-14		2
518	3	mango	Farm-14		4
480	3	olive	Farm-14		3
404	3	orange	Farm-14	reported as "citrus"	1
523	3	clover	Farm-19		4
485	3	corn	Farm-19		3
447	3	onion	Farm-19		2
409	3	wheat	Farm-19		1
413	3	mango	Farm-22		1
422	3	clover	Farm-24		2
384	3	corn	Farm-24		1
460	3	date palm	Farm-24		3
423	3	loofa	Farm-25		2
385	3	olive	Farm-25		1
453	3	date palm	Farm-27		2

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
415	3	mango	Farm-27	mixed varieties	1
721	3	beans	Farm-29	rotated with veg.	9
759	3	beets	Farm-29	rotated wtih veg	10
683	3	corn	Farm-29	between trees	8
569	3	eggplant	Farm-29		5
645	3	grapes	Farm-29		7
493	3	lemon	Farm-29		3
455	3	mandarin	Farm-29		2
531	3	onion	Farm-29		4
417	3	orange	Farm-29		1
607	3	pepper	Farm-29		6
418	3	cantaloupe	Farm-30		1
494	3	tomato	Farm-30		3
456	3	watermelon	Farm-30		2
381	3	apricot	Farm-31		1
419	3	grapes	Farm-31		2
495	3	orange	Farm-31		4
457	3	pear	Farm-31		3
387	3	olive	Farm-33		1
425	3	pasture	Farm-33		2
466	3	beet	Farm-35		3
428	3	olive	Farm-35	5800 trees	2
390	3	pomegranate	Farm-35	4800 trees	1
553	3	beans	Farm-11	between fruit	5
439	3	mandarin	Farm-11		2
477	3	mango	Farm-11		3
401	3	orange	Farm-11		1
515	3	peanuts	Farm-11	inter-cropped	4
408	3	mango	Farm-18		1
399	3	pear	Farm-9		1
458	3	beans	Farm-32		3
382	3	corn	Farm-32		1
5209	3	pasture	Farm-32		2
420	3	wheat	Farm-32		2
396	3	bananas	Farm-6	grown in greenhouse	1
434	3	orange	Farm-6	mandarin variety	2
472	3	orange	Farm-6	markot variety	3
510	3	orange	Farm-6	tangerine variety	4
867	4	80	Farm-20		1
842	4	1	Farm-26		1
880	4	1.5	Farm-26		2
977	4	10	Farm-17		4
939	4	20	Farm-17		3
901	4	50	Farm-17		2
863	4	65	Farm-17		1
923	4	5	Farm-1		3
961	4	5	Farm-1		4
885	4	7	Farm-1		2
847	4	8	Farm-1		1
848	4	4	Farm-2		1
886	4	4	Farm-2		2
924	4	4	Farm-2		3
962	4	4	Farm-2		4
1000	4	4	Farm-2		5
1038	4	4	Farm-2		6
1076	4	4	Farm-2		7
1114	4	4	Farm-2		8
1192	4	1	Farm-4		10
850	4	6	Farm-4		1
888	4	6	Farm-4		2
926	4	6	Farm-4		3
964	4	6	Farm-4		4
1002	4	6	Farm-4		5
1040	4	6	Farm-4		6
1078	4	6	Farm-4		7
1116	4	6	Farm-4		8
1154	4	6	Farm-4		9
851	4	0.75	Farm-5		1
889	4	0.75	Farm-5		2
927	4	0.75	Farm-5		3
965	4	0.75	Farm-5		4
854	4	20	Farm-8		1
892	4	30	Farm-8		2
1010	4	1	Farm-12		5

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
896	4	1.5	Farm-12		2
972	4	3	Farm-12		4
934	4	6.5	Farm-12		3
859	4	0.75	Farm-13		1
897	4	0.75	Farm-13		2
870	4	0.75	Farm-23		1
908	4	0.75	Farm-23		2
936	4	50	Farm-14		3
974	4	60	Farm-14		4
898	4	300	Farm-14		2
979	4	5	Farm-19		4
941	4	6	Farm-19		3
903	4	7	Farm-19		2
865	4	8	Farm-19		1
869	4	12	Farm-22		1
916	4	0.5	Farm-24		3
840	4	1	Farm-24		1
878	4	1	Farm-24		2
879	4	2	Farm-25		2
841	4	80	Farm-25		1
871	4	75	Farm-27		1
909	4	75	Farm-27		2
1139	4	1	Farm-29		8
949	4	2	Farm-29		3
987	4	2	Farm-29		4
1063	4	2	Farm-29		6
911	4	3	Farm-29		2
1101	4	4	Farm-29		7
1025	4	5	Farm-29		5
1177	4	5	Farm-29		9
1215	4	5	Farm-29		10
873	4	7	Farm-29		1
950	4	1	Farm-30		3
874	4	20	Farm-30		1
912	4	20	Farm-30		2
837	4	20	Farm-31		1
913	4	20	Farm-31		3
951	4	25	Farm-31		4
875	4	40	Farm-31		2
881	4	20	Farm-33		2
843	4	40	Farm-33		1
922	4	6	Farm-35		3
846	4	25	Farm-35		1
884	4	28	Farm-35		2
971	4	1	Farm-11		4
1009	4	1	Farm-11		5
933	4	5	Farm-11		3
857	4	7	Farm-11		1
895	4	7	Farm-11		2
864	4	31	Farm-18		1
855	4	40	Farm-9		1
852	4	6	Farm-6		1
890	4	20	Farm-6		2
928	4	20	Farm-6		3
966	4	20	Farm-6		4
1328	5	10	Farm-28		
1303	5	21	Farm-1		
1310	5	1	Farm-8		
1321	5	12	Farm-19		
1325	5	7	Farm-22		
1327	5	50	Farm-27		
1329	5	51	Farm-29		
1293	5	2	Farm-31		
1302	5	1	Farm-35		
1313	5	2	Farm-11		
1311	5	8	Farm-9		
1366	6	7	Farm-28		1
1404	6	7	Farm-28		2
1442	6	7	Farm-28		3
1480	6	7	Farm-28		4
1339	6	7	Farm-34		1
1377	6	7	Farm-34		2
1336	6	7	Farm-26		1
1374	6	7	Farm-26		2

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
1341	6	3	Farm-1		1
1379	6	3	Farm-1		2
1417	6	4	Farm-1		3
1455	6	4	Farm-1		4
1342	6	3	Farm-2		1
1380	6	3	Farm-2		2
1418	6	3	Farm-2		3
1456	6	3	Farm-2		4
1494	6	3	Farm-2		5
1532	6	3	Farm-2		6
1570	6	3	Farm-2		7
1608	6	3	Farm-2		8
1344	6	3	Farm-4		1
1382	6	3	Farm-4		2
1420	6	3	Farm-4		3
1458	6	7	Farm-4		4
1496	6	7	Farm-4		5
1534	6	7	Farm-4		6
1572	6	7	Farm-4		7
1610	6	7	Farm-4		8
1648	6	7	Farm-4		9
1686	6	7	Farm-4		10
1345	6	2	Farm-5		1
1383	6	2	Farm-5		2
1421	6	2	Farm-5		3
1459	6	2	Farm-5		4
1347	6	2	Farm-7		1
1385	6	2	Farm-7		2
1423	6	2	Farm-7		3
1348	6	3	Farm-8		1
1386	6	3	Farm-8		2
1352	6	1	Farm-12		1
1390	6	1	Farm-12		2
1428	6	1	Farm-12		3
1466	6	1	Farm-12		4
1504	6	1	Farm-12		5
1364	6	1.3	Farm-23		1
1402	6	1.3	Farm-23		2
1354	6	0	Farm-14		1
1468	6	0.5	Farm-14		4
1392	6	1	Farm-14		2
1430	6	2	Farm-14		3
1359	6	4	Farm-19		1
1397	6	4	Farm-19		2
1435	6	4	Farm-19		3
1473	6	4	Farm-19		4
1363	6	7	Farm-22		1
1365	6	3	Farm-27		1
1403	6	3	Farm-27		2
1367	6	3	Farm-29		1
1405	6	3	Farm-29		2
1443	6	3	Farm-29		3
1481	6	3	Farm-29		4
1519	6	3	Farm-29		5
1557	6	3	Farm-29		6
1595	6	3	Farm-29		7
1633	6	3	Farm-29		8
1671	6	3	Farm-29		9
1709	6	3	Farm-29		10
1368	6	7	Farm-30		1
1406	6	7	Farm-30		2
1444	6	7	Farm-30		3
1331	6	1	Farm-31		1
1369	6	1	Farm-31		2
1407	6	1	Farm-31		3
1445	6	1	Farm-31		4
1337	6	7	Farm-33		1
1340	6	1	Farm-35		1
1378	6	1	Farm-35		2
1351	6	2	Farm-11		1
1389	6	2	Farm-11		2
1427	6	2	Farm-11		3
1465	6	2	Farm-11		4
1503	6	2	Farm-11		5

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
1358	6	7	Farm-18		1
1349	6	7	Farm-9		1
1332	6	7	Farm-32		1
1370	6	7	Farm-32		2
1408	6	7	Farm-32		3
1384	6	7	Farm-6		2
1860	7	7	Farm-28		1
1898	7	7	Farm-28		2
1936	7	7	Farm-28		3
1974	7	7	Farm-28		4
1833	7	7	Farm-34		1
1871	7	7	Farm-34		2
1830	7	7	Farm-26		1
1868	7	7	Farm-26		2
1835	7	7	Farm-1		1
1873	7	7	Farm-1		2
1911	7	7	Farm-1		3
1949	7	7	Farm-1		4
1836	7	7	Farm-2		1
1874	7	7	Farm-2		2
1912	7	7	Farm-2		3
1950	7	7	Farm-2		4
1988	7	7	Farm-2		5
2026	7	7	Farm-2		6
2064	7	7	Farm-2		7
2102	7	7	Farm-2		8
1838	7	3	Farm-4		1
1876	7	3	Farm-4		2
1914	7	3	Farm-4		3
1952	7	7	Farm-4		4
1990	7	7	Farm-4		5
2028	7	7	Farm-4		6
2066	7	7	Farm-4		7
2104	7	7	Farm-4		8
2142	7	7	Farm-4		9
2180	7	7	Farm-4		10
1839	7	4	Farm-5		1
1877	7	4	Farm-5		2
1915	7	4	Farm-5		3
1953	7	4	Farm-5		4
1841	7	3	Farm-7		1
1879	7	3	Farm-7		2
1917	7	3	Farm-7		3
1842	7	7	Farm-8		1
1880	7	7	Farm-8		2
1847	7	0	Farm-13		1
1885	7	0	Farm-13		2
1962	7	2	Farm-14		4
1848	7	7	Farm-14		1
1886	7	7	Farm-14		2
1924	7	7	Farm-14		3
1929	7	7	Farm-19		3
1857	7	2	Farm-22		1
1859	7	7	Farm-27		1
1897	7	7	Farm-27		2
1861	7	7	Farm-29		1
1899	7	7	Farm-29		2
1937	7	7	Farm-29		3
1975	7	7	Farm-29		4
2013	7	7	Farm-29		5
2051	7	7	Farm-29		6
2089	7	7	Farm-29		7
2127	7	7	Farm-29		8
2165	7	7	Farm-29		9
2203	7	7	Farm-29		10
1862	7	7	Farm-30		1
1900	7	7	Farm-30		2
1938	7	7	Farm-30		3
1825	7	4	Farm-31		1
1863	7	4	Farm-31		2
1901	7	4	Farm-31		3
1939	7	4	Farm-31		4
1831	7	7	Farm-33		1
1834	7	3	Farm-35		1

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
1872	7	3	Farm-35		2
1845	7	7	Farm-11		1
1883	7	7	Farm-11		2
1921	7	7	Farm-11		3
1959	7	7	Farm-11		4
1997	7	7	Farm-11		5
1852	7	7	Farm-18		1
1843	7	7	Farm-9		1
1826	7	1	Farm-32		1
1864	7	1	Farm-32		2
1902	7	1	Farm-32		3
1878	7	7	Farm-6		2
2316	8	0.5	Farm-28		1
2354	8	0.5	Farm-28		2
2392	8	0.5	Farm-28		3
2430	8	0.5	Farm-28		4
2289	8	2	Farm-34		1
2327	8	2	Farm-34		2
2286	8	2	Farm-26		1
2324	8	2	Farm-26		2
2291	8	2	Farm-1		1
2329	8	2	Farm-1		2
2367	8	2	Farm-1		3
2405	8	2	Farm-1		4
2292	8	3	Farm-2		1
2330	8	3	Farm-2		2
2368	8	3	Farm-2		3
2406	8	3	Farm-2		4
2444	8	3	Farm-2		5
2482	8	3	Farm-2		6
2520	8	3	Farm-2		7
2558	8	3	Farm-2		8
2297	8	3.5	Farm-7		1
2335	8	3.5	Farm-7		2
2373	8	3.5	Farm-7		3
2298	8	3	Farm-8		1
2336	8	3	Farm-8		2
2303	8	0	Farm-13		1
2341	8	0	Farm-13		2
2380	8	6	Farm-14		3
2418	8	6	Farm-14		4
2304	8	7	Farm-14		1
2342	8	10	Farm-14		2
2385	8	12	Farm-19		3
2313	8	2	Farm-22		1
2315	8	2	Farm-27		1
2353	8	2	Farm-27		2
2317	8	3.5	Farm-29		1
2355	8	3.5	Farm-29		2
2393	8	3.5	Farm-29		3
2431	8	3.5	Farm-29		4
2469	8	3.5	Farm-29		5
2507	8	3.5	Farm-29		6
2545	8	3.5	Farm-29		7
2583	8	4	Farm-29		8
2621	8	4	Farm-29		9
2659	8	4	Farm-29		10
2318	8	18	Farm-30		1
2356	8	18	Farm-30		2
2394	8	18	Farm-30		3
2281	8	3	Farm-31		1
2319	8	3	Farm-31		2
2357	8	3	Farm-31		3
2395	8	3	Farm-31		4
2287	8	12	Farm-33		1
2440	8	0	Farm-36		5
2290	8	2	Farm-35		1
2328	8	2	Farm-35		2
2301	8	0.5	Farm-11		1
2339	8	0.5	Farm-11		2
2377	8	0.5	Farm-11		3
2415	8	0.5	Farm-11		4
2453	8	0.5	Farm-11		5
2308	8	6	Farm-18		1

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
2299	8	16	Farm-9		1
2282	8	2	Farm-32		1
2320	8	2	Farm-32		2
2358	8	2	Farm-32		3
2334	8	2	Farm-6		2
2772	9	0.5	Farm-28		1
2810	9	0.5	Farm-28		2
2848	9	0.5	Farm-28		3
2886	9	0.5	Farm-28		4
2745	9	2	Farm-34		1
2783	9	2	Farm-34		2
2742	9	2	Farm-26		1
2780	9	2	Farm-26		2
2747	9	2	Farm-1		1
2785	9	2	Farm-1		2
2823	9	2	Farm-1		3
2861	9	2	Farm-1		4
2748	9	2	Farm-2		1
2786	9	2	Farm-2		2
2824	9	2	Farm-2		3
2862	9	2	Farm-2		4
2900	9	2	Farm-2		5
2938	9	2	Farm-2		6
2976	9	2	Farm-2		7
3014	9	2	Farm-2		8
2753	9	3.5	Farm-7		1
2791	9	3.5	Farm-7		2
2829	9	3.5	Farm-7		3
2754	9	1.5	Farm-8		1
2792	9	1.5	Farm-8		2
2758	9	2.5	Farm-12		1
2796	9	2.5	Farm-12		2
2834	9	2.5	Farm-12		3
2872	9	2.5	Farm-12		4
2910	9	2.5	Farm-12		5
2770	9	24	Farm-23		1
2808	9	24	Farm-23		2
2836	9	6	Farm-14		3
2874	9	6	Farm-14		4
2760	9	7	Farm-14		1
2798	9	10	Farm-14		2
2769	9	2	Farm-22		1
2771	9	2	Farm-27		1
2809	9	2	Farm-27		2
3001	9	0	Farm-29		7
3039	9	0	Farm-29		8
3077	9	0	Farm-29		9
3115	9	0	Farm-29		10
2773	9	0.5	Farm-29		1
2811	9	0.5	Farm-29		2
2849	9	0.5	Farm-29		3
2887	9	0.5	Farm-29		4
2925	9	0.5	Farm-29		5
2963	9	0.5	Farm-29		6
2774	9	12	Farm-30		1
2812	9	12	Farm-30		2
2850	9	12	Farm-30		3
2737	9	3	Farm-31		1
2775	9	3	Farm-31		2
2813	9	3	Farm-31		3
2851	9	3	Farm-31		4
2743	9	6	Farm-33		1
2746	9	2	Farm-35		1
2784	9	2	Farm-35		2
2757	9	0.5	Farm-11		1
2795	9	0.5	Farm-11		2
2833	9	0.5	Farm-11		3
2871	9	0.5	Farm-11		4
2909	9	0.5	Farm-11		5
2764	9	4	Farm-18		1
2755	9	12	Farm-9		1
2738	9	2	Farm-32		1
2776	9	2	Farm-32		2
2814	9	2	Farm-32		3

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
2790	9	1	Farm-6		2
3223	10	drip	Farm-20		1
3261	10	drip	Farm-20		2
3299	10	drip	Farm-20		3
3201	10	drip	Farm-34		1
3239	10	drip	Farm-34		2
3198	10	drip	Farm-26		1
3236	10	drip	Farm-26		2
3219	10	drip	Farm-17		1
3257	10	drip	Farm-17		2
3295	10	drip	Farm-17		3
3333	10	sprinkler	Farm-17		4
3203	10	drip	Farm-1		1
3241	10	drip	Farm-1		2
3317	10	drip	Farm-1		4
3279	10	sprinker	Farm-1		3
3242	10	drip	Farm-2		2
3280	10	drip	Farm-2		3
3318	10	drip	Farm-2		4
3356	10	drip	Farm-2		5
3394	10	drip	Farm-2		6
3432	10	drip	Farm-2		7
3470	10	drip	Farm-2		8
3204	10	sprinkler	Farm-2		1
3206	10	drip	Farm-4		1
3244	10	drip	Farm-4		2
3282	10	drip	Farm-4		3
3320	10	drip	Farm-4		4
3358	10	drip	Farm-4		5
3396	10	drip	Farm-4		6
3434	10	drip	Farm-4		7
3472	10	drip	Farm-4		8
3510	10	drip	Farm-4		9
3548	10	spinkler	Farm-4		10
3245	10	drip	Farm-5		2
3283	10	drip	Farm-5		3
3207	10	sprinkler	Farm-5		1
3321	10	sprinkler	Farm-5		4
3209	10	flood	Farm-7		1
3247	10	flood	Farm-7		2
3285	10	flood	Farm-7		3
3210	10	drip	Farm-8		1
3248	10	drip	Farm-8		2
3214	10	drip	Farm-12		1
3252	10	drip	Farm-12		2
3290	10	drip	Farm-12		3
3328	10	drip	Farm-12		4
3366	10	drip	Farm-12		5
3215	10	flood	Farm-13		1
3253	10	flood	Farm-13		2
3226	10	flood	Farm-23		1
3264	10	flood	Farm-23		2
3216	10	drip	Farm-14		1
3254	10	drip	Farm-14		2
3292	10	drip	Farm-14		3
3330	10	drip	Farm-14		4
5210	10	drip	Farm-19		1
5211	10	drip	Farm-19		2
5212	10	drip	Farm-19		3
5213	10	drip	Farm-19		4
3221	10	sprinkler	Farm-19		1
3259	10	sprinkler	Farm-19		2
3297	10	sprinkler	Farm-19		3
3335	10	sprinkler	Farm-19		4
3225	10	drip	Farm-22		1
3196	10	flood	Farm-24		1
3234	10	flood	Farm-24		2
3272	10	flood	Farm-24		3
3197	10	drip	Farm-25		1
3235	10	drip	Farm-25		2
3227	10	drip	Farm-27		1
3265	10	drip	Farm-27		2
3229	10	drip	Farm-29		1
3267	10	drip	Farm-29		2

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
3305	10	drip	Farm-29		3
3343	10	drip	Farm-29		4
3381	10	drip	Farm-29		5
3419	10	drip	Farm-29		6
3457	10	drip	Farm-29		7
3495	10	drip	Farm-29		8
3533	10	drip	Farm-29		9
3571	10	drip	Farm-29		10
3230	10	drip	Farm-30		1
3268	10	drip	Farm-30		2
3306	10	drip	Farm-30		3
3193	10	drip	Farm-31		1
3231	10	drip	Farm-31		2
3269	10	drip	Farm-31		3
3307	10	drip	Farm-31		4
3199	10	drip	Farm-33		1
3202	10	drip	Farm-35		1
3240	10	drip	Farm-35		2
3213	10	drip	Farm-11		1
3251	10	drip	Farm-11		2
3289	10	drip	Farm-11		3
3327	10	drip	Farm-11		4
3365	10	drip	Farm-11		5
3220	10	drip	Farm-18		1
3211	10	drip	Farm-9	0.5 m between each drip	1
3194	10	drip	Farm-32		1
3270	10	sprinker	Farm-32		3
3232	10	sprinkler	Farm-32		2
3246	10	drip	Farm-6		2
3284	10	drip	Farm-6		3
3322	10	drip	Farm-6		4
3850	11	All year	Farm-2		6
3774	11	April	Farm-2		4
3736	11	August	Farm-2		3
3926	11	August	Farm-2		8
5216	11	December	Farm-2		5
3660	11	June	Farm-2		1
3698	11	June	Farm-2		2
3888	11	June	Farm-2		7
5227	11	May	Farm-2		4
3812	11	November	Farm-2		5
5218	11	December	Farm-4		4
5217	11	December	Farm-4		5
3928	11	December	Farm-4		8
3966	11	December	Farm-4		9
5225	11	January	Farm-4		8
5226	11	January	Farm-4		9
3776	11	November	Farm-4		4
3814	11	November	Farm-4		5
3662	11	Tree	Farm-4		1
3700	11	Tree	Farm-4		2
3738	11	Tree	Farm-4		3
3663	11	All year	Farm-5	pasture	1
3701	11	All year	Farm-5	pasture	2
3739	11	All year	Farm-5	pasture	3
3777	11	All year	Farm-5	pasture	4
3666	11	August	Farm-8		1
3704	11	August	Farm-8		2
3671	11	December	Farm-13		1
3709	11	October	Farm-13		2
3753	11	June	Farm-19		3
3677	11	November	Farm-19		1
3715	11	November	Farm-19		2
3791	11	October	Farm-19	Reported Oct 20	4
3691	11	April	Farm-25		2
5232	11	April	Farm-29		8
5239	11	April	Farm-29		9
5246	11	April	Farm-29		10
5222	11	December	Farm-29		4
5223	11	December	Farm-29		5
5224	11	December	Farm-29		6
5228	11	December	Farm-29		8
5235	11	December	Farm-29		9
5242	11	December	Farm-29		10

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
3913	11	February	Farm-29		7
5230	11	February	Farm-29		8
5237	11	February	Farm-29		9
5244	11	February	Farm-29		10
5229	11	January	Farm-29		8
5236	11	January	Farm-29		9
5243	11	January	Farm-29		10
5234	11	June	Farm-29		8
5241	11	June	Farm-29		9
5248	11	June	Farm-29		10
5231	11	March	Farm-29		8
5238	11	March	Farm-29		9
5245	11	March	Farm-29		10
5233	11	May	Farm-29		8
5240	11	May	Farm-29		9
5247	11	May	Farm-29		10
5219	11	November	Farm-29		4
5220	11	November	Farm-29		5
5221	11	November	Farm-29		6
3951	11	November	Farm-29		8
3989	11	November	Farm-29		9
4027	11	November	Farm-29		10
3799	11	October	Farm-29		4
3837	11	October	Farm-29		5
3875	11	October	Farm-29		6
3686	11	December	Farm-30		1
3762	11	December	Farm-30		3
3724	11	January	Farm-30		2
3655	11	September	Farm-33		1
3658	11	June	Farm-35		1
3696	11	September	Farm-35		2
3669	11	February	Farm-11		1
3707	11	February	Farm-11		2
3745	11	February	Farm-11		3
3783	11	February	Farm-11		4
3821	11	February	Farm-11		5
3650	11	May	Farm-32		1
5214	11	November	Farm-32		2
5215	11	November	Farm-32		3
3688	11	October	Farm-32		2
3726	11	October	Farm-32		3
4173	12	90 days	Farm-20		2
4211	12	90 days	Farm-20		3
4135	12	every 4 months	Farm-20		1
5263	12	April	Farm-1		3
5269	12	April	Farm-1		4
5280	12	August	Farm-1		1
5259	12	December	Farm-1		3
5265	12	December	Farm-1		4
5261	12	February	Farm-1		3
5267	12	February	Farm-1		4
5260	12	January	Farm-1		3
5266	12	January	Farm-1		4
4115	12	July	Farm-1		1
5279	12	July	Farm-1		2
4153	12	June	Farm-1		2
5271	12	June	Farm-1		4
5262	12	March	Farm-1		3
5268	12	March	Farm-1		4
5264	12	May	Farm-1		3
5270	12	May	Farm-1		4
4191	12	November	Farm-1		3
4229	12	November	Farm-1		4
5281	12	September	Farm-1		1
4192	12	All year	Farm-2		3
4116	12	April	Farm-2		1
5255	12	December	Farm-2		6
5256	12	December	Farm-2		7
5257	12	December	Farm-2		8
4268	12	June	Farm-2		5
4230	12	May	Farm-2		4
4154	12	November	Farm-2		2
5252	12	November	Farm-2		6
5253	12	November	Farm-2		7

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
5254	12	November	Farm-2		8
5249	12	October	Farm-2		6
5250	12	October	Farm-2		7
5251	12	October	Farm-2		8
4306	12	September	Farm-2		6
4344	12	September	Farm-2		7
4382	12	September	Farm-2		8
5297	12	August	Farm-4		1
4118	12	July	Farm-4		1
4232	12	June	Farm-4		4
4270	12	June	Farm-4		5
4308	12	June	Farm-4		6
4346	12	June	Farm-4		7
4384	12	June	Farm-4		8
4422	12	June	Farm-4		9
4460	12	June	Farm-4		10
5290	12	October	Farm-4		4
5291	12	October	Farm-4		5
5292	12	October	Farm-4		6
5293	12	October	Farm-4		7
5294	12	October	Farm-4		8
5295	12	October	Farm-4		9
5296	12	October	Farm-4		10
4156	12	September	Farm-4		2
4194	12	September	Farm-4		3
4119	12	All year	Farm-5	Pasture	1
4157	12	All year	Farm-5	Pasture	2
4195	12	All year	Farm-5	Pasture	3
4233	12	All year	Farm-5	Pasture	4
4121	12	August	Farm-7		1
4197	12	August	Farm-7		3
4122	12	no harvest yet	Farm-8	3 years from present	1
4160	12	no harvest yet	Farm-8	3 years from present	2
4126	12	August	Farm-12		1
4202	12	August	Farm-12		3
4240	12	November	Farm-12		4
4164	12	October	Farm-12		2
4278	12	September	Farm-12		5
4165	12	March	Farm-13		2
4127	12	May	Farm-13		1
5277	12	July	Farm-19		4
5282	12	June	Farm-19		1
5283	12	June	Farm-19		2
4247	12	June	Farm-19		4
4133	12	May	Farm-19		1
4171	12	May	Farm-19		2
4209	12	October	Farm-19		3
5278	12	July	Farm-22		1
4137	12	June	Farm-22		1
5286	12	August	Farm-25		1
4147	12	August	Farm-25		2
5285	12	July	Farm-25		1
5284	12	June	Farm-25		1
4109	12	May	Farm-25		1
5289	12	November	Farm-25		1
5288	12	October	Farm-25		1
5287	12	September	Farm-25		1
4139	12	August	Farm-27		1
5258	12	October	Farm-27		2
4177	12	September	Farm-27		2
4369	12	18 months to maturity	Farm-29		7
4142	12	April	Farm-30		1
4180	12	April	Farm-30		2
4218	12	April	Farm-30		3
5273	12	February	Farm-31		1
5274	12	February	Farm-31		2
5275	12	February	Farm-31		3
5276	12	February	Farm-31		4
4105	12	January	Farm-31		1
4143	12	January	Farm-31		2
4181	12	January	Farm-31		3
4219	12	January	Farm-31		4
4111	12	November	Farm-33		1
4114	12	no harvest yet	Farm-35		1

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
4152	12	no harvest yet	Farm-35		2
4125	12	no harvest yet	Farm-11		1
4163	12	no harvest yet	Farm-11		2
4201	12	no harvest yet	Farm-11		3
4239	12	no harvest yet	Farm-11		4
4277	12	no harvest yet	Farm-11		5
5298	12	August	Farm-18		1
4132	12	July	Farm-18		1
4123	12	August	Farm-9		1
5272	12	September	Farm-9		1
4144	12	October	Farm-32		2
4182	12	October	Farm-32		3
4106	12	September	Farm-32		1
4158	12	April	Farm-6		2
4196	12	December	Farm-6		3
4234	12	May	Farm-6		4
4569	13	5	Farm-34		1
4607	13	5	Farm-34		2
4647	13	1	Farm-1		3
4571	13	7	Farm-1		1
4609	13	7	Farm-1		2
4685	13	15	Farm-1		4
4726	13	1.7	Farm-4		5
4916	13	2.5	Farm-4		10
4612	13	8	Farm-4		2
4574	13	18	Farm-4		1
4688	13	30	Farm-4		4
4653	13	-999	Farm-7		3
4620	13	5	Farm-12		2
4696	13	5	Farm-12		4
4734	13	10	Farm-12		5
4658	13	32.5	Farm-12		3
4632	13	-999	Farm-23		2
4594	13	15	Farm-23		1
4660	13	6	Farm-14		3
4584	13	8	Farm-14		1
4622	13	8	Farm-14		2
4703	13	-999	Farm-19		4
4665	13	1	Farm-19		3
4589	13	1.2	Farm-19		1
4627	13	5	Farm-19		2
4593	13	0.083	Farm-22		1
4595	13	1.5	Farm-27		1
4633	13	10	Farm-27		2
4597	13	3	Farm-29		1
4635	13	3	Farm-29		2
4673	13	3	Farm-29		3
4749	13	7	Farm-29		5
4561	13	4	Farm-31		1
4599	13	4	Farm-31		2
4637	13	4	Farm-31		3
4675	13	4	Farm-31		4
4605	13	-999	Farm-33		2
4579	13	2	Farm-9		1
4562	13	1	Farm-32		1
4600	13	1	Farm-32		2
4638	13	1	Farm-32		3
4614	13	12.5	Farm-6		2
4652	13	12.5	Farm-6		3
4690	13	12.5	Farm-6		4
5391	14	trade/income generation	Farm-20		
5396	14	trade/income generation	Farm-28		
5371	14	trade/income generation	Farm-1		
5372	14	domestic use	Farm-2		
5409	14	trade/income generation	Farm-2		
5402	14	domestic use	Farm-4		
5403	14	suitable to soil	Farm-4		
5374	14	trade/income generation	Farm-4		
5375	14	domestic use	Farm-5		
5378	14	suitable to local environment	Farm-8		
5410	14	trade/income generation	Farm-8	crops are profitable	
5382	14	trade/income generation	Farm-12		
5400	14	domestic use	Farm-13		
5399	14	livestock feed	Farm-13		

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
5394	14	domestic use	Farm-23		
5389	14	suitable to soil	Farm-19		
5405	14	suitable to climate	Farm-25		
5406	14	suitable to water	Farm-25		
5365	14	trade/income generation	Farm-25		
5395	14	trade/income generation	Farm-27		
5397	14	suitable to water	Farm-29		
5398	14	trade/income generation	Farm-30	used to pay for land	
5361	14	farm purchased with current crops	Farm-31		
5404	14	suitable to climate	Farm-33		
5367	14	tolerant to salt	Farm-33		
5370	14	suitable to soil	Farm-35		
5411	14	trade/income generation	Farm-35	crops are profitable	
5381	14	low cost inputs	Farm-11	fertilizer is minimal	
5408	14	trade/income generation	Farm-11		
5401	14	domestic use	Farm-18		
5388	14	trade/income generation	Farm-18		
5407	14	trade/income generation	Farm-9	pear is profitable though not well suited to soil	
5376	14	suitable to local environment	Farm-6		
5412	14	trade/income generation	Farm-6	crops are profitable and exported	
5123	15	pests/disease	Farm-20	cotton worm	
5098	15	unsure about crop suitability	Farm-26		
5103	15	crop productivity	Farm-1	grapes	
5104	15	crop productivity	Farm-2	uses fertilizers	
5415	15	pests/disease	Farm-2	nematode	
5116	15	crop productivity	Farm-14	ultimately succeeded with citrus	
5413	15	crop productivity	Farm-19	onions, oranges	
5414	15	pests/disease	Farm-19	invasive grass	
5097	15	pests/disease	Farm-25	nematode	
5129	15	soil moisture	Farm-29		
5130	15	high land rental cost	Farm-30		
5102	15	crop productivity	Farm-35	not sure why trees die	
5418	15	high land rental cost	Farm-18		
5417	15	well malfunction	Farm-18		
5111	15	pests/disease	Farm-9	plants leaves dry out	
5416	15	crop productivity	Farm-32	due to salt on corn and wheat	
5161	16	sustainability of supply	Farm-20	too much pumping for irrigation	
5166	16	sustainability of supply	Farm-28		
5426	16	salinity	Farm-34	developed over last 7 years	
5427	16	sustainability of supply	Farm-34	no certainty in water amount	
5139	16	well malfunctions	Farm-34	due to eradic water supply	
5136	16	salinity	Farm-26		
5421	16	salinity	Farm-17	has caused kidney problems	
5157	16	well malfunctions	Farm-17	15 - 30 k LE for repair every 30 - 40 days	
5425	16	contamination	Farm-3	from burried trench	
5143	16	salinity	Farm-3		
5142	16	salinity	Farm-2		
5144	16	sustainability of supply	Farm-4	levels dropping and only supply for living	
5423	16	contamination	Farm-7	burried WW trenches next to well	
5422	16	salinity	Farm-7	gov't water is saline; salinity causes kidney disease	
5148	16	salinity	Farm-8	warned not to drink water	
5153	16	well malfunctions	Farm-13		
5428	16	salinity	Farm-14		
5154	16	sustainability of supply	Farm-14		
5163	16	well malfunctions	Farm-22	due to improper labour	
5168	16	salinity	Farm-30		
5131	16	no concerns	Farm-31		
5430	16	contamination	Farm-35	worried about drinking the water	
5140	16	salinity	Farm-35		
5420	16	low irrigation pressure	Farm-11		
5419	16	salinity	Farm-11	present in deeper water	
5151	16	sustainability of supply	Farm-11	depth of water is okay now,	

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
				but won't be	
5158	16	salinity	Farm-18		
5149	16	salinity	Farm-9	develops after pumping for an hour	
5424	16	sustainability of supply	Farm-9	concerned for impacts on domestic supply	
5132	16	salinity	Farm-32		
5146	16	salinity	Farm-6	new well could cost 150 k LE and would be saline	
5429	16	contamination	U2	thinks makes people sick	
5160	16	salinity	U2		
5204	17	hopes to increase land	Farm-28		
5179	17	depending on the situation, may sell or buy land	Farm-1		
5182	17	to plan the whole currently cropped area with trees and then expand the area of planted areas	Farm-4		
5186	17	better quality, production and assurance of quality	Farm-8		
5188	17	increase number of wells and will get 35 more F	Farm-10		
5191	17	according to the gov't, the land is zoned for buildings so the farm could not be expanded	Farm-13		
5202	17	going to make sprinklers once he drills a new well	Farm-23		
5192	17	more water available	Farm-14		
5197	17	would be interested in trying new crops that are more productive; wants to sell farm as its not very productive	Farm-19		
5173	17	to plant 5 feddans of wheat using sprinklers	Farm-25		
5203	17	digging shallow wells	Farm-27		
5205	17	5 feddans of peach; 5 feddans of beet; wants trees everywhere	Farm-29		
5206	17	having own land	Farm-30		
5169	17	wishes more water were availble for the farm; have a well but don't use it yet	Farm-31		
5175	17	to trade	Farm-33		
5178	17	erradication of high salinity in water	Farm-35		
5189	17	planning for animal and poultry project	Farm-11		
5187	17	to plant 25 more feddans and drill another well	Farm-9		
5170	17	increase land holding	Farm-32		
5184	17	achieve stability and enough trade; increase farms size; add one more well	Farm-6		
5052	18	each feddan gets 15-20 mins daily	Farm-28		
5025	18	irrigate once in the morning and once in the evening; 2 hours per feddan	Farm-34		
5022	18	irrigates 1 hour in the day and 1 hr at night	Farm-26		
5043	18	uses "hosh" method, where 2.5 F=1 1 hosh; 6 hosh (14F) are irrigated from 8am to 12; and another 14 F from 12 to 4; the whole farm is irrigated on rotation in 1 week	Farm-17		
5027	18	2 hours per 5 feddans	Farm-1		
5028	18	whole farm is on a rotated irrigation so each crop gets 3 hours each day in the summer, and 1-2 hours in the winter	Farm-2		
5030	18	2 hours of irrigation per feddan every day during the growing season for field crops; Trees every other day	Farm-4		
5031	18	uses drip and sprinklers (each crop usage not specified); no duration of each irrigation provided	Farm-5		
5034	18	day on, day off in winter, everyday in summer; 1.5 hours hours in winter;2-5 hours in summer	Farm-8		
5036	18	14.5 F are drip; 1.5 F are sprinklers	Farm-10		
5039	18	- every 18 days during the winter, 1 feddan gets 14 hours	Farm-13		
5050	18	irrigates for 24 hours every 5 days	Farm-23		
5045	18	only irrigates corn in the winter, and no specified amount of time for winter irrigation	Farm-19		
5021	18	Olive = every 2-3 f gets 1.5 hrs per day every 2-3 days in winter and every other day in summer, Loofa = 1.5 to 2 hrs every other day year round	Farm-25		
5051	18	every 4 feddans rotated for 2 hours	Farm-27		
5053	18	orange/mandarin/grapes every other day in winter, summer every day for 2 hours; veg 2 times per day in summer for 1.5 hrs in morning and 30 mins at night in winter, just at night	Farm-29		
5017	18	in summer all crops irrigated morning or evening for 3 hours each day; in winter ranges from 1 to 4 times per week at same number of hours	Farm-31		
5026	18	once every 10 days for pom in winter and 2 days every 7 weeks for olive; in summer, once every	Farm-35		

ID	UniqueQID	Response	RespondantID	Notes	CropNumber
		other day in summer for 2 hrs per day			
5037	18	summer = 30 mins per feddan per day and winter is every 2-3 days	Farm-11		
5044	18	every other day, 15 feddans are irrigated for 6-8 hours/day in the summer and less than 6 hours in the winter	Farm-18		
5018	18	2 hours per day per 2 feddans in summer; once weekly in winter	Farm-32		
5032	18	the irrigation is rotated through feddans	Farm-6		

E. Survey Well Information

ID	ResondantID	Survey	MonitoringPoint_ID	Pump_type	Water_Level	Well_Depth	WellDepth_masl	WaterLevel_Datum_masl	Changes_Water_Level	Changes_Water_Quality	Well_Age	Irrig/Ind_Use	Drink/Dom_Use	DateAssessed
36	Farm-20	2011 Fieldwork	F1		11	60	-79	-30	decline of 5 m over 7 years			1	1	29/09/2011
44	Farm-28	2011 Fieldwork	F10		9.5	65	-87	-31.5				1	1	28/09/2011
54	Farm-34	2011 Fieldwork	F11	electric	20	80	-101	-41	7 m		7	1	1	29/09/2011
42	Farm-26	2011 Fieldwork	F12	diesel	8	40	-54	-22			2		1	01/11/2011
28	Farm-17	2011 Fieldwork	F15	electric	unknown	140	-97				12	1		06/10/2011
8	Monestary-1	2011 Fieldwork	F16	electric	7.5	42	-62	-27.5		100 ppm of salinity over the year	10	1		25/10/2011
9	Monestary-1	2011 Fieldwork	F17		7.5	43	-58	-22.5		100 ppm of salinity over the year	7	1		25/10/2011
4	Farm-3	2011 Fieldwork	F18	electric	7.95	17	-29	-19.95	3 m			1	1	28/09/2011
2	Farm-1	2011 Fieldwork	F19		10	95	-106	-21	increases in winter; decreases in the summer		10	1		23/10/2011
37	Farm-20	2011 Fieldwork	F2		85	unknown		-107						29/09/2011
3	Farm-2	2011 Fieldwork	F20	electric	13	70	-74	-17		salinity changes throughout the year	7	1		06/10/2011
6	Farm-4	2011 Fieldwork	F21	electric	55	125	-88	-18		no change	9	1	1	06/10/2011
7	Farm-5	2011 Fieldwork	F22	electric	6	70	-85	-21	no changes noted	no changes noted	8	1	1	08/10/2011
13	Farm-7	2011 Fieldwork	F23	electric	4.5	15	-27	-16.5	0.5 m			1	1	29/09/2011
14	Farm-7	2011 Fieldwork	F24		unknown	unknown								29/09/2011
15	Farm-8	2011 Fieldwork	F25	electric	12	80	-71	-3	changes about 2 % each year	may be drinkingable after 72 hrs pumping	1	1	1	20/10/2011
16	Farm-8	2011 Fieldwork	F26		12	120	-105	3	changes about 2 % each year	may be drinkingable after 72 hrs pumping	1	1	1	20/10/2011
19	Farm-10	2011 Fieldwork	F27	electric	8	48	-67	-27				1	1	29/09/2011
23	Farm-12	2011 Fieldwork	F28		6	120	-141	-27	"summer decreases by 1m,winter increases by 25 cm",	has started to be a little saline	1			23/10/2011
25	Farm-13	2011 Fieldwork	F29	electric	1.5	12	-32	-21.5			8		1	08/10/2011
39	Farm-23	2011 Fieldwork	F30	electric	3	24	-43	-22				1	1	08/10/2011
27	Farm-14	2011 Fieldwork	F31		67	135	-100	-32		salinity in the summer because of higher demand on water	5	1	1	26/10/2011
33	Farm-19	2011 Fieldwork	F32	electric	34	196	-164	-2			6	1	1	09/10/2011
34	Farm-19	2011 Fieldwork	F33		51	105	-56	-2			15	1	1	09/10/2011
38	Farm-22	2011 Fieldwork	F34	electric	18	90	-79	-7	lower in the summer	quality has gotten worse with increases in minerals in		1	1	20/10/2011

ID	ResondantlD	Survey	MonitoringPoint_ID	Pump_type	Water_Level	Well_Depth	WellDepth_masl	WaterLevel_Datum_masl	Changes_Water_Level	Changes_Water_Quality	Well_Age	Irrig/Ind_Use	Drink/Dom_Use	DateAssessed
										last 3 years				
40	Farm-24	2011 Fieldwork	F35	diesel-flow rate = 0.45 m3/min	3.75	24	-36	-15.75	winter is 2.5 m deep; summer is 4 m deep	becomes less saline after several hours of pumping	10	1	1	27/09/2011
41	Farm-25	2011 Fieldwork	F36	electric	unknown	130	-118				4	1	1	09/10/2011
43	Farm-27	2011 Fieldwork	F37		3	100	-115	-18	fluctiates with seasons		20	1	1	23/10/2011
45	Farm-29	2011 Fieldwork	F38	diesel - 80 m3/hr	11	74	-72	-9		water quality increased over time since well was dug	3			20/10/2011
47	Farm-30	2011 Fieldwork	F39	electric	70	120	-78	-28			11	1	1	06/10/2011
20	Farm-11	2011 Fieldwork	F4	electric	31	74	-67	-24	decreases by 5 m in summer		2	1		25/10/2011
48	Farm-31	2011 Fieldwork	F40		35	120	-86	-1						26/10/2011
50	Farm-33	2011 Fieldwork	F41	electric	60	120	-107	-47			1	1		09/10/2011
51	Farm-33	2011 Fieldwork	F42		60	120	-112	-52			2	1		09/10/2011
53	Farm-36	2011 Fieldwork	F43		5	30	-47	-22						27/09/2011
55	Farm-35	2011 Fieldwork	F44	electric -40 hp; 80 kw generator; 4.7 Bar pressure;	70	250	-257	-77						15/10/2011
1	Farm-1	2011 Fieldwork	F45	electric	7	95	-99	-11	increases in winter; decreases in the summer		10	1		23/10/2011
17	Farm-8	2011 Fieldwork	F46		12	160	-155	-7	changes about 2 % each year	may be drinkingable after 72 hrs pumping	1	1	1	20/10/2011
29	Farm-17	2011 Fieldwork	F47		unknown	150	-105				12	1		06/10/2011
30	Farm-17	2011 Fieldwork	F48		unknown	150	-103				6	1		06/10/2011
46	Farm-29	2011 Fieldwork	F49		11	74	-73	-10			5			20/10/2011
21	Farm-11	2011 Fieldwork	F5		31	78	-70	-23	decreases by 5 m in summer		3	1	1	25/10/2011
32	Farm-18	2011 Fieldwork	F50	electric	unknown	unknown					5	1	1	06/10/2011
18	Farm-9	2011 Fieldwork	F54	electric - 115 m3/hr	unknown	unknown					0			15/10/2011
49	Farm-32	2011 Fieldwork	F56		unknown	unknown						1	1	23/10/2011
12	Farm-6	2011 Fieldwork	F59		unknown	unknown					30	1		08/10/2011
22	Farm-11	2011 Fieldwork	F6		31	73	-66	-24	decreases by 5 m in summer		4	1		25/10/2011
24	Farm-12	2011 Fieldwork	F60		unknown	unknown								23/10/2011
26	Farm-13	2011 Fieldwork	F61		1.5	25	-44	-20.5			18	1		08/10/2011
31	Farm-17	2011 Fieldwork	F62		unknown	160	-111				6	1		06/10/2011
11	Farm-6	2011 Fieldwork	F8		unknown	unknown					1	1		08/10/2011

ID	ResondantID	Survey	MonitoringPoint_ID	Pump_type	Water_Level	Well_Depth	WellDepth_masl	WaterLevel_Datum_masl	Changes_Water_Level	Changes_Water_Quality	Well_Age	Irrig/Ind_Use	Drink/Dom_Use	DateAssessed
10	Farm-6	2011 Fieldwork	F9	electric	unknown	90	-73				3	1	1	08/10/2011
120	K020_03	GWAHS-CS	KW1			100	-75							
129	K100_04	GWAHS-CS	KW10			140	-108							
130	K100_04	GWAHS-CS	KW11			170	-138							
131	K100_04	GWAHS-CS	KW12			185	-153							
132	K100_04	GWAHS-CS	KW13			185	-153							
133	K100_04	GWAHS-CS	KW14			170	-138							
134	K100_04	GWAHS-CS	KW15			140	-108							
135	K100_04	GWAHS-CS	KW16			200	-168							
136	K100_05	GWAHS-CS	KW17		60	200								
137	K100_06	GWAHS-CS	KW18		56	190	-142	-8						
138	K100_07	GWAHS-CS	KW19			150	-114							
121	K020_03	GWAHS-CS	KW2			150	-125							
139	K100_07	GWAHS-CS	KW20			150	-114							
140	K100_07	GWAHS-CS	KW21			160	-124							
141	K100_08	GWAHS-CS	KW22		7	180	-144	29			6			
142	K100_08	GWAHS-CS	KW23		7	190	-154	29			4			
143	K020_01	GWAHS-CS	KW24		6	200	-156	38						
144	K020_05	GWAHS-CS	KW25			90	-73				45			
145	K020_05	GWAHS-CS	KW26			60	-43				45			
146	K020_08	GWAHS-CS	KW27			89	-76							
147	K020_08	GWAHS-CS	KW28			89	-76							
148	K020_08	GWAHS-CS	KW29			89	-76							
122	K003_04	GWAHS-CS	KW3			72	-78				8			
149	K001_01	GWAHS-CS	KW30		13	42	-54	-25						
150	K100_02	GWAHS-CS	KW31		10	100	-96	-6						
151	K100_02	GWAHS-CS	KW32			100	-96							
152	K100_02	GWAHS-CS	KW33			100	-96							
153	K100_02	GWAHS-CS	KW34			150	-146							

ID	ResondantID	Survey	MonitoringPoint_ID	Pump_type	Water_Level	Well_Depth	WellDepth_masl	WaterLevel_Datum_masl	Changes_Water_Level	Changes_Water_Quality	Well_Age	Irrig/Ind_Use	Drink/Dom_Use	DateAssessed
154	K100_03	GWAHS-CS	KW35			85					48			
155	K100_03	GWAHS-CS	KW36			85					48			
156	K100_03	GWAHS-CS	KW37			85					2			
157	K100_03	GWAHS-CS	KW38			85					2			
158	K100_03	GWAHS-CS	KW39			100					48			
123	K003_04	GWAHS-CS	KW4			35	-41				8			
159	K020_06	GWAHS-CS	KW40		50	120	-91	-21			6			
160	K020_07	GWAHS-CS	KW41		20	102	-116	-34			2			
161	K003_02	GWAHS-CS	KW42											
162	K003_03	GWAHS-CS	KW43		4	40	-45	-9						
163	K003_03	GWAHS-CS	KW44		4	40	-45	-9						
164	K003_09	GWAHS-CS	KW45											
165	K001_07	GWAHS-CS	KW46											
166	K001_09	GWAHS-CS	KW47		2	25	-40	-17			4			
167	K001_10	GWAHS-CS	KW48		2	25	-46	-23			8			
168	K001_11	GWAHS-CS	KW49		2	29	-44	-17			8			
124	K003_05	GWAHS-CS	KW5			72	-78							
169	K003_01	GWAHS-CS	KW50		3	30	-49	-22						
170	K003_07	GWAHS-CS	KW51			22	-44							
171	K001_14	GWAHS-CS	KW52		3	20								
172	K003_08	GWAHS-CS	KW53			67								
173	K003_10	GWAHS-CS	KW54		3	35	-48	-16						
174	K003_11	GWAHS-CS	KW55		3	40								
175	K003_12	GWAHS-CS	KW56		36	36								
176	K003_13	GWAHS-CS	KW57		3	40	-55	-18						
177	K001_02	GWAHS-CS	KW58											
178	K001_03	GWAHS-CS	KW59		5	35	-48	-18						
125	K003_05	GWAHS-CS	KW6			35	-41							
179	K001_04	GWAHS-CS	KW60		3	18								

ID	ResondantID	Survey	MonitoringPoint_ID	Pump_type	Water_Level	Well_Depth	WellDepth_masl	WaterLevel_Datum_masl	Changes_Water_Level	Changes_Water_Quality	Well_Age	Irrig/Ind_Use	Drink/Dom_Use	DateAssessed
180	K001_05	GWAHS-CS	KW61		4.4	25					18			
181	K001_06	GWAHS-CS	KW62			24	-47							
182	K001_12	GWAHS-CS	KW63		2	24	-45	-23			8			
183	K001_13	GWAHS-CS	KW64		3	21								
126	K003_06	GWAHS-CS	KW7			30	-38							
127	K2	GWAHS-CS	KW8											
128	K100_04	GWAHS-CS	KW9			200	-168							
5	U1	GWAHS-CS	U1	electric	4.5	12	-28	-20.5					1	29/09/2011
35	U2	GWAHS-CS	U2	electric	5	35	-51	-21			7		1	02/11/2011
52	U3	GWAHS-CS	U3	electrica	4	12	-28	-20					1	29/09/2011

F. Monthly NDVI Files Used in Transient Model

Month	Year	StressPeriod	NDVI	SENSOR	Notes
1	1957	1	LM1_1972-08-31_savi.tif	LS_OLD	
2	1957	2	LM1_1972-08-31_savi.tif	LS_OLD	
3	1957	3	LM1_1972-08-31_savi.tif	LS_OLD	
4	1957	4	LM1_1972-08-31_savi.tif	LS_OLD	
5	1957	5	LM1_1972-08-31_savi.tif	LS_OLD	
6	1957	6	LM1_1972-08-31_savi.tif	LS_OLD	
7	1957	7	LM1_1972-08-31_savi.tif	LS_OLD	
8	1957	8	LM1_1972-08-31_savi.tif	LS_OLD	
9	1957	9	LM1_1972-08-31_savi.tif	LS_OLD	
10	1957	10	LM1_1972-08-31_savi.tif	LS_OLD	
11	1957	11	LM1_1972-08-31_savi.tif	LS_OLD	
12	1957	12	LM1_1972-08-31_savi.tif	LS_OLD	
1	1958	13	LM1_1972-08-31_savi.tif	LS_OLD	
2	1958	14	LM1_1972-08-31_savi.tif	LS_OLD	
3	1958	15	LM1_1972-08-31_savi.tif	LS_OLD	
4	1958	16	LM1_1972-08-31_savi.tif	LS_OLD	
5	1958	17	LM1_1972-08-31_savi.tif	LS_OLD	
6	1958	18	LM1_1972-08-31_savi.tif	LS_OLD	
7	1958	19	LM1_1972-08-31_savi.tif	LS_OLD	
8	1958	20	LM1_1972-08-31_savi.tif	LS_OLD	
9	1958	21	LM1_1972-08-31_savi.tif	LS_OLD	
10	1958	22	LM1_1972-08-31_savi.tif	LS_OLD	
11	1958	23	LM1_1972-08-31_savi.tif	LS_OLD	
12	1958	24	LM1_1972-08-31_savi.tif	LS_OLD	
1	1959	25	LM1_1972-08-31_savi.tif	LS_OLD	
2	1959	26	LM1_1972-08-31_savi.tif	LS_OLD	
3	1959	27	LM1_1972-08-31_savi.tif	LS_OLD	
4	1959	28	LM1_1972-08-31_savi.tif	LS_OLD	
5	1959	29	LM1_1972-08-31_savi.tif	LS_OLD	
6	1959	30	LM1_1972-08-31_savi.tif	LS_OLD	
7	1959	31	LM1_1972-08-31_savi.tif	LS_OLD	
8	1959	32	LM1_1972-08-31_savi.tif	LS_OLD	
9	1959	33	LM1_1972-08-31_savi.tif	LS_OLD	
10	1959	34	LM1_1972-08-31_savi.tif	LS_OLD	
11	1959	35	LM1_1972-08-31_savi.tif	LS_OLD	
12	1959	36	LM1_1972-08-31_savi.tif	LS_OLD	
1	1960	37	LM1_1972-08-31_savi.tif	LS_OLD	
2	1960	38	LM1_1972-08-31_savi.tif	LS_OLD	
3	1960	39	LM1_1972-08-31_savi.tif	LS_OLD	
4	1960	40	LM1_1972-08-31_savi.tif	LS_OLD	
5	1960	41	LM1_1972-08-31_savi.tif	LS_OLD	
6	1960	42	LM1_1972-08-31_savi.tif	LS_OLD	
7	1960	43	LM1_1972-08-31_savi.tif	LS_OLD	
8	1960	44	LM1_1972-08-31_savi.tif	LS_OLD	
9	1960	45	LM1_1972-08-31_savi.tif	LS_OLD	
10	1960	46	LM1_1972-08-31_savi.tif	LS_OLD	
11	1960	47	LM1_1972-08-31_savi.tif	LS_OLD	
12	1960	48	LM1_1972-08-31_savi.tif	LS_OLD	
1	1961	49	LM1_1972-08-31_savi.tif	LS_OLD	
2	1961	50	LM1_1972-08-31_savi.tif	LS_OLD	
3	1961	51	LM1_1972-08-31_savi.tif	LS_OLD	
4	1961	52	LM1_1972-08-31_savi.tif	LS_OLD	
5	1961	53	LM1_1972-08-31_savi.tif	LS_OLD	
6	1961	54	LM1_1972-08-31_savi.tif	LS_OLD	
7	1961	55	LM1_1972-08-31_savi.tif	LS_OLD	
8	1961	56	LM1_1972-08-31_savi.tif	LS_OLD	
9	1961	57	LM1_1972-08-31_savi.tif	LS_OLD	
10	1961	58	LM1_1972-08-31_savi.tif	LS_OLD	
11	1961	59	LM1_1972-08-31_savi.tif	LS_OLD	
12	1961	60	LM1_1972-08-31_savi.tif	LS_OLD	
1	1962	61	LM1_1972-08-31_savi.tif	LS_OLD	
2	1962	62	LM1_1972-08-31_savi.tif	LS_OLD	
3	1962	63	LM1_1972-08-31_savi.tif	LS_OLD	
4	1962	64	LM1_1972-08-31_savi.tif	LS_OLD	
5	1962	65	LM1_1972-08-31_savi.tif	LS_OLD	
6	1962	66	LM1_1972-08-31_savi.tif	LS_OLD	
7	1962	67	LM1_1972-08-31_savi.tif	LS_OLD	
8	1962	68	LM1_1972-08-31_savi.tif	LS_OLD	
9	1962	69	LM1_1972-08-31_savi.tif	LS_OLD	

Month	Year	StressPeriod	NDVI	SENSOR	Notes
10	1962	70	LM1_1972-08-31_savi.tif	LS_OLD	
11	1962	71	LM1_1972-08-31_savi.tif	LS_OLD	
12	1962	72	LM1_1972-08-31_savi.tif	LS_OLD	
1	1963	73	LM1_1972-08-31_savi.tif	LS_OLD	
2	1963	74	LM1_1972-08-31_savi.tif	LS_OLD	
3	1963	75	LM1_1972-08-31_savi.tif	LS_OLD	
4	1963	76	LM1_1972-08-31_savi.tif	LS_OLD	
5	1963	77	LM1_1972-08-31_savi.tif	LS_OLD	
6	1963	78	LM1_1972-08-31_savi.tif	LS_OLD	
7	1963	79	LM1_1972-08-31_savi.tif	LS_OLD	
8	1963	80	LM1_1972-08-31_savi.tif	LS_OLD	
9	1963	81	LM1_1972-08-31_savi.tif	LS_OLD	
10	1963	82	LM1_1972-08-31_savi.tif	LS_OLD	
11	1963	83	LM1_1972-08-31_savi.tif	LS_OLD	
12	1963	84	LM1_1972-08-31_savi.tif	LS_OLD	
1	1964	85	LM1_1972-08-31_savi.tif	LS_OLD	
2	1964	86	LM1_1972-08-31_savi.tif	LS_OLD	
3	1964	87	LM1_1972-08-31_savi.tif	LS_OLD	
4	1964	88	LM1_1972-08-31_savi.tif	LS_OLD	
5	1964	89	LM1_1972-08-31_savi.tif	LS_OLD	
6	1964	90	LM1_1972-08-31_savi.tif	LS_OLD	
7	1964	91	LM1_1972-08-31_savi.tif	LS_OLD	
8	1964	92	LM1_1972-08-31_savi.tif	LS_OLD	
9	1964	93	LM1_1972-08-31_savi.tif	LS_OLD	
10	1964	94	LM1_1972-08-31_savi.tif	LS_OLD	
11	1964	95	LM1_1972-08-31_savi.tif	LS_OLD	
12	1964	96	LM1_1972-08-31_savi.tif	LS_OLD	
1	1965	97	LM1_1972-08-31_savi.tif	LS_OLD	
2	1965	98	LM1_1972-08-31_savi.tif	LS_OLD	
3	1965	99	LM1_1972-08-31_savi.tif	LS_OLD	
4	1965	100	LM1_1972-08-31_savi.tif	LS_OLD	
5	1965	101	LM1_1972-08-31_savi.tif	LS_OLD	
6	1965	102	LM1_1972-08-31_savi.tif	LS_OLD	
7	1965	103	LM1_1972-08-31_savi.tif	LS_OLD	
8	1965	104	LM1_1972-08-31_savi.tif	LS_OLD	
9	1965	105	LM1_1972-08-31_savi.tif	LS_OLD	
10	1965	106	LM1_1972-08-31_savi.tif	LS_OLD	
11	1965	107	LM1_1972-08-31_savi.tif	LS_OLD	
12	1965	108	LM1_1972-08-31_savi.tif	LS_OLD	
1	1966	109	LM1_1972-08-31_savi.tif	LS_OLD	
2	1966	110	LM1_1972-08-31_savi.tif	LS_OLD	
3	1966	111	LM1_1972-08-31_savi.tif	LS_OLD	
4	1966	112	LM1_1972-08-31_savi.tif	LS_OLD	
5	1966	113	LM1_1972-08-31_savi.tif	LS_OLD	
6	1966	114	LM1_1972-08-31_savi.tif	LS_OLD	
7	1966	115	LM1_1972-08-31_savi.tif	LS_OLD	
8	1966	116	LM1_1972-08-31_savi.tif	LS_OLD	
9	1966	117	LM1_1972-08-31_savi.tif	LS_OLD	
10	1966	118	LM1_1972-08-31_savi.tif	LS_OLD	
11	1966	119	LM1_1972-08-31_savi.tif	LS_OLD	
12	1966	120	LM1_1972-08-31_savi.tif	LS_OLD	
1	1967	121	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
2	1967	122	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
3	1967	123	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
4	1967	124	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
5	1967	125	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
6	1967	126	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
7	1967	127	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
8	1967	128	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
9	1967	129	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
10	1967	130	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
11	1967	131	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
12	1967	132	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)

Month	Year	StressPeriod	NDVI	SENSOR	Notes
1	1968	133	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
2	1968	134	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
3	1968	135	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
4	1968	136	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
5	1968	137	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
6	1968	138	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
7	1968	139	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
8	1968	140	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
9	1968	141	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
10	1968	142	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
11	1968	143	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
12	1968	144	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
1	1969	145	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
2	1969	146	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
3	1969	147	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
4	1969	148	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
5	1969	149	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
6	1969	150	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
7	1969	151	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
8	1969	152	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
9	1969	153	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
10	1969	154	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
11	1969	155	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
12	1969	156	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
1	1970	157	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
2	1970	158	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
3	1970	159	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
4	1970	160	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
5	1970	161	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
6	1970	162	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
7	1970	163	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
8	1970	164	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
9	1970	165	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
10	1970	166	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
11	1970	167	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
12	1970	168	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
1	1971	169	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
2	1971	170	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)

Month	Year	StressPeriod	NDVI	SENSOR	Notes
3	1971	171	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
4	1971	172	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
5	1971	173	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
6	1971	174	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
7	1971	175	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
8	1971	176	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
9	1971	177	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
10	1971	178	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
11	1971	179	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
12	1971	180	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
1	1972	181	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
2	1972	182	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
3	1972	183	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
4	1972	184	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
5	1972	185	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
6	1972	186	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
7	1972	187	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
8	1972	188	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
9	1972	189	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
10	1972	190	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
11	1972	191	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
12	1972	192	LM1_1972-08-31_savi.tif	LS_OLD	ET Infilled with monthly average plus random factor based on 1 standard deviation (normal 1957 - 1987)
1	1973	193	LM1_1972-08-31_savi.tif	LS_OLD	
2	1973	194	LM1_1972-08-31_savi.tif	LS_OLD	
3	1973	195	LM1_1972-08-31_savi.tif	LS_OLD	
4	1973	196	LM1_1972-08-31_savi.tif	LS_OLD	
5	1973	197	LM1_1972-08-31_savi.tif	LS_OLD	
6	1973	198	LM1_1972-08-31_savi.tif	LS_OLD	
7	1973	199	LM1_1972-08-31_savi.tif	LS_OLD	
8	1973	200	LM1_1972-08-31_savi.tif	LS_OLD	
9	1973	201	LM1_1972-08-31_savi.tif	LS_OLD	
10	1973	202	LM1_1972-08-31_savi.tif	LS_OLD	
11	1973	203	LM1_1972-08-31_savi.tif	LS_OLD	
12	1973	204	LM1_1972-08-31_savi.tif	LS_OLD	
1	1974	205	LM1_1972-08-31_savi.tif	LS_OLD	
2	1974	206	LM1_1972-08-31_savi.tif	LS_OLD	
3	1974	207	LM1_1972-08-31_savi.tif	LS_OLD	
4	1974	208	LM1_1972-08-31_savi.tif	LS_OLD	
5	1974	209	LM1_1972-08-31_savi.tif	LS_OLD	
6	1974	210	LM1_1972-08-31_savi.tif	LS_OLD	
7	1974	211	LM1_1972-08-31_savi.tif	LS_OLD	
8	1974	212	LM1_1972-08-31_savi.tif	LS_OLD	
9	1974	213	LM1_1972-08-31_savi.tif	LS_OLD	
10	1974	214	LM1_1972-08-31_savi.tif	LS_OLD	
11	1974	215	LM1_1972-08-31_savi.tif	LS_OLD	
12	1974	216	LM1_1972-08-31_savi.tif	LS_OLD	
1	1975	217	LM1_1972-08-31_savi.tif	LS_OLD	
2	1975	218	LM1_1972-08-31_savi.tif	LS_OLD	
3	1975	219	LM1_1972-08-31_savi.tif	LS_OLD	
4	1975	220	LM1_1972-08-31_savi.tif	LS_OLD	
5	1975	221	LM1_1972-08-31_savi.tif	LS_OLD	
6	1975	222	LM1_1972-08-31_savi.tif	LS_OLD	
7	1975	223	LM1_1972-08-31_savi.tif	LS_OLD	
8	1975	224	LM1_1972-08-31_savi.tif	LS_OLD	

Month	Year	StressPeriod	NDVI	SENSOR	Notes
9	1975	225	LM1_1972-08-31_savi.tif	LS_OLD	
10	1975	226	LM2_1975-10-18_savi.tif	LS_OLD	
11	1975	227	LM2_1975-10-18_savi.tif	LS_OLD	
12	1975	228	LM2_1975-10-18_savi.tif	LS_OLD	
1	1976	229	LM2_1975-10-18_savi.tif	LS_OLD	
2	1976	230	LM2_1976-02-21_savi.tif	LS_OLD	
3	1976	231	LM2_1976-02-21_savi.tif	LS_OLD	
4	1976	232	LM2_1976-02-21_savi.tif	LS_OLD	
5	1976	233	LM2_1976-02-21_savi.tif	LS_OLD	
6	1976	234	LM2_1976-02-21_savi.tif	LS_OLD	
7	1976	235	LM2_1976-02-21_savi.tif	LS_OLD	
8	1976	236	LM2_1976-02-21_savi.tif	LS_OLD	
9	1976	237	LM2_1976-02-21_savi.tif	LS_OLD	
10	1976	238	LM2_1976-02-21_savi.tif	LS_OLD	
11	1976	239	LM2_1976-02-21_savi.tif	LS_OLD	
12	1976	240	LM2_1976-02-21_savi.tif	LS_OLD	
1	1977	241	LM2_1976-02-21_savi.tif	LS_OLD	
2	1977	242	LM2_1976-02-21_savi.tif	LS_OLD	
3	1977	243	LM2_1976-02-21_savi.tif	LS_OLD	
4	1977	244	LM2_1976-02-21_savi.tif	LS_OLD	
5	1977	245	LM2_1976-02-21_savi.tif	LS_OLD	
6	1977	246	LM2_1976-02-21_savi.tif	LS_OLD	
7	1977	247	LM2_1976-02-21_savi.tif	LS_OLD	
8	1977	248	LM2_1976-02-21_savi.tif	LS_OLD	
9	1977	249	LM2_1976-02-21_savi.tif	LS_OLD	
10	1977	250	LM2_1976-02-21_savi.tif	LS_OLD	
11	1977	251	LM2_1976-02-21_savi.tif	LS_OLD	
12	1977	252	LM2_1976-02-21_savi.tif	LS_OLD	
1	1978	253	LM2_1976-02-21_savi.tif	LS_OLD	
2	1978	254	LM2_1976-02-21_savi.tif	LS_OLD	
3	1978	255	LM2_1976-02-21_savi.tif	LS_OLD	
4	1978	256	LM2_1976-02-21_savi.tif	LS_OLD	
5	1978	257	LM3_1978-05-02_savi.tif	LS_OLD	
6	1978	258	LM3_1978-05-02_savi.tif	LS_OLD	
7	1978	259	LM3_1978-05-02_savi.tif	LS_OLD	
8	1978	260	LM3_1978-05-02_savi.tif	LS_OLD	
9	1978	261	LM3_1978-05-02_savi.tif	LS_OLD	
10	1978	262	LM3_1978-05-02_savi.tif	LS_OLD	
11	1978	263	LM3_1978-05-02_savi.tif	LS_OLD	
12	1978	264	LM3_1978-05-02_savi.tif	LS_OLD	
1	1979	265	LM3_1978-05-02_savi.tif	LS_OLD	
2	1979	266	LM3_1978-05-02_savi.tif	LS_OLD	
3	1979	267	LM3_1978-05-02_savi.tif	LS_OLD	
4	1979	268	LM3_1978-05-02_savi.tif	LS_OLD	
5	1979	269	LM3_1978-05-02_savi.tif	LS_OLD	
6	1979	270	LM3_1978-05-02_savi.tif	LS_OLD	
7	1979	271	LM3_1978-05-02_savi.tif	LS_OLD	
8	1979	272	LM3_1978-05-02_savi.tif	LS_OLD	
9	1979	273	LM3_1978-05-02_savi.tif	LS_OLD	
10	1979	274	LM3_1978-05-02_savi.tif	LS_OLD	
11	1979	275	LM3_1978-05-02_savi.tif	LS_OLD	
12	1979	276	LM3_1978-05-02_savi.tif	LS_OLD	
1	1980	277	LM3_1978-05-02_savi.tif	LS_OLD	
2	1980	278	LM3_1978-05-02_savi.tif	LS_OLD	
3	1980	279	LM3_1978-05-02_savi.tif	LS_OLD	
4	1980	280	LM3_1978-05-02_savi.tif	LS_OLD	
5	1980	281	LM3_1978-05-02_savi.tif	LS_OLD	
6	1980	282	LM3_1978-05-02_savi.tif	LS_OLD	
7	1980	283	LM3_1978-05-02_savi.tif	LS_OLD	
8	1980	284	LM3_1978-05-02_savi.tif	LS_OLD	
9	1980	285	LM3_1978-05-02_savi.tif	LS_OLD	
10	1980	286	LM3_1978-05-02_savi.tif	LS_OLD	
11	1980	287	LM3_1978-05-02_savi.tif	LS_OLD	
12	1980	288	LM3_1978-05-02_savi.tif	LS_OLD	
1	1981	289	LM3_1978-05-02_savi.tif	LS_OLD	
2	1981	290	LM3_1978-05-02_savi.tif	LS_OLD	
3	1981	291	LM3_1978-05-02_savi.tif	LS_OLD	
4	1981	292	LM3_1978-05-02_savi.tif	LS_OLD	
5	1981	293	LM3_1978-05-02_savi.tif	LS_OLD	
6	1981	294	LM3_1978-05-02_savi.tif	LS_OLD	
7	1981	295	LM3_1978-05-02_savi.tif	LS_OLD	
8	1981	296	LM3_1978-05-02_savi.tif	LS_OLD	
9	1981	297	LM3_1978-05-02_savi.tif	LS_OLD	
10	1981	298	LM3_1978-05-02_savi.tif	LS_OLD	

Month	Year	StressPeriod	NDVI	SENSOR	Notes
11	1981	299	LM3_1978-05-02_savi.tif	LS_OLD	
12	1981	300	LM3_1978-05-02_savi.tif	LS_OLD	
1	1982	301	LM5_1984-08-10_savi.tif	LS	
2	1982	302	LM5_1984-08-10_savi.tif	LS	
3	1982	303	LM5_1984-08-10_savi.tif	LS	
4	1982	304	LM5_1984-08-10_savi.tif	LS	
5	1982	305	LM5_1984-08-10_savi.tif	LS	
6	1982	306	LM5_1984-08-10_savi.tif	LS	
7	1982	307	LM5_1984-08-10_savi.tif	LS	
8	1982	308	LM5_1984-08-10_savi.tif	LS	
9	1982	309	LM5_1984-08-10_savi.tif	LS	
10	1982	310	LM5_1984-08-10_savi.tif	LS	
11	1982	311	LM5_1984-08-10_savi.tif	LS	
12	1982	312	LM5_1984-08-10_savi.tif	LS	
1	1983	313	LM5_1984-08-10_savi.tif	LS	
2	1983	314	LM5_1984-08-10_savi.tif	LS	
3	1983	315	LM5_1984-08-10_savi.tif	LS	
4	1983	316	LM5_1984-08-10_savi.tif	LS	
5	1983	317	LM5_1984-08-10_savi.tif	LS	
6	1983	318	LM5_1984-08-10_savi.tif	LS	
7	1983	319	LM5_1984-08-10_savi.tif	LS	
8	1983	320	LM5_1984-08-10_savi.tif	LS	
9	1983	321	LM5_1984-08-10_savi.tif	LS	
10	1983	322	LM5_1984-08-10_savi.tif	LS	
11	1983	323	LM5_1984-08-10_savi.tif	LS	
12	1983	324	LM5_1984-08-10_savi.tif	LS	
1	1984	325	LM5_1984-08-10_savi.tif	LS	
2	1984	326	LM5_1984-08-10_savi.tif	LS	
3	1984	327	LM5_1984-08-10_savi.tif	LS	
4	1984	328	LM5_1984-08-10_savi.tif	LS	
5	1984	329	LM5_1984-08-10_savi.tif	LS	
6	1984	330	LM5_1984-08-10_savi.tif	LS	
7	1984	331	LM5_1984-08-10_savi.tif	LS	
8	1984	332	LM5_1984-08-10_savi.tif	LS	
9	1984	333	LM5_1984-08-10_savi.tif	LS	
10	1984	334	LM5_1984-08-10_savi.tif	LS	
11	1984	335	LM5_1984-08-10_savi.tif	LS	
12	1984	336	LM5_1984-08-10_savi.tif	LS	
1	1985	337	LM5_1984-08-10_savi.tif	LS	
2	1985	338	LM5_1984-08-10_savi.tif	LS	
3	1985	339	LM5_1984-08-10_savi.tif	LS	
4	1985	340	LM5_1984-08-10_savi.tif	LS	
5	1985	341	LM5_1985-05-25_savi.tif	LS	
6	1985	342	LM5_1985-05-25_savi.tif	LS	
7	1985	343	LM5_1985-07-12_savi.tif	LS	
8	1985	344	LM5_1985-07-12_savi.tif	LS	
9	1985	345	LM5_1985-07-12_savi.tif	LS	
10	1985	346	LM5_1985-07-12_savi.tif	LS	
11	1985	347	LM5_1985-07-12_savi.tif	LS	
12	1985	348	LM5_1985-07-12_savi.tif	LS	
1	1986	349	LM5_1985-07-12_savi.tif	LS	
2	1986	350	LT5_1986-02-05_savi.tif	LS	
3	1986	351	LT5_1986-02-05_savi.tif	LS	
4	1986	352	LT5_1986-02-05_savi.tif	LS	
5	1986	353	LT5_1986-02-05_savi.tif	LS	
6	1986	354	LT5_1986-02-05_savi.tif	LS	
7	1986	355	LT5_1986-02-05_savi.tif	LS	
8	1986	356	LT5_1986-02-05_savi.tif	LS	
9	1986	357	LT5_1986-02-05_savi.tif	LS	
10	1986	358	LT5_1986-02-05_savi.tif	LS	
11	1986	359	LT5_1986-02-05_savi.tif	LS	
12	1986	360	LT5_1986-02-05_savi.tif	LS	
1	1987	361	LT5_1987-01-07_savi.tif	LS	
2	1987	362	LT5_1987-02-08_savi.tif	LS	
3	1987	363	LT5_1987-02-08_savi.tif	LS	
4	1987	364	LT5_1987-02-08_savi.tif	LS	
5	1987	365	LM5_1987-05-15_savi.tif	LS	
6	1987	366	LM5_1987-05-15_savi.tif	LS	
7	1987	367	LT5_1987-07-18_savi.tif	LS	
8	1987	368	LT5_1987-07-18_savi.tif	LS	
9	1987	369	LT5_1987-07-18_savi.tif	LS	
10	1987	370	LT5_1987-07-18_savi.tif	LS	
11	1987	371	LT5_1987-07-18_savi.tif	LS	
12	1987	372	LT5_1987-07-18_savi.tif	LS	

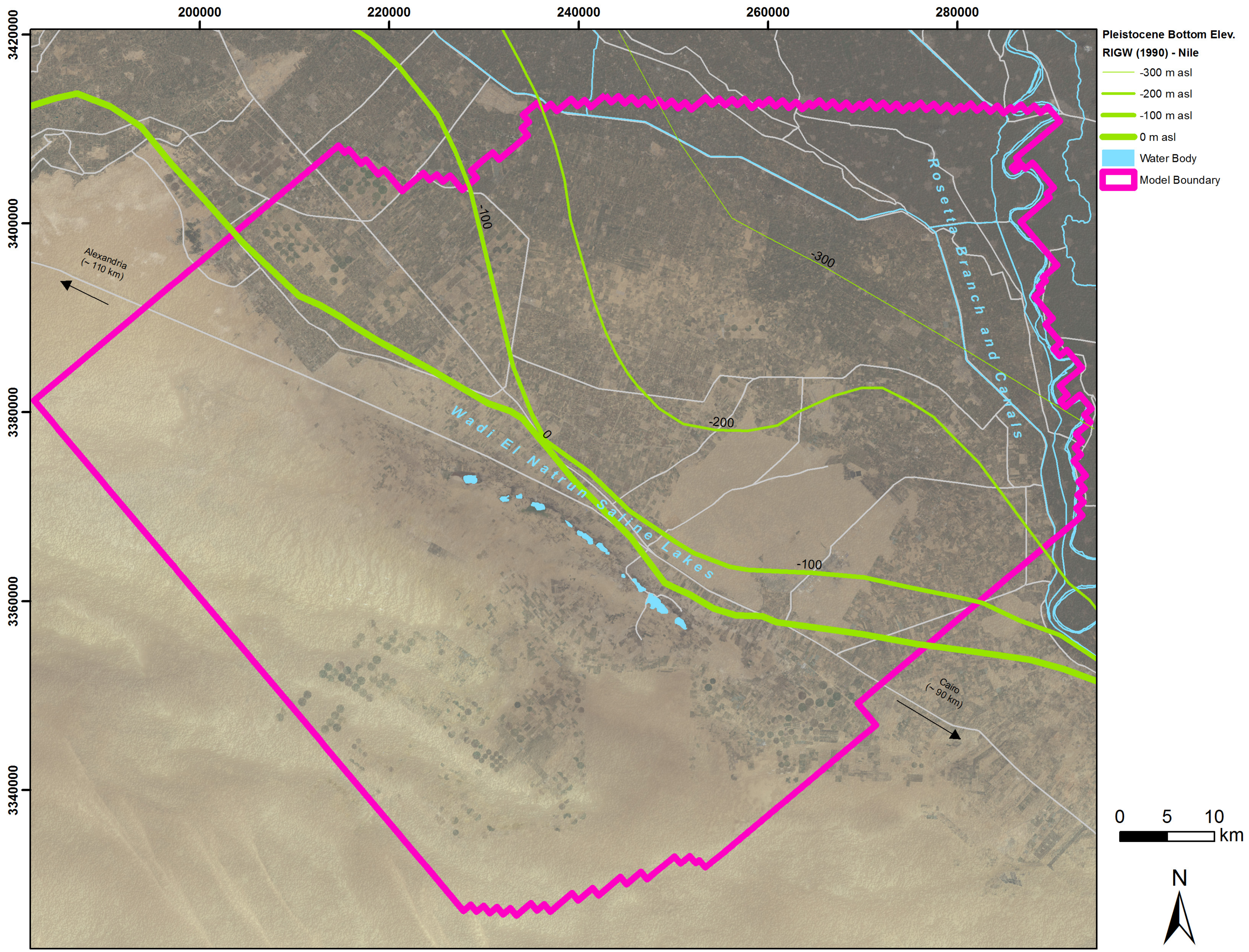
Month	Year	StressPeriod	NDVI	SENSOR	Notes
1	1988	373	LT5_1987-07-18_savi.tif	LS	
2	1988	374	LT5_1987-07-18_savi.tif	LS	
3	1988	375	LT5_1987-07-18_savi.tif	LS	
4	1988	376	LT5_1987-07-18_savi.tif	LS	
5	1988	377	LT5_1987-07-18_savi.tif	LS	
6	1988	378	LT5_1987-07-18_savi.tif	LS	
7	1988	379	LT5_1987-07-18_savi.tif	LS	
8	1988	380	LT5_1987-07-18_savi.tif	LS	
9	1988	381	LT5_1987-07-18_savi.tif	LS	
10	1988	382	LT5_1987-07-18_savi.tif	LS	
11	1988	383	LM4_1988-11-01_savi.tif	LS	
12	1988	384	LM4_1988-11-01_savi.tif	LS	
1	1989	385	LM4_1988-11-01_savi.tif	LS	
2	1989	386	LM4_1988-11-01_savi.tif	LS	
3	1989	387	LM4_1988-11-01_savi.tif	LS	
4	1989	388	8910nd_30e_31n_n_cl_pr.img	AVHRR	
5	1989	389	8910nd_30e_31n_n_cl_pr.img	AVHRR	
6	1989	390	8910nd_30e_31n_n_cl_pr.img	AVHRR	
7	1989	391	8910nd_30e_31n_n_cl_pr.img	AVHRR	
8	1989	392	8910nd_30e_31n_n_cl_pr.img	AVHRR	
9	1989	393	8910nd_30e_31n_n_cl_pr.img	AVHRR	
10	1989	394	8910nd_30e_31n_n_cl_pr.img	AVHRR	
11	1989	395	8910nd_30e_31n_n_cl_pr.img	AVHRR	
12	1989	396	8910nd_30e_31n_n_cl_pr.img	AVHRR	
1	1990	397	9001nd_30e_31n_n_cl_pr.img	AVHRR	
2	1990	398	9001nd_30e_31n_n_cl_pr.img	AVHRR	
3	1990	399	9001nd_30e_31n_n_cl_pr.img	AVHRR	
4	1990	400	9001nd_30e_31n_n_cl_pr.img	AVHRR	
5	1990	401	LT4_1990-05-15_savi.tif	LS	
6	1990	402	LT4_1990-05-15_savi.tif	LS	
7	1990	403	LT4_1990-05-15_savi.tif	LS	
8	1990	404	LT4_1990-08-03_savi.tif	LS	
9	1990	405	LT4_1990-08-03_savi.tif	LS	
10	1990	406	LT4_1990-08-03_savi.tif	LS	
11	1990	407	LT4_1990-08-03_savi.tif	LS	
12	1990	408	LT4_1990-08-03_savi.tif	LS	
1	1991	409	LT4_1990-08-03_savi.tif	LS	
2	1991	410	LT4_1990-08-03_savi.tif	LS	
3	1991	411	LT4_1990-08-03_savi.tif	LS	
4	1991	412	9110nd_30e_31n_n_cl_pr.img	AVHRR	
5	1991	413	9110nd_30e_31n_n_cl_pr.img	AVHRR	
6	1991	414	9110nd_30e_31n_n_cl_pr.img	AVHRR	
7	1991	415	9110nd_30e_31n_n_cl_pr.img	AVHRR	
8	1991	416	9110nd_30e_31n_n_cl_pr.img	AVHRR	
9	1991	417	9110nd_30e_31n_n_cl_pr.img	AVHRR	
10	1991	418	9128nd_30e_31n_n_cl_pr.img	AVHRR	
11	1991	419	9128nd_30e_31n_n_cl_pr.img	AVHRR	
12	1991	420	9128nd_30e_31n_n_cl_pr.img	AVHRR	
1	1992	421	9128nd_30e_31n_n_cl_pr.img	AVHRR	
2	1992	422	9128nd_30e_31n_n_cl_pr.img	AVHRR	
3	1992	423	9128nd_30e_31n_n_cl_pr.img	AVHRR	
4	1992	424	9210nd_30e_31n_n_cl_pr.img	AVHRR	
5	1992	425	9210nd_30e_31n_n_cl_pr.img	AVHRR	
6	1992	426	9210nd_30e_31n_n_cl_pr.img	AVHRR	
7	1992	427	9210nd_30e_31n_n_cl_pr.img	AVHRR	
8	1992	428	9210nd_30e_31n_n_cl_pr.img	AVHRR	
9	1992	429	9210nd_30e_31n_n_cl_pr.img	AVHRR	
10	1992	430	9210nd_30e_31n_n_cl_pr.img	AVHRR	
11	1992	431	9210nd_30e_31n_n_cl_pr.img	AVHRR	
12	1992	432	9210nd_30e_31n_n_cl_pr.img	AVHRR	
1	1993	433	9210nd_30e_31n_n_cl_pr.img	AVHRR	
2	1993	434	9304nd_30e_31n_n_cl_pr.img	AVHRR	
3	1993	435	9304nd_30e_31n_n_cl_pr.img	AVHRR	
4	1993	436	9304nd_30e_31n_n_cl_pr.img	AVHRR	
5	1993	437	9304nd_30e_31n_n_cl_pr.img	AVHRR	
6	1993	438	9304nd_30e_31n_n_cl_pr.img	AVHRR	
7	1993	439	9304nd_30e_31n_n_cl_pr.img	AVHRR	
8	1993	440	9304nd_30e_31n_n_cl_pr.img	AVHRR	
9	1993	441	9304nd_30e_31n_n_cl_pr.img	AVHRR	
10	1993	442	9304nd_30e_31n_n_cl_pr.img	AVHRR	
11	1993	443	9304nd_30e_31n_n_cl_pr.img	AVHRR	
12	1993	444	9304nd_30e_31n_n_cl_pr.img	AVHRR	
1	1994	445	9304nd_30e_31n_n_cl_pr.img	AVHRR	
2	1994	446	9304nd_30e_31n_n_cl_pr.img	AVHRR	

Month	Year	StressPeriod	NDVI	SENSOR	Notes
3	1994	447	9304nd_30e_31n_n_cl_pr.img	AVHRR	
4	1994	448	9304nd_30e_31n_n_cl_pr.img	AVHRR	
5	1994	449	9304nd_30e_31n_n_cl_pr.img	AVHRR	
6	1994	450	9304nd_30e_31n_n_cl_pr.img	AVHRR	
7	1994	451	9304nd_30e_31n_n_cl_pr.img	AVHRR	
8	1994	452	9304nd_30e_31n_n_cl_pr.img	AVHRR	
9	1994	453	9304nd_30e_31n_n_cl_pr.img	AVHRR	
10	1994	454	9304nd_30e_31n_n_cl_pr.img	AVHRR	
11	1994	455	9304nd_30e_31n_n_cl_pr.img	AVHRR	
12	1994	456	9304nd_30e_31n_n_cl_pr.img	AVHRR	
1	1995	457	9601nd_30e_31n_n_cl_pr.img	AVHRR	
2	1995	458	9601nd_30e_31n_n_cl_pr.img	AVHRR	
3	1995	459	9601nd_30e_31n_n_cl_pr.img	AVHRR	
4	1995	460	9601nd_30e_31n_n_cl_pr.img	AVHRR	
5	1995	461	9601nd_30e_31n_n_cl_pr.img	AVHRR	
6	1995	462	9601nd_30e_31n_n_cl_pr.img	AVHRR	
7	1995	463	9601nd_30e_31n_n_cl_pr.img	AVHRR	
8	1995	464	9601nd_30e_31n_n_cl_pr.img	AVHRR	
9	1995	465	9601nd_30e_31n_n_cl_pr.img	AVHRR	
10	1995	466	9601nd_30e_31n_n_cl_pr.img	AVHRR	
11	1995	467	9601nd_30e_31n_n_cl_pr.img	AVHRR	
12	1995	468	9601nd_30e_31n_n_cl_pr.img	AVHRR	
1	1996	469	9601nd_30e_31n_n_cl_pr.img	AVHRR	
2	1996	470	9604nd_30e_31n_n_cl_pr.img	AVHRR	
3	1996	471	9604nd_30e_31n_n_cl_pr.img	AVHRR	
4	1996	472	9610nd_30e_31n_n_cl_pr.img	AVHRR	
5	1996	473	9610nd_30e_31n_n_cl_pr.img	AVHRR	
6	1996	474	9610nd_30e_31n_n_cl_pr.img	AVHRR	
7	1996	475	9619nd_30e_31n_n_cl_pr.img	AVHRR	
8	1996	476	9619nd_30e_31n_n_cl_pr.img	AVHRR	
9	1996	477	9619nd_30e_31n_n_cl_pr.img	AVHRR	
10	1996	478	9619nd_30e_31n_n_cl_pr.img	AVHRR	
11	1996	479	9619nd_30e_31n_n_cl_pr.img	AVHRR	
12	1996	480	9619nd_30e_31n_n_cl_pr.img	AVHRR	
1	1997	481	9701nd_30e_31n_n_cl_pr.img	AVHRR	
2	1997	482	9704nd_30e_31n_n_cl_pr.img	AVHRR	
3	1997	483	9704nd_30e_31n_n_cl_pr.img	AVHRR	
4	1997	484	9710nd_30e_31n_n_cl_pr.img	AVHRR	
5	1997	485	9710nd_30e_31n_n_cl_pr.img	AVHRR	
6	1997	486	9710nd_30e_31n_n_cl_pr.img	AVHRR	
7	1997	487	9719nd_30e_31n_n_cl_pr.img	AVHRR	
8	1997	488	9719nd_30e_31n_n_cl_pr.img	AVHRR	
9	1997	489	9719nd_30e_31n_n_cl_pr.img	AVHRR	
10	1997	490	9728nd_30e_31n_n_cl_pr.img	AVHRR	
11	1997	491	9728nd_30e_31n_n_cl_pr.img	AVHRR	
12	1997	492	9728nd_30e_31n_n_cl_pr.img	AVHRR	
1	1998	493	9801nd_30e_31n_n_cl_pr.img	AVHRR	
2	1998	494	9801nd_30e_31n_n_cl_pr.img	AVHRR	
3	1998	495	9801nd_30e_31n_n_cl_pr.img	AVHRR	
4	1998	496	9801nd_30e_31n_n_cl_pr.img	AVHRR	REDO
5	1998	497	9801nd_30e_31n_n_cl_pr.img	AVHRR	REDO
6	1998	498	9801nd_30e_31n_n_cl_pr.img	AVHRR	REDO
7	1998	499	9819nd_30e_31n_n_cl_pr.img	AVHRR	
8	1998	500	9819nd_30e_31n_n_cl_pr.img	AVHRR	
9	1998	501	9819nd_30e_31n_n_cl_pr.img	AVHRR	
10	1998	502	LT5_1998-10-04_savi.tif	LS	
11	1998	503	LT5_1998-10-04_savi.tif	LS	
12	1998	504	LT5_1998-10-04_savi.tif	LS	
1	1999	505	LT5_1998-10-04_savi.tif	LS	
2	1999	506	LT5_1998-10-04_savi.tif	LS	
3	1999	507	LT5_1998-10-04_savi.tif	LS	
4	1999	508	LT5_1999-04-30_savi.tif	LS	
5	1999	509	LT5_1999-04-30_savi.tif	LS	
6	1999	510	LT5_1999-04-30_savi.tif	LS	
7	1999	511	LT5_1999-04-30_savi.tif	LS	
8	1999	512	LT5_1999-04-30_savi.tif	LS	
9	1999	513	LT5_1999-04-30_savi.tif	LS	
10	1999	514	LT5_1999-04-30_savi.tif	LS	
11	1999	515	LT5_1999-04-30_savi.tif	LS	
12	1999	516	LE7_1999-12-02_savi.tif	LS	
1	2000	517	LE7_1999-12-02_savi.tif	LS	
2	2000	518	LE7_2000-02-04_savi.tif	LS	
3	2000	519	LE7_2000-02-04_savi.tif	LS	
4	2000	520	LE7_2000-02-04_savi.tif	LS	

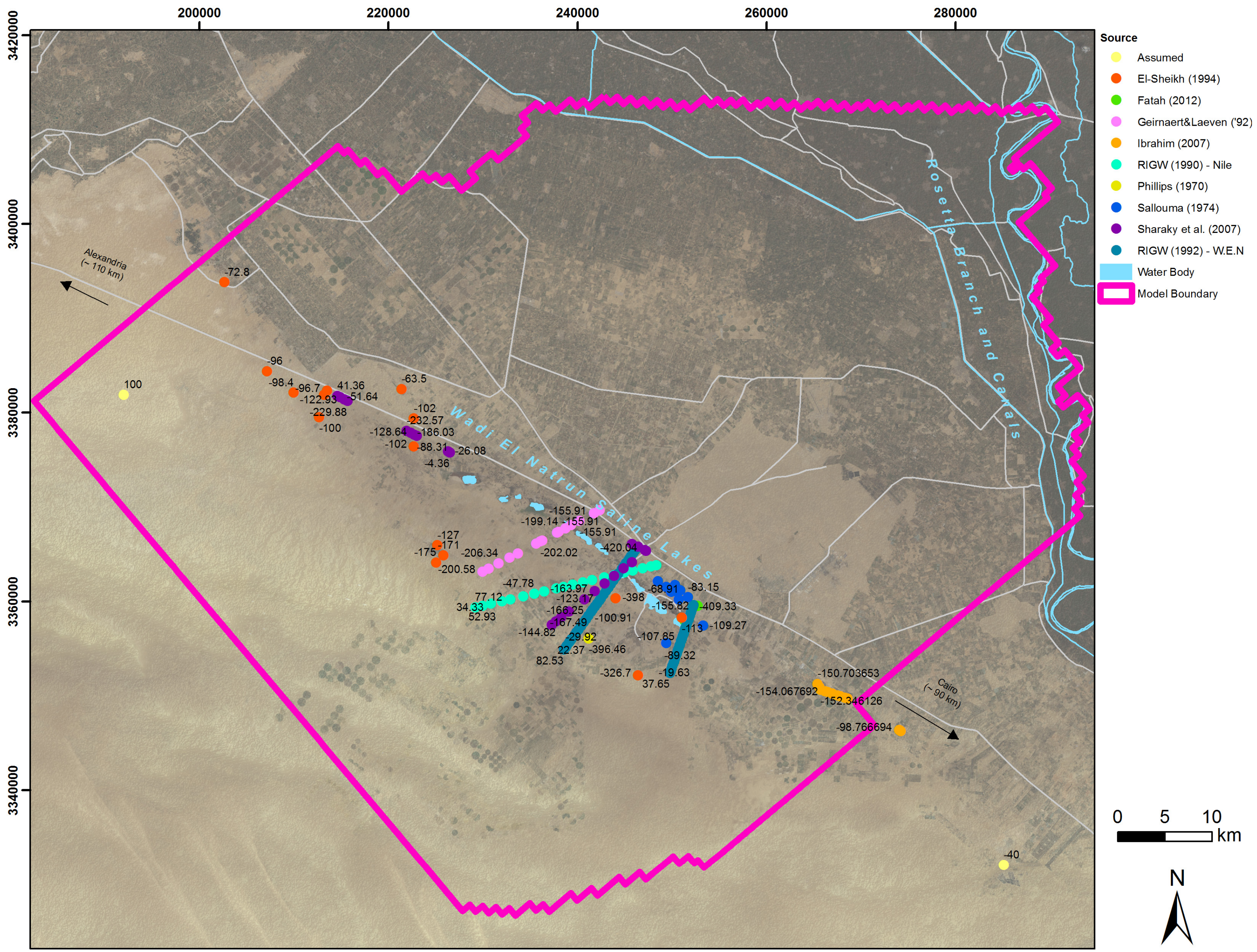
Month	Year	StressPeriod	NDVI	SENSOR	Notes
5	2000	521	LE7_2000-02-04_savi.tif	LS	
6	2000	522	LE7_2000-02-04_savi.tif	LS	
7	2000	523	LE7_2000-02-04_savi.tif	LS	
8	2000	524	LE7_2000-02-04_savi.tif	LS	
9	2000	525	LE7_2000-02-04_savi.tif	LS	
10	2000	526	LE7_2000-02-04_savi.tif	LS	
11	2000	527	LE7_2000-02-04_savi.tif	LS	
12	2000	528	LE7_2000-12-04_savi.tif	LS	
1	2001	529	LE7_2000-12-04_savi.tif	LS	
2	2001	530	0104nd_30e_31n_n_cl_pr.img	AVHRR	
3	2001	531	0104nd_30e_31n_n_cl_pr.img	AVHRR	
4	2001	532	0110nd_30e_31n_n_cl_pr.img	AVHRR	
5	2001	533	0110nd_30e_31n_n_cl_pr.img	AVHRR	
6	2001	534	0110nd_30e_31n_n_cl_pr.img	AVHRR	
7	2001	535	0119nd_30e_31n_n_cl_pr.img	AVHRR	
8	2001	536	0119nd_30e_31n_n_cl_pr.img	AVHRR	
9	2001	537	0119nd_30e_31n_n_cl_pr.img	AVHRR	
10	2001	538	LE7_2001-10-04_savi.tif	LS	
11	2001	539	LE7_2001-10-04_savi.tif	LS	
12	2001	540	LE7_2001-10-04_savi.tif	LS	
1	2002	541	LE7_2001-10-04_savi.tif	LS	
2	2002	542	LE7_2001-10-04_savi.tif	LS	
3	2002	543	LE7_2001-10-04_savi.tif	LS	
4	2002	544	LE7_2001-10-04_savi.tif	LS	
5	2002	545	LT5_2002-05-24_savi.tif	LS	
6	2002	546	LT5_2002-05-24_savi.tif	LS	
7	2002	547	LT5_2002-05-24_savi.tif	LS	
8	2002	548	LT5_2002-05-24_savi.tif	LS	
9	2002	549	LE7_2002-09-21_savi.tif	LS	
10	2002	550	0228nd_30e_31n_n_cl_pr.img	AVHRR	
11	2002	551	0228nd_30e_31n_n_cl_pr.img	AVHRR	
12	2002	552	0228nd_30e_31n_n_cl_pr.img	AVHRR	
1	2003	553	0301nd_30e_31n_n_cl_pr.img	AVHRR	
2	2003	554	0304nd_30e_31n_n_cl_pr.img	AVHRR	
3	2003	555	0304nd_30e_31n_n_cl_pr.img	AVHRR	
4	2003	556	0310nd_30e_31n_n_cl_pr.img	AVHRR	
5	2003	557	LE7_2003-05-03_savi.tif	LS	
6	2003	558	LE7_2003-05-03_savi.tif	LS	
7	2003	559	LT5_2003-07-14_savi.tif	LS	
8	2003	560	LT5_2003-07-14_savi.tif	LS	
9	2003	561	LT5_2003-07-14_savi.tif	LS	
10	2003	562	LT5_2003-10-18_savi.tif	LS	
11	2003	563	LT5_2003-10-18_savi.tif	LS	
12	2003	564	LT5_2003-10-18_savi.tif	LS	
1	2004	565	GM_LE7_2004-01-30_savi.tif	LS	Used gap-mask
2	2004	566	0404nd_30e_31n_n_cl_pr.img	AVHRR	
3	2004	567	0404nd_30e_31n_n_cl_pr.img	AVHRR	
4	2004	568	0404nd_30e_31n_n_cl_pr.img	AVHRR	
5	2004	569	0404nd_30e_31n_n_cl_pr.img	AVHRR	
6	2004	570	0404nd_30e_31n_n_cl_pr.img	AVHRR	
7	2004	571	GM_LE7_2004-07-08_savi.tif	LS	Used gap-mask
8	2004	572	GM_LE7_2004-07-08_savi.tif	LS	Used gap-mask
9	2004	573	GM_LE7_2004-07-08_savi.tif	LS	Used gap-mask
10	2004	574	GM_LE7_2004-07-08_savi.tif	LS	
11	2004	575	GM_LE7_2004-07-08_savi.tif	LS	
12	2004	576	GM_LE7_2004-12-31_savi.tif	LS	Used gap-mask
1	2005	577	GM_LE7_2004-12-31_savi.tif	LS	
2	2005	578	GM_LE7_2004-12-31_savi.tif	LS	
3	2005	579	GM_LE7_2005-03-05_savi.tif	LS	Used gap-mask
4	2005	580	0510nd_30e_31n_n_cl_pr.img	AVHRR	
5	2005	581	0510nd_30e_31n_n_cl_pr.img	AVHRR	
6	2005	582	0510nd_30e_31n_n_cl_pr.img	AVHRR	
7	2005	583	GM_LE7_2005-07-27_savi.tif	LS	Used gap-mask
8	2005	584	GM_LE7_2005-07-27_savi.tif	LS	Used gap-mask
9	2005	585	GM_LE7_2005-07-27_savi.tif	LS	Used gap-mask
10	2005	586	GM_LE7_2005-10-15_savi.tif	LS	Used gap-mask
11	2005	587	GM_LE7_2005-10-15_savi.tif	LS	Used gap-mask
12	2005	588	GM_LE7_2005-12-18_savi.tif	LS	Used gap-mask
1	2006	589	GM_LE7_2005-12-18_savi.tif	LS	
2	2006	590	0604nd_30e_31n_n_cl_pr.img	AVHRR	
3	2006	591	0604nd_30e_31n_n_cl_pr.img	AVHRR	
4	2006	592	GM_LE7_2006-04-09_savi.tif	LS	Used gap-mask
5	2006	593	GM_LE7_2006-04-09_savi.tif	LS	Used gap-mask
6	2006	594	GM_LE7_2006-04-09_savi.tif	LS	Used gap-mask

Month	Year	StressPeriod	NDVI	SENSOR	Notes
7	2006	595	GM_LE7_2006-04-09_savi.tif	LS	
8	2006	596	GM_LE7_2006-04-09_savi.tif	LS	
9	2006	597	GM_LE7_2006-04-09_savi.tif	LS	
10	2006	598	0628nd_30e_31n_n_cl_pr.img	AVHRR	
11	2006	599	GM_LE7_2006-11-03_savi.tif	LS	Used gap-mask
12	2006	600	GM_LE7_2006-12-21_savi.tif	LS	Used gap-mask
1	2007	601	GM_LE7_2006-12-21_savi.tif	LS	
2	2007	602	GM_LE7_2006-12-21_savi.tif	LS	
3	2007	603	GM_LE7_2007-03-11_savi.tif	LS	Used gap-mask
4	2007	604	GM_LE7_2007-03-11_savi.tif	LS	
5	2007	605	GM_LE7_2007-05-14_savi.tif	LS	Used gap-mask
6	2007	606	GM_LE7_2007-05-14_savi.tif	LS	Used gap-mask
7	2007	607	GM_LE7_2007-05-14_savi.tif	LS	
8	2007	608	GM_LE7_2007-08-02_savi.tif	LS	Used gap-mask
9	2007	609	GM_LE7_2007-08-02_savi.tif	LS	Used gap-mask
10	2007	610	GM_LE7_2007-08-02_savi.tif	LS	Used gap-mask
11	2007	611	GM_LE7_2007-08-02_savi.tif	LS	Used gap-mask
12	2007	612	GM_LE7_2007-08-02_savi.tif	LS	Used gap-mask
1	2008	613	0801nd_30e_31n_n_cl_pr.img	AVHRR	
2	2008	614	GM_LE7_2008-02-10_savi.tif	LS	Used gap-mask
3	2008	615	GM_LE7_2008-02-10_savi.tif	LS	Used gap-mask
4	2008	616	GM_LE7_2008-02-10_savi.tif	LS	
5	2008	617	GM_LE7_2008-02-10_savi.tif	LS	
6	2008	618	GM_LE7_2008-06-01_savi.tif	LS	Used gap-mask
7	2008	619	GM_LE7_2008-06-01_savi.tif	LS	
8	2008	620	GM_LE7_2008-06-01_savi.tif	LS	
9	2008	621	GM_LE7_2008-09-05_savi.tif	LS	Used gap-mask
10	2008	622	0828nd_30e_31n_n_cl_pr.img	AVHRR	
11	2008	623	0828nd_30e_31n_n_cl_pr.img	AVHRR	
12	2008	624	0828nd_30e_31n_n_cl_pr.img	AVHRR	
1	2009	625	GM_LE7_2009-01-27_savi.tif	LS	Used gap-mask
2	2009	626	GM_LE7_2009-01-27_savi.tif	LS	
3	2009	627	GM_LE7_2009-01-27_savi.tif	LS	
4	2009	628	GM_LE7_2009-04-17_savi.tif	LS	Used gap-mask
5	2009	629	GM_LE7_2009-04-17_savi.tif	LS	Used gap-mask
6	2009	630	GM_LE7_2009-04-17_savi.tif	LS	Used gap-mask
7	2009	631	GM_LE7_2009-04-17_savi.tif	LS	
8	2009	632	GM_LE7_2009-04-17_savi.tif	LS	
9	2009	633	GM_LE7_2009-09-24_savi.tif	LS	Used gap-mask
10	2009	634	0928nd_30e_31n_n_cl_pr.img	AVHRR	
11	2009	635	0928nd_30e_31n_n_cl_pr.img	AVHRR	
12	2009	636	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
1	2010	637	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
2	2010	638	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
3	2010	639	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
4	2010	640	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
5	2010	641	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
6	2010	642	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
7	2010	643	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
8	2010	644	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
9	2010	645	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
10	2010	646	GM_LE7_2009-12-13_savi.tif	LS	Used gap-mask
11	2010	647	GM_LE7_2010-11-14_savi.tif	LS	Used gap-mask
12	2010	648	GM_LE7_2010-11-14_savi.tif	LS	Used gap-mask
1	2011	649	GM_LE7_2010-11-14_savi.tif	LS	Used gap-mask
2	2011	650	GM_LE7_2010-11-14_savi.tif	LS	Used gap-mask
3	2011	651	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
4	2011	652	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
5	2011	653	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
6	2011	654	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
7	2011	655	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
8	2011	656	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
9	2011	657	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
10	2011	658	GM_LE7_2011-03-22_savi.tif	LS	Used gap-mask
11	2011	659	GM_LE7_2011-11-17_savi.tif	LS	Used gap-mask
12	2011	660	GM_LE7_2011-11-17_savi.tif	LS	Used gap-mask

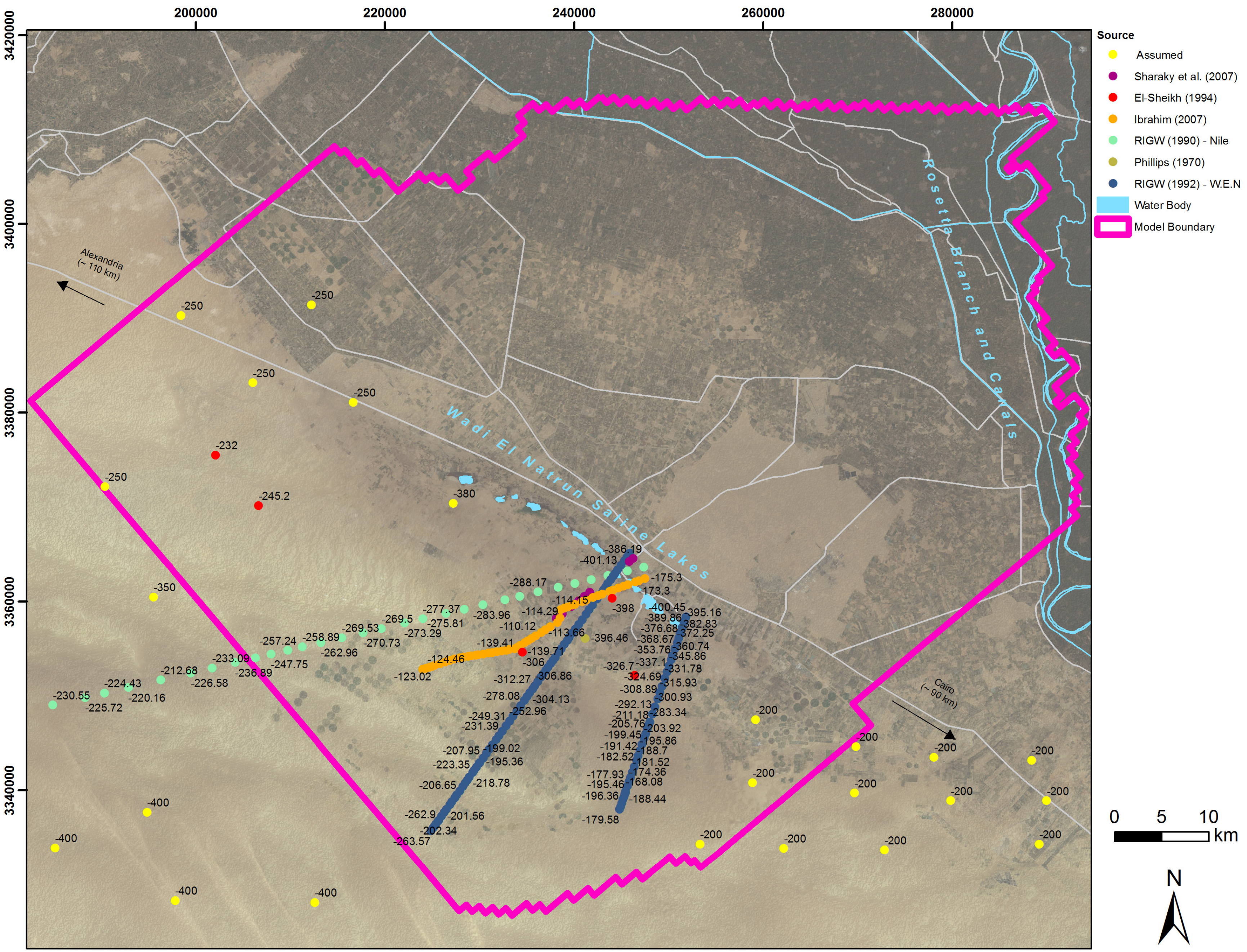
G. Pleistocene Aquifer Bottom



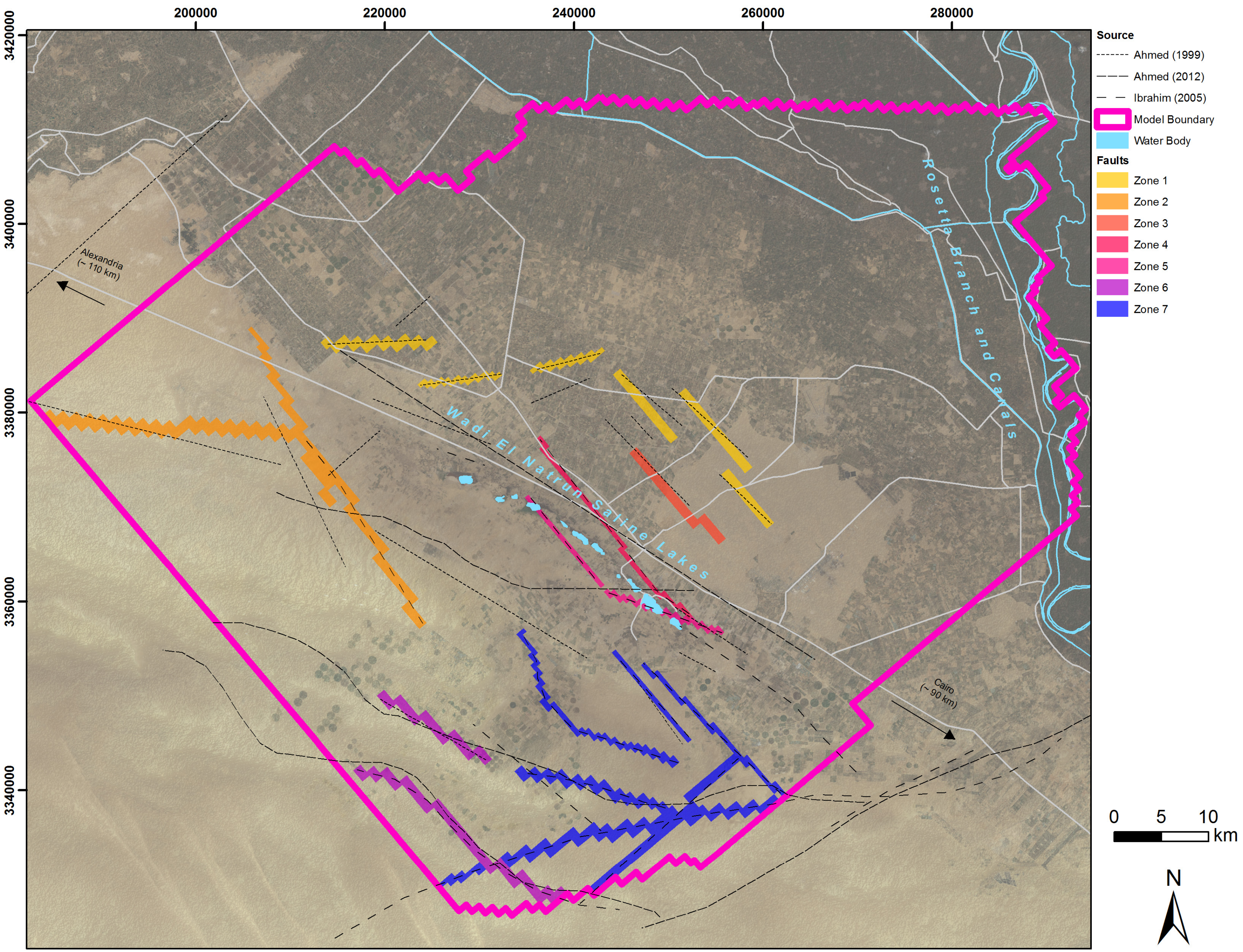
H. Pliocene Aquifer Bottom



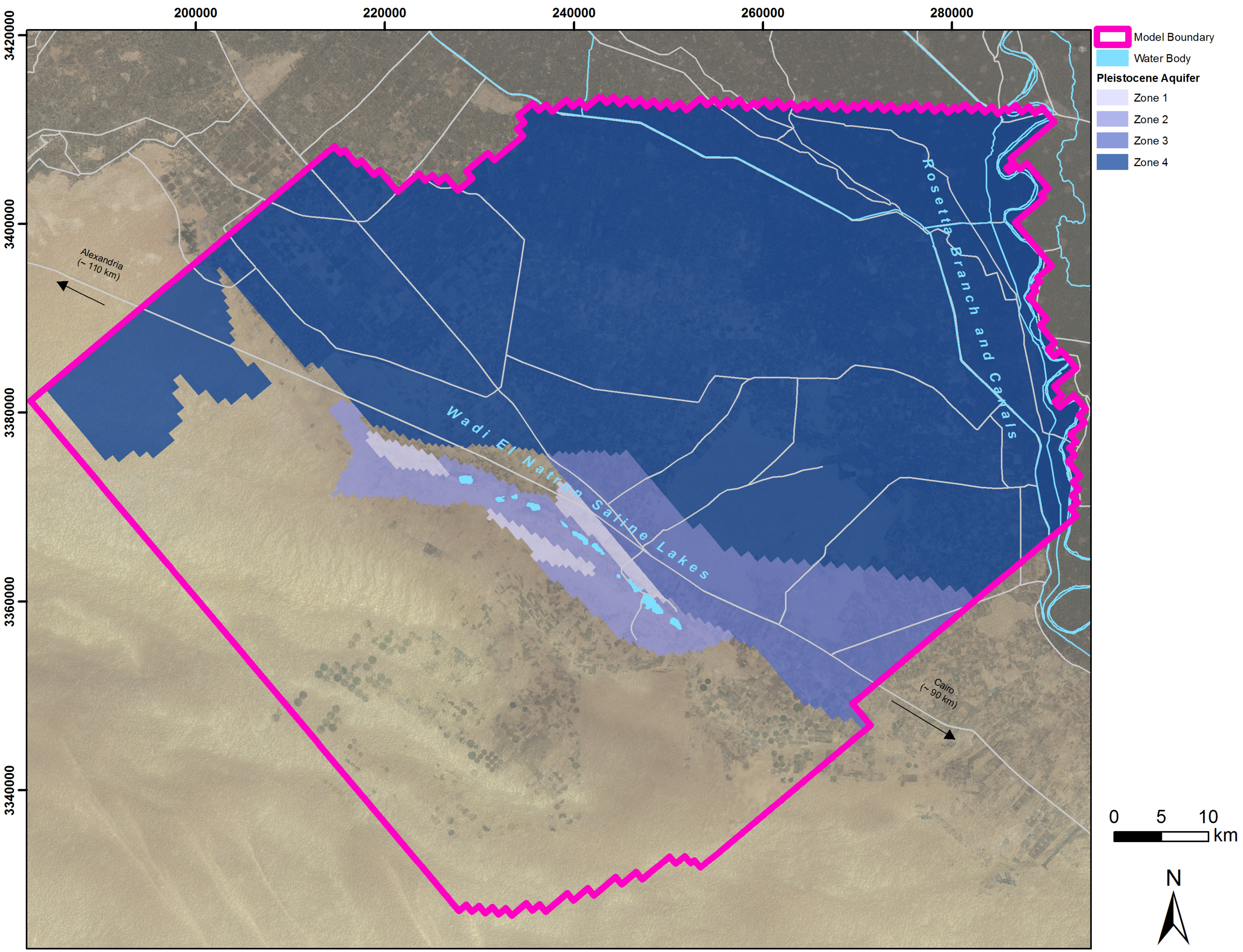
I. Miocene Aquifer Bottom



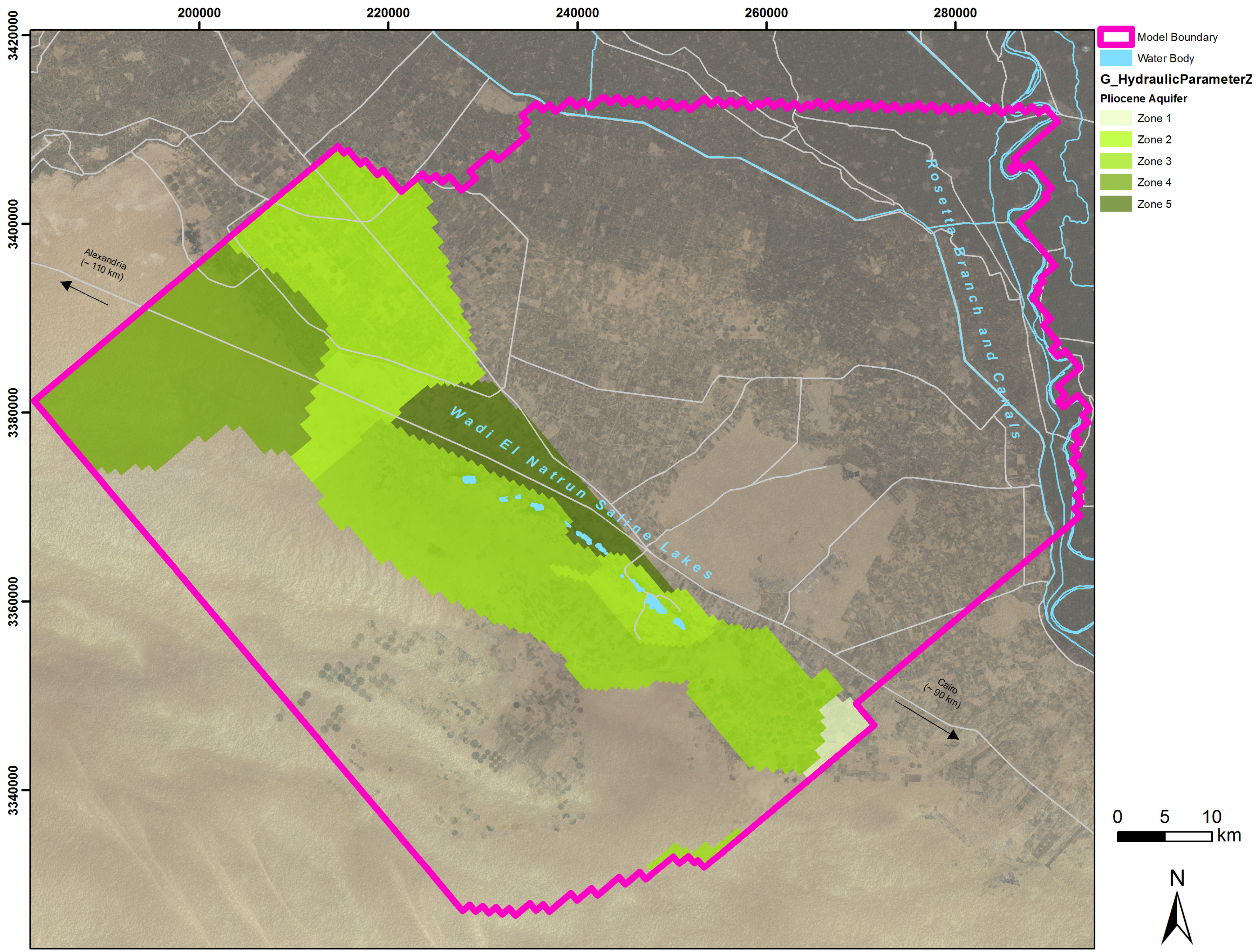
J. Model Fault Locations and Hydraulic Parameter Zones



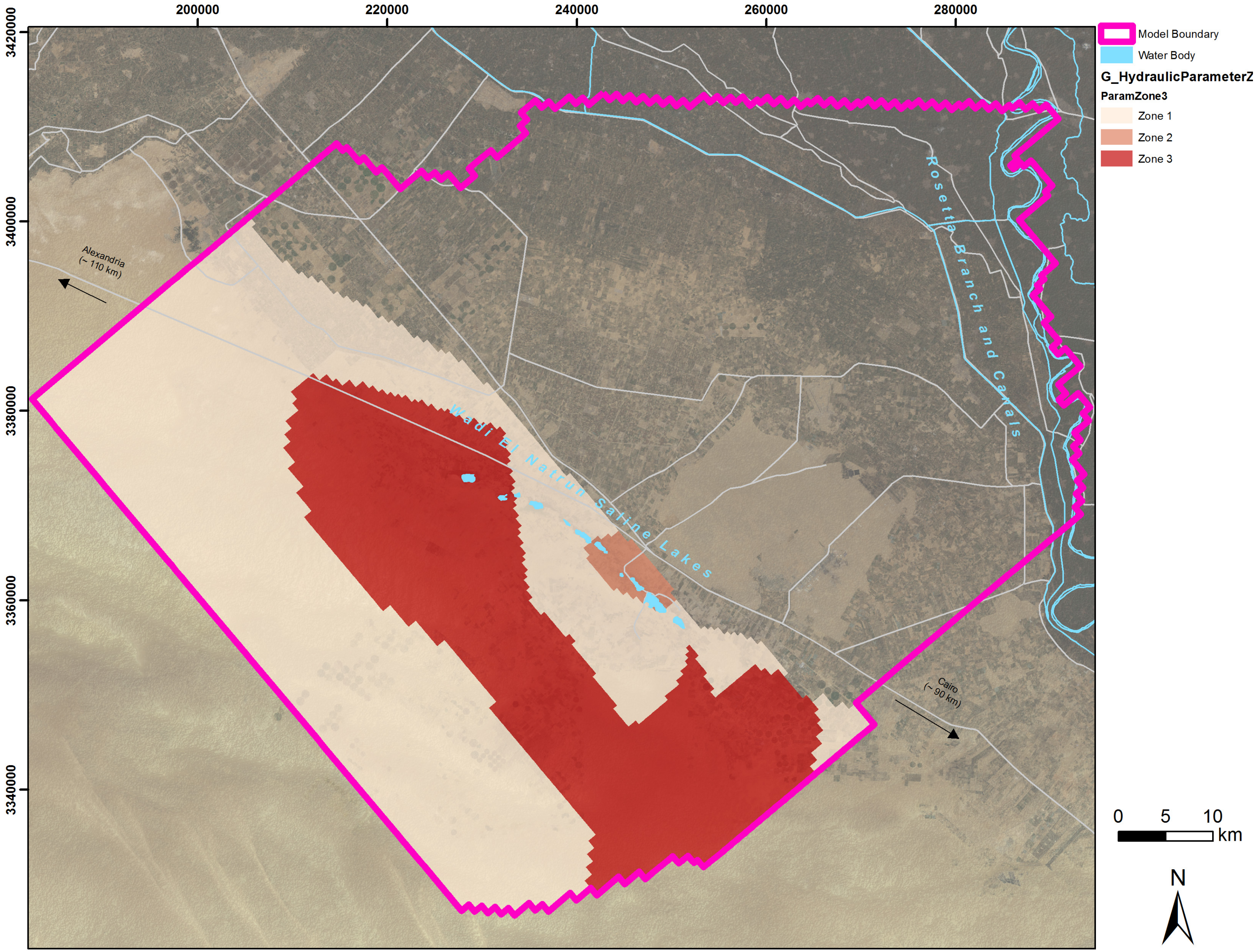
K. Pleistocene Aquifer Hydraulic Parameter Zones



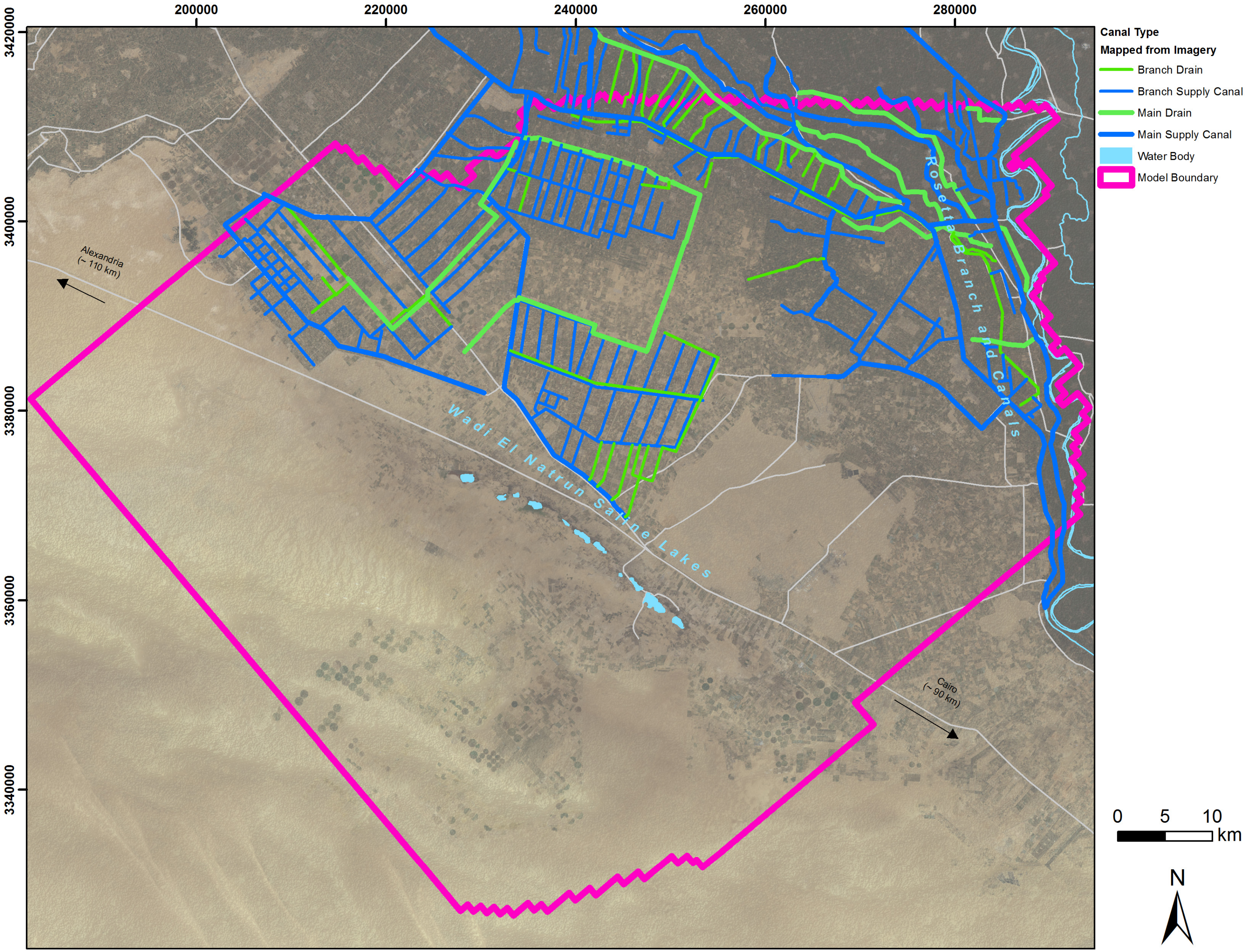
L. Pliocene Aquifer Hydraulic Parameter Zones



M. Miocene Aquifer Hydraulic Parameter Zones



N. Irrigation and Drainage Canals



O. Model Parameter Descriptions and Calibrated Values

PARAMETER NAME	Hydaulic Parameter Description	Calibrated Parameter Value [L = m] [T = day]
DRN_Irr	Drain conductance - Irrigation canals	1
DRN_Lake	Drain conductance - Lakes	1000
HK_F1	Hydraulic conductivity - Fault group 1	5000
HK_F2	Hydraulic conductivity - Fault group 2	9000
HK_F3	Hydraulic conductivity - Fault group 3	8000
HK_F4	Hydraulic conductivity - Fault group 4	10000
HK_F5	Hydraulic conductivity - Fault group 5	2000
HK_F6	Hydraulic conductivity - Fault group 6	2000
HK_F7	Hydraulic conductivity - Fault group 7	2000
HK1_0001m_	Hydarulic conductivity - Pleistocene Aquifer Zone 1	6000
HK1_20m_d	Hydarulic conductivity - Pleistocene Aquifer Zone 2	9000
HK1_50m_d	Hydarulic conductivity - Pleistocene Aquifer Zone 3	10000
HK1_90m_d	Hydarulic conductivity - Pleistocene Aquifer Zone 4	15000
HK2_0001m_	Hydarulic conductivity - Pliocene Aquifer Zone 1	500
HK2_15m_d	Hydarulic conductivity - Pliocene Aquifer Zone 2	100
HK2_20m_d	Hydarulic conductivity - Pliocene Aquifer Zone 3	400
HK2_40m_d	Hydarulic conductivity - Pliocene Aquifer Zone 4	800
HK2_47m_d	Hydarulic conductivity - Pliocene Aquifer Zone 5	300
HK3_15m_d	Hydarulic conductivity - Miocene Aquifer Zone 1	4000
HK3_30m_d	Hydarulic conductivity - Miocene Aquifer Zone 2	3000
HK3_7m_d	Hydarulic conductivity - Miocene Aquifer Zone 3	3100
SS_Mio1	Specific storage - Miocene Aquifer Zone 1	0.00001
SS_Mio2	Specific storage - Miocene Aquifer Zone 2	0.00002
SS_Mio3	Specific storage - Miocene Aquifer Zone 3	0.00003
SS_Pleist1	Specific storage - Pliestocene Aquifer Zone 1	0.0001
SS_Pleist2	Specific storage - Pliestocene Aquifer Zone 2	0.001
SS_Pleist3	Specific storage - Pliestocene Aquifer Zone 3	0.0001
SS_Pleist4	Specific storage - Pliestocene Aquifer Zone 4	0.001
SS_Plio1	Specific Storage - Pliocene Aquifer Zone 1	0.001
SS_Plio2	Specific Storage - Pliocene Aquifer Zone 2	0.0001
SS_Plio3	Specific Storage - Pliocene Aquifer Zone 3	0.00001
SS_Plio4	Specific Storage - Pliocene Aquifer Zone 4	0.0001
SS_Plio5	Specific Storage - Pliocene Aquifer Zone 5	0.001
SY_Mio	Specific yield - Miocene Aquifer	0.3
SY_Pleist1	Specific yield - Pleistocene Aquifer Zone 1	0.5
SY_Pleist2	Specific yield - Pleistocene Aquifer Zone 2	1

PARAMETER NAME	Hydaulic Parameter Description	Calibrated Parameter Value [L = m] [T = day]
SY_Pleist3	Specific yield - Pleistocene Aquifer Zone 3	0.5
SY_Pleist4	Specific yield - Pleistocene Aquifer Zone 4	1
SY_Plio	Specific yield - Pliocene Aquifer	0.9
VKCB_F1	Vertical conductance - Fault group 1	1
VKCB_F2	Vertical conductance - Fault group 2	10000
VKCB_F3	Vertical conductance - Fault group 3	10000
VKCB_F4	Vertical conductance - Fault group 4	10000
VKCB_F5	Vertical conductance - Fault group 5	10000
VKCB_F6	Vertical conductance - Fault group 6	10000
VKCB_F7	Vertical conductance - Fault group 7	10000
VKCB_Lyr1	Vertical conductance - Pleistocne Aquifer	0.1
VKCB_Lyr2	Vertical conductance - Pliocene Aquifer	0.1