Application of Remote Sensing in National Water Plans:

Demonstration cases for Egypt, Saudi-Arabia and Tunisia

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1 Introduction

Water shortage is a growing concern and in response to this many countries are developing national water plans in an attempt to allocate water more effectively. In the Middle-East, where water is extremely scarce these water plans are considered as a means to improved water resources planning, but the plans are often based on limited information and data and are always very much focused on water in rivers and groundwater, rather than considering all the components of the water balance in the broader hydrological context. Weaknesses in these water plans often are:

- Actual water use from irrigated areas is often assumed to be similar to water supplied.
- There is an emphasis on increasing the so-called water efficiency rather than aiming at increasing water productivity.
- Water consumption (=evaporation and transpiration) from natural vegetation or bare soils is not considered.
- Groundwater recharge is poorly understood and based only on groundwater observation wells.
- Net groundwater use, and to some extent surface water abstraction estimates are based on estimates of pumping hours and pump capacity rather than on actual abstractions.
- Analysis is based on “average” conditions.
- Water plans can be a reflection of preferred policies rather than based on unbiased analyses.

These issues make the estimated water consumption and the, from this derived, potential water allocations often unrealistic. It is however possible by using advanced remote sensing techniques to tackle most of the issues mentioned here. High resolution rainfall observations, accurate evapotranspiration estimates, and biomass production can be obtained at an unprecedented accuracy using remote sensing. Even changes in deep groundwater using changes in gravity fields can be monitored from remote sensing nowadays. Especially the high spatial coverage makes these remote sensing observations a unique product to support the national water plans.

Results based on completed studies in Tunisia, Egypt and Saudi-Arabia using advanced remote sensing techniques, are compared to information used in the national water plans of the three countries. This study assess to what extent these remote sensing observations can support the development of national water plans, improve the understanding of resource availability, better assess where water is consumed, and identify where losses are avoidable.

Based on this, the objective of this study is defined as:
Evaluate national water plans using completed remote sensing studies to explore whether these remote sensing observations can support the development of national water plans.

The subsidiary objectives can be summarized as:

- Compare existing water consumption as presented in national water plans to remote sensing estimates;
- Estimate groundwater recharge from remote sensing and compare to figures presented in the national water plans;

- Attempt to compare observed groundwater fluctuations from remote sensing to the understanding implied by national water plans;
- Report and discuss the main findings of the study.

As will be clear in reading this report, terminology is a constraint to understanding water plans and reports about the water sector. Water use, availability, withdrawals, recycling, re-use, return flows, efficiency, and consumption are among the various terms that appear – often without further definition. Recently, a number of papers and reports have appeared that suggest alternative terminology (Bos et al, 2008; Molden,1999; Keller and Keller 1995). Where appropriate, in this report we follow the terminology recommended by the International Commission of Irrigation (ICID), as set out by Perry (2007). This defines water use as follows:

- **Water use**: Water made available – deliberately, by rainfall or other natural means – to an identified activity. The term does not distinguish between uses that remove water from further use (evaporation from wet soil or wetlands; transpiration from irrigated crops, forests, etc.) and uses that have little quantitative impact on water availability (navigation, hydropower, most domestic uses).
- **Withdrawal**: Water abstracted from streams, groundwater or storage for any use, comprising the following fractions:
    - Consumed fraction (evaporation and transpiration) comprising:
        - Beneficial consumption: Water evaporated or transpired for the intended purpose – for example evaporation from a cooling tower, transpiration from an irrigated crop.
        - Non-beneficial consumption: Water evaporated or transpired for purposes other than the intended use – for example evaporation from water surfaces, weeds, waterlogged land.
    - Non-consumed fraction, comprising:
        - Recoverable fraction: water that can be captured and reused – for example, flows to drains that return to the river system and percolation from irrigated fields to aquifers; return flows from sewage systems.
        - Non-recoverable fraction: water that is lost to further use – for example, flows to saline groundwater sinks, deep aquifers that are not economically exploitable, or flows to the sea.

This accounting framework can be applied consistently across all sectors, and is essential in clearly understanding the impact of management or infrastructural changes for water availability at other locations in a water-scarce environment.

2 Mapping water use from space

2.1 Introduction

Our fresh water supplies are stretched, more and more, between inflow, stream needs and off-stream usage and consumption, between storage and natural flows, between agriculture and cities, between agriculture and recreation, and among agriculture, environment and endangered species (Ritter, 2005). At basin scale, ET (evapotranspiration) is, after rainfall, the second largest term of the water balance. In irrigation schemes and in wetlands, ET can be the dominant component of the water balance. Actual evapotranspiration (ET_{act}) has three distinct characteristics: (i) it reflects the presence of water (if there is ET, there must be moisture available), (ii) ET can be manipulated by diversions, abstractions, floods and other transfers to obtain vegetative growth - but unfortunately - (iii) it cannot be measured or estimated straightforwardly.

Traditional methods of measuring ET involve either the application of equations (such as Penman-Monteith) to compute *potential* ET – that is the maximum rate of evapotranspiration for the local climatic conditions – or measurement of physical parameters that can be used to estimate *actual* ET (such as a scintillometer, which measures disturbance of the air by the ET process), or direct estimation of water use by measuring water evaporated in a weighing lysimeter. None of these approaches is easy, and each requires that point estimates be extrapolated in time and space for many of the purposes we are interested in. Also, since *actual* ET varies depending on local water availability as well as climatic factors, an estimate of *potential* ET, or of *actual* ET at a specific location is not necessarily a good guide to reality at another location.

Because of these difficulties, water management has tended to focus on measurement of water deliveries soil moisture values. It is, however, more effective to manage water use – and thus ET - directly, and this requires some innovative tools that estimate ET_{act} with sufficient accuracy and at low costs.

Approaches have been developed over the last 25 years to estimate spatially distributed ET_{act} from the data collected by remote sensing. Different parts of the electro-magnetic spectrum can in principle be used in combination with a suite of interpretation algorithms and ground-based weather data to estimate ET_{act}. Assuming that the required accuracy is met by these remote sensing algorithms, a range of potential applications could be introduced (see table below). The applications of remotely sensed ET maps can be best divided into a number of different themes:

- Water accounting of basins and catchments
- Aquifer management
- Land use and water use planning
- Agriculture and forestry
- Ecological water use
- Irrigation scheduling and evaluation
- Drought early warning systems
- Hydrological modelling
- Weather and climate modelling

The introduction of measured ET into water management allows a paradigm shift in thinking directly about water consumption (that is, the physical removal of liquid water from the local hydrological cycle) instead of diversions, efficiency, and crop demand. The concept of restoring the balance between water supply from rainfall and water use from ET_{act} by controlling ET_{act}, and by that, affecting stream flow, recharge of aquifers, and meeting environmental flow requirements, is rather new (Bastiaanssen et al., 2008). ET as a management tool will take time before it is understood and accepted by water policy makers and water managers – and indeed it is a complementary source of information to the traditional measurements of flows and levels, not a substitute. Using spatially distributed ET_{act} information provides new opportunities, and the number of applications on spatial ET_{act} data is increasing at a steady pace.

Review papers on ET applications for water management have been prepared for the conditions in Asia by Bastiaanssen and Harshadeep (2005) and for the Western US by Allen et al. (2005; 2007). Use of spatial estimates of ET_{act} in climatic studies is reported by for instance Van der Hurk et al. (1997), Mohamed et al. (2005) and Anderson et al. (2007). A few international journal articles deal with the assimilation of ET data in hydrological models to facilitate model calibrations (e.g. Schuurmans et al., 2003). The performance of hydrological models can also be improved by calibrating of model parameters by optimizing the difference between modelled and remotely sensed-ET maps. Examples of model parameter optimization are provided by Ines and Honda (2004) and Immerzeel and Droogers (2008). A summary of calibrating a hydrological model from remotely sensed ET_{act} data in irrigation systems is provided in Bastiaanssen et al. (2007).

Table 1 contains a list of applications, separated into a category of real applications for which examples are available and into potential applications that are expected to become available in the near future.

Table 1: Potential applications of spatial ET maps based on research achievements and actual applications.

Topic	Actual applications	Potential applications
Water accounting of basins and catchments	• Identification of net water generation areas and net water consumption areas • Determination of problem areas (too wet or too dry) • (re) examining target water levels in surface drains • Water rights settlement and accounting	• Accumulated upstream rainfall surplus as an index for runoff • Water conservation • Rehabilitation of degraded land
Aquifer management	• Limit groundwater withdrawals and monitor compliance • Monitoring of net groundwater abstractions •	• Recharge options from rainfall surplus •
Land use and water use planning	• Regional scale development projects (replacing native by agricultural ecosystems)	• Land use change impact assessment • Introduction of consumption-based water rights • Water for agriculture vs. water for environment • Water for recreational purposes (ecotourism; golf courses) • Impact of bio-fuels on downstream water availability
Agriculture and forestry	• Drainage advice • Nitrogen application advice • Crop yield forecasting	• Green credits for CO_2 sequestration • Adapted cropping patterns for water resilience

	• Forest vitality • Forest thinning	
Ecological water use	• Combat alien invasive species • Health of wetlands • Impact of wetland change on atmospheric moisture recycling	• Water requirements for wetlands • Green credits for good management practices
Irrigation scheduling and evaluation	• Timing of irrigation • Amount of irrigation • Water productivity Estimation of losses from irrigation systems	• Separation beneficial T and non-beneficial E • Reliability of supplies in irrigation service • Uniformity of supplies in irrigation services • Adequacy of supplies in irrigation services
Drought early warning systems	• Timely warning of vegetation water stress • Distribution of water deficit across regions	• Vulnerability mapping •
Hydrological models	• Calibration of operational water distribution models • Calibration of unsaturated zone schematizations	• Optimizing water allocation • Appraising impact of climate change of flows and water levels • Revisit water management policies • Infrastructure investment needs
Weather and climate modelling	• Improved prediction for near-surface weather conditions • Impact of land use change on rainfall patterns	• Improved simulation of atmospheric state variables after assimilation of ET_{act} values •

2.2 SEBAL

SEBAL (Surface Energy Balance Algorithm for Land) provides a way to estimate and monitor actual ET, spatially distributed, without knowing soil moisture, land use or vegetation conditions. SEBAL solves the surface energy balance for heterogeneous terrain on the basis of reflected solar radiation and emitted thermal radiation (surface temperature). The actual ET (ET_{act}) fluxes from SEBAL reflect the effects of various natural factors that influence ET, such as moisture availability, presence of pests and disease, salinity, and other factors. The standard ET equations are designed to compute potential ET, or the level of ET that would occur under optimal or "pristine", although sometimes general corrections are applied for conditions where water is limiting limitations by using a reduction coefficient ($ET_{act}=\beta\ ET_{pot}$).

SEBAL is one of the first mathematical procedures that can operationally estimate spatially distributed ET_{act} from field to river basin scale over an unlimited array of land use types, including desert soil, open water bodies, sparse natural vegetation, rain fed crops, irrigated crops, etc. The SEBAL model solves the energy balance for every individual pixel, thereby providing the spatial sensitivity. Satellite images need to be cloud-free to be processed for energy balance purposes.

The three primary bio-physical inputs from images such as MODIS and Landsat into SEBAL are (i) surface temperature, (ii) surface albedo and (iii) Normalized Difference Vegetation Index (NDVI). All of these parameters are measured directly or derived from measurements recorded by satellite-based sensors. In addition to that, a mask identifying water surfaces is created. The water mask is meant for the assignment of particular values that are applicable to water only: emissivity, surface resistance, and soil heat flux/net radiation fraction. The latter fraction is relevant because the equations for soil heat flux for land and water are completely different. An existing generalized land use map is necessary to assign vegetation heights for the computation of the surface roughness for all pixels. This vegetation height is only considered for the turbulent parameters (i.e. momentum flux). The inputs to SEBAL consist of (i) satellite multi-spectral radiances, (ii) routine weather data and (iii) Digital Elevation Model.

SEBAL uses a set of algorithms to solve the energy balance at the earth's surface. The instantaneous ET flux is calculated for each pixel within a remotely sensed image as a 'residual' of the surface energy budget equation:

$$\lambda E = Rn - G - H \quad (1)$$

where λE is the latent heat flux (W/m2) (which can be equated to ET), Rn is the net radiation flux at the surface (W/m2), G is the soil heat flux (W/m2), and H is the sensible heat flux to the air (W/m2).

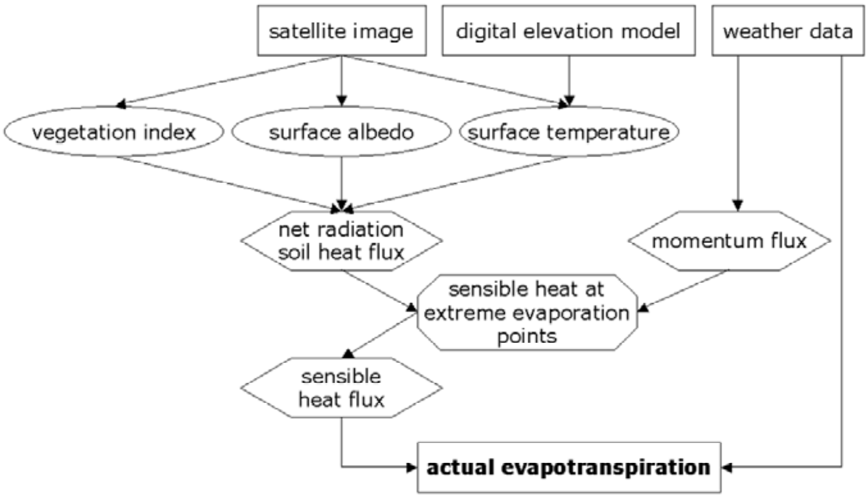

Table 2: Data flow and key steps for the determination of spatially distributed ET fluxes according to the SEBAL method

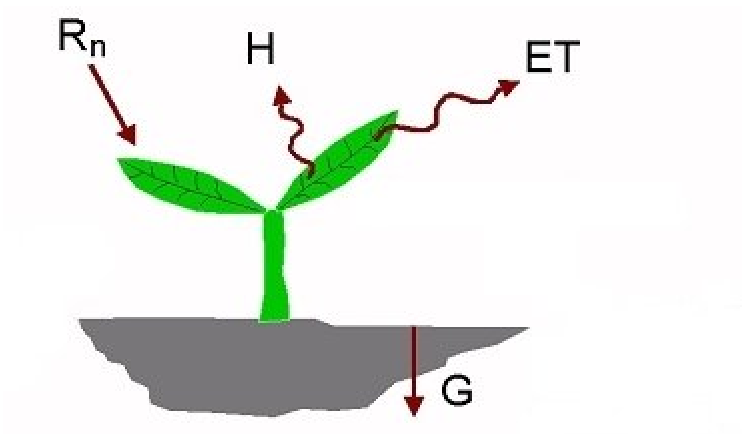

Table 3: Main terms of the Surface Energy Balance

Rn represents the actual radiant energy available at the surface. It is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes.

The standard 250 m Digital Elevation Model (DEM) has been used for the correction of air pressure and related air density and psychrometric constant at higher elevation. The DEM is also used to correct the absorbed solar radiation values, both for slope and aspect. Southern facing terrain, due to the angle of incidence, absorbs more solar radiation per unit land than the Northern facing slope.

Based on SEBAL several other comparable methods have been developed. The most common are:

- SEBS. Surface Energy Balance System.
- METRIC. Mapping Evapotranspiration at high resolution with Internalized Calibration.
- ETLook. Similar to SEBAL but based on microwave satellite data.

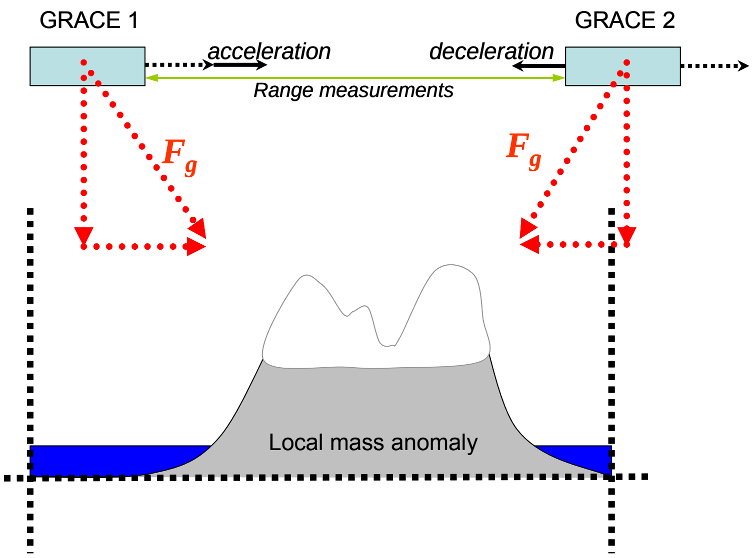

Figure 1. A schematic cartoon of the way in which GRACE measures the gravity field.

2.3 Groundwater Mapping

Groundwater has been very difficult to analyze over larger areas. Common practice was to use point observations from wells combined with statistical interpolation techniques to obtain spatially distributed groundwater maps. However, recently data from the GRACE satellite has become available to assess changes in terrestrial water over larger areas.

GRACE (Gravity Recovery And Climate Experiment) is a twin-satellite mission, developed to measure changes in the Earth's time-variable gravity field with unprecedented accuracy (Tapley et al., 2004). The main mission objective of GRACE is to map changes in mass due to the continental water cycle. On regional scale of a minimum longitudinal and latitudinal magnitude of about 300 km, it can be used to identify mass changes due to variations in water storage, which can assist in determination of groundwater depletion (Rodell and Famiglietti, 2002), ice melt (Velicogna and Wahr, 2006), residual basin-scale estimates of evaporation (Rodell et al., 2004) or validation of hydrological models (Ngo-Duc et al., 2007; Niu et al., 2007; Rodell et al., 2007; Tapley et al., 2004; Wahr et al., 2004).

GRACE consists of 2 polar orbiting satellites that are developed to fly at an altitude ranging from 300 to 500 km and are separated by a distance of about 200 km along track. The Earth's gravity field causes accelerations of the satellites where they approach an area of relatively high mass concentration, and decelerations where they move away from them (see Figure 1). The raw measurements consist of extremely accurate distances between the two satellites, measured by the High Accuracy Intersatellite Ranging System (HAIRS). The acceleration - deceleration behaviour of both satellites causes changes in these distances that can be translated back into mass (or gravity) configurations of the Earth.

Movements of mass are caused by many low and high frequency processes, some of the more important ones being gravitational pull by other bodies such as the Sun, Moon and nearby planets, atmospheric moisture redistribution, oceanic tides, but also deformation due to the later process and for instance post-glacial rebound. The high frequency processes that are expected to vary a great deal within one month of data acquisition are corrected in the processing of GRACE data by using several background models, prior to the gravity deconvolution. The most important are an oceanic model and an atmospheric model. The residual gravity signal then represents unmodelled signals such as hydrology, earthquakes and land deformation, and some noise, e.g. from instrumental errors and errors in the background models. The signal that is expected to vary the most on the monthly time scale is hydrology, which comprises terrestrial water storage changes that can be caused by variations in groundwater storage, soil moisture, snow pack and surface water as shown in. The hydrology signal is assumed to be constant within the period of observation (i.e. one month) and the time-averaged storage estimates are therefore assumed to be representative for the middle of the month. This means that, with the introduction of GRACE, we now have a first large-scale observation of basin-scale terrestrial water storage, that can contribute to validation of hydrological models.

GRACE data are available since May 2002. However data before July 2003 are not very accurate because of a relatively high level of noise in the signal. Also the GRACE data for September and October 2004 are of lower quality due to repeated tracks of the satellites. GRACE data are now processed in three centers: the Center for Space Research Texas (CSR), the GeoForschungsZentrum Potsdam (GFZ) and the Jet Propulsion Laboratory (JPL). The difference in their end-user products is mainly the use of different background models. Delft, University of Technology is developing its own solution procedure, which also allows for an estimation of uncorrelated errors in each monthly solution.

GRACE data products are expressed in mm equivalent water. Two factors are important when evaluating results. Firstly, no distinction between snow cover, soil moisture and deep groundwater storage can be made. Secondly, results are given relative to the long-term average from Apr-2002 to Apr-2006. This means that no absolute values of water storage can be provided and that no spatial differences in water stored can be observed. In other words GRACE detects only changes in stored water.

3 Egypt

3.1 Overview

Egypt is one of the most populous countries in Africa. Most of the 80 million inhabitants live near the banks of the Nile and the delta, in an area of about 40,000 square kilometers. In other words approximately 99% of the population uses only about 5.5% of the total land area.

The main water resources in Egypt originate outside its borders as rainfall in Egypt is very limited. South of Cairo, rainfall averages only around 2 to 5 mm per year. On a very thin strip of the northern coast the rainfall can be 410 mm, with most of falling between October and March. Egypt is therefore totally depended on Nile water entering Egypt at the southern border with Sudan.

Figure 2. Major control structures on the Nile in Egypt (source: MWRI, 2005).

The Aswan High Dam Reservoir plays a key role in water resources of Egypt. Aswan extends for 500 km along the Nile and covers an area of about 6,000 km^2, of which northern two-thirds (Lake Nasser) is in Egypt and one-third (Lake Nubia) in Sudan. The dam was completed in 1968 and the total capacity of the reservoir is 162 km^3. The dead storage is 31.6 km^3, the active storage of 90.7 km^3 and the emergency storage for flood protection is 41 km^3. Just downstream of Aswan High Dam is the Old Aswan Dam. Figure 4 compares the impact of the Aswan Dam on monthly flows in Egypt. Figure 2 and Figure 3 show the major control structures and the water allocation under standardized conditions for the Nile System.

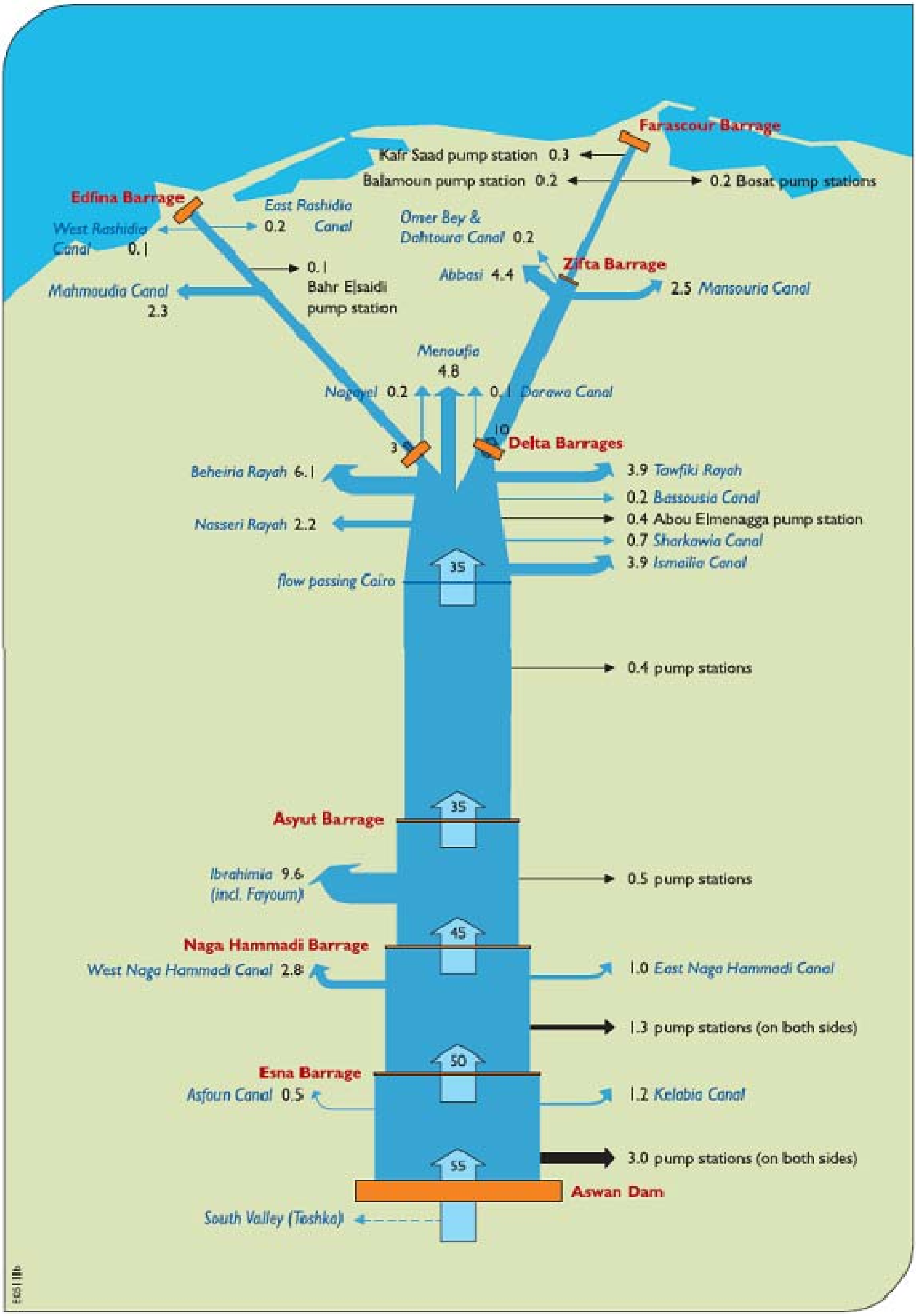

Figure 3. Typical water distribution of the Nile System (source: MWRI, 2005).

One of the main questions is how much water is actually consumed in contrast to the amount of water available. In this chapter a comparison will be made between published water records and information and actual observed ones using remote sensing. The purpose is to show that remote sensing can support national water plans as remote sensing provides an independent figure of the real water consumption by evaporation, as well as its distribution in time and space.

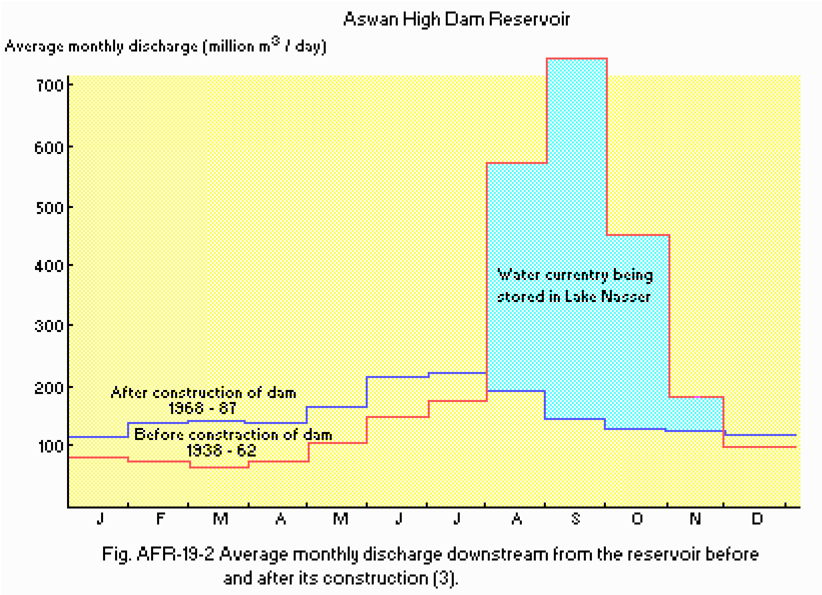

Figure 4. Comparing average monthly flows before and after construction Aswan dam. (source International Lake Environment Committee, 2008).

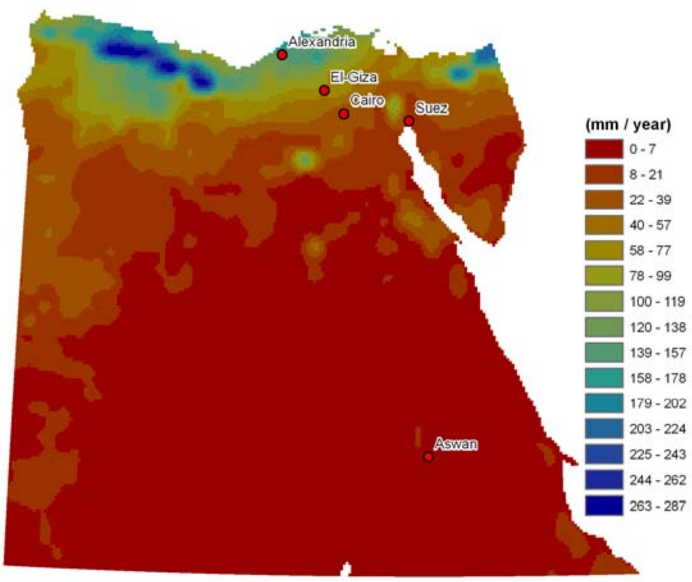

Figure 5. Annual precipitation in 2007 based on TRMM 3B43.

3.2 Climate

The climate of Egypt has two distinct seasons: a mild winter from November to April and a hot summer from May to October. Table 4 shows the climate conditions for Cairo. The total annual rainfall for Egypt as a whole averages 51 mm, while the potential evapotranspiration is 1936 mm. These data are derived from the CRU TS 2.0 dataset (New at al., 2002).

Rainfall is very low and concentrated near the coast. Figure 5 shows the annual precipitation for the year 2007 based on the TRMM satellite.

Table 4. Average climate conditions in Cairo.

Month	Prc.	Tmp. mean	Tmp. max.	Tmp. min.	Rel. hum.	Sun shine	ETo
	mm/m	°C	°C	°C	%	%	mm/m
Jan	5	13.1	18.6	7.6	60.5	69.2	74
Feb	4	14.6	20.6	8.6	55.6	69.1	92
Mar	2	17.2	23.6	10.8	52.1	72.3	138
Apr	1	21.5	28.7	14.3	42.9	72.4	177
May	0	24.9	32.4	17.3	40.9	75.6	234
Jun	0	27.4	34.8	20.0	44.2	85.5	247
Jul	0	28.2	35.3	21.2	51.2	82.9	240
Aug	0	28.1	34.9	21.3	55.2	83.7	217
Sep	0	26.4	32.9	19.8	55.3	78.0	181
Oct	0	23.5	29.6	17.5	55.4	82.2	157
Nov	2	18.9	24.5	13.2	58.5	76.9	102
Dec	5	14.6	19.8	9.4	60.7	64.2	76

3.3 Irrigated areas

Several studies have been conducted that assess irrigated areas at a global scale. Two of these studies are discussed and compared here. Firstly, the work commissioned by the Food and Agricultural (FAO) organization is assessed and secondly the Global Irrigated Area Mapping (GIAM) project of the International Water Management Institute (IWMI). These figures are compared with the analysis as presented in this study.

These two global datasets for irrigated areas were compared to two other data sets. The first one is based on the ETLook remote sensing methodology and the second one is FAO's AquaStat.

3.3.1 FAO map of irrigated areas

The Land and Water Division of the Food and Agriculture Organization of the United Nations and the Johann Wolfgang Goethe Universität, Frankfurt am Main are co-operating in the development of a global irrigation mapping facility. The first global digital map of irrigated areas on the basis of cartographic information and FAO statistics has a resolution of 0.5 degree and was developed in 1999. Since 1999 the methodology to produce the map has been improved which made it possible to increase the spatial resolution of the map to 5 minutes (about 10 km at the equator). The objective of the co-operation between the Johann Wolfgang Goethe Universität and FAO is to develop global GIS coverage of areas equipped for irrigation and to make it available to users in the international community. The data collected through the AQUASTAT surveys was used to improve the overall quality and resolution of the information. (Siebert et al, 2006)

Based on this dataset the total area equipped for irrigation in Egypt is reported at 3,422,178 ha for 2002. Figure 6 shows the different governorates and the areas equipped for irrigation expressed as percentage of the total area per grid cell.

3.3.2 Global irrigated area mapping

The IWMI study is based on the situation in 1999 and the approach is reported in Thenkabail et al (2006). The study reports the total area equipped for irrigation as 2,086,783 ha. The difference with FAO map is large (1,335, 395 ha) and it is unlikely that expansion of irrigated area in a time frame of three years can explain this difference.

3.3.3 Remote Sensing ETLook 2007

Results from the ETLook analysis (see hereafter) for 2007 are also used to assess to actual irrigated lands. This was conducted assuming that irrigated areas are all pixels with an ET > 200 mm and an ET < 1500 mm. This leads to an estimated area of 3,104,200 ha (Figure 8). This result is close to the FAO estimates. However, our assumption was made that an entire pixel is irrigated, while the other methods consider sub-pixel irrigated area fractions.

3.3.4 AQUASTAT

The AQUASTAT (2008) databases provide a wealth of information on the land and water resources of Egypt. The main AQUASTAT database provides information on water and agriculture by countries in the following main categories:

- Land use and population
- Climate and water resources
- Water use, by sector and by source
- Irrigation and drainage development
- Environment and health

The current database regroups data per 5-year period and shows for each variable the value for the most recent year during that period, if available. For example, if for the period 1998-2002 data are available for the year 1999 and for the year 2001, then the value for the year 2001 is shown. It should be noted however that for most variables no time series can be made available yet, due to lack of sufficient data.

According to AQUASTAT the area equipped for irrigation is 3,422,000 ha (2002) and the actual irrigated area is 3,246,000 ha (1993).

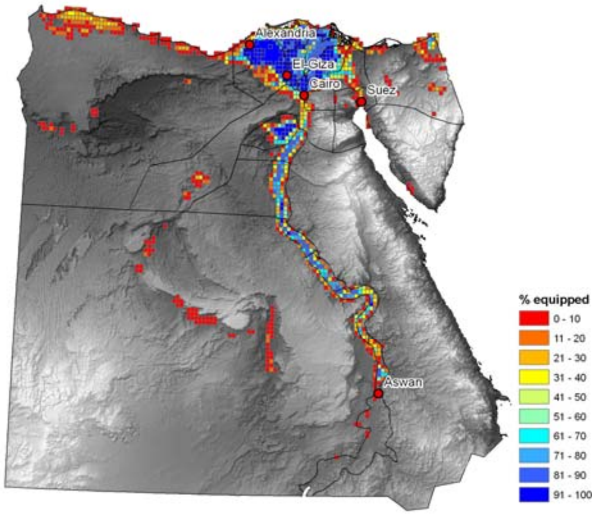

Figure 6. Total area equipped for irrigation based on the FAO dataset.

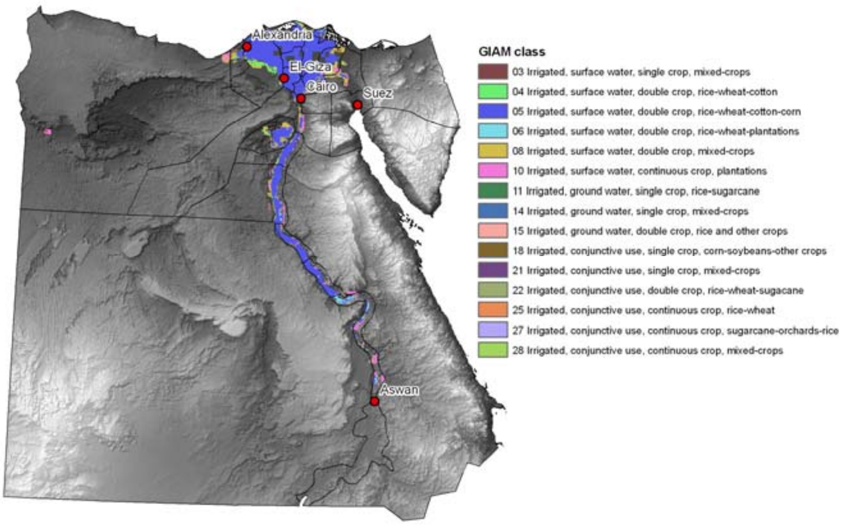

Figure 7. Total area equipped for irrigation based on the GIAM dataset.

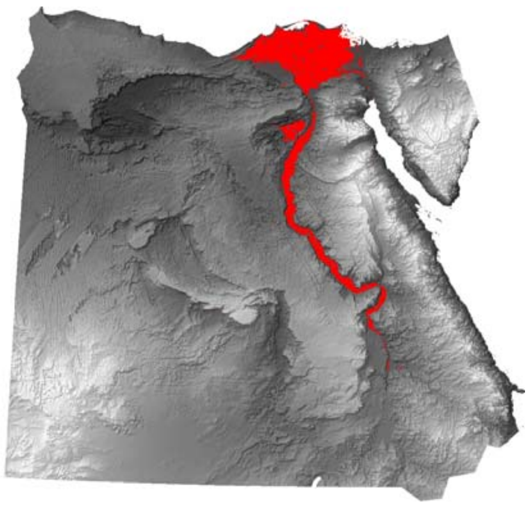

Figure 8. Irrigated area in 2007 (ET > 200mm and ET < 1500 mm).

3.4 Water use from remote sensing

Data from four completed remote sensing-based studies were compiled and used to evaluate the national water information for Egypt:

- Monitoring summer crops under changing irrigation practices: A Remote Sensing Study in the North-western Nile Delta for the Irrigation Improvement Project 1995 – 2002. (Bastiaanssen et al., 2003)
- Monitoring winter crops under changing irrigation practices: A Remote Sensing Study in the North-western Nile Delta for the Irrigation Improvement Project 1997/98 -2002/03. (Noordman and Pelgrum, 2004).
- Nile Basin Initiative study 2007.
- SEBAL, 2008

The final result of compiling data from these studies comprises the following data:

- May 1995 – Oct 1995 (monthly, 1 km, only delta)
- Nov 1997 – May 1998 (monthly, 1 km, only delta)
- Apr 2002 – Sep 2002 (monthly, 1 km, only delta)
- Nov 2002 – May 2003 (monthly, 1 km, only delta)
- Jan – Dec 2007 (monthly, 1 km, entire country)
- Oct 2007 – Sep 2008 (monthly, 1km, only delta)

This study will concentrate on the 2007 results, as this is the only dataset covering the entire country. Obviously, quality control and detection of trends will be conducted and reported here by inter-comparison with the other datasets.

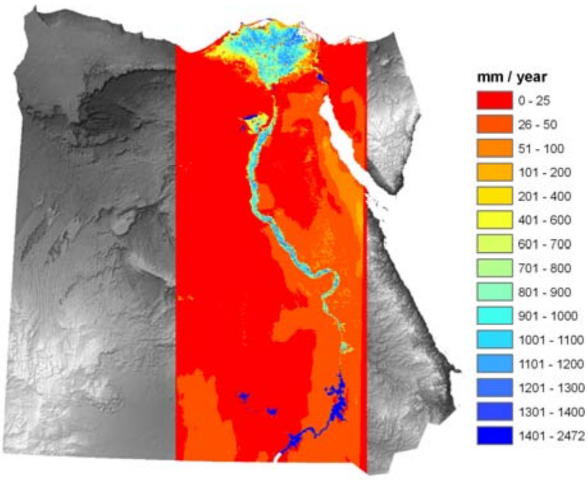

Figure 9. ETLook actual evapotranspiration for 2007.

3.4.1 Year 2007

A time series of ETLook estimates were available at 8 day intervals for 2007. The extent of the imagery is shown in Figure 9 and a detail of only the Delta in Figure 10. The volumetric consumptive use calculated on the basis of the actual evapotranspiration equals 53 km^3 for the entire scene. However, this figure includes the vast area of deserts where the ETLook is less accurate. So it is more realistic to evaluate only the irrigated areas (Figure 8), which leads to a total actual evapotranspiration of 26.3 km^3. Converting the 26.3 km^3 to millimeters for the irrigated areas yields 847 mm ET in 2007. Monthly ET values can be seen in Figure 11.

Open water evaporation from Lake Nasser and Toska depression has been evaluated as well using ETLook. Over 2007 total annual evaporation for Lake Nasser are 10.9 km^3. Total evaporation from the Toska depression is 1.9 km^3.

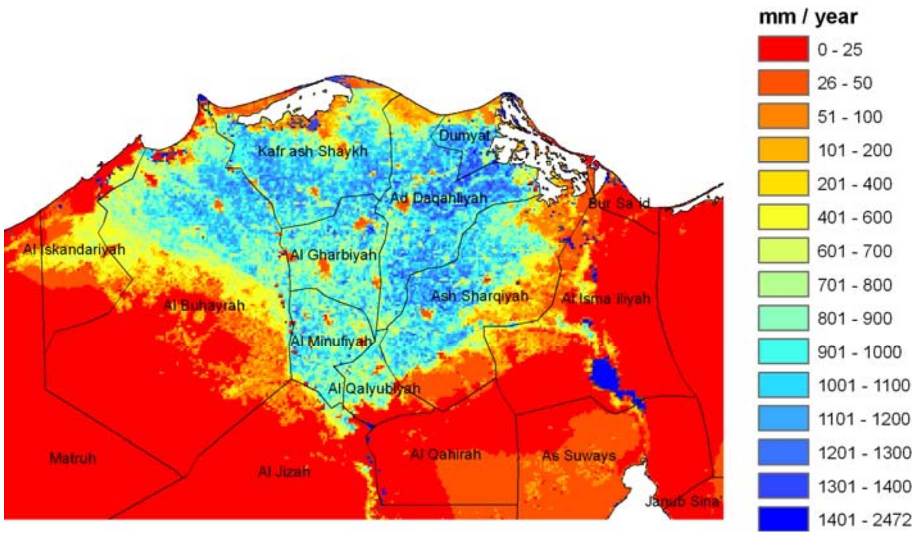

Figure 10. ETLook actual evapotranspiration for 2007 in the Nile delta.

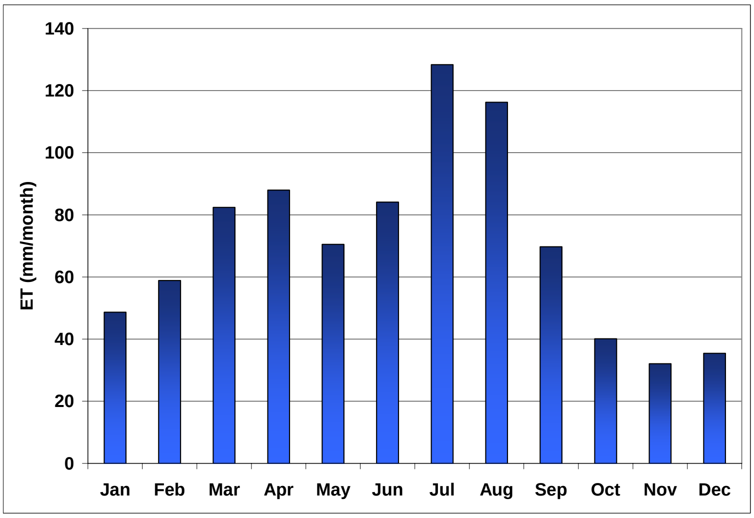

Figure 11. Actual evapotranspiration irrigated areas based on ETLook over 2007.

3.4.2 Comparing Nile Delta ETLook 2007 to other periods

ETLook 2007 was compared to other independent remote sensing derived actual evapo-transpiration estimates. For two winter seasons and two summer seasons SEBAL analysis were performed for the delta only. Table 5 shows that the difference between ET Look and SEBAL are between 20 and 30%, where ETLook is always lower than SEBAL. The following hypotheses were found for this difference:

- (i) Climate conditions were somewhat cooler and somewhat dryer during the ETLook observation period (Table 6).

- (ii) Different releases from Aswan Dam.
- (iii) Changes in land cover / land use / urban areas.
- (iv) SEBAL might overestimate somewhat since an older version was used; ETLook might underestimate somewhat since larger pixels were used. (personal communication dr. W. Bastiaanssen).

Based on the discussion above it was assumed that ETLook 2007 figures were 15% too low. So the best estimate of actual ET (real water consumption) in 2007 based on remote sensing analysis is 30.2 km^3 (26.3 * 1.15).

Recently an improved version of SEBAL was used to estimate ETact over the year 2008. According to this analysis the actual ET for irrigated crops in the formal irrigation area was 31.8 km^3. The analysis included also other land use types as can be seen in Figure 12. Important is to realize that part of the actual ET from the coastal wetlands is originating from sea water intrusion.

Table 5. Results of the comparison of the different available ET products over the same area (mm / period).

Period	SEBAL	ETLook (2007)	Diff (%)
Nov 97 / May 98	553	402	-27
Nov 02 / May 03	503	402	-20
May 95 / Oct 95	681	523	-23
April 02 / Sep 02	830	576	-31

Table 6. Climate data for Cairo for SEBAL and ETLook data periods.

Period	Tavg (oC)	Tavg (2007)	PCP (mm)	PCP (2007)
Nov 97 / May 98	18.6	17.4	37	12
Nov 02 / May 03	18.8	17.4	28	12
May 95 / Oct 95				
April 02 / Sep 02	27.0	25.3	20	7

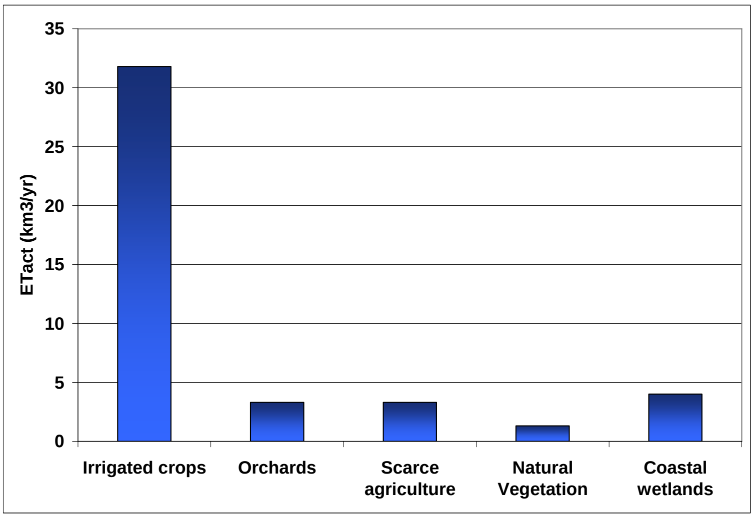

Figure 12. Actual ET for various land use derived using SEBAL over 2008.

3.5 Groundwater

Based on the GRACE satellite information trends in terrestrial water storage has been obtained en for the period 2003 to 2008. Figure 13 shows for the entire country these trends indicating that northern regions has become wetter and southern regions dryer. For the delta only this trend is even higher with for 2006 about 25 mm more terrestrial water compared to the other years. Note that figures relate to total terrestrial water, including root zone, shallow aquifers and deep aquifers. The average trend in the delta is 0.88 mm/month based on these time series. Given a total irrigated area in the delta of 20,837 km^2 this equals 0.22 km^3 / year.

It should be emphasized that the GRACE products are still in its experimental phase and no final conclusions should be based on these figures.

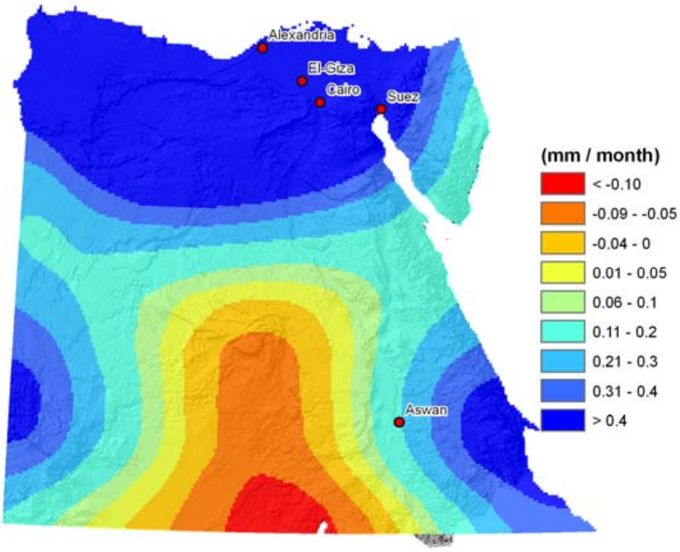

Figure 13. Trend in terrestrial water storage from the 2003-2008 based on GRACE data (based on 100 x 100 km^2).

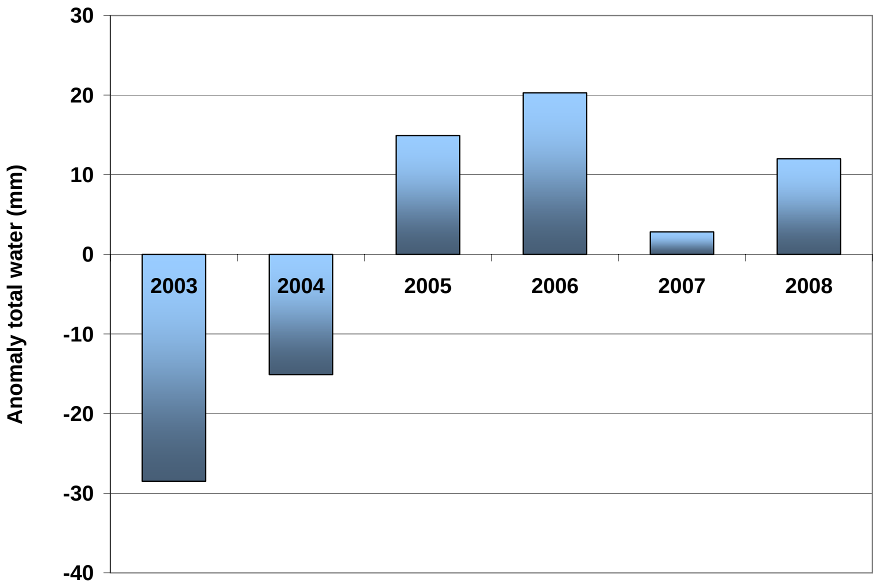

Figure 14. Anomalies in terrestrial water storage for the Nile Delta based on GRACE data.

3.6 Seepage

One aspect of water losses to be considered is seepage from the Nile into areas that are not irrigated. Obviously, seepage to agricultural lands cannot be considered as a real loss of water. The remote sensing analysis combined with the DEM of the area, has been used for this analysis (Figure 15).

To evaluate possible water loss due to seepage along the Nile a zone within 50 km of the axis of the Nile is analyzed. First the relative elevation of the surrounding terrain with respect to the Nile valley is determined. This achieved by relating the elevations of the Nile river bed to the surrounding area within this 50 km band (Figure 16).

The next step is to determine the actual water use in the non-irrigated areas as a function of elevation. The irrigated areas are removed from Figure 16 and the DEM is subdivided in elevation classes (Table 7).

For each zone the actual water use is determined using the 2007 ETLook data (Table 7). It is known that ETLook overestimates bare soil evaporation. From the Table it seems that this overestimation is around 30 to 35 mm as areas far from the Nile and at relative high elevations seepage losses and evaporation should be zero, but ETLook estimates about 30 to 35 mm.

From Table 7 we can conclude that there are some seepage losses. There is increased water use from distance class 1 to 5 up to a distance of roughly 20 km from the Nile river bed. Once annual actual ET equals 35 mm seepage is ignored. From Table 7 the total amount of seepage losses is estimated by summing the volumetric actual ET classes 1 to 5 and equals about 2.3 km^3.

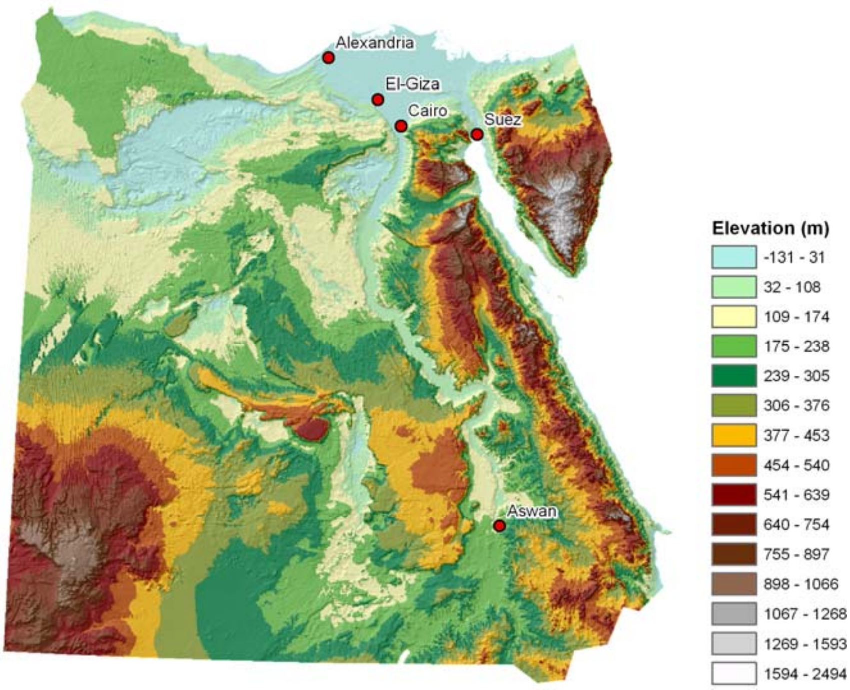

Figure 15 Digital elevation model.

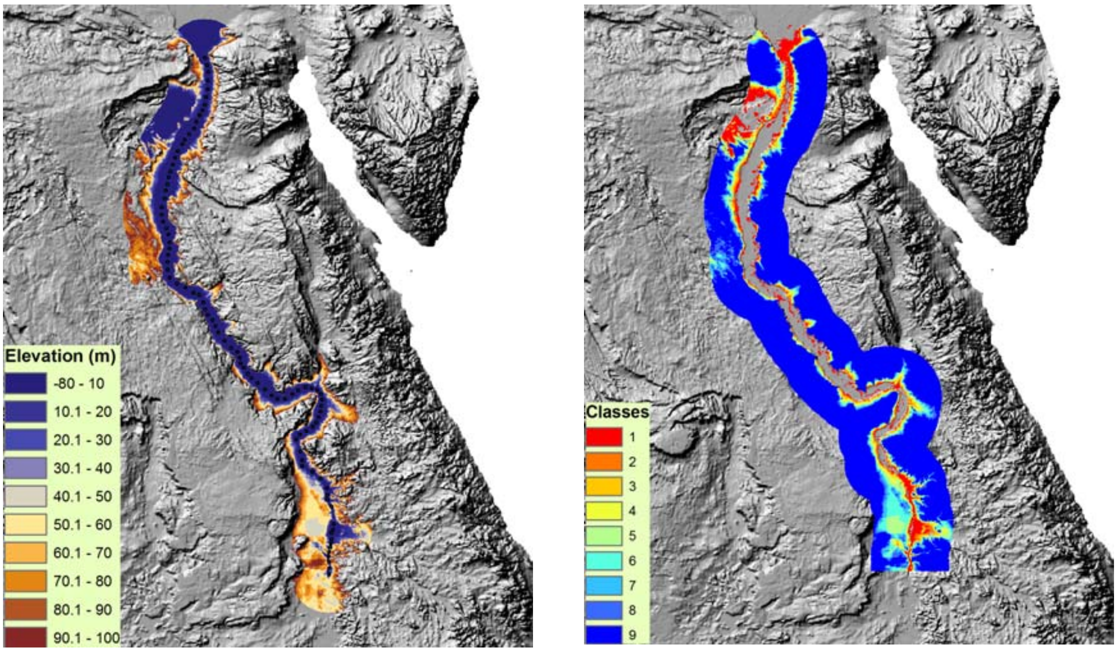

Figure 16. Relative elevation from Nile river bed within 50 km from the Nile (left) and Elevation zones outside the irrigated areas (right).

Table 7 Water use per elevation class

From (m)	To (m)	Class	Distance to Nile (m)	Area (km2)	ETact (mm)	ETact (BCM)
-100	10	1	15791	4371	403	1.76
10	20	2	11946	1829	121	0.22
20	30	3	13498	1879	74	0.14
30	40	4	15284	2035	42	0.09
40	50	5	18371	3035	40	0.12
50	60	6	20638	4035	35	0.14
60	70	7	21587	3432	32	0.11
70	80	8	24609	3514	34	0.12
80	1000	9	31205	53971	32	1.70

3.7 Analysis

Based on the results of the various remote sensing products and its analysis the following actual ET for various areas were extracted (under the assumption of):

- ET formal irrigation areas: 31.0 km^3 (based on the average SEBAL of 2007 and 2008)
- ET informal irrigation: 6.5 km^3 (based on SEBAL 2008)
- ET seepage: 2.3 km^3 (based on analysis under section 3.6)
- ET wetlands: 2 km^3 (SEBAL ET is 4 km^3 of which 50% originates of sea water intrusion)

In summary we can conclude that the actual ET according to remote sensing analysis for an average year is the sum of these four terms and equals 41.8 km^3 per year. Urban and industrial consumption has been estimated to be 1 km^3. Finally some outflow is committed to ensure releases of salt and to avoid sea water intrusion. No exact figures are known but we assume this will be in the order of 10% of the total releases from Aswan.

Although assumptions has been made to obtain these numbers the total consumption and committed outflow is about 50 km^3. This is lower than the 55 km^3 agreed allocations from Aswan and much lower than the observed releases of 68 km^3 (average 2007 and 2008).

These numbers as obtained from the remote sensing are compared to various publications and water plans. Although this seems to be straightforward it is complicated especially since terminology applied is often confusing. A short overview of some of the numbers published, including the terminology as used, is provided here.

Water resources:

km^3 y^{-1}	Source
55.5	Annual allocated flow of Nile under the Nile Waters Agreement of 1959. (Aquastat) – defined as releases from Aswan.
0.5	Internal surface water resources (Aquastat)
56	Renewable surface water resources (Aquastat)
73,2	Total water input (Aquastat)
85	Total external water resources (natural, Aquastat)
56.5	Total external water resources (actual, Aquastat)
55	Aswan releases (Oosterbaan, 1999)
62.5	Total water input 1993 (FAO, 1997)
71.5	Total water input 2000 (FAO, 1997)
56	Surface water resources 1993 (FAO, 1997)
58	Surface water resources 2000 (FAO, 1997)
69.7	Volume of water resources in Egypt (SIS, 2008)
55.5	Share of Nile water (SIS, 2008)
57.0	Average water release from Aswan 1970-1986 (Cowen, 2008)
65.7	Releases Aswan 2007 (records)
69.3	Releases Aswan hydrological year 2008 (records)
73.6	Renewable water resources: precipitation 18.1, external 55.5 (Arab Water Council)

Water use:

km^3 y^{-1}	Source
68.3	Total water use (Aquastat)
68.3	Total water withdrawal (Aquastat)
38	Crop use. (Oosterbaan, 1999)
32.5	ET from all land surface elements and coastal swamps Nile Delta and Suez canal (Bastiaanssen. 1994)
59.2	Total water-use in Egypt in 1990. (FAO, 2008)
49.7	Agricultural water-use in Egypt in 1990. (FAO, 2008)
46	Aswan releases for irrigation. (Oosterbaan, 1999)
47.4	Irrigation water demands 1993. (FAO, 1997)
57.4	Irrigation water demands 2000. (FAO, 1997)
48.8	Annual crop consumptive use. (Hefny, 2005)
54	Water diverted for agriculture. (Hefny, 2005)
31.0	This study, formal irrigated lands
38	Crop water consumption (MWRI, 2005)
40	ET of cropped area (pers. comm. Bayoumi Attia)
53.9	Sectoral abstractions: Irrigation 47.7, domestic 3.3, industry 4.4 (Arab Water Council)

Outflow:

$km^3\ y^{-1}$	Source
9	Outflow. (in text; Oosterbaan, 1999)
11	Outflow. (in figure; Oosterbaan, 1999)
0.3	Water released to the Mediterranean (Abu-Zeid and El-Shibin, 1997)

Irrigated area:

ha	Source
2,087,000	Area equipped for irrigation in 1999. (Thenkabail, 2006)
3,422,000	Total area equipped for irrigation in 2002. (Aquastat).
3,276,000	Irrigated area. (7.8 million feddan[1]; RDI, 1997),
4,420,000	Irrigation potential (Aquastat).
3,246,000	Equipped for irrigation. (Aquastat).
5,666,000	Cropping area (14.0 million acres; Abu-Zeid and El-Shibin, 1997)
2,940,000	Total cropped in 1990. Nile Valley: 840,000; Nile New Delta: 1,932,000; Coastal Valley: 126,000; Sinai Plains: 42,000. (FAO, 1997)
3,078,000	Area under irrigation. (FAO, 1997)
5,419,000	All irrigated crops, including multiple cropping per year. (Aquastat)
3,104,000	This study.
3,444,000	Cropped area (pers. comm. Bayoumi Attia)
3,246,000	Irrigated crop area (Arab Water Council)

Irrigation:

mm	Source
1200	Annual average crop consumptive use. (Oosterbaan, 1999)
1000 to 1400	Evaporation per year. (Bastiaanssen, 2004)
1300	Average water requirement (FAO, 1997)
1470	Irrigated crops abstraction: expressed as irrigated land (Arab Water Council)
888	Irrigated crops abstraction: expressed as irrigated harvested (Arab Water Council)

It is clear that based on these numbers and especially on the applied terminology, water resources is nit well defined. For water use, most of the confusion is explained by failure to distinguish between water diverted and water *consumed.* Especially in the case of Egypt, large quantities of water that are diverted for irrigation return to the river system through the extensive drainage network, and this water is often re-diverted downstream. Thus diversions are substantially higher than releases from Aswan. Further, over the last years releases from Aswan have been far above the 55.5 km^3 and are probably close to 70 km^3 (Attia Bayoumi, personal communication). Observations in 2007 and 2008 showed an average of 68 km^3.

The figures on actual water consumption vary even more, often as a result on vaguely used terminology – again, failing to distinguish between water applied to the crop, and water consumed by the crop. In this study we consider that only water that actually evaporates should be accounted as water consumed. Based on the various remote sensing analyses it is concluded that the actual ET over the formal irrigated areas is 31 km^3 for irrigated lands and another 6.5 km^3 for areas that are located at the periphery of the irrigated areas.

The question remains how the water balance can be closed. The few records found on outflow to the Mediterranean Sea show values of around 10 km^3. It is not clear whether evaporation from the downstream wetlands is included in these figures. The GRACE terrestrial water estimates show quite some increase in total water stored over the last few years. The

[1] 1 Feddan = 4200 m^2

evaporation from seepage water as estimated in one of the previous section might also be in the order of some 2 km^3.

In terms of water resources the Arab Water Council assumes that 18.0 km^3 is available from rainfall. This number is based on the average rainfall over the entire country of 18 mm. In our analysis we assume that only rainfall over the irrigated areas should be included as rainfall over desert will evaporate directly.

Based on these discussions a total water balance is presented in Table 8. Outflow to the sea is used as the closing term of the water balance as it can be considered as the most unreliable parameter. This balance is constructed using the best information currently available from various sources including the remote sensing analysis.

Table 8. Estimated water balances for the Nile Basin in Egypt for a representative year under current conditions.

In (km3)		Out (km3)	
Basin			
Outflow Aswan	68.0	ET formal irrigation	31.0
Rainfall	0.5	ET informal irrigation	6.5
Groundwater (net)	0.0	ET seepage	2.3
		ET wetlands	2.0
		Committed outlfow	6.8
		Industry/domestic	1.0
		Uncommitted outflow to sea	18.9
Total	*68.5*	*Total*	*68.5*

4 Saudi-Arabia

Saudi Arabia has very limited water resources, while irrigated agriculture has been promoted and subsidized substantially over the last decades. To evaluate the impact of these endeavors to increase food productions on water resources a comprehensive remote sensing study (Bastiaanssen et al, 2006) was completed that included a multi-year analysis of agricultural water consumption. In this chapter we will review and summarize the main findings of this study, and present an analysis in combination with information of other sources.

4.1 Overview

The Kingdom of Saudi Arabia (KSA) is the largest country of the Arabian Peninsula. It is bordered by Jordan on the northwest, Iraq on the north and northeast, Kuwait, Qatar, Bahrain, and the United Arab Emirates on the east, Oman on the southeast, and Yemen on the south. The Persian Gulf lies to the northeast and the Red Sea to its west. It has an estimated population of 27.6 million, and its size is approximately 2,150,000 km^2.

Saudi Arabia's geography is varied. From the western coastal region (Tihamah), the land rises from sea level to a peninsula-long mountain range (Jabal al-Hejaz) beyond which lies the plateau of Nejd in the center of the country. The southwestern 'Asir region has mountains as high as 3,000 m (9,840 ft) and is known for having the greenest and freshest climate in all of the country. The east is primarily rocky or sandy lowland continuing to the shores of the Persian Gulf. The geographically hostile Rub' al Khali ("Empty Quarter") desert along the country's imprecisely defined southern borders contains almost no life.

The Government of the Kingdom of Saudi Arabia (KSA) has launched significant subsidy programs from 1974 onwards to boost agricultural developments in the country to become less reliant on food imports. The subsidies reached a maximum of 150 million SR (about $40M) in the early 1980s, and shrunk to 20 million SR (about $5M) in 1995. These financial investments have largely been responsible for the establishment of agro-business industries in the remote deserts of the Kingdom. As a result, the production of cereals has increased steadily and significantly in the 10 years between 1982 and 1993. While cereals expanded impressively, vegetables and perennials have gone through a modest, but steady, growth. At the same time, alfalfa and other fodders have had a boost in the 1981 to 1983 period, and their acreage became rather constant after this step change in dairy production in 1983.

Since groundwater is the primary source of water for irrigation, and massive abstractions occurred in the 1980's, a signal was released by the Government of KSA in 1993 and 1994 to make the use of groundwater resources more sustainable, and to prevent groundwater consumption becoming too high. Considering the fact that irrigated agriculture consumes approximately 85% of the water withdrawals in the Kingdom, major changes in the use of water by the agricultural sector was – and will be – required. A proper balance between agricultural production, rural development and sustainable groundwater use has to be found. These fundamental directions have been recognized, and need to be implemented in the few years to come. (Bastiaanssen et al, 2006).

Figure 17: Overview of the Kingdom of Saudi Arabia.

4.2 Climate

Extreme heat and aridity are characteristic of most of Saudi Arabia. It is one of the few places in the world where summer temperatures above 50 °C have been recorded. In winter, frost or snow can occur in the interior and the higher mountains, although this only occurs once or twice in a decade. The average winter temperature range is 8° to 19 °C in January in interior cities such as Riyadh and 17° to 27 °C in Jeddah on the Red Sea coast. The average summer range in July is 29° to 42 °C in Riyadh and 26° to 38 °C in Jeddah. Annual precipitation is usually sparse (up to 100 mm in most regions), although sudden downpours can lead to violent flash floods in wadis. Annual rainfall in Riyadh averages 110 mm and falls almost exclusively between January and May; the average in Jeddah is 54 mm and occurs between November and January.

Figure 19 shows the spatial distribution of rainfall from 1998 tot 2007 based on data derived from the TRMM satellite. Rainfall varies from below 20 mm /year in the north-west and south-east of the country to over 200 mm near Jeddah on the Red Sea coast. The average for the entire country is 77 mm.

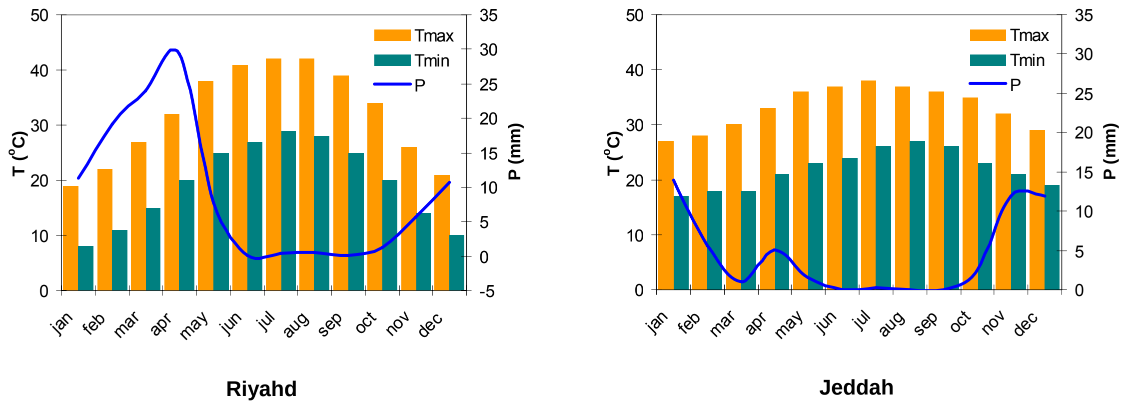

Figure 18: Average monthly climate conditions in Riyahd and Jeddah

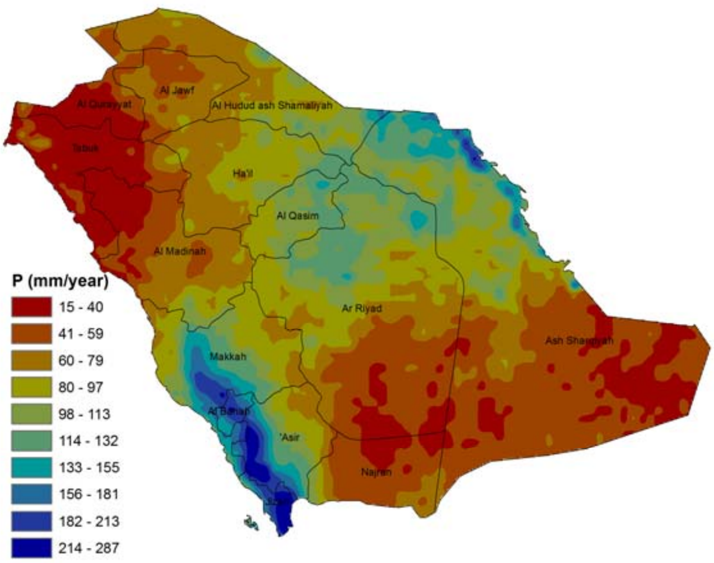

Figure 19: Average annual precipitation from 1998 to 2007 based on TRMM

4.3 Irrigated areas

The FAO report a total area of 1,730,767 ha to be equipped for irrigation (Figure 20), while the IWMI Global Irrigated Area Mapping (GIAM) projects reports a total of only 633,218 ha (Figure 21). The classification of the source of irrigation water is also doubtful for the GIAM map. All irrigation originated from surface water sources, while perennial rivers are non-existent in Saudi Arabia and the vast majority of irrigated agriculture consists of large scale groundwater based pivot irrigation systems (Figure 22).

According to census statistics acreages for irrigated agriculture are reported and shown in Table 9. Bastiaanssen *et al*. (2006) assessed irrigated areas from 1979 onwards using three different sources of satellite imagery (NOAA GIMMS, NOAA LAC/GAC and SPOT NDVI). Figure 23 shows a summary of the most recent data derived from data of the SPOT satellite.

Table 9 Census data on irrigated agriculture (Bastiaanssen *et al*, 2006).

	1997	**2000**
	(ha)	(ha)
Winter crops	772,600	610,807
Summer crops	342,738	312,840
Perrenial crops	147,929	196,302
Total	1,263,267	1,119,949

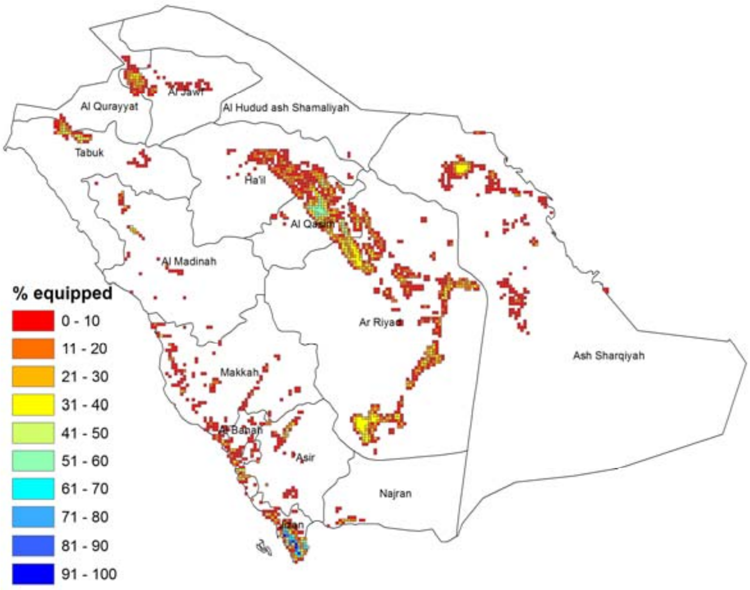

Figure 20. Total area equipped for irrigation based on the FAO dataset.

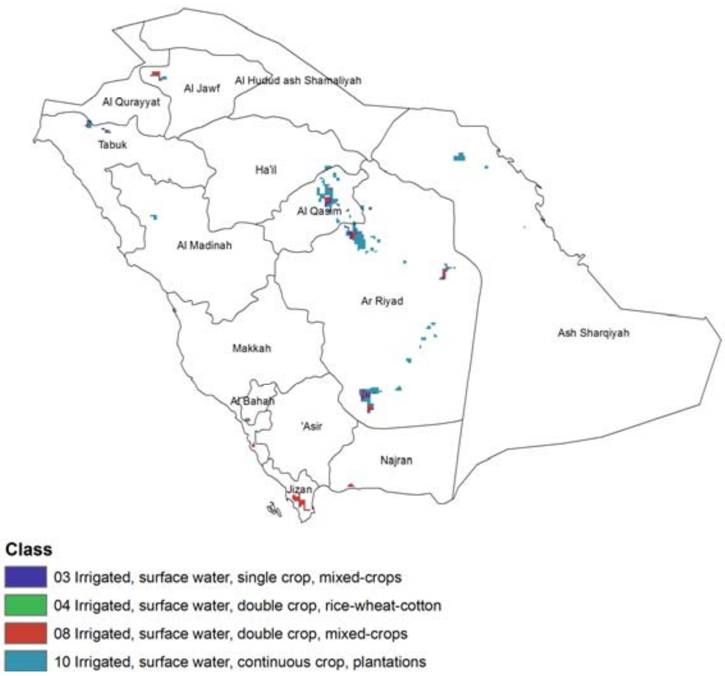

Figure 21. Total area equipped for irrigation based on the GIAM dataset.

Figure 22. Pivot irrigation in Al Qasim.

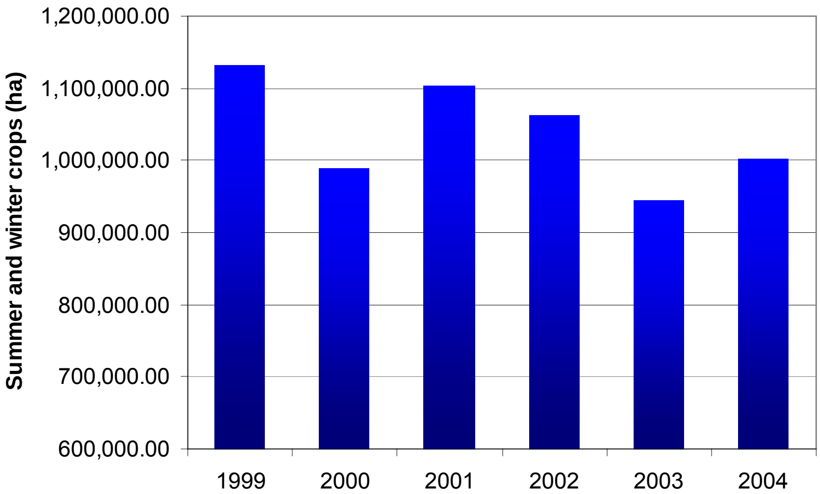

Figure 23. Irrigated areas based on SPOT NDVI data at 1 km resolution (Source: Bastiaanssen *et al*., 2006)

4.4 Water use from remote sensing

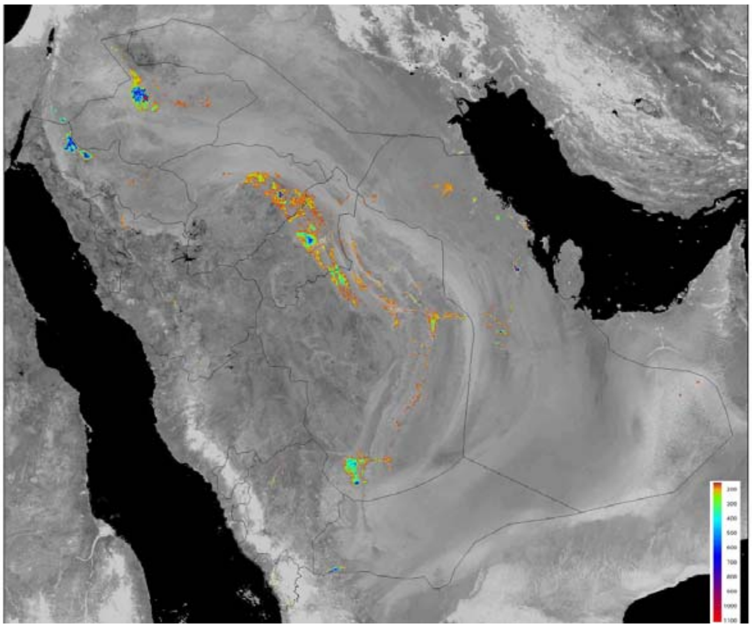

Figure 24.Annually accumulated evapotranspiration (mm) for KSA for a 1 km X 1 km grid in 2003 (Source: Bastiaanssen et al., 2006)

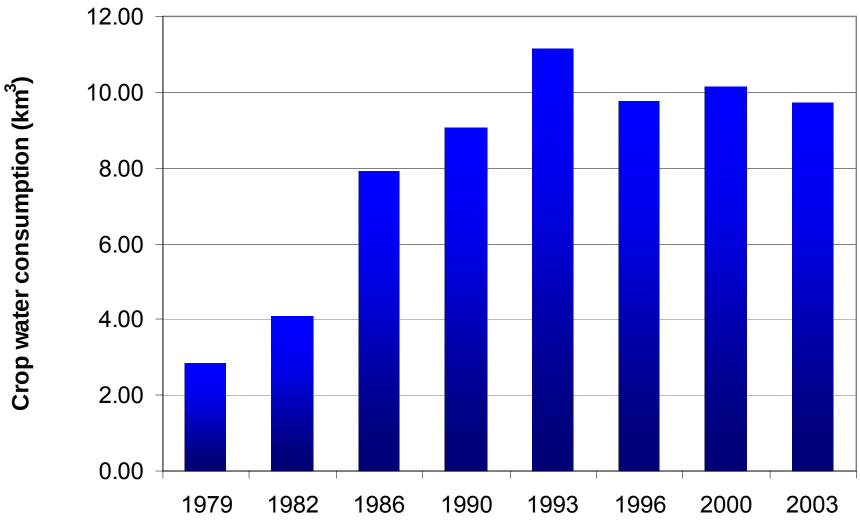

Figure 25.Annual crop water consumption for selected years for the entire KSA (Source: Bastiaanssen et al., 2006)

4.5 Groundwater

4.5.1 General

Groundwater in Saudi Arabia is found almost entirely in the many thick, highly permeable aquifers of large sedimentary basins to the North and the East as well as in the fractured rocks of the Arabian Shield. In most parts of central and eastern Saudi Arabia, an adequate and reliable supply of water is available from at least one of the eight principal aquifers (Figure 26).

The distinction between principal aquifers and secondary aquifers is based on their hydrological properties and aerial extent.

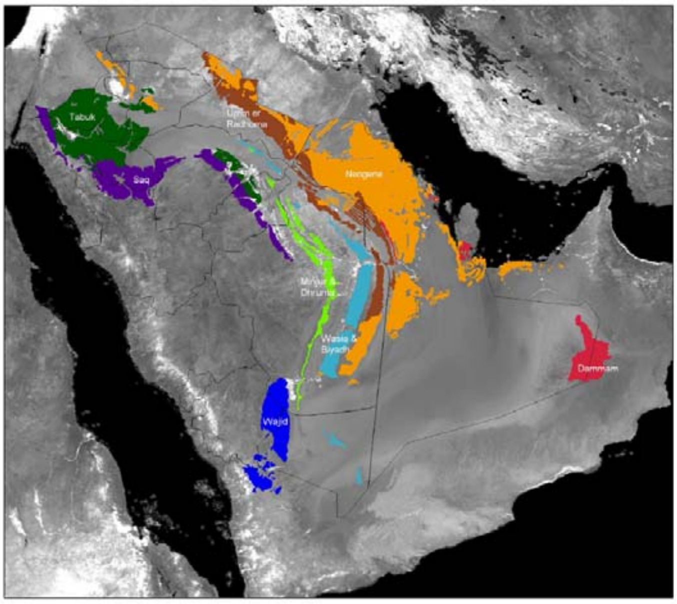

Figure 26. The eight principle aquifers in Saudi Arabia (Source: Bastiaansen *et al*., 2006)

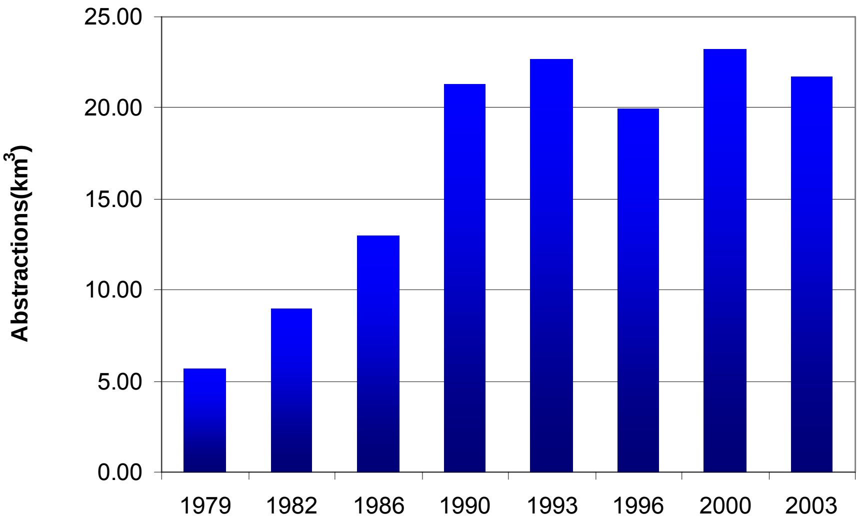

Figure 27. Groundwater abstractions (Source: Bastiaansen *et al*., 2006)

4.5.2 GRACE

Based on the GRACE satellite information trends in terrestrial water storage has been obtained en for the period 2003 to 2008. It is interesting to see that the most prominent trends in groundwater are indeed visible in Ha'il and Al Qasim where the largest amounts of groundwater are extracted. If we assume a downward trend occurs of 1.4 mm/month in 10% of the total area of the country, this equals 3.6 km^3 y^{-1} of net groundwater use. This figure is lower than the reported 10 to 20 km^3 and might be explained by the course resolution of GRACE which is not able to detect the more local scale high extraction rates. It should be emphasized that the GRACE products are still in its experimental phase and no final conclusions should be based on these figures.

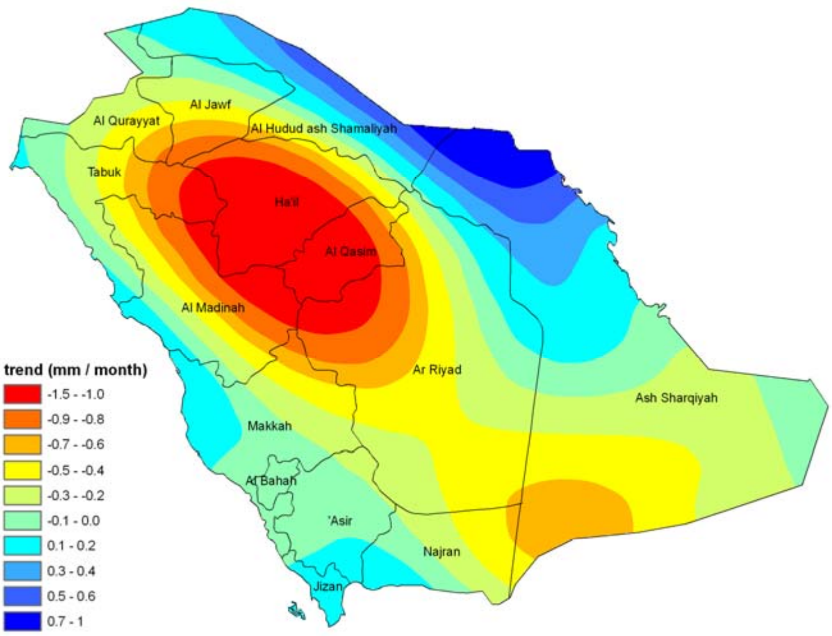

Figure 28. Trend in terrestrial water storage from the 2003-2008 based on GRACE data (based on 100 x 100 km^2).

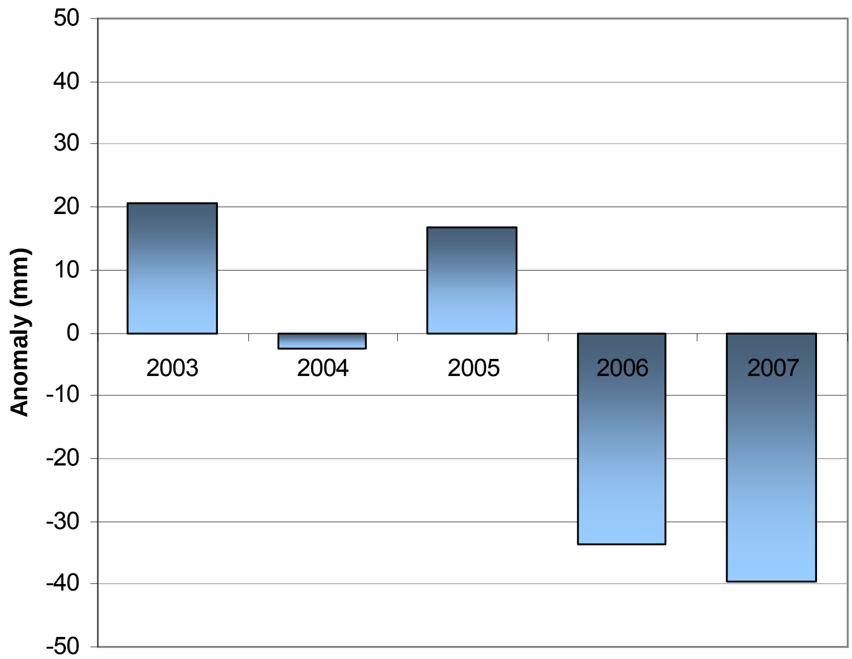

Figure 29. Anomalies in terrestrial water storage for the Ha'il and Al Qasim based on GRACE data.

4.6 Aquastat data

Total surface water resources have been estimated at 2.2 km³/year, most of it infiltrating to recharge the aquifers. About 1 km³ recharges the usable aquifers. The total (including fossil) groundwater reserves have been estimated at about 500 km³, of which 340 km³ are probably abstractable at an acceptable cost in view of the economic conditions of the country.

In 1992, total water withdrawal was estimated at 17 km³, of which 90% was for agricultural purposes (8.9% is withdrawn for domestic use and 1.1% for industrial use). In 1990, total water withdrawal was estimated at 16.3 km³. Desalinated water is used for municipal purposes, as it is too saline, even after treatment, for irrigation. Treated wastewater is used to irrigate non-edible crops, for landscape irrigation and for industrial cooling. However, most of the water used (> 13.5 km³) comes from non-renewable, deep aquifers. At the 1990 rate of abstraction, it is estimated that the usable reserves will last for a maximum of 25 to 30 years. The quality of the abstracted water is likely to deteriorate with time because of the flow from low quality water in the same aquifers towards the core of the depression at the point of use. In 1988, there were 4 667 multi-purpose government wells and 44 080 multipurpose private wells.

The most recent soil surveys (1989) and classifications put the area of land suitable for irrigated agriculture at about 10 million ha. However, as shown above, the limiting factor is water. At present, depletion of non-renewable fossil water is already taking place at a very fast rate. All agriculture is irrigated and in 1992 the water managed area was estimated at about 1.6 million ha, all equipped for full/partial control irrigation. Surface irrigation is practiced on the old agricultural lands, cultivated since before 1975, which represent about 34% of the irrigated area. Sprinkler irrigation is practiced on about 64% of the irrigated areas. The central pivot sprinkler system covers practically all the lands cropped with cereals. Normally, pumped groundwater from one deep well supplies one or two central pivots. The irrigation application efficiency of this method is estimated at between 70 and 85%. Vegetables and fruit trees are in general irrigated by drip and bubbler methods respectively. Groundwater is used on almost 96 % of the irrigated area, treated wastewater on 1 %).

In 1992, 428 000 ha were estimated to be cultivated by 1 070 large farms, with an area of more than 200 ha each. The total area of medium farms (5 - 200 ha) was 730 000 ha, comprising 7 300 farms. Small farms (< 5 ha) covered 450 000 ha, comprising 180 000 farms.
The average cost for irrigation development is about $US I 093, 372 and 251/ha for microirrigation, sprinkler irrigation and surface irrigation systems respectively. Water is free of charge.

The cropped area has more than tripled between 1977 and 1992. In general, there is only one cropping season. The major irrigated crop is wheat. In 1988, it consumed almost 40% of the total quantity of irrigation water while it covered almost 62 % of the irrigated area. Other major crops are fodder, other cereals (particularly sorghum and barley), fruit trees and vegetables. Since 1988, self sufficiency in wheat has been reached and part of the production is being exported. In 1992, wheat production was almost 4.1 million tons, while national demand was only about 1.2 million tons. Vegetables, fruits and dates and fodder are also exported.

In 1981 there began a change in agricultural cropping patterns by adopting new technologies, exercising extensive and effective agricultural extension, using improved seed varieties with high productivity and providing advanced plant protection services in line with modern agricultural methods.

The government's involvement in the agricultural sector has been extensive. During the 1980s food self-sufficiency, particularly in wheat and dairy products, became a major priority and, with the support of heavy subsidies, the added value in agriculture increased by more than 70% in the period 1985-91. Wheat production was even sufficient to enable Saudi Arabia to become the world's sixth largest wheat exporter. However despite its success, this policy is a threat to the country's water reserves. On economic grounds, the 1991/92 harvest was estimated to have cost the government around $US 480/ton compared with world prices for wheat of $US 100/ton. At present, the national goal is the diversification of agricultural production in order to meet the growing demand for other types of crops and to adjust the wheat production to the level of annual national consumption.

Because of the development of agriculture, which is by far the largest water user, the depletion of fossil groundwater takes place at very fast rates. It is expected that at the present rates of abstraction all the reserves will be used within the next 25 to 30 years. The Ministry of Planning has proposed a target to reduce annual irrigation water use from the current 15.3 km^3 to 14.7 km^3 by the year 2000. Measures to be taken are:

- implementation of effective irrigation schedules at farm level to deliver irrigation water according to actual crop need, which is expected to result in a saving of water of at least 30%;
- replacement of surface irrigation systems by sprinkler irrigation and micro-irrigation systems;
- shifting of some of the fodder and cereals areas from high water consumption zones to lower water consumption zones and cultivation of crops with lower water requirements;
- introduction of water meters at farm level to control the pumping of water.

Extensive pumping of groundwater has resulted in a significant drop in the groundwater level (for example 100 metres in the north-west in the last decade), requiring deeper and larger holes to be drilled and a higher head for pumping which results in a higher production cost. Groundwater quality has also deteriorated to the point where it can no longer be used for municipal supply without expensive treatment. Furthermore, only half the groundwater reserves are located near the areas of demand. The coastal areas suffer increasingly from sea water intrusion.

While Saudi Arabia is already by far the largest producer of desalinated water, future development will have to depend even more on the development of this source and on the reuse of treated wastewater. However, as up to present the desalinated water is still too saline for agricultural use, the problem of the rapid depletion of fossil water is still a long way from being solved.

Table 10 Annual Aquastat data on Saudi Arabia

Total renewable water resources (cubic km)	2.4
Irrigation water requirements (cubic km)	6.68
Water requirement ratio in percentages	43%
Water withdrawal for agriculture (cubic km)	15.42
Water withdrawal as percentage of renewable water resources	643%

4.7 Analysis

The main objective of the Saudi Arabia case is to evaluate whether remote sensing can contribute to the discussion on the impact of expansion of irrigated agriculture on the sustainability of water resources. The various components of the water balance (total water resources, water consumption, irrigated areas and production) were collected based on reports on completed studies and remote sensing analysis as described by Bastiaanssen (2006). The following tables provide the figures as reported by various studies.

In terms of water resources two very distinct figures were presented. Very high values are presented assuming that rainfall can be considered as total water resources. Although precipitation is low, given the large area of the country total rainfall in km^3 is high. Other figures presented in water resources consider that most of this rainfall evaporates directly and conclude that total renewable water resources are in the order of 2 to 3 km^3.

One would expect that the determination of the area under irrigation is a straight forward task for Saudi Arabia, as all green areas must be irrigated. However, quite a wide range of figures is presented, which can be partly explained by the use of different definitions. Some reports use the term “area equipped for irrigation”, while others use the actual green area. Another complicating factor is that the year and the time of the year should be included as some crops are grown for a particular season while others are perennial. Overall, one can conclude that there seems to be a trend over the years with highest area irrigated land (expressed as green areas) around 1995 and from then on a small decrease has been observed.

In Table 11 the water balance for the entire country has been constructed based on remote sensing analyses as well as additional data. It is clear that such a water balance is not very informative for policy makers, as the biggest numbers relate to uncontrollable water flows (precipitation and actual ET in deserts). This ET in desert areas can be labeled as non-beneficial consumption. Table 12 shows the water balance for irrigated areas only. It is clear that there is a substantial unsustainable water extraction from the groundwater.

Based on the annual groundwater abstraction data and the remote sensing figures on actual evapotranspiration the classical irrigation efficiency can be calculated. The total abstraction from 1975 to 2004 is estimated at 463 km^3, while the total ET equals 221 km^3 and this is equal to an overall efficiency of 48%. (Bastiaanssen *et al.*, 2006). This fraction of ET over groundwater abstraction is also shown in Figure 30 for various years. With the exception of 1986 fractions are more or less constant between 0.4 and 0.5.

Water resources:

$km^3\ y^{-1}$	Source
126.8	Precipitation equal to 59 mm (Aquastat)
2.2	Surface water (Aquastat)
2.2	Groundwater (Aquastat)
2.4	Total internal renewable water resources (Aquastat)
165.5	Precipitation equal to 77 mm (TRMM analysis)
126.8	Renewable water resources: all from precipitation (Arab Water Council)

Water consumption:

$km^3\ y^{-1}$	Source
15.4	Total water use (Aquastat)
6.7	Irrigation water requirement (Aquastat)

16.3-17.0	Groundwater abstractions (Aquastat)
10.0	ET from irrigated lands (Bastiaanssen, 2006)
20.0	Groundwater abstraction (Bastiaanssen, 2006)
17.4	Sectoral abstractions: Irrigation 15.3, domestic 1.5, industry 0.2 (Arab Water Council)

Irrigated area:

ha	Source
772,600	Census data winter crops 1997 (Bastiaanssen, 2006)
610,807	Census data winter crops 2000 (Bastiaanssen, 2006)
342,738	Census data summer crops 1997 (Bastiaanssen, 2006)
312,840	Census data summer crops 2000 (Bastiaanssen, 2006)
147,929	Census data perennial crops 1997 (Bastiaanssen, 2006)
196,302	Census data perennial crops 2000 (Bastiaanssen, 2006)
1,730,767	Area equipped for irrigation (FAO irrigated area map)
633,218	Area equipped for irrigation (IWMI GIAM).
1,039,108	All seasons summed (one area can counted twice if double cropped) (Bastiaanssen, 2006)
1,600,000	Area equipped for irrigation (Aquastat)
428,000	Cropped area in 1992 (Aquastat)
1,608,000	Irrigated crop area (Arab Water Council)

Irrigation:

mm	Source
1615	Irrigation application depth alfa alfa (Bastiaanssen, 2006)
1013	Irrigation application depth wheat (Bastiaanssen, 2006)
1177	Irrigation application depth corn (Bastiaanssen, 2006)
1000 to 1400	Irrigation application depth Rhodes grass (Bastiaanssen, 2006)
952	Irrigated crops abstraction: expressed as irrigated land (Arab Water Council)

Table 11. Estimated water balance for Saudi Arabia.

Country

In (km^3)		Out (km^3)	
Rainfall	146.1	ET irrigation	10.0
Groundwater abstractions	20.0	ET other	145.6
		Industry/domestic	2.0
		Seepage / recharge	8.5
Total	*166.1*	*Total*	*166.1*

Table 12. Estimated water balances for irrigated areas in Saudi Arabia.

Irrigated areas

In (km^3)		Out (km^3)	
Rainfall	0.5	ET irrigation	10.0
Groundwater abstractions	20.0	Industry/domestic	2.0
		Seepage / recharge	8.5
Total	*20.5*	*Total*	*20.5*

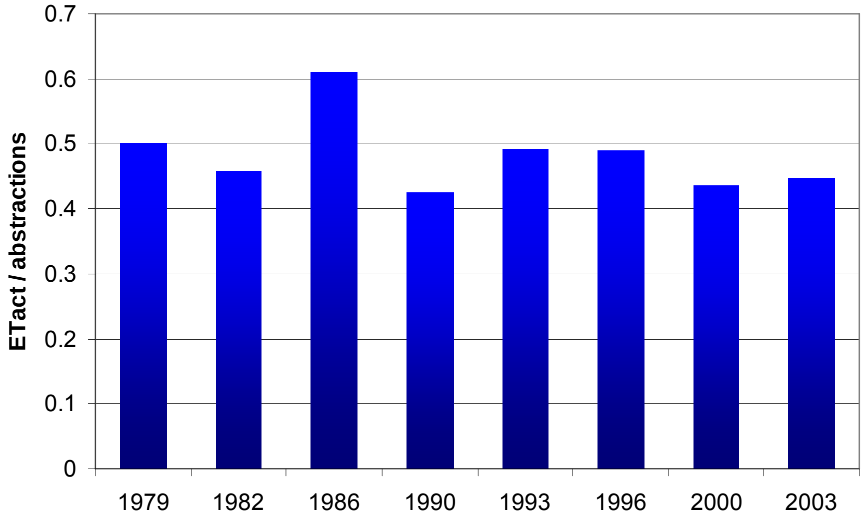

Figure 30. ETact divided by groundwater abstractions (Source: Bastiaanssen *et al*., 2006).

5.1 Overview

Tunisia has a total area of 193 610 km², of which almost 7% consists of lakes and saline depressions. The cultivable area is estimated at 8.7 million ha, which is about half the total area of the country. In 1993, the cultivated area was estimated at 4.25 million ha. Agriculture employed 30% of the labor force in 1993. During the period 1989-93 GDP increased about 5% per year. The importance of the agricultural sector in the economy decreased from 1960 to 1994: in 1960 it accounted for 24% of the country's GDP, while in 1994 this figure had fallen to 16%.

According to the Aquastat country profile are surface water resources estimated at 2.91 km^3/year, of which 2.31 km^3 are internally generated. About 1.5 km^3/year are exploitable at present through reservoirs. It will be possible in the future to exploit another 0.6 km^3 /year, if additional large water control works and groundwater recharge systems are built (18 large dams and 22 hillside dams). Internal renewable groundwater resources have been estimated at 1.21 km^3/year. Over the last 20 years, reuse of treated wastewater has developed. In 1990, water withdrawal was estimated at about 3.1 km^3/year, of which 88.7% for agricultural purposes. In 1992, the rural population with access to good drinking water within a distance of 3 km was estimated at 65 %, while 91 % of the urban population was connected to the drinking water supply network.

Figure 31. Administrative units and elevation of Tunisia.

Using water more productively in agriculture is a government priority. The Government of Tunisia adopted the National Programme for Saving Water in Irrigation (PNEE) in 1995. The main objectives of this program were to conserve scarce water resources, increase the economic value of water, and to maintain equilibrium between available water resources and water demand by irrigation.

As a result of the PNEE approximately 330,000 ha out of 414,000 ha irrigated lands were improved through introduction of improved technology (drip and sprinkler systems) and organizing Water user Associations. It was assumed that these interventions would reduce the losses of water, and improve management.

To evaluate the impacts of these programs, WaterWatch started a project on Tunisian agriculture that focused on savings both in irrigation water use as well as in crop water consumption by actual evapotranspiration. Details are described by Zwart and Bastiaanssen (2008), while this chapter describes the main findings emphasizing the role of remote sensing in these kinds of studies.

5.2 Climate

Tunisia has great geographical and climatic diversity. The Dorsal, an extension of the Atlas Mountains towards the north, weather can be characterized as a Mediterranean climate.The summers are hot and dry and winters are cold and wet. The South of Tunisia experiences very hot and humid weather. Rainfall in Tunisia is scanty and droughts are a common feature – especially in the south. Hot Sirocco winds are common.

Tunisia receives direct sun shine for most of the year. July and August are the hottest months. From October to May the temperature ranges between 12 degrees to 28 degrees. Tunisia receives an average annual rainfall of 1,520 mm, varying substantially from place to place. Figure 32 and Figure 33 show trends in annual rainfall and temperatures as well as monthly averages. Figure 34 shows the geographic trend in precipitation based on the TRMM satellite observations.

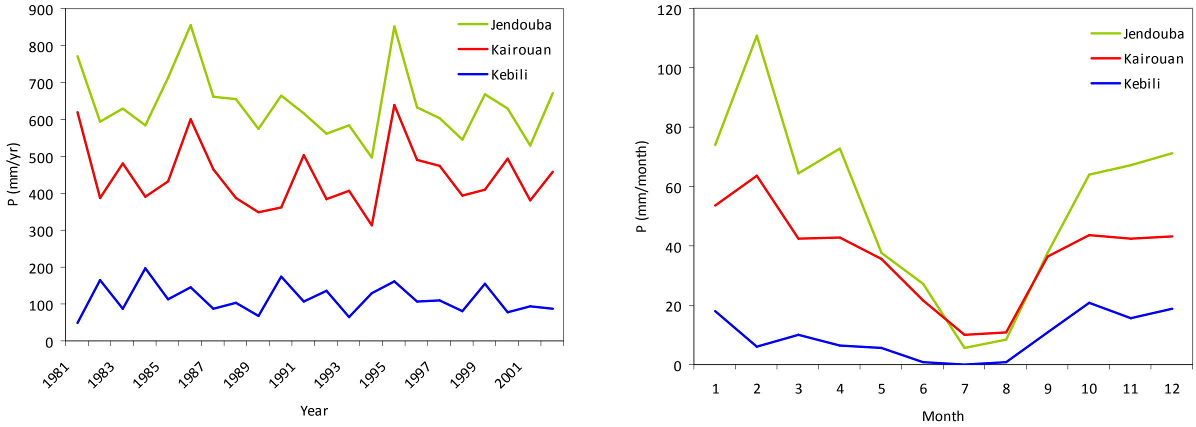

Figure 32. Annual and monthly average precipitation from 1981-2002 (CRU TS 2.1)

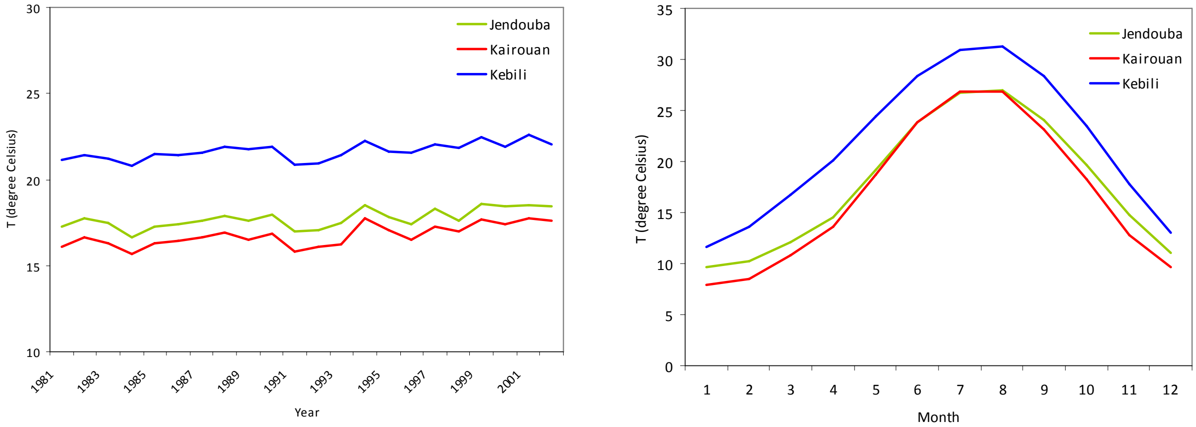

Figure 33. Annual and monthly average temperature from 1981-2002 (CRU TS 2.1)

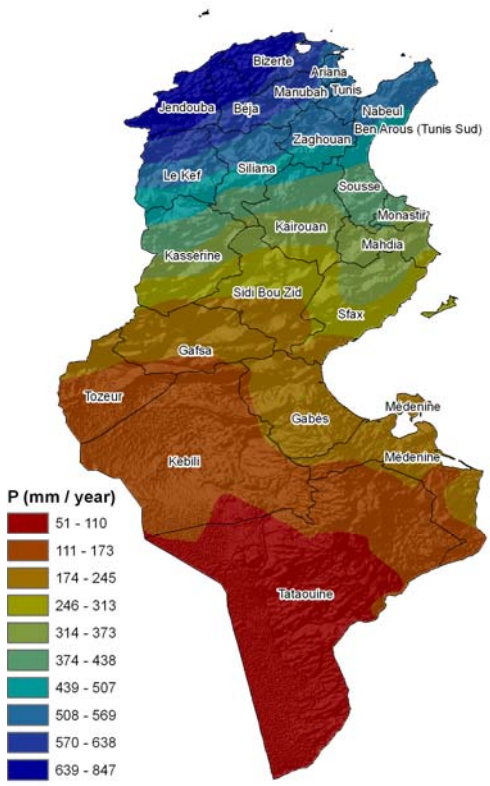

Figure 34. Average annual precipitation from 1998 / 2007 based on TRMM 3B43

5.3 Irrigated areas

Based on MODIS images Zwart and Bastiaanssen assessed the area under irrigation. According to their analysis irrigation extends over 4,539 km^2 – only 10% of the total cropped land. The FAOSTAT Global Map of Irrigated Areas (GMIA) data base suggest an area of 3,940 km^2, and the reference for their GMIA map was also the year 2000. There is a difference of 13% with the WaterWatch map, and this is very likely the fraction of the pixels flagged as irrigated that are occupied by trees, roads, canals, houses etc. The Global Irrigated Area Map of the International Water Management Institute (IWMI) indicates a total area of 1,091 km2. This number seems to be very low.

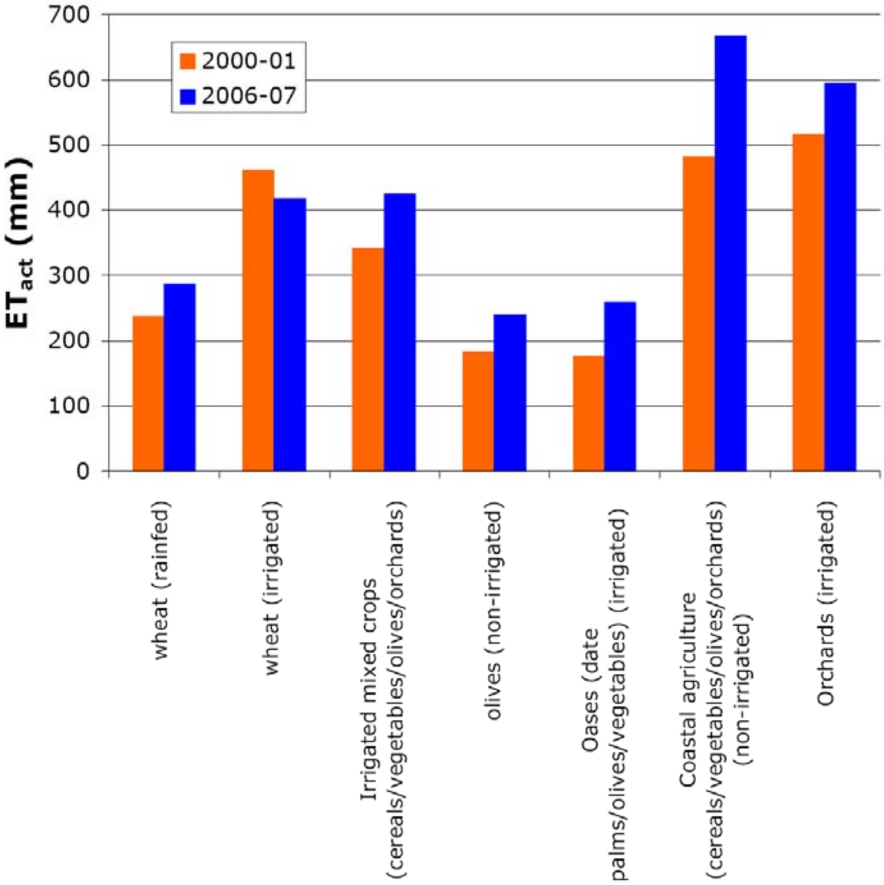

Figure 35. Actual evapotranspiration per crop (mm y^{-1}). Source: Zwart and Bastiaanssen, 2008.

5.4 Water use from remote sensing

Analysis based on MODIS were undertaken for the years 2000/2001 and 2006/2007 to assess the actual water consumption (evapotranspiration) for the agricultural lands. The following numbers were found (Zwart and Bastiaanssen, 2008):

- 1.691 km^3 2000/2001, irrigated agriculture
- 1.845 km^3 2006/2007, irrigated agriculture
- 9.564 km^3 2000/2001, rainfed agriculture
- 12.375 km^3 2006/2007, rainfed agriculture

It is striking rainfed agriculture is consuming substantially more water than irrigated agriculture, though of course consumption per hectare is considerably higher in irrigated agriculture. Conventional thinking would focus on irrigated agriculture as the only manageable water consumer. In fact, any change in land use has implications for local ET, runoff and infiltration. Whether natural vegetation consumes more or less water than rainfed agriculture is an interesting empirical question. In Tunisia, conversion of bare soils or natural vegetation to rainfed agriculture has been common practice in Tunisia and might have substantial impact on runoff and percolation fluxes to the groundwater.

Figure 35 shows the actual evapotranspiration for the dominant crops in the country for the two years when analyses were performed. The overall conclusion is that changes in actual evapotranspiration per hectare over these two years are not consistent. Interestingly, for irrigated wheat, a dominant crop, the actual evapotranspiration went down.

Figures of total water consumption as provided above are misleading when, as in Tunisia, part of the evapotranspiration from irrigated areas originates from rainfall. Adjusting for this by deducting an amount equal to the ET from nearby non-irrigated areas as a proxy for the rainfall contribution to irrigated areas, the following numbers were derived as estimates of evapo-transpiration from irrigation supplies:

- 0.594 km^3 2000/2001
- 0.473 km^3 2006/2007

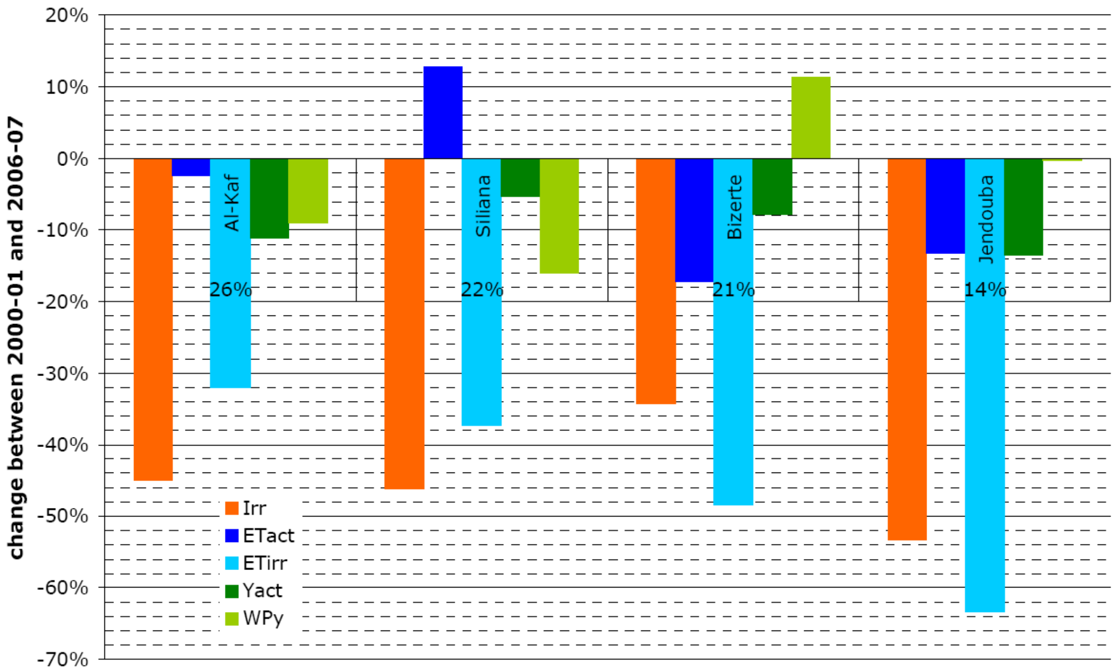

Figure 36. Impact of irrigation modernization in Tunisia for irrigated wheat for four governorates.
Water diversion (Irr), water consumption (ETact), water consumption due to irrigation (ETirr), grain yields (Yact) and water productivity (WPy). (Source: Zwart and Bastiaanssen, 2008)

Differences between the two years have been compared and presented in Figure 36 for four important wheat governorates. The apparent change in applied irrigation is remarkable, but since this figure is calculated "backwards" from the computed ET from irrigation and an assumed "irrigation efficiency" is not especially reliable. In any case, the higher rainfall in the year 2006/2007 would make a decline in applied water probable. (Unfortunately, no field data were available on actual deliveries). More interesting is that also the total evapotranspiration went down – perhaps explainable by the cooler. More humid conditions in the wetter year – and less explicable, that yield went down as well. Striking is the decrease in water productivity for three out of four of the governorates. Since exact data on the location where the modernization has taken place, firm conclusions are somewhat difficult. Two conclusions may be drawn: first that a combination of field and remote sensing data are needed to understand what the impact of changes in technology, management and weather are; and second, that despite very substantial investments in improved technology, there is no clear pattern in Tunisia of improved water productivity or actual savings in water or higher yields per hectare.

5.5 Groundwater

GRACE satellite information has been used to show trends in terrestrial water storage. Figure 37 show these changes for the period 2003 to 2008. Unexpectedly, because groundwater overdraft in irrigated coastal areas is a known problem, there seems to be an increase in total terrestrial water in the northern areas. Note that figures relate to total terrestrial water, including root zone, shallow aquifers and deep aquifers. Moreover, it might be that impact of sea-level rise is distorts the overall picture – but this would then apply to all coastal areas, which does not seem to be the case. More research in the use of GRACE is required to get more clarifications on this.

It should be emphasized that the GRACE products are still in its experimental phase and no final conclusions should be based on these figures.

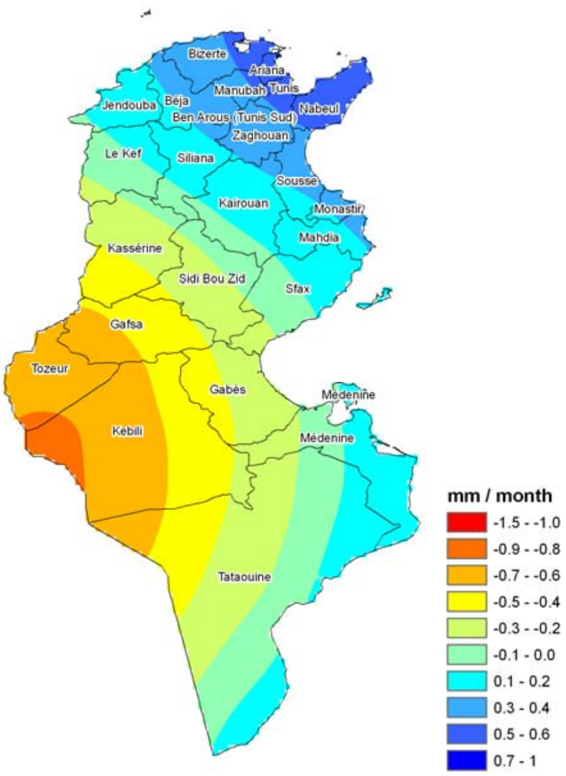

Figure 37. Trend in terrestrial water storage from the 2003-2008 based on GRACE data (based on 100 x 100 km²). Blue areas indicate increases in terrestrial water.

5.6 Analysis

Various sources of information have been combined in the following tables. It is clear that a wide range of numbers is reported for water resources, water consumption, irrigated area and irrigation.

In terms of *water resources* the Arab Water Council considers that all the rainfall that falls in the country can be in principle being classified as a resource. Most other authors, however, report much lower figures and use often only the amount of water in rivers and the groundwater potential.

A similar differentiation can be seen in the water consumption. All published papers agree in claiming that agriculture is the dominant consumer of water and that urban and industrial use is comparatively very low. Most reports concentrate only on irrigated agriculture. However, if one follows the logic that also rainfed agriculture consumes water, much higher figures on water consumption would be reported.

Estimates of irrigation and irrigated areas vary widely. Generally, the lowest estimate is presented by IWMI GIAM and seems to be unrealistic. Other figures presented might differ since some are based on the official statistics, while others are based on actual observations by remote sensing. A complicating factor for the Tunisia case is that the distinction between rainfed and irrigated areas is not always clear, as supplemental irrigation is common.

One of the main issues for Tunisia is whether the modernization of agriculture has led to the expected savings in water. The analysis was limited by lack of information on the exact location of the modernized areas; lack of information about irrigation deliveries; no information on the base line condition before modernization started and, finally, the impact of year-to-year whether conditions on the analysis. Even the definition of "savings" is not simple – less water delivered? Less water evapo-transpirated? Higher water productivity?

These issues might be addressed by including the following points in the analysis:

- **What are water savings**
  Water savings in irrigated agriculture are often measured in terms of applying less water to a crop, with consequent assumed savings in "losses". It has often been debated that reductions in losses are often in the same order as the reduction in reuse of water, with the net result that no savings are realized at all. Another approach is to consider that the only consumption of water is the actual evapotranspiration, which can be split in beneficial and non-beneficial. For the Tunisian case it was concluded, based on the remote sensing analysis, that the actual evapotranspiration for irrigated land was genearlly higher is the later (wetter) year. Finally, the ultimate indicator to evaluate whether modernization of agriculture has been successful is to look at the water productivity (= yield divided by ETact). The analysis indicates for most areas a lower water productivity for the years 2007/2007 compared to 2000/2001, leading to the conclusion that modernization did not have the anticipated positive effect. Again, this may be a result of the different rainfall pattern, but the mixed results show no clear pattern that would support a conclusion that improved irrigation teschnology has resulted in reduced water consumption, or increased water productivity.
- **Lack of local information**
  There is a tendency to assume that with the advance in remote sensing local information is less needed. Although partly true, this is scale dependent and, moreover,

some information cannot be observed by satellites. Most relevant information lacking for this Tunisian case is: location and year of modernization, application of irrigation amounts, and source of irrigation.

- **No base line information**
  Modernization started in 1995. The analysis however used 2000/2001 as base line. Since no detailed information was available on which areas were already modernized in 2000/2001, this base line probably included already some modernized areas.
- **Impact of weather conditions**
  The two years included in the analysis were significantly different in terms of precipitation. It is therefore hard to draw firm conclusions on changes in actual evapotranspiration and water productivity relevant to modernization only. While using simulation models that can be fed by whatever whether conditions and modernization assumptions might help in this area, the basis should be a continuous monitoring and integration of field and remote sensing data.

Water resources:

$km^3\ y^{-1}$	Source
3.2	Accessible water (Bahri, 2002)
2.8	Available water (Bahri, 2002)
4.7	Total volume of water resources (Mtimet, 2004)
5	Natural Renewable Water Resources (earthtrends.wri.org)
3	Surface water produce internally (earthtrends.wri.org)
4.1	Total renewable water resources (FAO quoted in AWC 2004)
34.5	Gross water resources (Arab Water Council)

Water consumption:

$km^3\ y^{-1}$	Source
2.8	Total withdrawals (earthtrends.wri.org)
11.3	ETact all crops 2000/2001 (Zwart and Bastiaanssen, 2008)
14.2	ETact all crops 2006/2007 (Zwart and Bastiaanssen, 2008)
1.7	ETact irrigated crops 2000/2001 (Zwart and Bastiaanssen, 2008)
1.8	ETact irrigated crops 2006/2007 (Zwart and Bastiaanssen, 2008)
2.7	Irrigated crops abstraction (Arab Water Council)
1.9	Utilized freshwater withdrawals (Arab Water Council)
3.1	Withdrawals (Arab Water Council)

Irrigated area:

ha	Source
400,000	surface suitable for irrigation (Mtimet, 2004)
109,100	Area equipped for irrigation (IWMI GIAM).
394,000	Irrigated agriculture (FAOSTAT Global Map of Irrigated Areas)
453,900	Irrigated agriculture (Zwart and Bastiaanssen, 2008)
385,000	Irrigated crop area land (Arab Water Council)
308,000	Irrigated crop area harvested (Arab Water Council)

Irrigation:

mm	Source
155	0.705 km^3 2000/2001 (Zwart and Bastiaanssen, 2008)
122	0.555 km^3 2006/2007 (Zwart and Bastiaanssen, 2008)
701	Irrigated crops abstraction: expressed as irrigated land (Arab Water Council)
877	Irrigated crops abstraction: expressed as irrigated harvested (Arab Water Council)

6 Conclusions and Recommendation

The objective of this study was to explore in what way remote sensing observations can support the development of national water plans. Geographic focus was on Egypt, Saudi Arabia and Tunisia and the methodological approach was based on using existing information and reports combined with remote sensing analyses.

For the three countries selected for this study three different challenges were identified. For the Egypt case the water balance for the country was addressed. For Saudi Arabia the discussion was geared towards the impact of the existing irrigation and its consequences for groundwater resources. Finally, for the Tunisia case the main question was whether irrigation modernization was really successful in making better use of scarce water resources. This report described how remote sensing can contribute to national water planning, and understanding the implications of alternative strategies.

General conclusions drawn for this study can be summarized as:

- Water planning strategies for the same country or area are often based on different numbers. The main reason for this lies in the poorly specified or confusing terminology often applied.
- The biggest water user as agreed in all water planning documents is agriculture. Remote sensing offers an independent and unbiased estimate of the real water consumption in agriculture: actual evapotranspiration.
- The focus in almost every dataset is on irrigated agriculture only, ignoring the fact that rainfed agriculture is consuming water as well.
- Water resources are often high on the political agenda. It is therefore likely that some figures presented in water planning documents are sensitive.
- Many planning documents lack the input from advanced tools such as remote sensing, models, statistical analysis etc. When combined with conventional data, such tools and analyses can greatly strengthen the quality of analysis and planning at national, regional and local levels.

Based on the analysis described in this report the following **recommendations** can be made:

- Appropriate use of terminology in National Water Plans, and other studies, is essential to compare, share and understand these plans. The most important term, actual water consumption by the crop, is often the least accurately described. It is therefore recommended that all crop water consumption is always described as the actual evapotranspiration of the crop.
- Remote sensing can be considered as an unbiased source of information. Issues like irrigated areas, crop water consumption and, although still in its inception phase, groundwater and soil moisture contents, can be observed from space. Although for some of these issues the actual numbers are not yet entirely reliable, the spatial representation (relative accuracy) is very high. This is a critical point: while the debate about whether ET at a particular location is 5.7 mm/day or 6 mm/day may never be entirely resolved, the estimate that ET in the first location is 5% lower than in the second is much more reliable, and is often as important when assessing the pattern of water use. It is strongly recommended to use remote sensing information to support national water plans.

- Various attempts to derive an uniform framework of definitions have achieved some progress: increasingly, the discussion is framed in terms of fractions rather than efficiency, and careful distinctions are drawn between consumptive and non-consumptive use. However, adoption is not universal, and especially when irrigation is supplemented by rainfall, some distinctions are hard to quantify. Presenting information uniformly terms of consumed water, where possible identifying beneficial and non-beneficial consumption, will be a good step in making these plans more robust and comparable to each other.
- Remote sensing offers the unique opportunity to look retrospectively at certain components at a very high spatial resolution. This is especially true now that LANDSAT archives are freely available. However, some processes can not be observed and, moreover, remote sensing can never look forwards. It is therefore be recommended to integrated remote sensing with modelling tools to include all processes and allow scenario based analyses.

The following paragraphs describe the country specific conclusions and recommendations.

6.1 Egypt

The studies undertaken for Egypt aimed inform discussions on the real water balance of the Nile Basin. To date, water balances have been based on measured streamflow at key points, estimates of crop water consumption, and estimates (as a closing term) of flows to the Mediterranean.

In the study we summarized and reviewed several remote sensing analyses that provide additional information on the water balance. Based on this analysis the water balance has been derived and is shown in Figure 38. The following conclusions can be drawn. Firstly, the remote sensing analysis of agricultural water consumption shows that a value of 37.5 km^3 is a realistic estimate. This is in general much lower than other values reported which can largely explained by the different definitions being used. More specifically, water consumption is often confused with water withdrawals (or crop water requirements) which are in general higher due to reuse of drainage water and percolated water. Secondly, release from Aswan are reported much higher than the official statistic of 55.5 km^3 and as a results the outflow to the sea must be more than twice as high as generally reported, while crop water use is rather lower than potential in many areas.

Comparing these results to the Arab Water Council report of 2004 reveals some striking differences. Annual water use according AWC for Egypt is 60.3 km^3, while total annual freshwater withdrawals are 57.7 km^3. It is not completely clear where these two terms refer to, but they do not represent the actual consumption in the Nile Basin. Our analysis is based on remote sensing and provides the real consumption of water defined as actual evapo-transpiration and is 42 km^3. If we include consumption by domestic use and industry and the required outflow to the Mediterranean Sea to control salinity and salt water intrusion, total beneficial water consumption and committed outflows would be 50 km^3. Measurements from Aswan show that on as much as 68 km^3 has been released which leads to the conclusion that almost 20 km^3 is uncommitted outflow to the sea what might be recovered. While the surplus water is the result of several years of good inflows into Aswan, and possibly uncontrolled releases as a result, it is surprising that full crop water requirements are still not met.

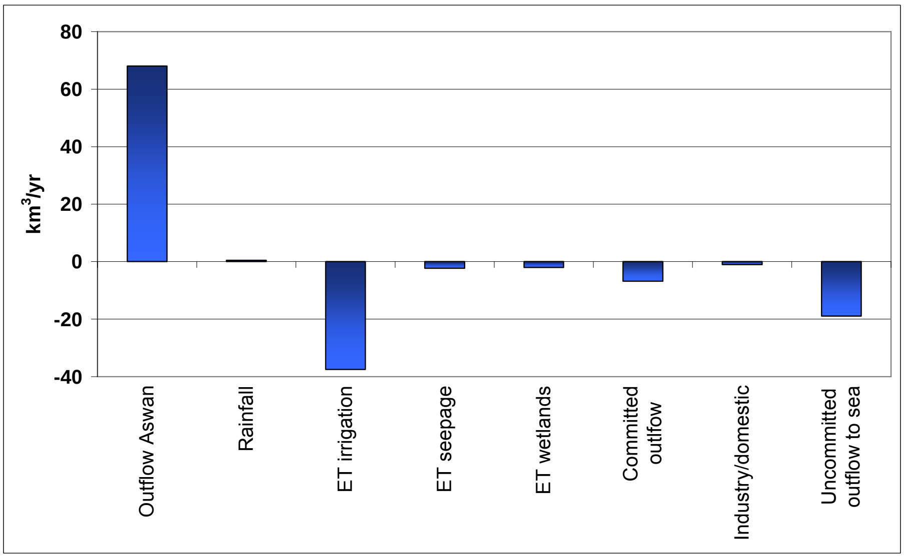

Figure 38. Water balance for Egypt based on remote sensing analysis and statistics.

6.2 Saudi Arabia

Saudi Arabia launched a significant subsidy programs from 1974 onwards to boost agricultural developments in the country to become less reliant on food imports. Investments were used for the establishment of agro-business industries in the remote deserts of the country. As a result, the production of cereals has increased steadily and significantly between 1982 and 1993. While cereals expanded impressively, vegetables and perennials have shown modest, but steady, growth as well.

Since groundwater is the primary source of water for irrigation, and massive abstractions occurred in the 1980's, Government policies set out in 1993 and 1994 aimed to make the use of groundwater resources more sustainable, and to prevent groundwater consumption becoming too high. Considering the fact that irrigated agriculture consumes approximately 85% of the water withdrawals in the country, major changes in the use of water by the agricultural sector was – and will be – required to achieve this. A proper balance between agricultural production, rural development and sustainable groundwater use has to be found. In order to evaluate the impact of this expansion of irrigation on water resources, various studies have been undertaken to evaluate what the consequences of this expansion is. (Bastiaanssen et al, 2006).

Based on various completed studies and the remote sensing analysis the most striking results, conclusions and recommendations can be summarized as:

- The extent of irrigated areas is uncertain. The Saudi case, where all green areas must be irrigated, should make such a classification straight forward. Official statistics and observed irrigated areas do not fully agree. In the Saudi case some crops are perennial, others are seasonal, making the definition somewhat more complex. However, based on the definition that irrigated area is every location being green at one particular moment in the year, it is clear that there is a clear trend in the area under irrigation. In 1999 the area peaked with 1.1 million hectare and from then on a gradually decrease started with as result around 0.95 million hectare over recent years.
- The amount of water abstracted from the groundwater, the only source for irrigation, also reduced over the last few years to around 20 km^3 per year. Water consumption

through evapotranspiration, was around 10 km^3 per year. Conventional irrigation analysis would suggest that the “irrigation efficiency” is 50% which is rather low for such hi-tech irrigation. For the specific case of Saudi the difference between water supply and crop evapotranspiration is essentially non-recoverable because percolation to the groundwater will take centuries and might pass saline layers.

- This “classical” irrigation efficiency of 50% is of interest. All irrigation systems in the country use pressurized center pivot systems. The arid climate, combined with frequent winds, makes the use of center pivot systems a rather wasteful choice of technology with high non-beneficial consumptive use.
- Groundwater levels are observed using well data, but these show only local trends. In this study the GRACE satellite data were also used. Although still in its inception phase of application some general trends can be observed over the period 2003 to 2008 (Figure 39). It is interesting to see that the most prominent trends in groundwater are indeed visible in Ha’il and Al Qasim where the largest amounts of groundwater are extracted. If we assume a downward trend occurs of 1.4 mm/month in 10% of the total area, this equals 3.6 km^3 y^{-1} of net groundwater use. This figure is lower than the reported 10 to 20 km^3 and might be explained by the course resolution of GRACE which is not able to detect the more local scale high extraction rates.

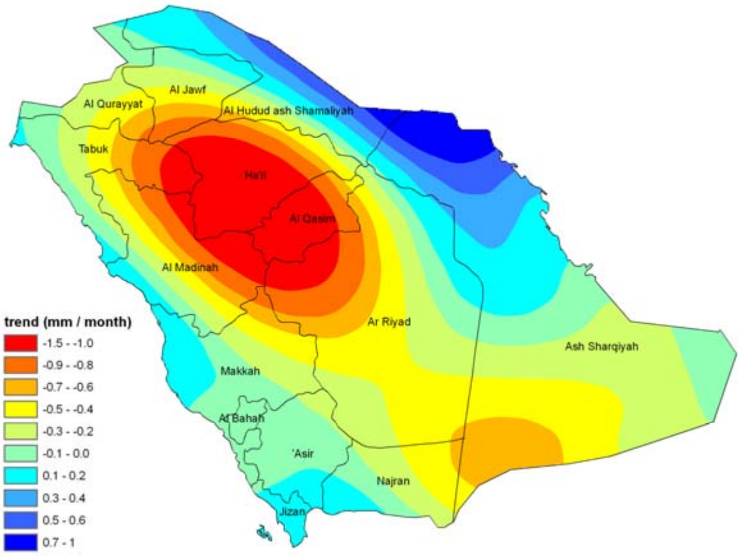

Figure 39. Trend in terrestrial water storage from the 2003-2008 based on GRACE data (based on 100 x 100 km^2).

6.3 Tunisia

Tunisia initiated the National Programme for Saving Water in Irrigation (PNEE) in 1995 to address water shortage. The main objectives of this program were to increase the economic value of water, and to maintain the balance between available water resources and water demand by irrigation – basically to “save water”. As a result of the PNEE approximately 330,000 ha out of 414,000 ha irrigated lands were improved. It is, however, uncertain what the impact of the investments has been on the water cycle and water availability at the national scale.

Modernization, like sprinkler and drip irrigation technology, reduce seepage and percolation and may lead to reduced application of irrigation water. However, the crop transpiration will tend to increase (which is why yields increase) and only if this increase is achieved by reducing non-beneficial evaporation can we be sure that total consumption is reduced. Excess water applied to field and seepage from canals may eventually be reused, and should not be considered as a loss from the basin unless hydrological analysis confirms that such flows are no recoverable. In fact, the aquifers below many irrigation perimeters in Tunisia are in decline due to over-abstraction, so it is rather likely that much of the nominally “saved” water is in any case being recovered.

To evaluate these issues WaterWatch started a project on Tunisian agriculture that focused on savings both in irrigation water as well as in crop water consumption by assign the actual evapotranspiration. Details are described by Zwart and Bastiaanssen (2008), while the relevant chapter in this report describes the main findings emphasizing the role of remote sensing in these kinds of studies.

One of the main questions for Tunisia is whether the modernization of irrigation systems has led to the expected savings in water. Complicating factors in answering this question can be summarized as: (i) no clear definition what “savings” mean in the absence of hydrological analysis; (ii) lack of information on the exact location of the modernized areas; (iii) no information on the base line condition before modernization started; (iv) no information about actual surface deliveries, and (v) the complicating impact of year-to-year weather variations.

These issues might be overcome by including the following points in future analyses:

- **What are water savings**
  Water savings in irrigated agriculture are often measured in terms of applying less water to a crop, with consequent assumed savings in “losses”. It has often been debated that reductions in losses are often in the same order as the reduction in reuse of water, with the net result that no savings are realized at all. Another approach is to consider that the only consumption of water is the actual evapotranspiration, which can be split in beneficial and non-beneficial. For the Tunisian case it was concluded, based on the remote sensing analysis, that the actual evapotranspiration for irrigated land was generally higher in the later (wetter) year. Finally, the ultimate indicator to evaluate whether modernization of agriculture has been successful is to look at the water productivity (= yield divided by ETact). The analysis indicates for most areas a lower water productivity for the years 2006/2007 compared to 2000/2001, leading to the conclusion that modernization did not have the anticipated positive effect. Again, this may be a result of the different rainfall pattern, but the mixed results show no clear pattern that would support a conclusion that improved irrigation technology has resulted in reduced water consumption, or increased water productivity.
- **Lack of local information**
  There is a tendency to assume that with the advance in remote sensing local information is less needed. Although partly true, this is scale dependent and, moreover, some information cannot be observed by satellites. Most relevant information lacking for this Tunisian case was: location and year of modernization, application of irrigation amounts, and source of irrigation.
- **No base line information**
  Modernization started in 1995. The analysis however used 2000/2001 as base line. Since no detailed information was available on which areas were already modernized in 2000/2001, this base line probably included already some modernized areas.
- **Impact of weather conditions**

The two years included in the analysis were significantly different in terms of precipitation. It is therefore hard to draw firm conclusions on changes in actual evapotranspiration and water productivity relevant to modernization only. While using simulation models that can be fed by whatever whether conditions and modernization assumptions might help in this area, the basis should be a continuous monitoring and integration of field and remote sensing data.

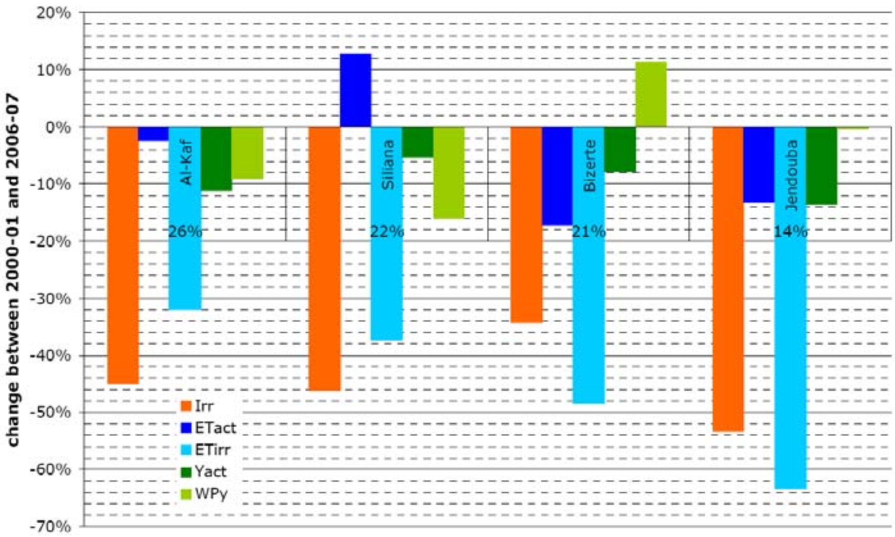

Figure 40. Impact of irrigation modernization in Tunisia for irrigated wheat for four governorates.

Water diversion (Irr), water consumption (ETact), water consumption due to irrigation (ETirr), grain yields (Yact) and water productivity (WPy). (Source: Zwart and Bastiaanssen, 2008)

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