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GROUNDWATER LOSSES BY EVAPORATION FROM THE NUBIAN AQUIFER, EGYPT

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CONTENTS

SUMMARY

In this report a number of studies are reviewed and arguments are brought forward to support the standpoint that natural groundwater losses by evaporation from the Nubian aquifer system (Egypt and Sudan) have not properly been estimated so far.

The practical relevance of these evaporation losses stems from the fact that the development of the oases of Kharga, Dhakhla, Farafra and Bahariya (the so-called New Valley) relies on groundwater use only, since this region is practically rainless. On the basis of published data on the aquifer's groundwater balance it will be shown that groundwater evaporation losses are larger than groundwater extraction by pumping.

In Section 1 the history of the 'Transnational Project on the Major Regional Aquifer in North-East Africa', which is presently being undertaken in Egypt and Sudan, is briefly summarized to illustrate how well the proposed research program fits into the current activity of the Groundwater Research Institute, Ministry of Irrigation, Egypt.

In Sections 2 and 3 the groundwater modeling studies performed so far about the Nubian aquifer system are reviewed, especially in relation with the procedures applied to estimate the groundwater evaporation losses and with their relative entity in comparison with groundwater extraction by pumping. It is concluded that the figures published so far indicate that groundwater evaporation losses are larger than groundwater extraction by pumping. It is also pointed out that these estimations are not based on any measurements of actual evaporation from the areas where it takes place: the oases of Kharga, Dhakla, Farafra and Bahariya and the depressions of Siwa and Qattara (see Fig. 1).

In Section 4 it is emphasized that the uncertainty on groundwater evaporation losses implies that the economically safe yield of the Nubian aquifer, as established by means of numerical simulation studies, should not be regarded as an accurately known quantity.

In Section 5 a short synopsis is given, while in Sections 6, 7 and 8 the items of interest to the Egyptian counterpart (the Groundwater Research Institute) are discussed in some detail.

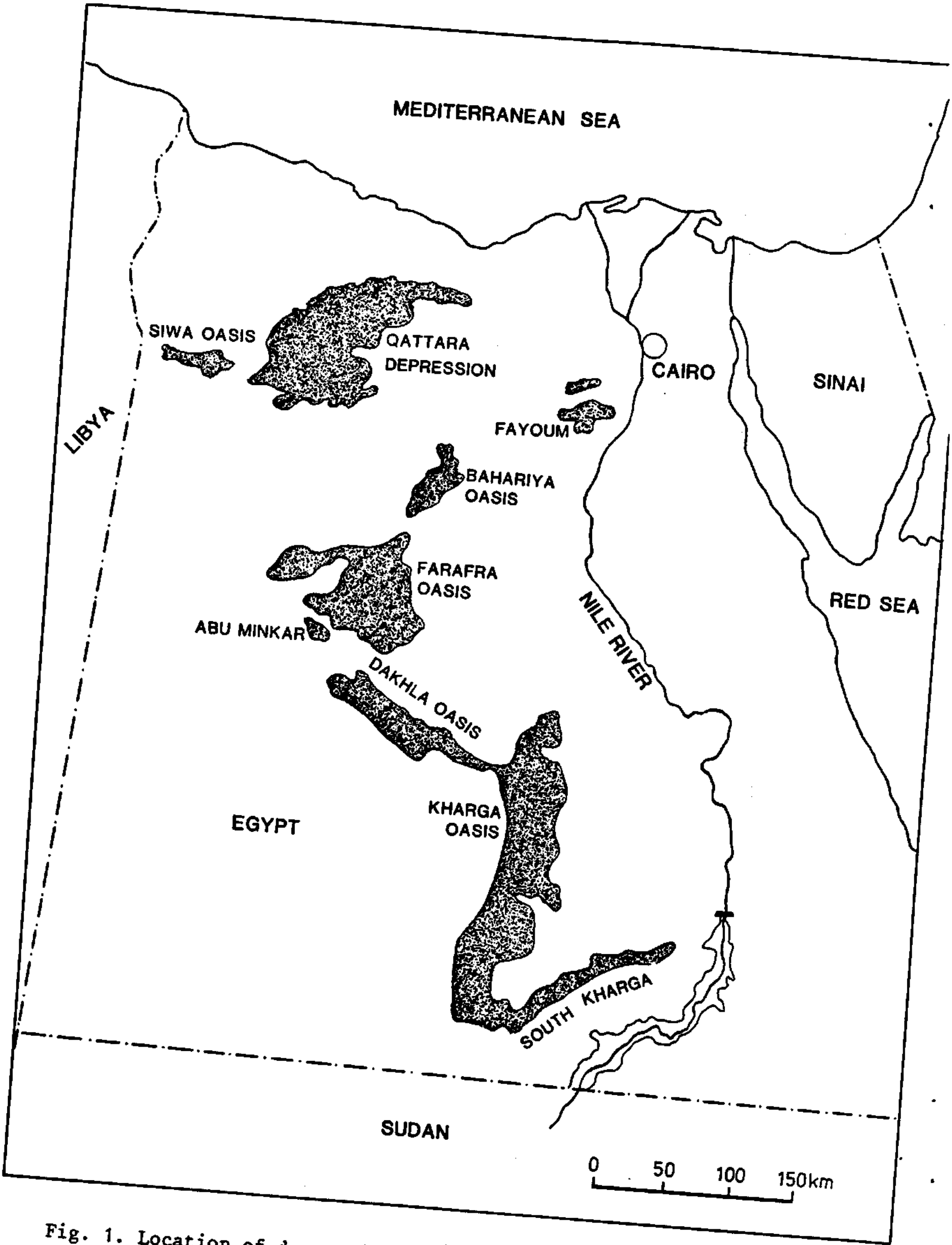

Fig. 1. Location of depressions in the Western Desert of Egypt (adapted from AMER et al., 1981)

1. INTRODUCTION

This report deals with the estimation of a large fraction of the available groundwater resources in the Western Desert of Egypt and, more generally in the Sahara. The standpoint of this author is that natural groundwater losses by evaporation in the barren depressions of the Western Desert amount to a large fraction of the aquifer's economically-safe yield. The New Valley in the Western Desert, i.e. the oases of Kharga, Dakhla, Farafra, Bahariya and Siwa, is the only one area in Egypt outside the Nile Valley where expansion of agriculture is possible. This expansion relies on the use of groundwater as the area is essentially rainless. The development of agriculture in this area has been the subject of a number of studies in the last 50 years. Especially in the last 20 years, these studies have demonstrated the economic viability of the development of the New Valley.

The need for a thorough understanding of the groundwater reservoirs of North Africa has been stressed repeatedly by various international bodies. To this respect must be mentioned the UNESCO ministerial conferences on the application of science and technology held at Dakar in 1972 (CASTAFRICA) and at Rabat in 1976 (CASTARAB) and the United Nations Conference on Desertification (UNCOD) held at Nairobi in 1977. The latter conference has a special relevance in this context, since a feasibility study for the 'Transnational Project on the Major Regional Aquifer in North-East Africa' was presented at that conference. The conference called for immediate initial action to be undertaken on this project.

A project proposal for North-East Africa covering Chad, Egypt, Libya and Sudan, was therefore prepared and submitted to UNEP. The Sudanese component began in September 1983, while activities in Egypt started in 1984. The Egyptian institution responsible for the execution is the Groundwater Research Institute of the Ministry of Irrigation.

The short-term objectives of 'Transnational Project' explicitly include the up-grading of national institutions in the general field of water management and the selection of adequate modern techniques to improve land and water use.

It can be concluded that the present research project, which deals with the estimation of groundwater losses by evaporation from the Nubian aquifer in Egypt, fits perfectly into the framework described above. To illustrate the practical relevance of these matters the role of groundwater use in the development of Egypt will be mentioned.

The depressions in the Western Desert of Egypt are commonly referred to as 'The New Valley'. This term underscores the fact that the oases, which are present in these depressions, are the only one area outside the Nile delta (the 'Old Valley') where development is feasible. These areas are practically rainless, so development plans can only be implemented by making use of groundwater. Because groundwater evaporation losses are at present larger than groundwater extraction, the accuracy of long term forecasts of groundwater availability and cost relies heavily on the accuracy of the estimated groundwater losses by evaporation. These matters will be considered in more detail in the following sections.

2. SIMULATION OF GROUNDWATER FLOW BY MODELS IN THE NUBIAN SANDSTONE AQUIFER AND EVAPORATION LOSSES

The Nubian sandstone aquifer, or portions of it, has been the subject of a number of groundwater simulation studies. The results of these investigations have been presented by SALEM (1965), BORELLI et al. (1968), EZZAT (1975, 1977), BARBER and CARR (1976), NOUR et al. (1979), AMER et al. (1981), ANONYMOUS (1983), HEINL and HOLLANDER (1984). The latter authors presented an outline of the groundwater simulation model being developed in the framework of the German 'Special Research Project Arid Areas', carried out at the Technological University of Berlin. This model will include the area covering parts of Egypt, Sudan, Chad and Libya to extend the model boundaries up to the geological boundaries of the aquifer. Another groundwater model relating to the same area is under development at the Groundwater Research Institute of the Ministry of Irrigation, Cairo, in cooperation with the Department of Irrigation and Hydraulics at Cairo University.

The issue of groundwater evaporation losses in the depressions of the Western Desert has been dealt with in many different ways. In the next section some remarks will be given on the methods applied to estimate groundwater evaporation losses. Here a brief overview will be given of the comments given by the above listed authors about the sensitivity of model calculations to the estimates of groundwater evaporation losses.

AMER et al. (1981) state that presently available estimations of natural losses had a 'high ranking incredibility'. Therefore they decided to calibrate the groundwater model with increased natural losses. It appeared that the model was highly sensitive to the losses by surface evaporation. This study, as the companion paper by NOUR et al. (1979), was intended to evaluate the quantities of exploitable water, defined as that amount of water which could be extracted before the groundwater table reaches a given threshold. No reduction in natural evaporation as a consequence of the groundwater table drawdown was taken into account.

The detailed simulation exercise executed on behalf of the 'Regional Development Plan for New Valley' by EUROCONSULT/PACER Consultants under contract from the Ministry of Development (Ref. ANONYMOUS, 1983) included an evaluation of the model sensitivity to the calculation of natural evaporation. The sensitivity analysis was restricted to a time span of 21 years only (1960 to 1981) and this choice makes the interpretation of the results more difficult, since the propagation velocity of disturbances is rather low. The sensitivity analysis was, moreover, restricted to the interaction between the Qattara depression and the main body of the aquifer. Groundwater evaporation losses from the Qattara depression were assumed to be nihil and this resulted in a considerable increase in water table elevations in the Qattara. This demonstrated the sensitivity of the simulated piezometry to the estimations of groundwater evaporation losses. In the southern depressions (see Fig. 1) the water head increase, however, was much smaller, thus indicating that the reduction in groundwater evaporation losses from the Qattara did not affect to a great extent the simulated piezometry in the oases. In the opinion of the present author, however, the time span considered in the sensitivity analysis was too short (21 years) for such definitive conclusions to be drawn.

To conclude these remarks it will be mentioned that in the development of the model described by HEINL and HOLLANDER (1984) strong emphasis has been placed on studying the reaction of the system to different regimes of recharge and discharge.

3. CALCULATIONS OF EVAPORATION LOSSES IN THE DEPRESSIONS OF THE NUBIAN AQUIFER

In this section a number of examples of studies on groundwater evaporation losses from the Nubian aquifer will be reviewed and the methods to estimate them briefly discussed.

In Table 1 the values given by NOUR et al. (1979) are presented. It should be noted that groundwater evaporation losses are much larger than extraction by pumping, namely a factor 2.5.

In Table 2 the results presented in ANONYMOUS (1981), as obtained in the framework of the 'Study Qattara Depression' are given. A substantial difference with the previous case (see Table 1) is that actual evaporation was estimated on the basis of a map giving the different types of salt crusts. The type and permeability of the crust were considered to be effective in controlling the evaporation rate. Two major shortcomings of the approach applied in that study are the implicit assumption that water vapour flow was nihil and the circumstance that insufficient soil textural data were available, as to properly estimate the capillary rise flux from the groundwater table to the surface. It should also be considered that the values in Table 2 apply to a relatively small part, i.e. 4507 km^2 only, of the entire Qattara depression.

Finally the results obtained on behalf of the 'Regional Development Plan for New Valley' are presented in Table 3. Here the losses by evaporation are much lower than extraction by wells, but the method applied to estimate these losses should be considered in more detail. The values in Table 3 have been obtained by means of a groundwater simulation model (see also Section 2) by prescribing in the relevant polygons an upper limit of the aquifer and then defining as natural losses the total water excess with respect to this upper limit. The upper limit is taken as the surface elevation in those areas where the shallow aquifer is phreati phreatic. There are two difficulties with the values in Table 3:

- it is assumed that no capillary rise occurs, i.e. when the calculated groundwater table level drops below the ground surface, groundwater evaporation losses are nihil;
- no data are given as regards the extension of each discharge area and, therefore, no comparison can be made with the values in Tables 1 and 2.

Table 1. Groundwater extraction by pumping and groundwater evaporation losses in the depressions of the Western Desert, Egypt (after NOUR et al., 1979)

Depressions	Groundwater extraction ($m^3 \cdot d^{-1}$)	Groundwater evaporation ($m^3 \cdot d^{-1}$)
Siwa	$0.12 \cdot 10^6$	$0.3 \cdot 10^6$
Qattara	-	$1.4 \cdot 10^6$
Farafra and Bahariya	$0.145 \cdot 10^6$	$0.4 \cdot 10^6$
Dakhla	$0.557 \cdot 10^6$	$0.14 \cdot 10^6$
Kharga	$0.226 \cdot 10^6$	$0.19 \cdot 10^6$
South Kharga	-	$0.1 \cdot 10^6$
Total	$1.05 \cdot 10^6$	$2.53 \cdot 10^6$

Table 2. Groundwater evaporation losses in the Qattara depression, Egypt (after ANONYMOUS, 1981)

Unit	Specific evaporation ($mm \cdot a^{-1}$)	Area (km^2)	Evaporation ($m^3 \cdot d^{-1}$)
Salt crust, mainly thin and fragile	124	329	$0.11 \cdot 10^6$
Salt crust, varying thickness and structure, scarce vegetation	83	80	$0.02 \cdot 10^6$
Salt crust, polygonal forms, hard, often rough structure	52	907	$0.13 \cdot 10^6$
Salt crust, thick and solid	34	1818	$0.17 \cdot 10^6$
Salt crust with varying structure	83	376	$0.09 \cdot 10^6$
Sand cover on previous units	50	994	$0.14 \cdot 10^6$
Open water	1300	2.5	$0.01 \cdot 10^6$
Total		4507	$0.67 \cdot 10^6$

Table 3. Different terms ($m^3 \cdot a^{-1}$) of the groundwater balance for 198(
(after ANONYMOUS, 1983)

	Total outflow				Total inflow through boundaries	Chan in stora
	by wells	by evaporation	through boundaries	total		
Kharga	$89.8 \cdot 10^6$	2.5		92.3		
Dakhla	198.6	3.5		202.1		
Farafra	1.3	0		1.3		
Bahariya	34.1	18.5		52.6		
South Qattara		90.0		90.0		
Western front			12.7	12.7	57.1	
Southern front					259.9	
Eastern front			8.7	8.7		
Total	323.8	114.5	21.4	459.7	317.9	154.9

It can be concluded that so far no experimental validation has been provided of the different estimates of evaporation, which have been considered in the simulation studies of the Nubian aquifer. Moreover, some of the assumptions seem to be physically unacceptable. Notwithstanding this all the studies point to the fact that groundwater evaporation losses are comparable with extraction by pumping.

4. EVAPORATION LOSSES AND THE ECONOMICALLY-SAFE YIELD OF THE AQUIFER

The scope of most of the simulation studies mentioned in Section 2 was to estimate the amount of water which could be extracted at an acceptable cost, i.e. with the groundwater drawdown remaining within a pre-established limit.

With the exception of the simulation exercise carried out in the framework of the 'Regional Development Plan for New Valley', no account has been taken of the contribution of reduced evaporation as a partial offset to the increased extraction by pumping.

To illustrate the relevance of this point, a number of different estimates of groundwater evaporation losses are compared in Table 4 with

Table 4. Discharge ($m^3 \cdot a^{-1}$) according to present and previous studies (after ANONYMOUS, 1983)

Source	Kharga		Dakhla		Farafra		Bahariya		South Qattara	Net flow across boundaries
	extraction	evaporation	extraction	evaporation	extraction	evaporation	extraction	evaporation	evaporation	
(1)	$51.8 \cdot 10^6$	$54.1 \cdot 10^6$	114.2	36.7	0.8	5.8	25.5	29.4	87.3	318
(2)	36.5	30.6	97.5	18.9	0.7	-	18.9	-	288.7	491
(3)	36.5	18.25	73.0	9.5	8.3	-	29.2	-	-	174
(4)	37.9	0	87.4	0	-	-	-	-	-	125
(5)	36.5	18.5	85.9	13.5	0.1	-	29.7	19.5	90.0	296

		Area covered by the model
(1)	Amer et al., 1980	: Western Desert and Eastern Desert
(2)	Ezzat, 1975	: Kharga, Dakhla, Farafra, Bahariya area and Eastern Desert
(3)	Borelli et al., 1968	: Western Desert and Eastern Desert
(4)	Barber and Carr, 1976	: Kharga and Dakhla area
(5)	Euroconsult/Pacer, 1982 (present study)	: Kharga, Dakhla, Farafra and Bahariya area

the corresponding figures for man-made extraction. It appears that the differences in groundwater evaporation losses are rather large and this points to the inaccuracy of such calculations.

A more interesting result is obtained by calculating the mean value of both extraction and groundwater evaporation losses for each area and then obtaining the total amount of extraction respectively losses. The result thus obtained is that the total extraction amounts to $167.2 \cdot 10^6$ $m^3 \cdot a^{-1}$ and the natural losses to $225.3 \cdot 10^6$ $m^3 \cdot a^{-1}$.

It appears that the above mentioned figures provide sufficient basis to state that the economically safe yield of the aquifer cannot be determined when natural losses are not properly evaluated, together with their decrease due to increased man-made extraction.

5. SYNOPSIS OF PLANNED RESEARCH PROJECT

The investigations into the groundwater evaporation losses from the Nubian aquifer amount to a case-study in the framework of a research project being undertaken by the Institute for Land and Water Management Research (ICW), and dealing with groundwater evaporation losses in the Saharan belt. This research project has been described in some detail by MENENTI (1984).

The objectives of the research project are:

a) to estimate the total groundwater evaporation losses from the Nubian aquifer;
b) to establish whether the soil surface properties in the natural discharge areas are changing during a yearly cycle because of the alternating effect of evaporation and rainfall;
c) to establish whether areas where, after concentration of rainfall by run-off, recharge occurs or did occur, are present in the Western Desert of Egypt.

The practical scope of this project as regards the Nubian aquifer has been illustrated in the preceding sections.

A list of the successive steps involved in the research program can be given as specified below:

- a map with location of playas will be prepared on the basis of existin and available maps and reports and of photographic satellite imagery;

- a geohydrological synthesis about the aquifer systems of the Saharan belt will be worked out in the form of reports and maps;
- a number of different remote sensing techniques and data analyses procedures will be applied to several sites in Egypt and in the Sahara. Satellite data of different resolution will be applied (METEOSAT, DMSP, NOAA, LANDSAT, SHUTTLE);
- the soil water regime in unsaturated - saturated soil will be studied for steady and unsteady state conditions, with the help of numerical simulation models developed at the Institute for Land and Water Management Research. The relevant soil hydrological properties will be determined on undisturbed soil cores and the results of calculations tested against measurements of soil water content and of shallow groundwater table depth;
- collection of field data and selection of test sites. Two test sites in Egypt have been selected:
  - . western portion of the Qattara depression to carry out the part of the project dealing with evaporation and mapping of hypersaline soils;
  - . Bir Tarfawi area to carry out the part of the project dealing essentially with the mapping of recent clayey crusts, as deposited by run-off and ponding.

The data collection program will be described in detail in the next section.

6. FIELD DATA COLLECTION PROGRAM

This section, as the following Sections 7 and 8, is of direct interest to the Egyptian counterpart and is, therefore, presented in some detail.

Two different kinds of data will be collected, i.e. soil hydrological data, and data on soil optical properties, reflected and emitted radiance. Accordingly there will be two teams, termed Team A and B hereinafter, operating simultaneously but independently from each other in each test-site. Two vehicles, based in Cairo, will be needed for work in the Qattara depression and two vehicles, based at Bir Tarfawi, for work there. Transfer of Teams A and B from Cairo to Bir Tarfawi will take place by means of the aircraft of the General Petroleum Company. More details on the schedule of field work are given below.

6.1. Field data collection scheme

Team	Item	Qattara	Bir Tarfaw
A	K(h)-relationship, i.e. the unsaturated capillary conductivity vs. pressure head	2 depths x 10 profiles	2 depths profiles
	h(θ)-relationship, i.e. pressure head vs. soil water content	4 depths x 20 profiles	4 depths profiles
	θ(z), i.e. soil water content vs. depth	10 depths x 30 profiles	10 depths profiles
	shallow groundwater table depth	30 points	15 points
B	α_0, emispherical reflectance, i.e. ratio of global reflected to global incoming radiation	5 plots	2 plots
	$\alpha_0(\lambda)$, spectral reflectance	5 plots	2 plots
	$\alpha_0(\gamma,\psi)$, bidirectional reflectance	5 plots	2 plots
	T_0, surface radiation temperature	5 plots	2 plots

6.2. Field data collection schedule

The following schedule of field trips applies:

- November 1985, first visit to the test sites, a week stay at each one
- March 1986, data collection trip to the two test sites; 2 weeks at Qattara, 1 week at Bir Tarfawi
- June 1986, ibid
- August 1986, ibid
- November 1986, last data collection trip; 2 weeks at Qattara, 1 week at Bir Tarfawi

The following detailed schedule applies to each data collection trip

Friday: Cairo - Qattara

Saturday through Thursday (next week): field work

Friday: Qattara - Cairo

Saturday: Cairo - Bir Tarfawi (by GPC aircraft)

Sunday through Friday: field work

Saturday: Bir Tarfawi - Cairo (by GPC aircraft)

6.3. Additional laboratory experiments

In addition to the field data mentioned above it would be desirable to perform the following determinations:

a) adsorption isotherms of soil samples from the top soil;
b) reflectance of top soil samples as a function of soil water content;
c) mineralogical analyses of soil, brine and crust samples;
d) porosity and permeability of surficial crust samples.

6.4. Meteorological data

Meteorological data are needed to choose the best periods for the field trips, in relation with the expected rainfall pattern, to support the analysis of field and satellite data and to calculate evaporation in combination with the satellite data.

The following data are needed:

- statistical analyses of historical rainfall record at Siwa (44 years);
- daily values of rainfall, air temperature, air humidity, solar radiation, wind speed during the period of field activity: July 1985 to December 1986;
- radiosoundings on the dates of satellite data acquisitions.

7. EVALUATION OF RESULTS

The calculations of actual evaporation will be evaluated by means of groundwater simulation models of the Nubian sandstone aquifer. The new estimations of actual evaporation will give new boundary conditions in the discharge areas.

The following models are available:

1) finite element model for the Nubian aquifer system, described by AMER et al. (1981). Institution responsible for its use: GARPAD (Eng. Saleh Nour), Ministry of Land Reclamation;
2) groundwater model for the Nubian aquifer system, described by HEINL and HOLLANDER (1984); Institution: Technical University, Berlin;
3) groundwater model of Euroconsult. Institution: Ministry of Development, Cairo;

4) groundwater model of Groundwater Research Institute and IBM, Cairo.
Institution: Groundwater Research Institute, Cairo.

This evaluation exercise will be carried out according to the following list of activities:

7.1. Assessment of the relation between the evaporation map and the relevant water bearing formations, as established on the basis of available data and reports.
7.2. Preparation of input data and execution of simulations.
7.3. Preparation of report and maps to illustrate the results of the evaluation study.

These activities, in principle, will take place in Cairo.

8. STUDY TRIPS

In the framework of the project, to facilitate the exchange of knowledge and to guarantee continuity of cooperation between the participating individuals, the following study trips to the Netherlands are planned:

2 stays of 10 days by senior staff;
2 stays of 2 months each by junior staff.

9. CONCLUSIONS AND OUTLOOK

From the data and comments given in Sections 2 through 4 it can be concluded that much remains to be done as regards the actual entity of groundwater evaporation losses from the Nubian aquifer. A more accurate estimation of this term of the water balance is needed in relation with the planned development of groundwater in the New Valley of the Western Desert of Egypt. Furthermore an improved understanding of the hydrological regime of the depressions in the Western Desert would also be helpful to understand better the groundwater flow regime in the entire aquifer system.

To tackle this issue, field experiments dealing with soil water flow and with the surface energy balance will be performed in the

Qattara depression and in the area of Bir Tarfawi.

To calculate total losses by evaporation, digital satellite data will be combined with the ground measurements to map actual evaporation.

The problems which remain to be solved relate especially to the arrangements which have to be done to implement the field activity.

On the positive side one should count the wealth of available data and studies dealing with the Nubian aquifer.

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