RESEARCH ON CROP WATER USE, SALT AFFECTED SOILS AND DRAINAGE IN THE ARAB REPUBLIC OF EGYPT

A REVIEW WITH RECOMMENDATIONS

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS 1975

FRONT COVER:	Date palms
BACK COVER:	Coin issued by the Arab Republic of Egypt, illustrating the Aswan High Dam. The Arabic legend reads "Produce more food."

Research on crop water use, salt affected soils and drainage in the Arab Republic of Egypt

RESEARCH ON CROP WATER USE, SALT AFFECTED SOILS AND DRAINAGE IN THE ARAB REPUBLIC OF EGYPT

a review with recommendations

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PREFACE

In Egypt research on soil science and related fields of science has been carried out since the establishment of the 'Agricultural Chemistry Section' of the Ministry of Agriculture early in this century. When the Departments of Soils in the Colleges of Agriculture came into being such research was also done as part of the requirements to obtain M.Sc. and Ph.D. degrees. The research results are therefore to be found in many local and foreign journals, theses and reports.

Dr. M.M. EL GABALY, former Minister of Agriculture and Land Reclamation, and Dr. K. STINO, former Superintendent of the Agricultural Research Centre, expressed the need of having a review of the work done, to be able to better understand the existing problems, to gain an insight in the research necessary in the future and to have a basis to establish a comprehensive research programme. They also pointed out that priority for such a review should be given to the research done on crop water use, on salt affected soils and on drainage.

FAO responded to this wish by appointing Dr. RIJTEMA as Consultant to participate during two months in making a review of the work done in Egypt in the three mentioned fields and particularly to re-interpret the existing data on crop water use. A committee was formed in which were nominated by FAO: Dr. ABOUKHALED, Mr. ARRAR, Dr. KADRY and Dr. RIJTEMA, and by the Minister of Agriculture and Land Reclamation of Egypt: Dr. BALBA, Dr. BISHAY and Dr. TAHER.

The duties of this committee were stated by the former Minister of Agriculture and Land Reclamation as being to:

- review and evaluate the past work in the above mentioned fields;
- visit several research institutes and experimental stations;
- suggest further studies in these fields and evaluate the requirements of the research centres to be able to carry out these studies.

At its first meeting on January 17, 1973, the committee, realizing that comprehensively reviewing all experimental work done in Egypt in the mentioned fields would be too time consuming, set itself, without claiming to give a full coverage, the following objectives:

- To establish a standardized card system giving an outline of each item reviewed, allowing the addition of items and updating in the future.
- To write a discussion and re-interpretation of the available data on crop water use.
- To give general outlines of the works reviewed in each field, with the pertinent references.
- To write general discussions of and comments on the work done in each field.
- To give recommendations concerning further work in the mentioned fields of study and the requirements to achieve satisfactory results.

To this end the committee set up three groups:

- a crop water use group consisting of Dr. RIJTEMA and Dr. ABOUKHALED;
- a salt affected soils group consisting of Dr. BALBA, Dr. KADRY and Dr. TAHER;
- a drainage group consisting of Mr. ARRAR and Dr. BISHAY.

Efforts were made to have the reports of these three groups contain as much information as possible to obtain in the limited amount of time on published work as well as recent unpublished data of studies still in progress. The committee visited several institutes and research stations to receive information on the work in progress and to assess the now available equipment as well as future equipment requirements. In this context the committee wishes to express its gratitude for the aid and cooperation given by the members of institutes and experimental stations in Egypt in collecting published research and in giving freely access to unpublished data relevant to the committee's task. To research workers whose work is not covered in this review although it should have been, the committee extends its apologies; within the given time it was not possible to write a really exhaustive review. Thanks are also due to the constructive efforts made by the Foreign Agricultural Relations Office of the Ministry of Agriculture of Egypt and the Secretariat of the FAO Regional Office in Cairo on behalf of the committee.

The members of the committee frequently gathered in working sessions to discuss the various subjects investigated and the advances made.

This report, to be submitted together with the established card system to the Minister of Agriculture and Agrarian Reform, the Minister of Land Reclamation and the FAO Regional Office in Cairo, contains in sequence: the conspectus of the committee's recommendations, the report on research in the field of crop water use, the report on research in the field of salt affected soils and the report on research in the field of drainage. A list of references is included in each report.

The committee expresses its hope that this review with recommendations will benefit Egypt as well as other countries in the same region.

CONTENTS

GENERAL RECOMMENDATIONS

BY THE COMMITTEE

TRAINING

- As the development of irrigation agriculture primarily depends upon the availability of agricultural engineers specialized in irrigation and drainage, agricultural machinery and rural development, it is imperative that the subject matter of the curricula in the fields of agricultural engineering of the Colleges of Agriculture is enlarged.

RESEARCH COORDINATION

- Research work in the fields of crop water use, salt affected soils and drainage in Egypt is to be coordinated at a national level.
- In addition the making of a national plan to coordinate, finance and support agricultural and related research in the fields not investigated by the committee is urgently recommended.
- To carry out thorough investigations and obtain applicable results some standardized form of cooperation of research workers in related disciplines is needed.

EXISTING RESEARCH ORGANIZATIONS

The agricultural research centres in Egypt can be divided in two categories: those at Cairo and Alexandria, and the agricultural experimental stations scattered over the country.

- The Cairo and Alexandria centres are fairly equipped and staffed and are capable to carry out their research. In some cases their laboratories lack modern apparatus. The establishment of central laboratories equipped with expensive modern equipment to serve a group of laboratories with certain determinations will reduce the cost and will ease the standardization of methods and units.
- The agricultural experimental stations in the different climatic and soil zones are usually situated where most of the applications and field work should be carried out. In order to have them function in an efficient manner, a national plan is to be adopted to supply these stations with their requirements of qualified researchers as well as equipment, chemicals and other necessary supplies. Attention should be given to the provision of adequate living facilities and means of transportation for the staff of these stations. The Colleges of Agriculture at Alexandria, Assiut or Kafr El Sheikh for example are reasonably staffed with qualified persons while the experimental stations in their neighbourhood are not.
  Applied research in the experimental stations is to be augmented and to be put under the direct supervision of qualified researchers. Although, generally speaking, a satisfactory number of qualified staff members is present, in most centres the specialists in soil morphology, soil physics, soil and plant biochemistry and hydrology are small in number and they have unsatisfactory facilities.
- A national plan is recommended for the establishment of lysimeters and field stations situated in locations representing the to be mentioned nine agroclimatologic zones and the different soils in the country.
- Technicians, laboratory assistants and workshops are badly needed in all stations and institutes; they constitute the backbone of research laboratories. Efforts should be made to satisfy this need in order to have the researchers and the expensive apparatus operate efficiently.
- The libraries in most of the research stations are not sufficiently supplied with books or periodicals. This basic requisite for raising the efficiency of the applied research effort is to be supplied.
- Research work in the field requires a dependable

means of transportation at hand. The majority of the institutes suffers from a lack of transportation means. An appropriate solution is to be realized.

- There exists a satisfactory number of periodicals for publishing agricultural research and one periodical specialized in soil science. The standard of published work is to be improved, this will also motivate the improvement of the research work in process.
- Round table discussions, symposia and conferences deserve more attention. They are means to improve the exchange of ideas, techniques and experience among specialists working in closely related fields.

CREATION PILOT AREAS

To provide optimum conditions for plant growth, optimum crop - water - soil fertility relationships are to be realized. A prerequisite for such optimum conditions is the maintenance of sound salt and water balances by means of the installation and use of appropriate field irrigation and drainage networks and a timely application of cultural and land preparation practices in accordance with the needs of the pertinent soils.

- To be able to achieve this, it is of extreme importance that at the national level a master plan be made of a field experimental programme to be implemented in representative Pilot Experimental and Development Areas in each of the to be mentioned nine agroclimatic zones, where the technical criteria for optimum timing and execution of soil irrigation and management practices particularly under reclaimed salt affected soil conditions can be determined.
- A complete and detailed characterization of the soil and hydrologic conditions at the experimental sites is to precede the formulation of the field experimental programme.
- It is proposed that the field experiments are executed both as:

  multi-variant single or double factor experiments, and
  multi-variant multi-factor experiments.
- The factors of the experiments have to be selected from each of the following facets: cultural practices, cropping pattern, irrigation and drainage practices, amendment application and fertilizer use.
- In coordination with the applied research work in the pilot areas a soil fertility test and demonstration programme is to be carried out at the national level.
- It is proposed that concurrently with this field experimental and soil fertility test and demonstration programme field investigations are made in the pilot areas on alternative systems of land and water use based on the economic input - output ratio for agricultural production assessment. The components of the alternative systems of land and water use are to be selected in conformity with the country's agricultural development plan.
- It is urged that all specialized government agencies responsible for the sectors of University education, research, extension and development projects in each of the to be mentioned nine agroclimatologic zones participate at the national level throughout planning, programming and implementation of the field experimental test and demonstration facets of the research, test and demonstration programme.

RESEARCH APPLICATION

Soil survey and classification

- A systematic soil survey and classification which identifies taxonomic soil units according their pedogenetic condition, geomorphologic origin and edaphic constituents has as yet not been incorporated in the regular methodology of soil survey and classification operations in the Arab Republic of Egypt. It is recommended that the system of definitions of soil units adopted by the FAO/UNESCO Soil Map of the World Project will be used with modifications to suit the local conditions and specific land utilization and development requirements.
- It is also recommended that methods for field investigation and laboratory determinations are standardized and, if possible, simplified.
- Field experiment layouts and soil - crop - water relationship parameters are to be standardized with a view to application at a country-wide level, i.e.

in representative areas of the to be mentioned nine agroclimatic zones.

Crop water use

The review of published and unpublished work on water use and soil-water relations covered fifteen crops: cotton, beams, corn, wheat, sugar cane, clover, alfalfa, barley, rice, flax, sesame, groundnut, onions, potatoes and cucumbers. Of these only cotton and corn were studied in depth.

Based on an analysis of the meteorologic data gained from 24 stations, the country was divided into NINE AGROCLIMATIC ZONES namely: COASTAL, CENTRAL DELTA, DESERT DELTA, GIZA, LATITUDE 29-27.5°N, LATITUDE 27.5-26°N, DAKHLA, KHARGA 26-25°N and ASWAN 25-24°N.

The maximum evaporative demand and crop water use were calculated for each zone by the combination method of PENMAN as modified by RIJTEMA.

The following recommendations are made:

- Standardization of wind measurements at 2 m height.
- Exclusive use of standard pans for evaporation measurements, especially at sites where crop water requirement studies are performed.
- As the evaporative demand gradient has a direct relationship with crop water use, the calculation of crop water requirements should be done according the combined energy balance - vapour transport method (a modification of PENMAN's method).
- Net radiation measurements should be made at a few sites located in the Coast, Central and Upper Egypt districts.
- Irrigation intervals with non-stress conditions have been tabulated for three soil textural groups and for different crops. These data should be verified experimentally. The main crop growing factor that must be ascertained is the irrigation timing in relation to evaporative demand, soil moisture potential and plant growing stage. In relation to this, climatologic and phenologic observations and water use data should be standardized on a 10-day period.
- It also will be necessary to establish soil water retention curves and to report on salinity aspects and water table levels.
- The review of the research work done has revealed the crucial need to approach the problems of crop water use, salt affected soils and drainage in a team work study group in order to arrive at meaningful interpretations of the data gathered in each of the three disciplines. (This was strikingly demonstrated when the total dry matter production data were plotted against total water use giving frequently a curvilinear rather than a linear relationship. This indicating that limiting factors such as salinity and nutrient deficiency interfere in the water use - production relationship.)
- In a future Applied Research Programme on Irrigation the experiments will have to be designed in such a manner that all crop production factors are at their optimum with the exception of the variables timing, frequency, quantity and irrigation method. A team work approach by agroclimatologists, crop physiologists and soil scientists (soil physicists in particular) is recommended.
- The selection and methodology of the experiments on crop water use should follow the outline given in the chapter Crop Water Use of this Report in order to obtain optimum results.

Salt affected soils

The review of published and unpublished work on on salt affected soils did show that the following aspects were insufficiently covered:

- the leaching process and its dynamics,
- the physico-chemical reactions of soil-salt systems,
- the determination of the required spacing and depth of different kinds of drains,
- the techniques to deal with impermeable soil layers,
- the effects of salts on clay minerals,
- the techniques to utilize saline waters in irrigation,
- the effects of salinity on plant physiological and biochemical processes,
- the salt balance in irrigated soils in the presence of growing plants,
- the effect of the abnormally high Mg content of the soils in the north of the Delta on their physical and chemical properties and their nutritional status.

It is furthermore recommended that

- the criteria for the methodology of soil and water analyses and field investigations are established in accordance with the remarks made in the section Conclusions of the chapter Salt Affected Soils of this Report.

D r a i n a g e

Drainage investigations in the past were focused on determining the soil hydrological properties as needed for the formulae that specify the depth and spacing of field drains. Drainage criteria to establish the optimum depth of water tables with regard to high crop yields and adequate salt and water balances were not sufficiently studied. Drain tile laying methods and materials are also partially neglected fields. It is recommended that:

- an integrated research programme on land drainage in relation to irrigation and the crop production factors is carried out in the mentioned 9 main agro-climatologic zones of the country. In the integrated research programme:

- the optimum depth of the water table for different crops in relation to crop yield, irrigation requirement and salinization hazard should be investigated,
- the drainage criteria under Egyptian conditions should be determined. This will include the drainage discharge and the permissible fluctuation of the water table. It will be possible to ascertain at the same time the water requirement by determining the water balance for different crops. Networks of piezometers, observation wells and discharge measurements are necessary to obtain hydrologic data.

In accordance with the fact that Egypt is launching a very impressive programme of tile construction work, as indicated in the first section of the chapter Drainage of this Report:

- attention should be given to tile laying methods and drainage materials. This line of research work should be directed to test, from the technical and economic point of view, alternative methods of tile laying (trenching and different types of trenchers) and drainage materials, including the use of different types of pipes (concrete, clay tiles and plastic) as well as the uses of different types of envelope materials.

Soil surveys showed the existence of soils with very low permeabilities in the Delta (less than 1.0 cm/day as measured by the auger hole method). It is therefore emphasized that:

- studies should be made on soils with low permeability on the viability of using tile drainage as opposed to open drainage;
- to accurately evaluate the effect of drainage work on crop yield a multi-variant analysis, using a computer programme, should be initiated;
- useful information can be obtained from the present drainage research with some little improvements (see the second section of the chapter Drainage of this Report). Every effort should be made to compile, analyse and write down the results of these studies in report form;
- results obtained from experimental fields should be applicable to a much wider area. The soils and the hydrological and topographical conditions of the site should be representative for the project areas and not only for the limited experimental station areas belonging to the Ministry of Irrigation, the Ministry of Agriculture or the Universities. Selection of sites of experimental fields must therefore be based on the results of studies on the various conditions in the project areas;
- more cooperation is needed between agriculture engineers and civil engineers in order to arrive at the right solutions.

CROP WATER USE

BY P.E.RIJTEMA AND A.ABOUKHALED

INTRODUCTION

Part of the work done on crop water use in irrigation experiments deals with the determination of crop coefficients, using empirical formulae. The large variety of empirical relations (Blaney and Criddle, Quijano, Hargreaves, Thornthwaite, Munson, Hamon, Turc, Christiansen and Patil, Jensen and Haise, Papadakis, Makkink, Olivier, Eagleman) used by for instance EL SHAL (1966), ABDEL RASOOL et al (1970), GIBALI et al (1971), GIBALI (1972, unpublished) and FARRAG (1973, unpublished), MOGHRABY (1969) leads to many different values for these crop coefficients. The equation derived by EL SHAL (1966) also belongs to the category of empirical relations. The derived crop coefficients used in these formulae are changing under different growing conditions, which must lead to the conclusion that they are only valid under the conditions of the performed experiments. Resulting from a lack of lysimeter data with optimum water supply conditions, crop coefficients for peak water use in accordance with the high values of evapotranspiration obtained by different authors using short irrigation intervals are not available. It must be concluded that the in Egypt generally applied Blaney and Criddle formula as a basis for irrigation experiments and even irrigation design is of limited value.

Climatologically, the Arab Republic of Egypt is too much differentiated to expect uniform meteorological conditions. Based on the available meteorological data a subdivision of the area in agroclimatic zones has been made. A second reason for subdivision in these zones was the fact that in the publications on irrigation research generally no or insufficient meteorological data were given, making it impossible to evaluate the given experimental irrigation data in accordance with the local meteorological conditions during the experiment.

For this reason an evaluation on basis of the long term mean meteorological conditions in the region was the only one possible.

With the aid of the available meteorological data additional data were derived necessary for the calculation of the net radiation in the agroclimatological zones. These data were used for the calculation of maximum crop water use.

The turbulent exchange of both sensible heat (large scale advection) and water vapour transport are predominant under semi arid and arid conditions, exceeding even the net radiation term on a 24-hour basis. This has been strongly emphasized in neighbouring countries such as the Bekaa area of Lebanon (VINK et al, 1969; ABOUKHALED et al, 1969-1971; SARRAF et al, 1969-1971).

None of the above mentioned empirical equations reflect the actual meteorological conditions sufficiently. Even the calculations based on the physically sound Penman equation for open water evaporation and an empirically derived reduction factor, do not give the large evapotranspiration values which are found under arid conditions, except when crop coefficients are introduced exceeding unity. However, in that case it appears that the crop coefficient is both dependent on climatological conditions and the crop itself. The combined energy balance - vapour transport method as presented by McIlroy gives already a better description of crop water use. It has the disadvantage, however, that it requires the wet bulb temperature depression at the evaporating surface, which value strongly depends on the moisture conditions of the soil. Moreover, the empirical wind function is to be determined from lysimeter data using an iterative procedure. The necessity of this procedure is, particularly for crops with highly varying surface properties which influence the uncertainties in the wet bulb depression at the evaporating surface, a major objection to use this method for practical purposes.

The combined energy balance - vapour transport approach used in the present report has been tested with data from frequently irrigated lysimeters in various arid regions, for example Tunisia (RIJTEMA, 1965) and in Iran (SLABBERS, 1970). Measured lysimeter data from Lebanon (ABOUKHALED and SARRAF, 1969, 1972) show similar results. This method has as main advantage that it does not require empirically derived crop coefficients dependent on the climatological conditions. It directly gives the maximum amounts of atmospheric evaporative demand in dependence of crop development as crop height and fraction of soil cover. This demand equals the maximum crop water use under non--stress conditions.

The calculation of actual evapotranspiration is based on soil physical conditions, as well as on maximum crop water use and crop properties. Generally speaking insufficient soil physical data were available in connection with the presented experimental irrigation data. On basis of standardized soil physical data, the soil types were subdivided in three main soil groups: fine, medium and coarse textured soils. In this situation it was useless to apply very refined methods for the calculation of actual crop water use. A simplified procedure was therefore introduced for the calculation of actual crop water use in relation to maximum crop water use, crop type, soil type and the length of the irrigation interval. In dependence of rooting depth, crop type and maximum crop water use, the amount of water which can be extracted under non-stress conditions from the soils of the three soil groups is given. Then crop production is discussed in relation to climate, water use, fertility level and soil water potential.

In connection with the small of time available, only for two crops (cotton and corn) an evaluation of the experimental data from irrigation research has been performed on basis of the given theoretical approach. In most cases the experimental data did fit reasonably well with those calculated on basis of the theory evolved. For other crops only a review has been given of the available experimental data.

Based on the theoretical considerations and the available experimental data, a number of recommendations are given for future applied irrigation research. It is strongly recommended that this research is directed towards investigations related to the application of stress conditions at different stages of plant growth in order to determine at what situations water can be saved without or with only a slight reduction in crop yield. In this manner a sound approach to irrigation project design can be obtained.

METEOROLOGICAL DATA

Available measured data

The available meteorological data can broadly be classified into two main groups. The first group includes the long-term mean values of some meteorological factors which have been observed during more than twenty years. The second group consists of data from stations which started during the last twenty years. In the present analysis the available meteorological data of 24 stations have been used for the determination of agroclimatological zones. A brief survey of available data of meteorological factors gives the following results.

A i r t e m p e r a t u r e. Monthly mean values of maximum and minimum air temperature were computed from the available daily values observed. The maximum and minimum thermometers are freely exposed in lowered screens with the bulbs at a height of 160 to 170 cm above surface. The long-term mean values of maximum and minimum temperatures for the different stations are given in table 1 and 2, respectively. Table 3 gives the data of the mean temperature, either calculated from 3-hourly observations or from $\frac{1}{2}(T_{max} + T_{min})$.

R e l a t i v e h u m i d i t y. Monthly mean values of relative humidity at 06, 12 and 18 hours U.T. were calculated from the available daily values at these hours. The relative humidity (in %) is obtained from dry and wet bulb readings using Jellink's psychrometer tables. Corrections for windspeed or atmospheric pressure are not applied. Values of the monthly mean daytime relative humidity as calculated from the available data are given in table 4.

C l o u d i n e s s (total cover). Monthly mean values of total cloud cover at 06, 12 and 18 hours U.T. or from observations taken at the eight synoptic hours, were calculated from the available values at these hours. Mean monthly values of cloud cover are given in table 5.

Table 1. Mean monthly maximum temperature in °C

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	17.9	18.0	20.4	22.6	25.9	29.0	29.8	30.5	29.0	27.3	24.1	19.4
Alexandria	31 22	29 57	18.5	19.2	21.2	23.8	26.6	28.4	29.7	30.6	29.5	27.8	24.5	20.5
Marsa Matruh	31 20	27 14	18.1	18.9	20.3	22.7	25.5	27.8	29.2	29.9	28.7	27.0	23.4	19.7
Port Said	31 17	32 18	18.1	18.6	20.2	22.5	25.6	28.5	30.4	30.8	29.2	27.3	24.1	19.8
Sakha	31 07	30 57	19.4	20.6	23.0	27.1	31.2	32.0	34.0	33.6	32.1	29.9	25.9	21.5
Mansoura	31 03	31 23	19.6	20.6	23.3	27.2	33.3	33.7	32.7	33.5	32.6	28.8	25.9	21.3
Dabaa	30 56	28 28	18.0	19.0	20.5	22.8	25.2	27.9	29.2	29.8	28.6	26.9	23.6	19.8
Borg El Arab	30 54	29 33	16.7	17.7	19.0	24.6	26.0	28.9	29.3	30.4	27.3	27.3	23.1	19.5
Gemmeiza	30 43	31 07	19.6	20.7	23.3	27.8	32.0	34.1	34.6	34.7	32.8	30.5	25.7	21.8
Tahrir	30 39	30 42	19.7	20.5	24.0	28.0	31.8	34.4	34.6	34.9	32.5	30.3	25.8	21.5
Ismailia	30 35	30 26	19.9	21.1	23.9	28.7	31.2	35.1	35.1	35.1	32.8	30.3	25.7	21.6
Belbes	30 24	31 35	19.1	20.1	24.3	28.4	31.9	34.7	34.4	34.3	32.1	30.7	25.6	21.6
Giza	30 02	31 13	19.5	21.0	24.3	28.3	31.8	34.8	34.3	34.4	32.6	30.2	25.4	21.3
Beni Suef	29 04	31 06	20.8	22.5	25.6	30.1	34.3	36.0	26.8	36.6	34.4	21.8	26.8	22.2
Menia	28 05	30 44	20.7	22.4	25.8	30.6	34.9	36.4	36.7	36.4	33.4	31.4	26.8	22.0
Mallawi	27 42	30 45	21.6	23.8	26.9	31.9	34.8	35.3	35.4	34.8	32.4	31.2	27.0	22.6
Assiut	27 11	31 06	20.8	22.6	26.6	31.8	36.1	37.7	36.8	36.9	34.9	31.1	26.6	22.3
Shandaweel	26 26	31 38	22.5	24.6	28.2	33.3	36.5	27.5	37.5	37.6	34.2	31.8	28.8	24.0
Sohag	26 34	31 42	22.4	24.2	28.3	33.4	36.5	38.2	37.4	37.5	34.4	32.1	28.5	23.7
Kom Ombo	24 29	32 56	24.1	26.0	30.0	35.1	39.0	41.0	40.5	41.0	38.6	36.2	30.5	25.6
Aswan	24 02	32 53	24.2	26.5	30.7	35.7	40.3	42.0	41.9	42.0	40.0	37.5	32.7	26.5
Bahariya	28 20	28 54	19.9	22.4	25.4	30.0	34.5	36.3	36.9	36.8	34.1	31.0	26.1	21.5
Dakhla	25 29	29 00	21.4	23.7	27.6	32.7	37.1	38.2	38.6	38.5	35.7	33.2	27.7	22.3
Kharga	25 26	30 34	22.3	24.4	28.3	33.1	37.6	38.6	39.1	39.4	26.5	34.0	28.6	23.9

Table 2. Mean monthly minimum temperature in °C

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	12.0	11.9	13.9	14.8	17.4	21.2	23.1	24.0	22.0	20.3	17.2	13.3
Alexandria	31 22	29 57	9.3	9.5	11.2	13.4	16.5	20.2	22.6	22.8	21.2	17.7	14.7	11.1
Marsa Matruh	31 20	27 14	8.1	8.4	9.7	11.8	14.5	18.2	20.2	21.0	19.7	16.8	13.3	10.0
Port Said	31 17	32 18	11.4	12.0	13.6	16.8	19.6	22.4	24.1	24.9	23.8	21.8	18.5	13.6
Sakha	31 07	30 57	6.1	6.3	7.9	10.4	14.2	17.0	19.0	18.4	17.7	15.6	12.6	8.3
Mansoura	31 03	31 23	7.1	7.5	9.4	12.0	15.7	18.7	20.5	20.6	19.1	17.2	14.0	9.3
Dabaa	30 56	28 28	7.3	7.9	9.5	12.0	14.8	18.4	20.9	21.2	19.7	17.1	13.2	9.4
Borg El Arab	30 54	29 33	6.4	8.0	8.8	10.8	15.0	18.1	19.9	19.4	18.6	14.9	12.1	8.8
Gemmeiza	30 43	31 07	5.3	5.7	7.4	10.1	14.2	17.3	19.3	19.2	17.2	15.0	13.2	8.6
Tahrir	30 39	30 42	7.9	8.1	10.2	12.5	15.2	18.9	20.4	20.9	18.8	16.6	13.3	9.6
Ismailia	30 35	.30 26	7.1	7.7	9.9	13.0	16.1	19.5	20.9	21.2	19.2	16.4	12.8	8.9
Belbes	30 24	31 35	8.0	8.2	10.6	13.2	16.3	20.1	21.3	21.5	19.1	17.1	15.2	9.8
Giza	30 02	31 13	6.4	6.7	10.2	12.1	15.3	18.9	20.2	20.4	18.6	16.0	12.3	8.3
Beni Suef	29 04	31 06	5.0	5.9	8.5	12.0	16.2	18.6	20.1	20.3	18.4	15.8	11.6	7.6
Menia	28 05	30 44	4.0	5.2	7.9	11.9	16.4	19.0	20.3	20.5	18.6	15.6	11.5	6.9
Mallawi	27 42	30 45	2.6	4.2	6.9	11.4	15.5	17.8	18.8	18.7	17.0	14.4	9.7	5.8
Assiut	27 11	31 06	6.8	7.5	10.6	14.9	19.6	21.6	22.3	22.4	20.1	18.0	12.8	8.8
Shandaweel	26 26	31 38	4.7	9.0	8.9	13.6	17.9	20.0	20.5	21.1	20.4	18.0	12.3	7.8
Sohag	26 34	31 42	5.4	6.0	9.0	13.5	17.6	20.3	20.5	21.0	20.0	17.8	12.4	6.9
Kom Ombo	24 29	32 56	7.8	8.5	11.9	16.3	20.5	22.5	23.2	23.3	21.5	18.9	13.8	9.4
Aswan	24 02	32 53	9.5	.10.6	14.2	18.6	23.5	25.1	26.1	26.4	24.0	21.7	16.5	13.2
Bahariya	28 20	28 54	4.7	6.3	8.9	12.7	17.3	19.2	20.6	20.7	18.7	15.9	11.3	6.7
Dakhla	25 29	29 00	4.4	6.0	9.5	14.3	20.0	22.5	23.1	22.9	20.6	17.4	11.8	6.6
Kharga	25 26	30 34	5.9	7.4	11.1	15.7	21.2	23.3	23.3	23.0	21.5	18.6	13.0	8.3

Table 3. Mean monthly temperature in °C

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	14.7	14.8	16.8	18.5	21.4	25.1	26.3	27.1	25.5	23.6	20.5	16.1
Alexandria	31 22	29 57	13.7	14.2	15.9	18.3	21.4	24.3	26.0	26.6	25.3	22.7	19.4	15.5
Marsa Matruh	31 20	27 14	12.8	13.4	14.9	17.4	20.2	23.2	25.0	25.6	24.4	21.8	18.2	14.4
Port Said	31 17	32 18	14.3	14.8	16.4	18.8	22.0	25.0	26.7	27.4	26.1	24.1	20.9	16.3
Sakha	31 07	30 57	12.8	13.4	15.4	18.8	22.7	25.0	26.5	26.0	24.9	22.8	19.2	14.9
Mansoura	31 03	31 23	11.9	12.3	15.2	17.7	21.4	25.6	25.8	25.8	24.0	21.9	18.2	13.7
Dabaa	30 56	28 28	12.7	12.8	15.1	17.1	19.3	23.3	25.0	25.4	23.8	21.3	18.0	14.1
Borg El Arab	30 54	29 33	12.9	13.0	14.2	17.9	20.6	24.0	25.2	25.9	24.7	21.9	17.5	14.4
Gemmeiza	30 43	31 07	12.4	13.2	15.4	19.0	23.1	25.7	27.0	27.0	25.0	22.8	19.4	15.2
Tahrir	30 39	30 42	13.2	13.8	17.3	14.3	22.7	26.4	26.8	27.0	24.9	22.3	18.6	14.5
Ismailia	30 35	30 26	12.7	13.6	16.4	20.3	23.2	26.9	27.4	27.5	25.4	22.5	18.5	14.4
Belbes	30 24	31 35	13.2	13.8	17.2	20.3	23.9	26.8	26.2	26.2	25.3	23.1	18.9	15.2
Giza	30 02	31 13	12.3	13.6	16.4	19.9	23.3	26.5	27.0	26.8	25.3	22.8	18.6	14.1
Beni Suef	29 04	31 06	12.9	14.2	17.0	21.0	25.2	27.3	28.4	28.5	26.4	23.8	19.2	14.9
Menia	28 05	30 44	11.9	13.3	16.6	21.2	25.7	27.8	28.5	28.3	25.6	23.2	18.4	13.7
Mallawi	27 42	30 45	12.1	14.0	16.9	21.6	25.2	26.6	27.1	26.8	24.7	22.8	18.3	14.2
Assiut	27 11	31 06	13.6	15.1	18.6	23.8	27.6	30.0	29.8	30.4	27.5	24.4	19.4	15.2
Shandaweel	26 26	31 38	13.6	16.8	18.6	23.4	27.2	28.8	29.0	29.4	27.3	24.9	20.6	15.9
Sohag	26 34	31 42	14.0	14.7	18.8	23.4	26.8	30.0	28.8	29.2	27.0	24.8	20.1	14.9
Kom Ombo	24 29	32 56	15.8	17.3	21.0	25.7	29.9	31.9	32.0	32.2	30.1	27.3	22.0	17.4
Aswan	24 02	32 53	16.8	18.6	22.4	27.2	31.9	33.6	34.0	34.2	32.0	29.6	24.0	19.8
Bahariya	28 20	28 54	12.3	14.4	17.2	21.4	25.9	27.8	28.7	28.8	26.4	23.4	18.7	14.1
Dakhla	25 29	29 00	12.9	14.8	18.6	23.5	28.6	30.4	30.8	30.7	28.2	25.3	19.8	14.4
Kharga	25 26	30 34	14.1	15.9	19.7	24.4	29.4	31.0	31.2	31.2	29.0	26.0	20.8	16.1

Table 4. Mean monthly relative humidity during daytime in %

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06	74	66	61	66	63	67	71	69	68	67	70	72
Alexandria	31 22	29 57	70	67	65	65	67	70	72	71	68	68	70	71
Marsa Matruh	31 20	27 14	65	64	63	64	67	70	73	72	67	66	66	68
Port Said	31 17	32 18	73	70	68	71	71	72	73	73	70	69	72	74
Sakha	31 07	30 57	74	73	70	64	60	63	67	69	70	71	74	76
Mansoura	31 03	31 23	75	67	66	58	52	57	69	71	68	67	71	71
Dabaa	30 56	28 28	66	61	60	59	60	68	70	67	66	68	67	62
Borg El Arab	30 54	29 33	74	69	63	59	64	61	71	70	66	64	66	61
Gemmeiza	30 43	31 07	77	75	71	64	60	61	67	69	71	71	75	77
Tahrir	30 39	30 42	67	60	59	54	50	53	62	63	63	66	72	66
Ismailia	30 35	30 26	61	63	45	38	41	43	53	55	52	58	61	61
Belbes	30 24	31 35	64	59	51	47	45	47	57	61	61	61	65	61
Giza	30 02	31 13	73	68	62	57	53	55	62	66	66	66	73	71
Beni Suef	29 04	31 06	58	52	46	40	36	38	44	47	51	52	55	63
Menia	28 05	30 44	58	53	48	41	36	40	45	50	55	55	60	62
Mallawi	27 42	30 45	70	65	55	44	40	49	56	62	66	68	72	74
Assiut	27 11	31 06	46	41	32	24	22	26	34	35	39	46	48	49
Shandaweel	26 26	31 38	67	61	50	39	34	40	47	48	54	61	62	66
Sohag	26 34	31 42	55	55	42	31	25	28	39	41	43	43	52	56
Kom Ombo	24 29	32 56	41	31	24	19	17	17	22	24	26	30	39	46
Aswan	24 02	32 53	36	31	24	20	18	19	21	23	26	29	36	41
Bahariya	28 20	28 54	55	51	48	40	37	38	38	43	48	50	55	58
Dakhla	25 29	29 00	45	42	35	28	25	27	25	27	34	39	45	48
Kharga	25 26	30 34	47	43	35	30	29	29	29	31	35	39	43	50

Table 5. Mean monthly cloud cover in Octas

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'												
Alexandria	31 22	29 57	3.6	3.6	3.2	2.6	2.3	1.2	1.4	1.5	2.0	2.4	3.4	3.9
Marsa Matruh	31 20	27 14	3.4	3.5	3.4	2.8	2.8	1.2	1.1	1.3	1.8	2.7	3.5	3.9
Port Said	31 17	32 18	3.0	2.9	2.9	2.1	2.0	0.9	0.9	1.1	1.3	1.7	2.8	3.3
Sakha	31 07	30 57	3.1	2.9	2.5	2.0	1.5	1.0	1.2	1.4	1.5	2.1	2.7	3.0
Mansoura	31 03	31 23	2.8	2.9	2.5	1.9	2.0	0.7	0.2	0.8	0.9	1.5	2.4	3.1
Dabaa	30 56	28 28												
Borg El Arab	30 54	29 33												
Gemmeiza	30 43	31 07												
Tahrir	30 39	30 42												
Ismailia	30 35	30 26	3.2	3.4	3.4	2.7	3.0	1.3	1.1	1.3	1.4	2.1	2.9	3.6
Almara	30 06	31 22	2.5	2.6	2.4	2.0	2.2	0.9	1.1	1.1	1.1	1.5	2.1	2.8
Giza	30 02	31 13	3.0	2.9	2.7	2.1	2.1	0.8	0.9	1.1	1.2	1.8	2.5	3.3
Beni Suef	29 04	31 06	2.1	2.0	1.6	1.5	1.5	0.4	0.2	0.3	0.4	0.8	1.6	2.4
Menia	28 05	30 44												
Mallawi	27 42	30 45	1.4	1.7	1.4	1.7	1.3	0.2	0.3	0.3	0.3	0.8	1.1	2.1
Assiut	27 11	31 06	1.0	1.4	1.0	1.0	1.3	0.1	0.1	0.1	0.2	0.4	0.8	1.8
Shandaweel	26 26	31 38	1.0	1.3	1.3	1.2	1.1	0.2	0.2	0.2	0.1	0.4	1.1	1.5
Sohag	26 34	31 42												
Kom Ombo	24 29	32 56												
Aswan	24 02	32 53	1.3	1.1	1.1	1.0	1.1	0.3	0.4	0.5	0.4	0.7	1.0	1.3
Bahariya	28 20	28 54	1.7	1.5	1.3	0.9	1.2	0.1	0.1	0.2	0.3	0.7	1.5	2.1
Dakhla	25 29	29 00	1.4	1.1	1.0	0.7	1.0	0.2	0.2	0.2	0.1	0.3	0.9	1.4
Kharga	25 26	30 34	1.2	1.0	0.9	0.8	1.0	0.2	0.2	0.1	0.1	0.4	0.8	1.3

P i c h e e v a p o r a t i o n . Monthly mean values of Piche evaporation were computed from daily readings available. Evaporation readings were measured by a Piche tube freely exposed in sloping double-roofed lowered screens. The white evaporation disc has an effective area of 10.1 cm^2 situated at 140 to 150 cm above surface. Monthly mean values of Piche evaporation are given in table 6.

C l a s s - A p a n e v a p o r a t i o n . Mean monthly values of class-A pan evaporation were only available from the agrometeorological station at Giza. These class-A pan evaporation data are inserted in table 6.

R a i n f a l l . Mean monthly rainfall is given as the total rainfall over the month. When the amount of rainfall is less than 0.1 mm, the symbol Tr (trace) was entered. The amount of rainfall measured includes the water equivalent of solid precipitation (if any) as for example hail. The amount of rainfall is normally measured by ordinary rain gauges. The rim of the gauges is at 90 to 100 cm above surface. Mean monthly totals of rainfall are given in table 7.

W i n d v e l o c i t y . Wind velocity was measured either with cup anemometers or with Dines pressure tube anemographs. Their heads were freely exposed and were erected at different heights, ranging from 19 to 2 m above surface. The monthly mean surface wind-velocity was given as the arithmetic mean of the surface wind velocity observations at 06, 12 and 18 hours U.T. Since for agrometeorological purposes the wind velocity at 2 m height is required, the available data of wind velocity were reduced for the 2 m level by means of:

$$u_z = u_h \log \frac{z}{z_o} \left(\log \frac{h}{z_o}\right)^{-1} \quad (1)$$

where u_z = calculated wind velocity at z cm in $m.s^{-1}$
z = required height above surface in cm (= 200 cm)
z_o = surface roughness length in cm
h = actual measuring height above surface in cm
u_h = actual measured wind velocity at h cm in $m.s^{-1}$

Assuming z_o = 2 cm, the equation reduces to:

$$u_{200} = 2\, u_h (\log 0.5\, h)^{-1} \quad (2)$$

The calculated data of mean monthly wind velocity at 2 m height in $m.s^{-1}$ are given in table 8.

Table 6. Mean monthly evaporation (where not otherwise indicated Piche) in $mm.day^{-1}$

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	3.1	3.6	4.2	4.5	5.2	5.1	5.3	5.0	3.8	4.3	3.6	3.5
Alexandria	31 22	29 57	4.2	4.6	5.2	5.4	5.8	5.7	5.5	5.6	5.8	5.4	4.4	3.8
Marsa Matruh	31 20	27 14	7.5	7.1	8.1	8.7	8.5	9.0	9.3	9.4	9.7	8.4	7.4	6.6
Port Said	31 17	32 18	4.7	5.4	6.5	6.4	6.8	7.4	7.5	7.3	7.8	6.9	5.9	4.5
Sakha	31 07	30 57	2.2	2.7	3.5	5.0	6.5	6.7	5.7	5.0	4.8	3.0	2.8	2.1
Mansoura	31 03	31 23	2.5	3.8	4.6	7.1	9.2	9.8	6.4	5.2	5.7	5.6	4.1	3.3
Dabaa	30 56	28 28	5.0	6.3	6.1	7.5	6.9	6.9	7.7	6.8	7.5	6.6	5.6	6.6
Borg El Arab	30 54	29 33	5.7	5.4	9.2	10.2	10.3	11.2	10.7	9.6	10.3	10.3	7.3	7.1
Gemmeiza	30 43	31 07	2.1	3.1	4.3	5.6	7.2	7.9	6.8	5.5	4.8	4.0	3.0	2.3
Tahrir	30 39	30 42	4.5	6.2	9.1	10.2	11.8	12.5	10.4	9.3	7.6	6.9	4.7	5.2
Ismailia	30 35	30 26	4.2	5.0	7.5	10.6	10.1	11.9	10.3	9.3	7.8	6.1	4.5	4.1
Belbes	30 24	31 35	5.7	6.6	9.6	11.6	11.6	13.8	10.8	9.7	9.1	8.6	6.4	6.6
Giza (Piche)	30 02	31 13	5.8	7.2	10.3	14.5	17.8	18.4	15.7	13.5	12.1	10.7	7.9	5.6
(CLASS-A PAN)			3.3	4.5	6.4	8.5	11.2	12.8	11.1	9.7	8.9	6.9	4.5	3.3
Beni Suef	29 04	31 06	2.8	3.8	5.1	7.4	9.4	10.1	9.0	8.1	7.0	5.6	3.6	2.6
Menia	28 05	30 44	4.5	5.8	7.7	10.2	14.0	15.0	13.6	11.7	9.1	7.9	6.0	4.6
Mallawi	27 42	30 45	2.0	3.1	4.7	7.4	9.6	9.3	6.8	5.2	4.4	3.4	2.4	1.7
Assiut	27 11	31 06	7.3	9.3	12.6	17.6	22.2	23.2	19.8	18.8	17.8	12.6	7.9	7.2
Shandaweel	26 26	31 38	2.6	3.7	5.6	8.4	10.2	9.7	8.1	7.8	6.6	4.6	3.6	2.7
Sohag	26 34	31 42	2.4	3.3	5.2	7.5	8.6	8.8	7.4	7.5	6.7	5.0	3.4	2.7
Kom Ombo	24 29	32 56	5.5	6.7	9.5	12.4	14.7	15.4	14.5	14.3	13.2	10.3	7.5	5.4
Aswan	24 02	32 53	3.6	10.0	13.9	17.0	17.2	21.8	20.1	20.0	19.0	16.9	11.8	9.0
Bahariya	28 20	28 54	5.3	6.7	8.6	11.1	13.5	14.0	13.3	12.5	10.5	8.6	6.3	5.1
Dakhla	25 29	29 00	7.9	9.9	13.6	18.1	22.6	24.3	23.0	22.2	20.3	16.0	11.2	7.9
Kharga	25 26	30 34	7.5	8.8	12.9	16.2	19.8	21.5	20.8	19.2	18.5	15.4	10.7	7.9

Table 7. Mean monthly precipitation in mm/month (Tr = trace)

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	52.2	27.1	8.8	1.3	2.9	Tr	0.0	0.0	1.5	14.2	15.7	60.6
Alexandria	31 22	29 57	49.1	31.3	12.4	3.1	2.0	Tr	0.0	0.4	0.5	9.2	27.7	56.1
Marsa Matruh	31 20	27 14	27.1	16.4	13.7	2.3	3.2	Tr	0.0	0.0	0.6	15.4	26.7	38.7
Port Said	31 17	32 18	15.6	15.0	9.7	3.9	3.7	0.0	0.0	0.0	0.1	7.7	12.0	23.9
Sakha	31 07	30 57	14.2	12.9	6.7	2.6	2.9	Tr	0.0	2.4	0.1	3.9	6.9	13.6
Mansoura	31 03	31 23	10.2	7.5	5.6	2.5	4.3	0.7	0.0	0.0	0.1	4.5	6.2	10.5
Dabaa	30 56	28 28	31.7	14.9	12.9	1.2	2.9	0.0	0.0	0.0	1.9	13.6	27.1	43.7
Borg El Arab	30 54	29 33	32.9	9.0	17.0	Tr	Tr	0.0	0.0	0.0	0.0	1.4	27.8	15.9
Gemmeiza	30 43	31 07	8.1	6.1	3.5	1.6	2.9	Tr	0.0	0.0	0.1	3.2	7.1	17.9
Tahrir	30 39	30 42	10.0	6.9	1.1	1.1	0.7	0.0	0.0	0.0	0.3	1.7	4.5	7.6
Ismailia	30 35	30 26	7.4	2.1	7.3	0.7	4.6	0.0	0.0	0.0	0.0	2.9	9.6	3.1
Belbes	30 24	31 35	7.4	2.9	1.5	1.1	0.2	0.0	0.0	0.0	0.0	1.0	3.3	3.1
Giza	30 02	31 13	5.3	4.7	0.9	0.3	1.1	0.0	0.0	Tr	0.0	0.3	2.0	5.6
Beni Suef	29 04	31 06	0.3	2.0	1.1	0.8	Tr	Tr	0.0	0.0	Tr	0.1	0.1	3.6
Menia	28 05	30 44	0.0	1.2	0.3	0.4	0.6	0.0	0.0	0.0	0.1	0.6	0.2	0.7
Mallawi	27 42	30 45	Tr	1.1	0.8	Tr	0.1	0.0	0.0	0.0	Tr	0.1	Tr	0.6
Assiut	27 11	31 06	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Shandaweel	26 26	31 38	Tr	0.2	Tr	0.0	Tr	0.0	0.0	0.0	0.0	0.0	Tr	0.8
Sohag	26 34	31 42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Tr	Tr
Kom Ombo	24 29	32 56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.2	0.0
Aswan	24 02	32 53	0.1	Tr	0.1	0.3	0.6	Tr	0.0	0.0	Tr	0.2	0.1	Tr
Bahariya	28 201	28 54	Tr	1.2	0.0	0.6	0.1	0.2	Tr	0.0	Tr	0.2	0.7	1.3
Dakhla	25 29	29 00	Tr	0.4	Tr	Tr	0.2	Tr	0.0	0.0	0.0	Tr	Tr	0.1
Kharga	25 26	30 34	0.1	0.4	Tr	Tr	0.3	Tr	0.0	0.0	0.0	Tr	0.1	0.4

Table 8. Computed mean monthly wind velocity at 2 m height in $m.s^{-1}$

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	$31^{\circ}33'$	$31^{\circ}06'$												
Alexandria	31 22	29 57	3.00	3.11	3.17	2.92	2.75	2.78	3.00	2.71	2.46	2.20	2.30	2.78
Marsa Matruh	31 20	27 14	4.46	4.18	4.32	4.04	3.48	3.76	3.69	3.41	3.20	3.06	3.55	4.18
Port Said	31 17	32 18	3.21	3.56	3.76	3.34	2.84	2.56	2.35	1.91	2.18	3.59	3.00	3.25
Sakha	31 07	30 57	1.3	1.4	1.7	1.5	1.5	1.5	1.3	1.3	1.1	1.0	1.1	1.1
Mansoura	31 03	31 23	2.48	2.78	2.74	2.66	2.44	2.18	1.72	1.32	1.46	1.58	2.02	2.53
Dabaa	30 56	28 28	3.16	4.59	4.30	4.30	3.47	4.23	4.52	3.56	3.45	2.82	3.72	4.01
Borg El Arab	30 54	29 33												
Gemmeiza	30 43	31 07	0.83	1.17	0.92	0.92	0.83	0.83	0.75	0.67	0.67	0.75	0.67	0.75
Tahrir	30 39	30 42	3.14	3.59	3.81	3.64	3.56	3.28	2.97	2.53	2.42	2.42	2.47	3.03
Ismailia	30 35	30 26	1.57	1.80	2.12	1.85	1.71	1.44	1.71	1.57	1.35	1.44	1.17	1.44
Belbes	30 24	31 35												
Giza	30 02	31 13	2.00	2.10	2.40	2.40	2.70	2.90	2.70	2.10	1.90	2.20	1.90	1.80
Beni Suef	29 04	31 06	1.01	1.15	1.22	1.77	1.51	1.58	1.22	1.22	1.94	1.87	1.15	1.30
Menia	28 05	30 44												
Mallawi	27 42	30 45	1.48	1.48	1.78	2.00	2.96	2.52	1.26	1.26	2.00	1.41	1.18	1.26
Assiut	27 11	31 06	1.56	2.04	2.19	2.33	2.86	2.82	2.48	2.36	2.98	2.44	2.04	1.68
Shandaweel	26 26	31 38												
Sohag	26 34	31 42												
Kom Ombo	24 29	32 56	1.22	1.35	1.65	1.53	1.31	1.48	1.31	1.44	1.35	1.31	1.44	1.22
Aswan	24 02	32 53	1.45	1.86	2.18	2.26	2.50	2.02	1.61	1.78	1.78	1.86	1.29	1.61
Bahariya	28 20	28 54	1.00	1.00	1.08	1.17	1.30	1.33	1.17	1.08	1.08	1.00	0.92	0.92
Dakhla	25 29	29 00	1.92	2.00	2.34	2.50	2.67	2.58	2.58	2.42	2.58	2.17	1.83	1.67
Kharga	25 26	30 34	0.75	0.92	1.17	1.33	1.42	1.67	1.25	1.08	1.67	1.33	0.92	0.84

Table 9. Mean monthly values of relative duration of bright sunshine in %

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Alexandria	$31^{\circ}22'$	$29^{\circ}57'$	72	68	73	75	81	86	87	89	85	82	76	63
Almara	30 06	31 22	'2	75	74	74	78	84	84	85	86	84	80	71
Giza	30 02	31 13	68	72	73	75	80	86	85	85	85	82	78	70

Table 10. Mean monthly global radiation in $cal.day^{-1}.cm^{-2}$

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Giza	30 02	31 13	275	367	443	563	620	664	647	605	531	412	311	250

R e l a t i v e d u r a t i o n o f b r i g h t s u n s h i n e . Actual duration of bright sunshine is measured at Alexandria, Almara and Giza by suitably exposed Campbell-Stokes sunshine recorders. The data of mean monthly relative duration of bright sunshine are listed in table 9.

S o l a r a n d s k y - r a d i a t i o n . Global radiation is measured at Giza only. The data are obtained from the records of a Robitzseh acdinograph. The Robitzseh values are regularly compared with the records of an Epply pyrheliometer installed at the station. Mean monthly values of global radiation are given in table 10.

S u b d i v i s i o n i n a g r o c l i m a t o - l o g i c a l a r e a s

Meteorological factors can be used to describe the agrometeorological conditions for crop growth in a country. Climatologically the Arab Republic of Egypt is too much differentiated to expect uniform agrometeorological conditions, so a subdivision in separate areas must be made before additional meteorological data, necessary for the determination of crop water use, can be calculated. This subdivision in agroclimatological areas has been based on a combination of temperature, vapour pressure and wind velocity.

T e m p e r a t u r e . The mean temperature can be used in the Blaney and Criddle method for the calculation of the monthly consumptive use factor F. Calculated values of this consumptive use factor are given in table 11. They suggest that only very small gradients exist in the Delta area. A gradial increase of F from Lower Egypt to Upper Egypt indicates that a subdivision of Egypt in 3 zones can be made.

A second temperature element to describe agroclimatological conditions is the mean daily temperature amplitude. This amplitude is in fact the result of incoming solar radiation and net longwave radiation losses. Moreover it depends on vapour pressure and wind conditions. The mean monthly values of $T_{max} - T_{min}$ in ^{o}C are given in table 12. It follows from this table that Lower Egypt is to be subdivided into at least 2 agroclimatological areas. The coastal area with amplitudes varying from 6 ^{o}C in winter to 10 to 11 ^{o}C in summer, and the sites in Lower Egypt which show values varying from 10 ^{o}C in winter up to 18 ^{o}C in summer indicate that large climatological gradients exist in Lower Egypt. For Middle and Upper Egypt, on the other hand, the gradients based on temperature amplitude are not pronounced.

V a p o u r p r e s s u r e . Actual vapour pressure was calculated from the mean daytime humidity and the corresponding daytime temperature. As such actual vapour pressure does not give much information. More information can be obtained from the mean vapour pressure deficit over 24 hours, which was calculated as the difference between the saturated vapour pressure at mean monthly temperature and the calculated actual vapour pressure during daytime. The mean monthly values of the vapour pressure deficit are given in table 13. An analysis of these data leads to the conclusion that Lower Egypt is to be subdivided into a coastal area (Alexandria, Baltim, Port Said), a more central part of the Delta (Sakha, Mansoura, Gemmeiza) and an area bordering the desert (Tahrir, Belbes). The area around Giza possibly has intermediate climatological conditions.

The vapour pressure deficit data of Mallawi and Assiut deviate from the general picture. With respect to Mallawi, this might be due to particular local conditions, since the temperature amplitude also shows deviations from the neighbouring stations. The large values of the vapour pressure deficit at Assiut are probably due to a false interpretation of the relative humidity data. The given mean data for Assiut were practically equal to the values measured at the neighbouring stations at 12.00 hours U.T.

The other stations in Middle and Upper Egypt show a gradient in vapour pressure deficit which goes parallel with the change in latitude. A subdivision of these regions can be made on basis of latitude.

Table 11. Mean monthly consumptive use factor F (Blaney and Criddle) in mm/month

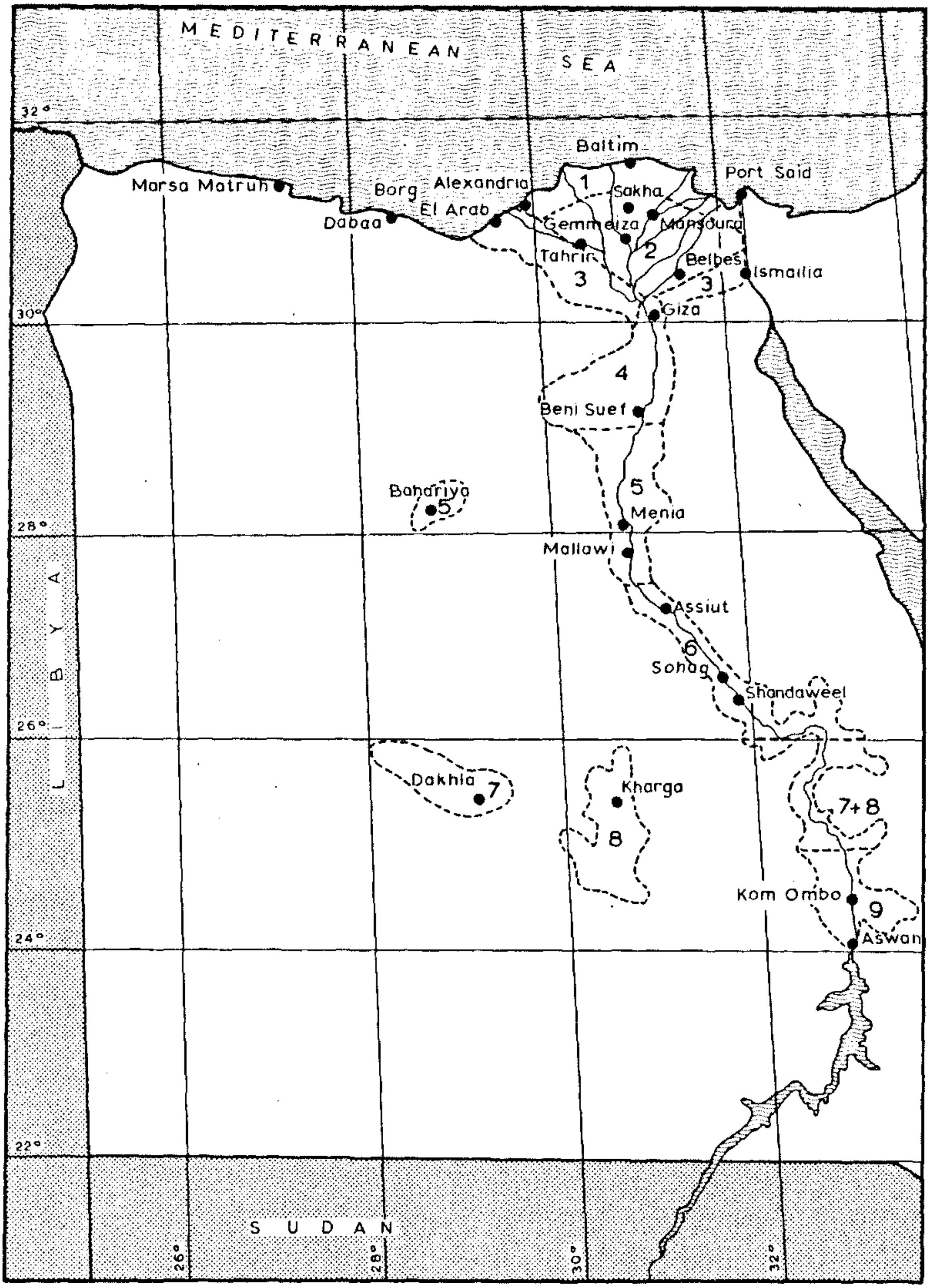
Site	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	107.83	104.23	132.49	144.53	171.33	186.75	195.62	189.04	165.74	150.60	125.34	110.32
Port Said	107.39	104.10	130.78	145.55	173.67	186.11	198.46	191.14	167.84	152.14	126.47	110.81
Alexandria	104.49	102.34	129.05	143.74	171.33	183.33	194.26	187.01	164.98	147.26	121.75	108.33
Mansoura	97.53	96.25	126.37	141.39	171.33	187.23	193.38	183.60	160.04	144.39	117.82	102.49
Dabaa	99.98	97.67	125.68	138.75	172.99	179.82	190.81	182.95	158.96	141.88	116.94	103.57
Borg El Arab	101.87	98.49	122.52	142.17	167.79	181.99	190.76	184.06	162.72	144.39	115.52	104.84
Tahrir	102.83	101.06	134.38	147.75	177.00	192.42	197.83	188.66	163.47	145.84	119.10	105.10
Ismailia	102.14	100.37	130.98	151.76	177.87	191.80	198.98	190.79	165.42	146.54	119.89	105.81
Belbes	102.83	101.06	134.00	151.74	182.25	194.16	195.16	185.69	165.00	148.75	120.09	107.37
Menia	101.04	100.98	132.50	155.05	188.50	195.50	203.62	193.84	155.04	151.34	121.45	106.16
Assiut	107.22	107.12	139.36	164.44	194.06	202.29	207.41	202.44	172.06	153.84	125.22	111.62
Sohag	105.21	103.65	139.73	163.64	194.41	207.50	207.56	198.87	171.02	154.51	123.69	108.19
Kom Ombo	116.80	115.57	148.85	170.95	202.84	207.60	213.36	206.22	182.31	167.28	135.47	120.42

Table 12. Mean monthly values of (T_{max} - T_{min}) in ^{o}C (2 x the daily temperature amplitude)

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	5.9	6.1	6.5	7.8	8.5	7.8	6.7	6.5	7.0	7.0	6.9	6.1
Alexandria	31 22	29 57	9.2	9.7	10.0	10.4	10.1	8.2	7.1	7.8	8.3	10.1	9.8	9.4
Marsa Matruh	31 20	27 14	10.0	10.5	10.6	10.9	11.0	9.6	9.0	8.9	9.0	10.2	10.1	9.7
Port Said	31 17	32 18	6.7	6.6	6.6	5.7	6.0	6.1	6.3	5.9	5.4	5.5	5.6	6.2
Sakha	31 07	30 57	13.3	14.3	15.1	16.7	17.0	16.0	15.0	15.2	14.4	14.3	13.3	13.2
Mansoura	31 03	31 23	12.5	13.1	13.9	15.2	17.6	15.0	12.2	12.9	13.5	11.6	11.9	12.0
Dabaa	30 56	28 28	10.7	11.1	11.0	10.8	10.4	9.5	8.3	8.6	8.9	9.8	10.4	10.4
Borg El Arab	30 54	29 33	10.3	9.7	10.2	13.8	11.0	10.8	9.4	11.0	8.7	12.4	11.0	10.7
Gemmeiza	30 43	31 07	14.3	15.0	15.9	17.7	17.8	16.8	15.3	15.5	15.6	15.5	12.5	13.2
Tahrir	30 39	30 42	11.8	12.4	13.8	15.5	16.6	15.5	14.2	14.0	13.7	13.7	12.5	11.9
Ismailia	30 35	30 26	12.8	13.4	14.0	15.7	15.1	15.6	14.2	13.9	13.6	13.9	12.9	12.7
Belbes	30 24	31 35	11.1	11.9	13.7	15.2	15.6	14.6	13.1	12.8	13.0	13.6	10.4	11.8
Giza	30 02	31 13	13.1	14.3	15.3	16.2	16.4	16.0	14.2	14.0	14.1	14.3	13.1	13.0
Beni Suef	29 04	31 06	15.8	16.6	17.1	18.1	18.1	17.4	16.7	16.3	16.0	16.0	15.2	14.6
Menia	28 05	30 44	16.7	17.2	17.9	18.7	18.5	17.4	16.4	15.9	14.8	15.8	15.3	15.1
Mallawi	27 42	30 45	19.0	19.6	20.0	20.5	19.3	17.5	16.6	16.1	15.4	16.8	17.3	16.8
Assiut	27 11	31 06	14.0	15.1	16.0	16.9	16.5	16.1	14.5	14.5	14.8	13.1	13.8	13.5
Shandaweel	26 26	31 38	17.8	15.6	19.3	19.7	18.6	17.5	17.0	16.4	13.8	13.8	16.5	16.2
Sohag	26 34	31 42	17.0	18.2	19.3	19.9	18.9	17.9	16.9	16.5	14.4	14.3	16.1	16.8
Kom Ombo	24 29	32 56	16.3	17.5	18.1	18.8	18.5	18.5	17.3	17.7	17.1	17.3	16.7	16.2
Aswan	24 02	32 53	14.7	15.9	16.5	17.1	16.8	16.9	15.8	15.6	16.0	15.8	15.2	13.3
Bahariya	28 20	28 54	15.2	16.1	16.5	17.3	17.2	17.1	16.2	16.1	15.4	15.1	14.8	14.8
Dakhla	25 29	29 00	17.0	17.7	18.1	18.4	17.1	15.7	15.5	15.6	15.1	15.8	15.9	15.7
Kharga	25 26	30 34	16.4	17.0	17.2	17.4	16.4	15.3	15.8	16.4	15.0	15.4	15.6	15.6

Table 13. Mean monthly values of vapour pressure deficit (24-hour mean) in mmHg

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'	2.2	4.7	4.6	4.2	5.6	5.9	5.1	6.0	5.8	5.3	3.9	2.7
Alexandria	31 22	29 57	2.7	3.1	3.7	4.3	4.7	4.8	4.8	5.2	5.7	5.0	3.6	2.8
Marsa Matruh	31 20	27 14	3.1	3.3	3.8	4.2	4.3	4.4	4.1	4.9	5.3	5.1	4.2	3.0
Port Said	31 17	32 18	2.3	2.8	3.4	3.4	4.0	3.9	4.7	4.8	5.4	4.9	3.6	2.5
Sakha	31 07	30 57	2.0	2.1	2.9	4.6	6.8	6.9	6.3	5.7	5.0	4.3	2.9	1.6
Mansoura	31 03	31 23	1.7	2.7	3.4	5.4	8.0	8.8	5.6	5.2	5.2	4.9	3.2	2.4
Dabaa	30 56	28 28	2.9	3.6	4.2	5.0	5.5	5.0	5.0	6.0	5.6	4.5	3.9	3.7
Borg El Arab	30 54	29 33	2.0	2.6	3.6	5.3	5.1	6.9	4.8	5.4	5.9	5.6	4.0	3.9
Gemmeiza	30 43	31 07	1.6	1.8	2.7	4.7	6.9	7.8	6.5	5.9	4.8	4.3	2.7	1.8
Tahrir	30 39	30 42	3.2	3.9	5.1	6.7	9.1	10.5	8.0	7.7	6.9	5.2	3.1	3.3
Ismailia	30 35	30 26	3.5	3.5	7.0	10.9	11.5	13.7	11.0	10.4	10.1	7.2	5.1	3.9
Belbes	30 24	31 35	3.3	4.0	6.4	8.4	11.0	12.4	9.2	8.0	7.6	6.6	4.5	4.1
Giza	30 02	31 13	2.1	2.9	4.6	5.9	8.7	10.1	8.9	7.0	6.6	5.4	3.0	6.6
Beni Suef	29 04	31 06	4.0	5.1	7.1	10.3	14.3	15.5	14.5	13.6	11.0	10.1	6.4	3.8
Menia	28 05	30 44	3.7	5.0	6.6	10.3	14.8	15.3	14.3	12.4	9.4	8.1	5.1	3.6
Mallawi	27 42	30 45	2.4	3.3	5.6	8.6	13.2	11.7	9.9	8.0	5.9	5.0	3.1	2.1
Assiut	27 11	31 06	5.7	7.0	10.3	16.1	20.8	23.4	19.3	19.5	15.4	11.0	7.8	5.9
Shandaweel	26 26	31 38	2.9	4.6	7.1	12.1	16.7	16.2	14.0	14.0	10.6	7.4	5.5	3.6
Sohag	26 34	31 42	4.6	4.8	8.6	14.0	19.0	21.6	16.6	16.2	13.7	12.1	7.3	4.8
Kom Ombo	24 29	32 56	7.3	9.7	13.6	19.5	25.5	28.6	26.7	26.3	21.9	18.0	11.1	7.3
Aswan	24 02	32 53	8.6	10.5	14.9	20.9	28.2	30.7	30.5	29.8	25.1	20.9	13.1	9.4
Bahariya	28 20	28 54	4.2	5.3	6.9	10.5	14.7	16.0	16.7	15.2	11.9	9.4	6.2	4.3
Dakhla	25 29	29 00	5.5	6.7	9.8	14.9	21.0	22.5	23.8	22.9	17.6	13.6	8.6	5.7
Kharga	25 26	30 34	5.7	7.1	10.4	15.1	21.0	23.5	23.7	22.0	18.1	14.4	9.5	6.1



Map of part of the Arab Republic of Egypt with the 24 meteorological stations of which the data were used for the determination of the agroclimatological areas distinguished in the text

Wind velocity. As the mean wind velocity data at 2 m height were obtained by calculation using data measured at different levels (table 8), it is possible that considerable errors were introduced. The large variations in wind velocity between neighbouring stations, however, cannot be explained by errors in the reduction formula used. These variations are mainly due to local conditions in open and sheltered areas. A crude control of wind velocity data can be obtained by comparing those from stations with practically equal conditions of temperature and vapour pressure deficit, with data of the Piche evaporimeter. Differences in wind velocity are reflected in the Piche evaporation when other meteorological conditions are almost equal. Comparison of both factors generally show good agreement, with perhaps the exception for Mallawi station, where the small values of the Piche evaporation do not agree with the high wind velocity data.

Based on the above discussion of some meteorological factors, it must be concluded that the Delta area is to be subdivided in a Coastal Area, a Central Area and a Desert Border Area. Middle and Upper Egypt agroclimatologically can be subdivided on basis of latitude. The following 9 agroclimatological areas are therefore distinguished (see map):

1. Coastal area
2. Central Delta area
3. Desert Delta area
4. Giza area
5. Area latitude 29° - 27.5° N
6. Area latitude 27.5° - 26° N
7. Dakhla area } 26° - 25° N
8. Kharga area }
9. Aswan area 25° - 24° N

From the above it also must be concluded that the Blaney and Criddle consumptive use factor F insufficiently reflects the differences in agrometeorological conditions for crop water requirements. It will be necessary to determine the crop coefficients experimentally for the different regions.

A much better approach for the calculation of crop water requirements under different agrometeorological conditions can be obtained by using a combined energy balance - vapour transport method in which all available data are used. However, for such an approach measured or calculated data of net radiation are required. As solar radiation is measured at Giza alone and relative duration of bright sunshine at three places only, a discussion of some derived additional meteorological data is required.

Calculation of additional data

Radiation. For the calculation of global radiation an empirical relation can be used of the form:

$$H_{sh} = (a + bn/N)H_a \qquad (3)$$

where H_{sh} is global radiation and H_a solar radiation at the top of the atmosphere both in $cal.day^{-1}.cm^{-2}$, n/N relative duration of bright sunshine and a and b empirical constants. Mean monthly values of H_a for a

Table 14. Mean total daily solar radiation at the top of the atmosphere in $cal.day^{-1}.cm^{-2}$

Site	J	F	M	A	M	J	J	A	S	O	N	D
Mersa Matruh	491	598	735	861	945	971	961	890	792	657	527	455
Alexandria	491	598	735	861	945	971	961	890	792	657	527	455
Sakha	491	598	735	861	945	971	961	890	792	657	527	455
Gemmeiza	491	598	735	861	945	971	961	890	792	657	527	455
Giza	506	611	745	868	946	971	960	894	799	667	540	469
Beni Suef	521	624	753	871	945	969	958	896	805	677	554	484
Mallawi	534	636	762	875	944	966	955	898	811	608	566	499
Shandaweel	554	653	776	880	943	962	952	900	819	703	586	521
Aswan	586	681	795	887	938	954	944	903	831	726	619	557
Bahariya	534	636	762	875	944	966	955	898	811	688	566	499
Dakhla	572	669	786	884	940	957	948	902	826	716	606	542
Kharga	572	669	786	884	940	957	948	902	826	716	606	542

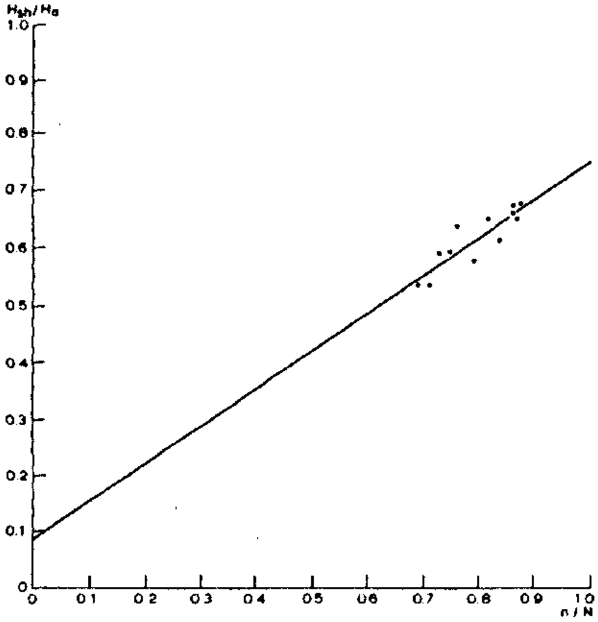


Fig. 1. Relationship between the ratio global radiation over radiation at the top of the atmosphere (H_{sh}/H_a) and the relative duration of bright sunshine (n/N) at Giza

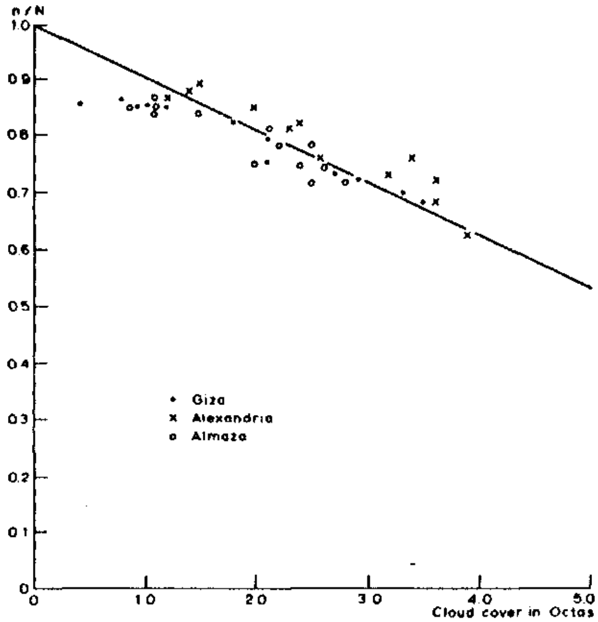


Fig. 2. Relationship between relative duration of bright sunshine and cloud cover estimates at three sites

number of stations, as derived from the Smithonian Meteorological Tables, are given in table 14. As data of H_{sh} are only measured at Giza, where also data of n/N are available, these data will be used for the determination of the constants a and b. In Fig. 1 the relationship between H_{sh}/H_a and the mean values of n/N is presented. From this figure it follows that the constants a and b have the value 0.09 and 0.68 respectively.

For the stations, where the hours of bright sunshine are not recorded, use can be made of the mean cloud cover estimates. The relationship between the relative duration of bright sunshine n/N and mean cloud cover has been derived with aid of the data of both factors measured at Alexandria, Almaza and Giza. This relation is shown in Fig. 2. For the available range of cloud cover data and n/N values the relation can be approximated by a linear equation:

$$n/N = 1 - 0.094 m_c \qquad (4)$$

where m_c is the cloud cover in Octas.

Combination of this relation with the equation for the calculation of global radiation gives:

$$H_{sh} = (0.77 - 0.064 m_c) H_a \qquad (5)$$

For the present it had to be assumed that this relation holds throughout the country. It should be realized, however, that the relations given for the calculation of global radiation should be tested before they are used for the calculation of the radiation during short periods. In this respect it is recommended that both radiation and duration of bright sunshine measurements are performed at a few other sites. From these measurements and those already performed at Giza, interpolation will give more reliable results for other areas.

For the calculation of net radiation it was necessary to use an empirical approach to net longwave radiation. Assuming surface temperature equal to air temperature, net longwave radiation is:

$$^{nt}H_{lo} = \sigma T_a^4 \; (0.56 - 0.092\sqrt{e_a})(0.10 + 0.90 n/N) \qquad (6)$$

where $^{nt}H_{lo}$ is net longwave radiation in $cal.day^{-1}.cm^{-2}$, σ, the constant of Boltzmann (118.10^{-9} $cal. day^{-1}.cm^{-2}.^{o}K^{-4}$), e_a actual vapour pressure in mmHg and n/N relative duration of bright sunshine. In the calculations the relative duration of bright sunshine was replaced by its relation with cloud cover, see eq. (4).

Table 15. Mean monthly values of net radiation, in mm.day^{-1} water equivalent for open water (H_{nt1}), wet bare soil (H_{nt2}) and cropped soil with full cover (H_{nt3})

Area		J	F	M	A	M	J	J	A	S	O	N	D
1. Coastal	H_{nt1}	1.85	2.62	4.04	5.54	7.20	8.25	8.67	7.92	6.38	4.48	2.63	1.39
	H_{nt2}	1.35	2.07	3.30	4.65	6.16	7.15	7.56	6.86	5.48	3.74	2.09	0.99
	H_{nt3}	0.92	1.56	2.65	3.86	5.23	6.14	6.55	5.92	4.67	3.08	1.61	0.62
2. Central Delta	H_{nt1}	1.66	2.51	3.95	5.35	6.55	7.92	8.23	7.71	6.14	4.26	2.48	1.33
	H_{nt2}	1.20	1.93	3.23	4.47	5.54	6.80	7.11	6.67	5.25	3.68	1.93	0.91
	H_{nt3}	0.77	1.42	2.58	3.67	4.62	5.81	6.12	5.74	4.41	2.86	1.44	0.53
3. Desert Delta	H_{nt1}	1.59	2.44	3.96	5.28	6.50	7.74	8.20	7.52	6.12	4.36	2.58	1.30
	H_{nt2}	1.13	1.06	3.25	4.41	5.49	6.53	7.08	6.49	5.23	3.78	2.04	0.87
	H_{nt3}	0.70	1.35	2.60	3.61	4.56	5.64	6.08	5.57	4.39	2.96	1.54	0.50
4. Giza	H_{nt1}	1.86	2.75	4.24	5.67	6.70	7.90	8.17	7.75	6.32	4.58	2.87	1.57
	H_{nt2}	1.38	2.16	3.49	4.78	5.71	6.31	7.08	6.72	5.42	3.85	2.31	1.13
	H_{nt3}	0.96	1.62	2.80	3.98	4.80	5.77	6.08	5.80	4.58	3.18	1.78	0.72
5. Latitude 29° - 27.5° N	H_{nt1}	2.12	3.04	4.53	5.81	6.75	7.76	8.21	7.69	6.72	4.65	2.89	1.80
	H_{nt2}	1.52	2.32	3.64	4.80	5.62	6.52	7.00	6.55	5.69	3.81	2.22	1.27
	H_{nt3}	0.99	1.68	2.84	3.88	4.63	5.40	5.90	5.52	4.75	3.06	1.64	0.79
6. Latitude 27.5 - 26° N	H_{nt1}	2.50	3.69	5.02	6.01	6.72	8.11	8.09	7.77	6.75	5.25	3.44	2.36
	H_{nt2}	1.83	2.94	4.12	4.96	5.61	6.87	6.85	6.59	5.69	4.36	2.74	1.76
	H_{nt3}	1.23	2.27	3.28	4.02	4.61	5.78	5.74	5.54	4.77	3.56	2.08	1.23
7. Dakhla 26° - 25° N	H_{nt1}	2.32	3.40	4.70	5.90	6.63	7.45	7.32	6.93	6.21	4.78	2.92	2.15
8. Kharga	H_{nt2}	1.68	2.60	3.74	4.80	5.51	6.22	6.12	5.78	5.15	3.88	2.20	1.56
	H_{nt3}	1.08	1.88	2.89	3.83	4.48	5.11	5.00	4.73	4.12	3.04	1.54	0.97
9. Aswan 25° - 24° N	H_{nt1}	2.26	3.21	4.27	5.27	5.73	6.60	6.53	6.22	5.63	4.19	3.11	2.27
	H_{nt2}	1.57	2.41	3.32	4.19	4.45	5.39	5.34	5.11	4.58	3.32	2.36	1.61
	H_{nt3}	0.94	1.68	2.48	3.21	3.61	4.29	4.26	4.08	3.64	2.51	1.68	1.03

Table 16. Mean monthly values of open water evaporation after Penman (E_o) in mm.day^{-1}

Site	Lat. N	Long. E	J	F	M	A	M	J	J	A	S	O	N	D
Baltim	31°33'	31°06'												
Alexandria	31 22	29 57	1.83	2.51	3.58	4.68	5.98	6.91	7.46	6.88	5.64	4.07	2.48	1.60
Marsa Matruh	31 20	27 14												
Port Said	31 17	32 18												
Sakha	31 07	30 57												
Mansoura	31 03	31 23	1.42	2.24	3.35	4.78	6.06	7.26	6.86	6.32	5.11	3.69	2.24	1.40
Dabaa	30 56	28 28												
Borg El Arab	30 54	29 33												
Gemmeiza	30 43	31 07												
Tahrir	30 39	30 42	1.92	2.75	4.13	5.40	6.83	7.86	7.66	6.90	5.63	4.01	2.38	1.73
Ismailia	30 35	30 26												
Belbes	30 24	31 35												
Giza	30 02	31 13	1.56	2.34	3.73	5.00	6.46	7.70	7.65	6.86	5.58	4.21	2.45	1.48
Beni Suef	29 04	31 06	1.85	2.62	3.91	5.40	6.65	7.63	7.59	7.10	6.21	4.58	2.77	1.71
Menia	28 05	30 44												
Mallawi	27 42	30 45												
Assiut	27 11	31 06												
Shandaweel	26 26	31 38	2.23	3.25	4.56	6.04	7.14	8.32	7.90	7.60	6.58	4.83	3.21	2.13
Sohag	26 34	31 42												
Kom Ombo	24 29	32 56												
Aswan	24 02	32 53	2.76	4.00	5.57	6.95	8.14	8.51	7.98	7.87	7.04	5.67	4.00	2.94
Bahariya	28 20	28 54												
Dakhla	25 29	29 00	2.53	3.47	5.02	6.72	7.97	8.74	8.60	8.01	7.31	5.52	3.42	2.37
Kharga	25 26	30 34	2.13	3.04	4.48	6.00	7.14	8.16	7.83	7.28	6.81	5.00	3.04	2.08

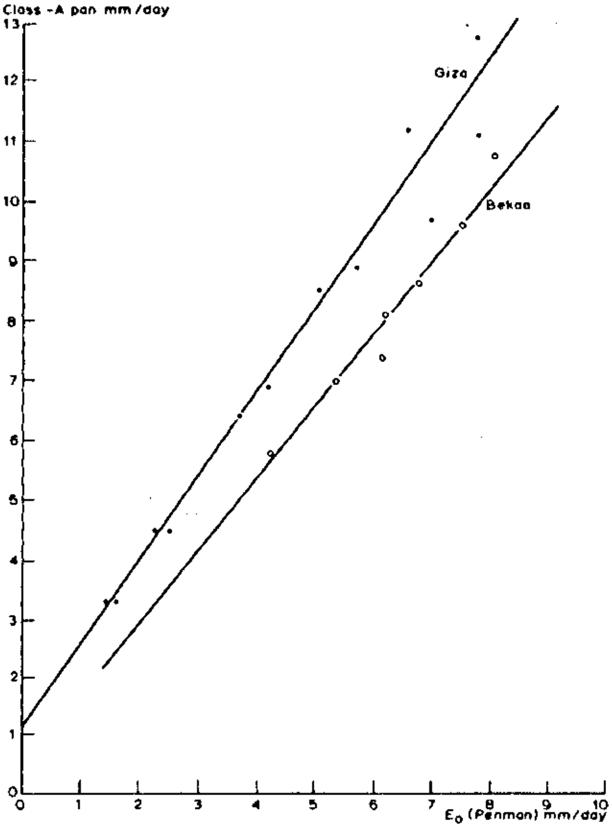


Fig. 3. Relationship between Class-A pan evaporation and calculated (Penman) values of E_o at Giza (Egypt) and Bekaa (Lebanon)

Calculated values of net radiation over 24 hours for the 9 agroclimatological areas are presented in table 15 (expressed in mm water equivalent, for respectively open water, wet bare soil and cropped soil with full cover). These data show only very slight variation in the Delta, caused by difference in vapour pressure. Net radiation decreases with latitude due to great energy losses under the conditions of clear sky, high temperature and low vapour pressure.

E v a p o r a t i o n . Evaporation from a free water surface was calculated with the formula of Penman. The results are given in table 16. The results show a gradual increase in open water evaporation with latitude. The differences are not very large, however, giving a similar picture as Blaney and Criddle's consumptive use factor F. The relationship between the calculated E_o and measured Class-A pan data at Giza is presented in Fig. 3, showing that the ratio between Class-A pan and E_o is in the order of 1.5 to 1.6. This ratio has been found in various other arid countries. Some available data from Sudan seems to give a ratio in the order of 1.7 to 1.8. As no other Class-A pan data were available at other locations, no confirmation could be obtained whether this ratio changes with latitude. It is recommended that Class-A pans are installed at more sites, in order to check the results now obtained.

It is obvious that E_o data do not reflect crop water requirements without introducing experimentally determined crop coefficients. The coefficients given by Penman only hold for very short crops under the meteorological conditions of a temperate humid climate.

CALCULATION OF CROP WATER USE

G e n e r a l a p p r o a c h

Recent investigations for both humid and arid climatic conditions have shown that real evapotranspiration can be calculated using the combined energy balance - vapour transport method. The general equation is (RIJTEMA, 1965 1969):

$$E_{re} = \frac{\delta H_{nt} + \gamma\, f(z_o,d)\, u^{0.75}(\varepsilon_a - e_a)}{\delta + \gamma\{1 + f(z_o,d)\, u^{0.75}\, r_c\}} \qquad (7)$$

where E_{re} = real evapotranspiration in $mm.day^{-1}$

δ = slope temperature - vapour pressure curve in $mbar.^oC^{-1}$

H_{nt} = net radiation in $mm.day^{-1}$ = $\{(1 - \alpha)H_{sh} - {}^{nt}H_{lo}\}$

α = reflection coefficient

H_{sh} = global radiation in $cal.day^{-1}.cm^{-2}$

${}^{nt}H_{lo}$ = net longwave radiation in $cal.day^{-1}.cm^{-2}$

γ = psychrometer constant in $mbar.^oC^{-1}$

$f(z_o,d)u^{0.75}$ = vapour transport coefficient in $mm.day^{-1}.mbar^{-1}$

z_o = roughness length of the evaporating surface in cm

d = zero-plane displacement in relation to earth surface in cm

u = wind velocity at 2 m height in $cm.s^{-1}$

ε_a = saturated vapour pressure in mbar at mean air temperature

e_a = actual vapour pressure in mbar
r_c = surface diffusion resistance in mbar.day.mm^{-1}

This equation is very similar to Penman's equation. The major differences are:

- differences in reflection coefficient (albedo),
- effect of crop roughness in relation to crop height,
- introduction of a surface diffusion resistance related to soil cover and soil moisture conditions.

Maximum water use

With full cover

The so-called maximum atmospheric evaporative demand can be calculated from equation (7) assuming the surface diffusion resistance to equal zero, which means that the evaporating surface behaves as a wet surface. Under this assumption equation (7) reduces for the calculation of maximum water use by full cover crops to:

$$E_{max} = \frac{\delta H_{nt} + \gamma\, f(z_o,d)\, u^{0.75}(\epsilon_a - e_a)}{\delta + \gamma} \qquad (8)$$

Combination of equation (7) and (8) leads to a simplified expression for the calculation of actual evapotranspiration in cases of partial soil cover:

$$E_{re} = \frac{\delta + \gamma}{\delta + \gamma\{1 + f(z_o,d)\, u^{0.75}\, r_c\}} E_{max} \qquad (9)$$

In the formulae various factors are present which are related to properties of the evaporating surface. The data used in the present study are given below.

Albedo of the evaporating surface. Although the albedo is by no means a constant, because it varies with season, time of day and colour of the evaporating surface, in the present study it will be considered as a constant since evapotranspiration will be calculated as long time mean value. Therefore the following values will be used:

open water : 0.05
cropped surface: 0.24
wet bare soil : 0.15

Vapour transport coefficient. The vapour transport coefficient $f(z_o,d)u^{0.75}$ depends on both crop roughness and wind velocity. Data of $f(z_o,d)$ based on investigations on grass (RIJTEMA, 1965) and later tested on different crops under both humid and arid climatic conditions (RIJTEMA, 1965, 1969; FEDDES, 1971; SLABBERS, 1970), in relation to crop height are given in table 17. The relation between wind velocity in m.s^{-1} at 2 m height and $u^{0.75}$ is given in table 18.

Calculated potential evapotranspiration values. Maximum water use by a full cover crop (grass) with a height of 10 cm in various areas of Egypt is presented in Fig. 4. The marked difference between Kharga and Dakhla is mainly due to differences in vapour transport coefficient (wind).

Table 17. Values of $f(z_o,d)$ in relation to crop height when using 24-hour mean vapour pressure deficits in mbar. The values must be divided by 0.75 when the vapour pressure deficits are expressed in mmHg

Crop height cm	0	1	2	3	4	5	6	7	8	9
0	0.15	0.17	0.19	0.26	0.33	0.39	0.43	0.47	0.51	0.56
10	0.60	0.62	0.64	0.66	0.68	0.70	0.72	0.74	0.76	0.78
20	0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89
30	0.90	0.91	0.92	0.92	0.93	0.94	0.95	0.95	0.96	0.97
40	0.98	0.99	0.99	1.00	1.01	1.02	1.02	1.03	1.04	1.05
50	1.05	1.06	1.07	1.07	1.08	1.09	1.09	1.10	1.10	1.11
60	1.11	1.12	1.12	1.13	1.13	1.14	1.14	1.15	1.15	1.16
70	1.17	1.17	1.18	1.18	1.19	1.19	1.19	1.20	1.20	1.20
80	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.23	1.23	1.23
90	1.24	1.24	1.24	1.24	1.24	1.24	1.25	1.25	1.25	1.25

Table 18. Values of $u^{0.75}$ in relation to wind velocity at 2 m height (u)

u $m.s^{-1}$	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	0.00	0.12	0.24	0.36	0.48	0.59	0.68	0.76	0.84	0.92
1	1.00	1.07	1.14	1.21	1.28	1.35	1.42	1.49	1.56	1.62
2	1.68	1.75	1.81	1.87	1.93	1.99	2.05	2.11	2.17	2.23
3	2.28	2.34	2.40	2.46	2.51	2.56	2.62	2.68	2.70	2.78
4	2.80	2.89	2.94	2.99	3.04	3.09	3.14	3.19	3.24	3.29
5	3.34	3.39	3.44	3.49	3.54	3.59	3.64	3.69	3.74	3.79
6	3.84	3.89	3.94	3.99	4.03	4.07	4.12	4.17	4.22	4.27
7	4.31	4.36	4.40	4.44	4.48	4.52				

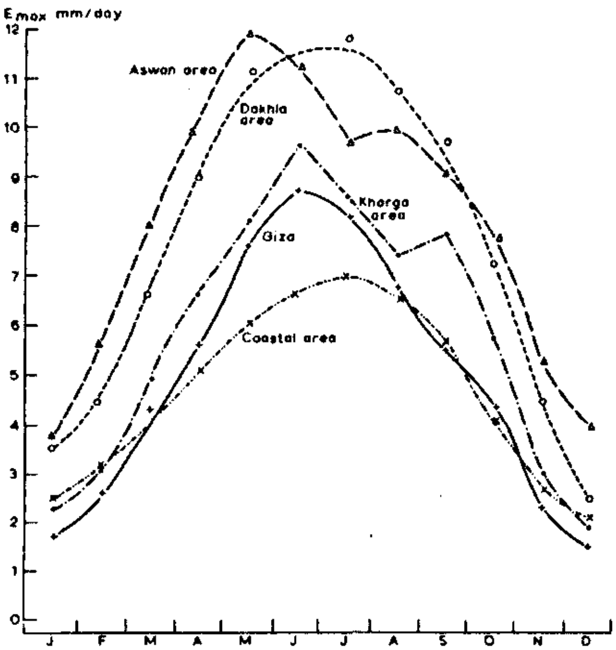


Fig. 4. Calculated potential evapotranspiration (E_{max}) for grass, height 10 cm, in various areas in Egypt

With partial cover

Reductions in actual evapotranspiration as compared to atmospheric evaporative demand occur as soon as the surface resistance does not equal zero. The magnitude of the surface resistance is determined by soil cover and water supply conditions of the crop. In the present study no attention will be given to the influence of moisture stress conditions on the value of the surface resistance, however, as the required information necessary for such calculations is missing.

The effect of soil cover on the evaporation rate strongly depends on the moisture conditions of the topsoil. Under wet topsoil conditions the reducing influence of soil cover on evapotranspiration is almost completely compensated for by the evaporation from the bare soil. With increasing dessication of the soil, evaporation is reduced by the dry top layer. As the value of r_c in relation to soil cover appeared to be practically independent of the type of crop (RIJTEMA, 1969; FEDDES, 1971), the data given in table 19 have been used in the present study. When working on basis of vapour pressure deficits in mmHg, the given data must be multiplied by 0.75.

For first predictions of evapotranspiration as long term mean values for irrigated fields, the top-

Table 19. Relationship between r_c in $mbar.day.mm^{-1}$ and the fraction of soil cover for two moisture conditions of the topsoil

Topsoil condition	Soil cover fraction										
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Medium dry	4.48	3.11	2.30	1.69	1.21	0.80	0.46	0.25	0.11	0.00	0.00
Dry	9.46	6.31	4.48	3.17	2.28	1.58	1.05	0.55	0.23	0.11	0.00

soil conditions were considered medium dry. For wet topsoil conditions during and directly after irrigation and for wet topsoil conditions of rice fields a correction was applied based on the evaporation from wet soils, using the following relation (see also eq. (9)):

$$E = \frac{\delta + \gamma}{\delta + \gamma(1 + f(z_o,d)u^{0.75}\ r_c)} E_{max} + \left(1 - \frac{\delta + \gamma}{\delta + \gamma(1 + f(z_o,d)u^{0.75}\ r_c)} E_s\right) \quad (10)$$

where E_{max} is the maximum evapotranspiration from a full cover crop (see eq. (8)) and E_s the evaporation from wet bare soil.

Tables of atmospheric evaporative demand

Tables of evaporative demand have been prepared for the different agroclimatological zones, based on the general level of the meteorological conditions. The tables 20 through 28 have been set up in such a way that they can be easily adjusted to particular local conditions.

The first part of each table gives the standardized meteorological data of temperature, vapour pressure deficit and wind velocity of the agroclimatological zone, as used in the calculation of maximum evaporative demand.

The second part gives the mean monthly values of $\frac{\delta}{\delta + \gamma} H_{nt2}$ and $\frac{\delta}{\delta + \gamma} H_{nt3}$ of wet bare soil and cropped surfaces with full soil cover. As these values vary only slightly throughout the country, it may be assumed that the given values are constant in a given agroclimatological zone.

The third part contains the vapour transport term $\frac{\delta}{\delta + \gamma} f(z_o,d)u^{0.75} (\varepsilon_a - e_a)$ for crop heights varying from zero (bare soil) to 90 cm. For taller crops it is assumed that the calculated values for 90 cm also hold, as $f(z_o,d)$ becomes almost constant at that height. The magnitude of the vapour transport strongly depends on wind velocity and vapour pressure deficit. For local conditions with deviating wind velocity or vapour pressure deficit or both this term is to be adjusted. The procedure to be used is given underneath.

The fourth part of the table gives the calculated mean monthly maximum evaporative demand of the agroclimatological zone in dependence of crop height. The data at zero crop height refer to evaporation from wet bare soil.

The reduction factors to be used in cases of partial soil cover are given in the fifth part of the table. The data are given for the winter and the summer half year. The data at zero soil cover refer to the evaporation from medium dry soils.

The tables can easily be adjusted to particular local conditions, making the following assumptions:

- the given values of $\frac{\delta}{\delta + \gamma} H_{nt2}$ and $\frac{\delta}{\delta + \gamma} H_{nt3}$ do not change within the agroclimatological zone,
- the reduction factors for partial soil cover can be used throughout the given agroclimatological zone.

The error introduced in the calculated maximum evaporative demand by both assumptions is not very large. The mentioned quantities vary only slightly within any given zone. The main effect of particular local conditions on maximum evaporations occurs in the vapour transport term. Calculating now for local conditions the term $u^{0.75}(\varepsilon_a - e_a)$ and dividing this value by the corresponding term of the standardized zone data yields the correction factor for the vapour transport term. Multiplying the values of $\frac{\gamma}{\delta + \gamma} f(z_o,d)u^{0.75} (\varepsilon_a - e_a)$ by this correction factor and adding the corresponding value of $\frac{\delta}{\delta + \gamma} H_{nt2}$ at zero crop height or $\frac{\delta}{\delta + \gamma} H_{nt3}$ respectively gives the adjusted maximum evaporation data for the given location. An example of the calculation of the correction term for the local conditions at Mallawi Station and its influence on the maximum evapotranspiration of a 90 cm tall crop is given in table 29.

Table 20. Atmospheric evaporative demand in the Coastal area

STANDARDIZED METEOROLOGICAL DATA

	J	F	M	A	M	J	J	A	S	O	N	D
T °C	13.7	14.2	15.9	18.3	21.4	24.3	26.0	26.6	25.3	22.7	19.4	15.5
$(\varepsilon_a - e_a)$ mmHg	2.7	3.1	3.7	4.3	4.7	4.8	4.8	5.2	5.7	5.0	3.6	2.8
u_{200} m.s^{-1}	3.0	3.1	3.2	2.9	2.8	2.8	3.0	2.7	2.5	2.2	2.3	2.8
$u^{0.75}(\varepsilon_a - e_a)$	6.15	7.26	8.88	9.60	10.21	10.41	10.94	10.98	11.33	9.05	6.73	6.08

NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES

	J	F	M	A	M	J	J	A	S	O	N	D
$\frac{\delta}{\delta+\gamma}H_{nt2}$	0.81	1.26	2.08	3.07	4.31	5.21	5.67	5.21	4.05	2.69	1.42	0.62
$\frac{\delta}{\delta+\gamma}H_{nt3}$	0.55	0.95	1.67	2.54	3.66	4.48	4.91	4.50	3.46	2.22	1.09	0.39

VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta+\gamma} f(z_o,d)u^{0.75}(\varepsilon_a - e_a)$

	J	F	M	A	M	J	J	A	S	O	N	D
0 cm crop height	0.49	0.57	0.66	0.65	0.61	0.56	0.55	0.53	0.59	0.51	0.43	0.45
10	1.97	2.26	2.62	2.60	2.44	2.25	2.19	2.11	2.36	2.02	1.72	1.80
20	2.63	3.03	3.51	3.49	3.28	3.01	2.93	2.82	3.16	2.71	2.30	2.41
30	2.95	3.40	3.94	3.91	3.68	3.37	3.29	3.17	3.54	3.04	2.58	2.70
40	3.22	3.71	4.30	4.27	4.01	3.68	3.59	3.46	3.86	3.31	2.82	2.95
50	3.45	3.96	4.60	4.57	4.29	3.94	3.84	3.70	4.13	3.54	3.01	3.15
60	3.64	4.19	4.86	4.83	4.53	4.16	4.06	3.91	4.37	3.74	3.18	3.33
70	3.84	4.41	5.11	5.09	4.77	4.38	4.27	4.12	4.60	3.94	3.35	3.51
80	3.96	4.56	5.28	5.25	4.92	4.52	4.41	4.25	4.75	4.07	3.46	3.62
90	4.06	4.66	5.41	5.38	5.05	4.63	4.52	4.35	4.86	4.17	3.54	3.71

MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN MM.DAY^{-1}

	J	F	M	A	M	J	J	A	S	O	N	D
0 cm crop height	1.30	1.83	2.74	3.72	4.92	5.77	6.22	5.74	4.64	3.20	1.85	1.07
10	2.52	3.21	4.29	5.14	6.10	6.73	7.10	6.61	5.82	4.24	2.81	2.19
20	3.18	3.98	5.18	6.03	6.94	7.49	7.84	7.32	6.62	4.93	3.39	2.80
30	3.50	4.35	5.61	6.45	7.34	7.85	8.20	7.67	7.00	5.26	3.67	3.09
40	3.77	4.66	5.97	6.81	7.67	8.16	8.50	7.96	7.32	5.53	3.91	3.34
50	4.00	4.91	6.27	7.11	7.95	8.42	8.75	8.20	7.59	5.76	4.10	3.54
60	4.19	5.14	6.53	7.37	8.19	8.64	8.97	8.41	7.83	5.96	4.27	3.72
70	4.39	5.36	6.78	7.63	8.43	8.86	9.18	8.62	8.06	6.16	4.44	3.90
80	4.51	5.55	6.95	7.79	8.58	9.00	9.32	8.75	8.21	6.29	4.55	4.01
90	4.61	5.61	7.08	7.92	8.71	9.11	9.43	8.85	8.32	6.39	4.66	4.10

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.27	0.34	0.41	0.49	0.57	0.67	0.78	0.86	0.94	1.00	1.00
Summer	0.32	0.40	0.47	0.55	0.63	0.72	0.82	0.89	0.75	1.00	1.00

Table 21. Atmospheric evaporative demand in the Central Delta area

	J	F	M	A	M	J	J	A	S	O	N	D
STANDARDIZED METEOROLOGICAL DATA												
$T\ ^{o}C$	11.9	12.3	15.2	17.7	21.4	25.6	25.8	25.8	24.0	21.9	18.2	13.7
$(\epsilon_a - e_a)$ mmHg	1.7	2.7	3.4	5.4	8.0	8.8	5.6	5.2	5.2	4.9	3.2	2.4
$u_{200}\ m.s^{-1}$	2.5	2.8	2.7	2.7	2.4	2.2	1.7	1.3	1.5	1.6	2.0	2.5
$u^{0.75}\ (\epsilon_a - e_a)$	3.38	5.86	7.18	11.40	15.42	15.92	8.35	6.29	7.02	6.96	5.38	4.78
NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES												
$\frac{\delta}{\delta + \gamma} H_{nt2}$	0.70	1.12	2.04	2.95	3.88	5.10	5.33	5.00	3.83	2.61	1.27	0.55
$\frac{\delta}{\delta + \gamma} H_{nt3}$	0.45	0.82	1.63	2.42	3.23	4.35	4.59	4.30	3.22	2.03	0.95	0.32
VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta + \gamma} f(z_o,d)u^{0.75}\ (\epsilon_a - e_a)$												
0 cm crop height	0.32	0.49	0.53	0.77	0.94	0.80	0.49	0.32	0.38	0.40	0.24	0.38
10	1.30	1.97	2.12	3.10	3.72	3.18	1.97	1.26	1.52	1.62	1.15	1.53
20	1.73	2.63	2.83	4.14	4.97	4.26	2.65	1.69	2.00	2.16	1.54	2.04
30	1.94	2.95	3.18	4.65	5.58	4.78	2.95	1.90	2.28	2.42	1.73	2.29
40	2.12	3.22	3.47	5.07	6.09	5.21	3.22	2.07	2.49	2.65	1.86	2.50
50	2.27	3.44	3.71	5.41	6.50	5.57	3.44	2.21	2.66	2.83	2.02	2.69
60	2.40	3.64	3.92	5.73	6.94	5.90	3.64	2.34	2.82	2.99	2.13	2.83
70	2.53	3.84	4.13	6.03	7.25	6.21	3.84	2.46	2.96	3.15	2.25	2.98
80	2.61	3.96	4.27	6.23	7.49	6.41	3.96	2.54	3.06	3.25	2.32	3.07
90	2.67	4.06	4.37	6.38	7.66	6.56	4.06	2.60	3.13	3.33	2.38	3.15
MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$												
0 cm crop height	1.02	1.61	2.57	3.72	4.82	5.90	5.82	5.32	4.21	3.01	1.56	0.93
10	1.75	2.79	3.75	5.52	6.95	7.53	6.56	5.56	4.74	3.65	2.10	1.85
20	2.18	3.45	4.46	6.56	8.20	8.61	7.24	5.99	5.25	4.19	2.49	2.36
30	2.39	3.77	4.81	7.07	8.81	9.13	7.54	6.20	5.50	4.45	2.68	2.61
40	2.57	4.04	5.10	7.49	9.32	9.56	7.81	6.37	5.71	4.68	2.81	2.82
50	2.72	4.26	5.34	7.83	9.73	9.92	8.03	6.51	5.88	4.86	2.97	3.01
60	2.85	4.46	5.55	8.15	10.17	10.25	8.23	6.64	6.04	5.02	3.08	3.15
70	2.28	4.66	5.76	8.45	10.48	10.56	8.43	6.76	6.18	5.18	3.20	3.30
80	3.06	4.78	5.29	8.65	10.72	10.76	8.55	6.84	6.28	5.28	3.27	3.39
90	3.12	4.88	6.00	8.80	10.89	10.91	8.65	6.90	6.35	5.36	3.33	3.47

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.28	0.35	0.43	0.50	0.58	0.66	0.78	0.87	0.94	1.00	1.00
Summer	0.38	0.47	0.54	0.62	0.69	0.78	0.86	0.91	0.96	1.00	1.00

Table 22. Atmospheric evaporative demand in the Desert Delta area

STANDARDIZED METEOROLOGICAL DATA												
	J	F	M	A	M	J	J	A	S	O	N	D
T °C	13.2	13.8	17.3	19.3	22.7	26.4	26.8	27.0	24.9	22.3	18.6	14.5
$(\varepsilon_a - e_a)$ mmHg	3.2	3.9	5.1	6.7	9.1	10.5	8.0	7.7	6.9	5.2	3.1	3.3
u_{200} $m.s^{-1}$	3.1	3.6	3.8	3.6	3.6	3.3	3.0	2.5	2.4	2.4	2.5	3.0
$u^{0.75}(\varepsilon_a - e_a)$	7.49	10.22	13.91	17.55	23.82	25.81	18.23	15.33.	13.31	10.03	6.17	7.52
NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES												
$\frac{\delta}{\delta+\gamma}H_{nt2}$	0.68	1.11	2.11	3.00	3.95	4.90	5.38	4.93	3.87	2.68	1.37	0.53
$\frac{\delta}{\delta+\gamma}H_{nt3}$	0.42	0.81	1.69	2.46	3.28	4.22	4.62	4.23	3.25	2.10	1.03	0.33
VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta+\gamma} f(z_o,d)u^{0.75}(\varepsilon_a - e_a)$												
0 cm crop height	0.60	0.82	0.97	1.12	1.34	1.29	0.87	0.74	0.69	0.58	0.41	0.59
10	2.40	3.27	3.90	4.48	5.34	5.15	3.50	2.95	2.78	2.34	1.62	2.34
20	3.21	4.38	5.21	5.99	7.14	6.90	4.67	3.88	3.71	3.12	2.17	3.14
30	3.60	4.91	5.85	6.72	8.00	7.75	5.25	4.34	4.16	3.50	2.44	3.52
40	3.93	5.36	6.38	7.34	8.74	8.45	5.72	4.84	4.55	3.82	2.66	3.84
50	4.20	5.73	6.82	7.84	9.34	9.03	6.11	5.16	4.06	4.09	2.84	4.10
60	4.44	6.06	7.21	8.30	9.87	9.55	6.47	5.46	5.14	4.32	3.00	4.26
70	4.68	6.38	7.60	8.71	10.40	10.08	6.82	5.75	5.41	4.56	3.17	4.57
80	4.83	6.59	7.85	9.02	10.72	10.39	7.04	5.82	5.59	4.70	3.27	4.72
90	4.96	6.76	8.05	9.25	11.20	10.65	7.22	6.10	5.74	4.82	3.36	4.84
MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$												
0 cm crop height	1.28	1.93	3.08	4.12	5.29	6.19	6.25	5.67	4.56	3.26	1.78	1.12
10	2.82	4.08	5.59	6.94	8.62	9.37	8.12	7.18	6.03	4.44	2.65	2.65
20	3.63	5.19	6.90	8.45	10.42	11.12	9.29	7.11	6.96	5.22	3.20	3.45
30	4.02	5.72	7.54	9.18	11.28	11.97	9.87	8.57	7.41	5.60	3.47	3.83
40	4.35	6.17	8.07	9.80	12.02	12.67	10.34	9.07	7.80	5.92	3.69	4.15
50	4.62	6.54	8.51	10.30	12.62	13.25	10.73	9.39	8.11	6.19	3.87	4.41
60	4.86	6.87	8.90	10.76	13.15	13.77	11.09	9.69	8.39	6.42	4.03	4.67
70	5.10	7.19	9.29	11.20	13.68	14.30	11.44	9.98	8.66	6.66	4.20	4.88
80	5.25	7.40	9.54	11.48	14.00	14.61	11.66	10.05	8.84	6.80	4.30	5.03
90	5.38	7.57	9.74	11.71	14.48	14.87	11.84	10.33	8.99	6.92	4.39	5.15

REDUCTION FACTOR											
Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.25	0.32	0.39	0.47	0.55	0.65	0.76	0.85	0.93	1.00	1.00
Summer	0.29	0.38	0.45	0.52	0.61	0.70	0.80	0.88	0.94	1.00	1.00

Table 23. Atmospheric evaporative demand in the Giza area

STANDARDIZED METEOROLOGICAL DATA

	J	F	M	A	M	J	J	A	S	O	N	D
T °C	12.3	13.6	16.4	19.9	23.3	26.5	27.0	26.8	25.3	22.8	18.6	14.1
$(\varepsilon_a - e_a)$ mmHg	2.1	2.9	4.6	5.9	8.7	10.1	8.9	7.0	6.6	5.4	3.0	2.6
u_{200} $m.s^{-1}$	2.0	2.1	2.4	2.4	2.7	2.9	2.7	2.1	1.9	2.2	1.9	1.8
$u^{0.75}$ $(\varepsilon_a - e_a)$	3.53	5.07	8.88	11.89	18.34	22.52	18.77	12.23	10.70	9.76	1.86	4.06

NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES

	J	F	M	A	M	J	J	A	S	O	N	D
$\frac{\delta}{\delta + \gamma} H_{nt2}$	0.80	1.32	2.23	3.25	4.11	4.73	5.38	5.11	4.01	2.77	1.55	0.69
$\frac{\delta}{\delta + \gamma} H_{nt3}$	0.56	0.99	1.78	2.70	3.46	4.32	4.62	4.41	3.39	2.29	1.19	0.44

VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta + \gamma} f(z_o,d) u^{0.75} (\varepsilon_a - e_a)$

	J	F	M	A	M	J	J	A	S	O	N	D
0 cm crop height	0.30	0.40	0.64	0.73	1.03	1.13	0.90	0.59	0.56	0.55	0.32	0.32
10	1.181	1.58	2.56	2.92	4.11	4.51	3.61	2.35	2.22	2.19	1.28	1.26
20	1.58	2.12	3.43	3.90	5.50	6.03	4.82	3.14	2.98	2.93	1.71	1.69
30	1.78	2.38	3.84	4.37	6.17	6.75	5.41	3.52	3.34	3.38	1.92	1.89
40	1.94	2.59	4.19	4.77	6.73	7.37	5.90	3.85	3.64	3.59	2.10	2.07
50	2.07	2.77	4.48	5.10	7.20	7.88	6.31	4.12	3.89	3.84	2.24	2.21
60	2.19	2.93	4.73	5.39	7.61	8.33	6.66	4.35	4.11	4.06	2.37	2.34
70	2.31	3.09	4.99	5.68	8.02	8.80	7.03	4.59	4.34	4.27	2.50	2.37
80	2.38	3.19	5.15	5.86	8.27	9.07	7.26	4.73	4.47	4.41	2.58	2.54
90	2.44	3.26	5.28	6.00	8.48	9.28	7.44	4.85	4.59	4.52	2.64	2.60

MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$

	J	F	M	A	M	J	J	A	S	O	N	D
0 cm crop height	1.10	1.72	2.87	3.98	5.14	5.86	6.28	5.70	4.57	3.32	1.87	1.01
10	1.74	2.57	4.34	5.62	7.57	8.80	8.23	6.76	5.61	4.48	2.47	1.70
20	2.14	3.11	5.21	6.60	8.96	10.35	9.44	7.55	6.37	5.22	2.90	2.13
30	2.34	3.37	5.62	7.07	9.63	11.07	10.03	7.93	6.73	5.57	3.11	2.33
40	2.50	3.58	5.97	7.47	10.19	11.69	10.52	8.26	7.03	5.88	3.29	2.51
50	2.63	3.76	6.26	7.80	10.66	12.20	10.93	8.53	7.28	6.13	3.43	2.65
60	2.75	3.92	6.51	8.09	11.07	12.65	11.28	8.76	7.50	6.35	3.56	2.78
70	2.87	4.08	6.77	8.38	11.48	13.12	11.65	9.00	7.73	6.56	3.69	2.81
80	2.94	4.18	6.93	8.56	11.73	13.39	11.88	9.14	7.86	6.70	3.77	2.98
90	3.00	4.25	7.06	8.70	11.94	13.60	12.06	9.26	7.98	6.81	3.83	3.04

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.31	0.39	0.47	0.54	0.63	0.71	0.81	0.89	0.95	1.00	1.00
Summer	0.35	0.43	0.51	0.59	0.66	0.75	0.84	0.90	0.96	1.00	1.00

Table 24. Atmospheric evaporative demand in the Area latitude 29° - 27.5° N

STANDARDIZED METEOROLOGICAL DATA

	J	F	M	A	M	J	J	A	S	O	N	D
T °C	12.9	14.2	17.0	21.0	25.2	27.3	28.4	28.5	26.4	23.8	19.2	14.9
$(\varepsilon_a - e_a)$mmHg	4.0	5.1	7.1	10.3	14.3	15.5	14.5	13.6	11.0	10.1	6.4	3.8
u_{200} $m.s^{-1}$	1.0	1.2	1.2	1.4	1.5	1.6	1.2	1.2	1.4	1.4	1.2	1.3
$u^{0.75}(\varepsilon_a - e_a)$	4.00	5.81	8.10	13.19	19.30	22.00	16.52	15.50	14.09	12.92	7.20	4.60

NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES

	J	F	M	A	M	J	J	A	S	O	N	D
$\frac{\delta}{\delta+\gamma}H_{nt2}$	0.90	1.42	2.37	3.36	4.16	4.96	5.39	5.04	4.27	2.78	1.51	0.79
$\frac{\delta}{\delta+\gamma}H_{nt3}$	0.58	1.02	1.85	2.72	3.42	4.10	4.54	4.25	3.56	2.23	1.12	0.49

VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta+\gamma} f(z_o,d)u^{0.75}(\varepsilon_a - e_a)$

	J	F	M	A	M	J	J	A	S	O	N	D
0 cm crop height	0.33	0.45	0.57	0.79	1.01	1.06	0.76	0.71	0.73	0.70	0.47	0.35
10	1.31	1.81	2.26	3.17	4.02	4.23	3.05	2.86	2.94	2.79	1.87	1.40
20	1.75	2.43	3.03	4.24	5.37	5.65	4.08	3.82	3.93	3.74	2.50	1.87
30	1.97	2.72	3.40	4.75	6.03	6.34	4.57	4.28	4.41	4.19	2.81	2.10
40	2.15	2.98	3.71	5.19	6.58	6.82	5.00	4.68	4.82	4.57	3.07	2.29
50	2.30	3.18	3.96	5.55	7.04	7.39	5.34	5.00	5.15	4.88	3.28	2.45
60	2.43	3.36	4.19	5.86	7.44	7.81	5.64	5.29	5.45	5.16	3.46	2.59
70	2.56	3.54	4.41	6.17	7.83	8.24	5.94	5.56	5.74	5.44	3.65	2.73
80	2.64	3.66	4.56	6.37	8.09	8.51	6.14	5.75	5.92	5.62	3.77	2.82
90	2.70	3.74	4.67	6.54	8.30	8.71	6.29	5.89	6.07	5.76	3.86	2.89

MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$

	J	F	M	A	M	J	J	A	S	O	N	D
0 cm crop height	1.23	1.87	2.94	4.15	5.17	6.02	6.15	5.75	5.00	3.48	1.98	1.14
10	1.89	2.83	4.11	5.89	7.44	8.33	7.59	7.11	6.50	5.02	2.99	1.89
20	2.33	3.45	4.88	6.96	8.79	9.75	8.62	8.07	7.49	5.97	3.62	2.36
30	2.55	3.74	5.25	7.47	9.45	10.44	9.11	8.53	7.97	6.42	3.93	2.59
40	2.73	4.00	5.56	7.91	10.00	10.92	9.54	8.93	8.38	6.80	4.19	2.78
50	2.88	4.20	5.81	8.27	10.46	11.49	9.88	9.25	8.71	7.11	4.40	2.94
60	3.01	4.38	6.04	8.58	10.86	11.91	10.18	9.54	9.01	7.39	4.58	3.08
70	3.14	4.56	6.26	8.89	11.25	12.34	10.48	9.81	9.30	7.67	4.77	3.22
80	3.22	4.68	6.41	9.09	11.51	12.61	10.68	10.00	9.48	7.85	4.89	3.31
90	3.28	4.76	6.52	9.26	11.72	12.81	10.83	10.14	9.63	7.99	4.98	3.38

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.40	0.49	0.56	0.64	0.71	0.79	0.86	0.92	0.96	1.00	1.00
Summer	0.46	0.55	0.62	0.60	0.76	0.83	0.89	0.94	0.97	1.00	1.00

Table 25. Atmospheric evaporative demand in the Area latitude 27.5° - 26° N

STANDARDIZED METEOROLOGICAL DATA

	J	F	M	A	M	J	J	A	S	O	N	D
T °C	13.6	16.8	18.6	23.4	27.2	28.8	29.0	29.4	27.3	24.9	20.6	15.9
$(\varepsilon_a - e_a)$ mmHg	4.2	5.3	7.1	12.1	16.7	16.2	16.0	15.0	11.9	9.4	6.2	4.3
u_{200} $m.s^{-1}$	1.4	1.6	1.8	1.8	1.8	2.0	1.5	1.6	1.8	1.1	1.2	1.3
$u^{0.75}(\varepsilon_a - e_a)$	5.38	7.52	11.08	18.88	26.05	27.20	21.60	21.30	18.57	10.05	7.07	5.20

NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES

$\frac{\delta}{\delta+\gamma}H_{nt2}$	1.12	1.88	2.76	3.57	4.27	5.36	5.34	5.14	4.32	3.22	1.89	1.11
$\frac{\delta}{\delta+\gamma}H_{nt3}$	0.75	1.45	2.20	2.89	3.50	4.51	4.48	4.32	3.63	2.63	1.44	0.78

VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta+\gamma} f(z_o,d)u^{0.75}(\varepsilon_a - e_a)$

0 cm crop height	0.42	0.54	0.73	1.06	1.25	1.20	0.95	0.94	0.89	0.52	0.44	0.38
10	1.68	2.16	2.92	4.22	5.00	4.78	3.80	3.75	3.57	2.10	1.75	1.54
20	2.16	2.90	3.90	5.65	6.69	6.40	5.09	5.02	4.77	2.80	2.34	2.06
30	2.52	3.25	4.38	6.34	7.50	7.18	5.70	5.63	5.35	3.14	2.63	2.30
40	2.75	3.55	4.78	6.91	8.19	7.84	6.22	6.15	5.85	3.43	2.87	2.52
50	2.94	3.79	5.11	7.39	8.75	8.37	6.65	6.56	6.24	3.67	3.06	2.69
60	3.10	4.00	5.40	7.81	9.25	8.85	7.04	6.94	6.60	3.88	3.24	2.84
70	3.27	4.22	5.70	8.24	9.75	9.32	7.41	7.32	6.95	4.08	3.42	2.99
80	3.38	4.36	5.88	8.50	10.08	9.63	7.65	7.55	7.18	4.22	3.52	3.09
90	3.46	4.47	6.03	8.72	10.31	9.87	7.85	7.74	7.36	4.32	3.62	3.17

MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$

0 cm crop height	1.54	2.42	3.49	4.63	5.52	6.56	6.29	6.08	5.21	3.74	2.33	1.49
10	2.43	3.61	5.12	7.11	8.50	9.29	8.28	8.07	7.20	4.73	3.19	2.32
20	2.91	4.35	6.10	8.54	10.19	10.91	9.57	9.34	8.40	5.43	3.78	2.84
30	3.27	4.70	6.58	9.23	11.00	11.69	10.18	9.95	8.98	5.77	4.07	3.08
40	3.50	5.00	6.98	9.80	11.69	12.35	10.70	10.47	9.48	6.06	4.31	3.30
50	3.69	5.24	7.31	10.26	12.25	12.88	11.13	10.88	9.87	6.30	4.50	3.47
60	3.85	5.45	7.60	10.60	12.75	13.26	11.52	11.26	10.23	6.51	4.68	3.62
70	4.02	5.67	7.90	11.13	13.25	13.83	11.89	11.64	10.58	6.71	4.86	3.77
80	4.13	5.81	8.08	11.39	13.58	14.14	12.13	11.87	10.81	6.85	4.96	3.87
90	4.21	5.92	8.23	11.61	13.81	14.38	12.33	12.06	10.99	6.95	5.06	3.95

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.41	0.50	0.57	0.65	0.72	0.80	0.87	0.93	0.97	1.00	1.00
Summer	0.43	0.52	0.60	0.67	0.74	0.81	0.88	0.93	0.97	1.00	1.00

Table 26. Atmospheric evaporative demand in the Dakhla area, 26° - 25° N

STANDARDIZED METEOROLOGICAL DATA

	J	F	M	A	M	J	J	A	S	O	N	D
T °C	12.9	14.8	18.6	23.5	28.6	30.4	30.8	30.7	28.2	25.3	19.8	14.4
$(\varepsilon_a - e_a)$mmHg	5.5	6.7	9.8	14.9	21.0	22.5	23.8	22.9	17.6	13.6	8.6	5.7
u_{200} $m.s^{-1}$	1.9	2.0	2.3	2.5	2.7	2.6	2.6	2.4	2.6	2.2	1.8	1.7
$u^{0.75}$ $(\varepsilon_a - e_a)$	8.91	11.26	18.31	29.63	44.30	46.10	48.80	44.20	36.10	24.60	13.41	8.49

NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES

$\frac{\delta}{\delta+\gamma}H_{nt2}$	0.96	1.57	2.46	3.34	3.92	4.68	4.44	4.19	3.86	2.80	1.54	0.93
$\frac{\delta}{\delta+\gamma}H_{nt3}$	0.61	1.12	1.89	2.62	3.14	3.79	3.68	3.36	3.12	2.18	1.20	0.57

VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta+\gamma} f(z_o,d)u^{0.75}$ $(\varepsilon_a - e_a)$

0 cm crop height	0.73	0.86	1.21	1.60	2.03	1.94	2.05	1.86	1.66	1.28	0.86	0.66
10	2.93	3.42	4.84	6.41	8.15	7.76	8.20	7.43	6.64	5.12	3.43	2.65
20	3.92	4.58	6.47	8.57	10.90	10.38	10.97	9.94	8.88	6.85	4.59	3.54
30	4.39	5.14	7.26	9.61	12.21	11.63	12.30	11.13	9.96	7.68	5.15	3.98
40	4.79	5.61	7.92	10.50	13.32	12.70	13.42	12.15	10.88	8.39	5.62	4.33
50	5.12	5.99	8.47	11.21	14.25	13.59	14.35	13.00	11.61	8.96	6.01	4.63
60	5.42	6.34	8.95	11.85	15.08	14.35	15.17	13.72	12.29	9.48	6.35	4.90
70	5.71	6.58	9.44	12.50	15.90	15.12	16.00	14.50	12.95	9.98	6.70	5.16
80	5.90	6.89	9.74	12.90	16.40	15.61	16.50	14.98	13.36	10.30	6.91	5.33
90	6.04	7.06	9.98	13.21	16.80	16.00	16.90	15.32	13.70	10.57	7.09	5.46

MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$

0 cm crop height	1.69	2.43	3.67	4.94	5.95	6.62	6.49	6.05	5.52	4.08	2.40	1.59
10	3.54	4.54	6.73	9.03	11.29	11.55	11.88	10.79	9.76	7.30	4.63	2.62
20	4.53	5.70	8.36	11.19	14.04	14.17	14.65	13.30	12.00	9.03	5.79	4.11
30	5.00	6.26	9.15	12.23	15.35	15.42	15.98	14.49	13.08	9.86	6.35	4.55
40	5.40	6.73	9.81	13.12	16.46	16.49	17.10	15.51	14.00	10.57	6.82	4.90
50	5.73	7.11	10.36	13.83	17.39	17.38	18.03	16.36	14.73	11.14	7.21	5.20
60	6.03	7.46	10.84	14.47	18.22	18.14	18.85	17.08	15.41	11.66	7.55	5.47
70	6.32	7.70	11.83	15.12	19.04	18.91	19.68	17.86	16.07	12.16	7.90	5.73
80	6.51	8.01	11.63	15.52	19.54	19.40	20.18	18.34	16.48	12.48	8.11	5.90
90	6.65	8.18	11.87	15.83	19.94	19.79	20.58	18.68	16.82	12.75	8.29	6.03

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.33	0.41	0.49	0.56	0.64	0.73	0.82	0.90	0.95	1.00	1.00
Summer	0.38	0.47	0.54	0.62	0.69	0.77	0.86	0.92	0.96	1.00	1.00

Table 27. Atmospheric evaporative demand in the Kharga area, 26^o - 25^o N

	J	F	M	A	M	J	J	A	S	O	N	D
STANDARDIZED METEOROLOGICAL DATA												
T ^oC	14.1	15.9	19.7	24.4	29.4	31.0	31.2	31.2	29.0	26.3	20.8	16.1
$(\varepsilon_a - e_a)$mmHg	5.7	7.1	10.4	15.1	21.0	22.5	23.7	22.0	18.1	14.4	9.5	6.1
u_{200} $m.s^{-1}$	0.8	0.9	1.2	1.3	1.4	1.7	1.2	1.1	1.7	1.3	0.9	0.8
$u^{0.75}$ $(\varepsilon_a - e_a)$	4.79	6.53	11.85	18.27	26.90	33.53	27.00	23.55	26.96	17.42	8.73	5.12
NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES												
$\frac{\delta}{\delta + \gamma} H_{nt2}$	1.02	1.64	2.54	3.55	4.30	4.91	4.90	4.62	4.02	2.91	1.54	0.98
$\frac{\delta}{\delta + \gamma} H_{nt3}$	0.66	1.18	1.96	2.83	3.50	4.04	4.02	3.78	3.22	2.28	1.08	0.61
VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta + \gamma} f(z_o,d)u^{0.75} (\varepsilon_a - e_a)$												
0 cm crop height	0.37	0.48	0.76	0.95	1.18	1.41	1.08	0.94	1.19	0.87	0.52	0.38
10	1.50	1.94	3.03	3.80	4.74	5.64	4.33	3.76	4.75	3.59	2.10	1.52
20	2.00	2.59	4.05	5.08	6.33	7.55	5.79	5.04	6.35	4.66	2.80	2.03
30	2.24	2.90	4.55	5.70	7.11	8.46	6.49	5.65	7.14	5.23	3.14	2.28
40	2.45	3.17	4.96	6.22	7.75	9.23	7.08	6.16	7.78	5.71	3.43	2.49
50	2.62	3.39	5.30	6.65	8.29	9.87	7.57	6.59	8.31	6.10	3.67	2.66
60	2.77	3.58	5.61	7.04	8.76	10.43	8.00	6.97	8.80	6.45	3.88	2.81
70	2.92	3.78	5.91	7.41	9.24	11.00	8.44	7.35	9.26	6.80	4.09	2.96
80	3.01	3.90	6.10	7.65	9.53	11.35	8.71	7.59	9.56	7.02	4.22	3.06
90	3.08	3.99	6.25	7.84	9.76	11.62	8.92	7.76	9.80	7.20	4.32	3.13
MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$												
0 cm crop height	1.39	2.12	3.30	4.50	5.48	6.32	5.98	5.56	5.21	3.78	2.06	1.36
10	2.16	3.12	4.99	6.63	8.24	9.68	8.35	7.54	7.97	5.87	3.18	2.13
20	2.66	3.77	6.01	7.91	9.83	11.59	9.81	8.82	9.57	6.94	3.88	2.64
30	2.90	4.08	6.51	8.53	10.61	12.50	10.51	9.43	10.36	7.51	4.22	2.89
40	3.11	4.35	6.92	8.05	11.25	13.27	11.10	9.94	11.00	7.99	4.51	3.10
50	3.28	4.57	7.26	9.48	11.79	13.91	11.59	10.37	11.53	8.38	4.75	3.27
60	3.43	4.76	7.57	9.87	12.26	14.47	12.02	10.75	12.02	8.73	4.96	3.42
70	3.58	4.96	7.87	10.24	12.74	15.04	12.46	11.13	12.48	9.08	5.17	3.57
80	3.67	5.08	8.06	10.48	13.03	15.39	12.73	11.37	12.78	9.30	5.30	3.67
90	3.74	5.17	8.21	10.67	13.26	15.66	12.94	11.54	13.02	9.48	5.40	3.74

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.46	0.56	0.63	0.70	0.76	0.83	0.89	0.94	0.97	1.00	1.00
Summer	0.50	0.59	0.66	0.72	0.99	0.85	0.91	0.94	0.98	1.00	1.00

Table 28. Atmospheric evaporative demand in the Aswan area, 25^{0} - 24^{0} N

STANDARDIZED METEOROLOGICAL DATA

	J	F	M	A	M	J	J	A	S	O	N	D
$T\ ^{0}C$	16.8	18.6	22.4	27.2	31.9	33.6	34.0	34.2	32.0	29.6	24.0	19.8
$(\varepsilon_a - e_a)$ mmHg	8.6	10.5	14.9	20.9	28.2	30.7	30.5	29.8	25.1	20.9	13.1	9.4
$u_{200}\ m.s^{-1}$	1.4	1.9	2.2	2.3	2.5	2.0	1.6	1.8	1.8	1.9	1.7	1.6
$u^{0.75}\ (\varepsilon_a - e_a)$	11.01	17.00	26.96	39.10	56.15	51.60	43.30	46.50	39.15	33.85	19.53	13.34

NET RADIATION TERM FOR BARE SOIL AND CROPPED SURFACES

$\frac{\delta}{\delta + \gamma} H_{nt2}$	1.00	1.61	2.36	3.18	3.56	4.36	4.37	4.19	3.66	2.59	1.72	1.09
$\frac{\delta}{\delta + \gamma} H_{nt3}$	0.60	1.12	1.76	2.44	2.89	3.48	3.49	3.34	2.91	1.96	1.22	0.70

VAPOUR TRANSPORT TERM $\frac{\gamma}{\delta + \gamma} f(z_o,d) u^{0.75} (\varepsilon_a - e_a)$

0 cm crop height	0.79	1.12	1.56	1.88	2.24	1.96	1.56	1.67	1.57	1.49	1.05	0.85
10	3.17	4.49	6.26	7.52	8.98	7.85	6.24	6.70	6.26	5.97	4.22	3.42
20	4.24	5.90	8.27	8.79	12.00	10.50	8.35	8.95	8.38	7.99	5.64	4.57
30	4.75	6.73	9.39	11.29	13.47	11.78	9.36	10.04	9.40	8.95	6.33	5.12
40	5.19	7.35	10.24	12.31	14.70	12.85	10.21	10.96	10.25	9.76	6.90	5.59
50	5.54	7.85	10.95	13.17	15.70	13.70	10.92	11.71	10.95	10.44	7.38	5.98
60	5.86	8.30	11.58	13.90	16.60	14.51	11.52	12.40	11.59	11.05	7.80	6.32
70	6.18	8.75	12.20	14.67	17.51	15.30	12.19	13.05	12.21	11.63	8.22	6.66
80	6.37	9.03	12.60	15.13	18.08	15.80	12.57	13.49	12.60	12.01	8.49	6.88
90	6.53	9.25	12.90	15.50	18.50	16.20	12.88	13.81	12.91	12.30	8.70	7.05

MEAN MONTHLY MAXIMUM EVAPORATIVE DEMAND E_{MAX} IN $MM.DAY^{-1}$

0 cm crop height	1.79	2.73	3.92	5.06	5.80	6.32	5.93	5.86	5.23	4.08	2.77	1.94
10	3.77	5.61	8.02	9.96	11.87	11.33	9.73	10.04	9.17	7.93	5.44	4.12
20	4.84	7.02	10.13	11.23	14.89	13.98	11.84	12.29	11.29	9.95	6.86	5.27
30	5.35	7.85	11.15	13.73	16.36	15.26	12.85	13.38	12.31	10.91	7.55	5.82
40	5.79	8.47	12.00	14.75	17.59	16.33	13.70	14.30	13.16	11.72	8.12	6.29
50	6.14	8.97	12.71	15.61	18.59	17.21	14.41	15.05	13.86	12.40	8.60	6.68
60	6.46	9.42	13.34	16.34	19.49	17.99	14.01	15.74	14.50	13.01	9.02	7.02
70	6.78	9.87	13.96	17.11	20.40	18.78	15.68	16.39	15.12	13.59	9.44	7.36
80	6.97	10.15	14.36	17.57	20.97	19.28	16.06	16.83	15.51	13.97	9.71	7.58
90	7.13	10.37	14.66	17.94	21.39	19.68	16.37	17.15	15.82	14.26	9.92	7.75

REDUCTION FACTOR

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Winter	0.37	0.46	0.53	0.61	0.69	0.77	0.85	0.91	0.26	1.00	1.00
Summer	0.44	0.53	0.60	0.67	0.74	0.81	0.88	0.93	0.97	1.00	1.00

Table 29. Example (for station Mallawi) of calculation of correction factors for adjustment to local conditions

	J	F	M	A	M	J	J	A	S	O	N	D
AGROCLIMATIC AREA LATITUDE 29^{o} - 27.5^{o} N												
u	1.0	1.2	1.2	1.4	1.5	1.6	1.2	1.2	1.4	1.4	1.2	1.3
$u^{0.75}$	1.00	1.14	1.14	1.28	1.35	1.42	1.14	1.14	1.28	1.28	1.14	1.21
$\varepsilon_a - e_a$	4.0	5.1	7.1	10.3	14.3	15.5	14.5	13.6	11.0	10.1	6.4	3.8
$u^{0.75}(\varepsilon_a - e_a)$	4.00	5.81	8.10	13.19	19.30	22.00	16.52	15.50	14.09	12.92	7.30	4.60
LOCAL (MALLAWI)												
u	1.5	1.5	1.8	2.0	3.0	2.5	1.3	1.3	2.0	1.4	1.2	1.3
$u^{0.75}$	1.35	1.35	1.56	1.68	2.28	1.49	1.21	1.21	1.68	1.28	1.14	1.21
$\varepsilon_a - e_a$	2.4	3.3	5.6	8.6	13.2	11.7	9.9	8.0	5.9	5.0	3.1	2.1
$u^{0.75}(\varepsilon_a - e_a)$	3.24	4.45	8.74	14.45	30.50	23.25	11.98	9.68	9.91	6.40	3.53	2.54
$\frac{u^{0.75}(\varepsilon_a - e_a)\text{ LOCAL}}{u^{0.75}(\varepsilon_a - e_a)\text{ AREA}}$	0.81	0.77	1.08	1.09	1.56	1.06	0.73	0.63	0.70	0.50	0.49	0.55
$\frac{\gamma}{\delta + \gamma} f(z_o,d)u^{0.75}(\varepsilon_a - e_a)$ 90 CM CROP, AREA	2.70	3.74	4.67	6.54	8.30	8.71	6.29	5.89	6.07	5.76	3.86	2.89
$\frac{\gamma}{\delta + \gamma} f(z_o,d)u^{0.75}(\varepsilon_a - e_a)$ 90 CM CROP, LOCAL	2.19	2.88	5.05	7.13	12.95	9.23	4.59	3.71	4.25	2.88	1.89	1.59
$\frac{\gamma}{\delta + \gamma} H_{nt3}$ AREA	0.58	1.02	1.85	2.72	3.42	4.10	4.54	4.25	3.56	2.23	1.12	0.49
E_{MAX} 90 CM CROP, LOCAL	2.77	3.90	6.90	9.85	16.37	13.33	9.13	7.96	7.81	5.11	3.01	2.08
E_{MAX} 90 CM CROP, AREA	3.28	4.76	6.52	9.26	11.72	12.81	10.83	10.14	9.63	7.99	4.98	3.38

Actual water use

Transpiration of water by crops may be regarded as being a continuous flow of water caused by potential gradients from the soil through the roots of the plants to the leaves, where it is transformed by energy into water vapour and from there transported into the atmosphere by diffusion caused by vapour pressure gradients. Since transpiration reduces the water content of an initially wet soil, there is a progressive increase in soil moisture suction and hence in the general level of the diffusion pressure deficit of the plant. The diffusion pressure deficit should be greatest in the leaves, since they constitute the final stage of the liquid water pathway. The degree to which the diurnal pressure deficit develops depends on the transpiration rate relative to the absorption of water. On occasions, even when soil water appears to be freely available, the atmospheric evaporative demand can be so high during daytime that temporary water deficits develop, sometimes sufficient to cause visible wilting. Under such conditions reduction in transpiration occurs at high levels of soil water availability.

Simplified approach

In the present study it is assumed that real evapotranspiration equals maximum atmospheric evaporative demand until a certain fraction of the maximum available soil moisture has been depleted. Beyond this, evapotranspiration reductions occur and real evapotranspiration will depend on both remaining available soil moisture and maximum evaporative demand. Under these assumptions the following relations hold:

$$E_{re} = E_{max} = -\frac{dM_t}{dt} \qquad M_t \geq aM_o \tag{11}$$

$$E_{re} = \frac{M_t}{aM_o} E_{max} = -\frac{dM_t}{dt} \qquad M_t \leq aM_o \tag{12}$$

where M_o is the maximum available soil moisture, M_t the available soil moisture at time t and a the fraction of remaining soil moisture at which the reduction in transpiration starts.

Integration of both equations yields:

$$\int_{t=o}^{t=t'} E_{max}\, dt = -\int_{M_o}^{aM_o} dM_t \qquad \text{or}$$

$$E_{max}\, t' = (1 - a)M_o \tag{13}$$

and

$$\int_{t=t'}^{t=t} \frac{E_{max}\, dt}{aM_o} = -\int_{aM_o}^{M_t} \frac{dM_t}{M_t} \qquad \text{or}$$

$$\frac{M_t}{aM_o} = e^{-\frac{E_{max}(t - t')}{aM_o}} \tag{14}$$

Substitution gives:

$$E_{re} = E_{max}\, e^{-\frac{E_{max}(t - t')}{aM_o}} \tag{15}$$

The integrated water use during time t ($t \geq t'$) equals:

$$\int_{t=o}^{t=t} E_{re}\, dt = \int_{t=o}^{t=t'} E_{max}\, dt + \int_{t=t'}^{t=t} E_{max}\, e^{-\frac{E_{max}(t - t')}{aM_o}}\, dt$$

$$= E_{max}\, t' + aM_o \left[1 - e^{-\frac{E_{max}(t - t')}{aM_o}}\right] \tag{16}$$

Substituting for $t' = \frac{(1 - a)M_o}{E_{max}}$ yields:

$$\int_{t=o}^{t=t} E_{re}\, dt = M_o \left[1 - a\, e^{-\left(\frac{E_{max}\, t}{aM_o} - \frac{1 - a}{a}\right)}\right] \tag{17}$$

Considering t as the irrigation interval gives as mean daily evapotranspiration over the irrigation interval:

$$\bar{E}_{re} = \frac{M_o}{t}\left[1 - a\, e^{-\left(\frac{E_{max}\, t}{aM_o} - \frac{1 - a}{a}\right)}\right] \tag{18}$$

provided $t \geq \frac{(1 - a)M_o}{E_{max}}$

Equation (18) describes real evapotranspiration in terms of the soil profile by M_o (depending both on soil properties and rooting depth), irrigation interval t and maximum evaporative demand. The coefficient a depends on the evaporative atmospheric demand. It is well known that under conditions of low evapotranspiration demand the soil water can be almost depleted to wilting point without any reduction in transpiration, whereas the reduction at high demands already starts when the soil is still almost at field capacity. So under conditions of low evaporation a approaches zero, whereas it approaches 1.0 when the maximum evaporation rate is high.

The coefficient a also depends on the type of crop since the leaf water potential at which the transpiration rate due to stomatal control starts to reduce differs from crop to crop. It is to be expected that at the same maximum evaporative demand the coefficient a will increase with increasing critical leaf water potential.

Many field studies on evapotranspiration in Egypt are based on soil sampling data taken two days after irrigation and one day before the next one. Evapotranspiration in that case is calculated as the difference in water volume of the sampled soil layers at both dates. It further is generally assumed that the evapotranspiration rate of the first two days of the irrigation cycle equals the mean rate of the period sampled. The possible consequences of this procedure can be discussed quantitatively with the aid of the given approach to real evapotranspiration. Two cases must be distinguished: the first one for $t' \geq 2$ and the second for $t' \leq 2$.

For $t' \geq 2$

$$\int_{t=2}^{t=t} E_{re}\, dt = \int_{t=2}^{t=t'} E_{max}\, dt + \int_{t=t'}^{t} E_{max}\, e^{-\frac{E_{max}(t-t')}{aM_o}}\, dt$$

$$= E_{max}(t'-2) + aM_o\left[1 - e^{-\frac{E_{max}(t-t')}{aM_o}}\right]$$

$$= M_o\left[1 - a\, e^{-\left(\frac{E_{max}\, t}{aM_o} - \frac{1-a}{a}\right)}\right] - 2\, E_{max} \qquad (17a)$$

The mean evapotranspiration rate over the sampled period (t - 2) equals:

$$\bar{E}_{re(t-2)} = \frac{M_o}{t-2}\left[1 - a\, e^{-\left(\frac{E_{max}\, t}{aM_o} - \frac{1-a}{a}\right)}\right] - \frac{2}{t-2} E_{max} \qquad (18a)$$

For $t' \leq 2$:

$$\int_{t=2}^{t=t} E_{re}\, dt = \int_{t=2}^{t} E_{max}\, e^{-\frac{E_{max}(t-t')}{aM_o}}\, dt$$

$$= aM_o\left[e^{-\frac{E_{max}(2-t')}{aM_o}} - e^{-\frac{E_{max}(t-t')}{aM_o}}\right]$$

$$= aM_o\left[e^{-\left(\frac{2E_{max}}{aM_o} - \frac{1-a}{a}\right)} - e^{-\left(\frac{tE_{max}}{aM_o} - \frac{1-a}{a}\right)}\right] \qquad (17b)$$

The mean evaporation rate over the sampled period (t - 2) equals in that case:

$$\bar{E}_{re(t-2)} = \frac{aM_o}{t-2}\left[e^{-\left(\frac{2E_{max}}{aM_o} - \frac{1-a}{a}\right)} + - e^{-\left(\frac{tE_{max}}{aM_o} - \frac{1-a}{a}\right)}\right] \qquad (18b)$$

The maximum difference in calculated evapotranspiration will be present when $t' \geq 2$.

Assuming E_{max} = 15 mm/day, M_o = 100 mm, t = 10 days and a = 0.7 will give a mean evapotranspiration rate over the whole irrigation cycle when using equation (18):

$$\bar{E}_{re} = \frac{100}{10}\left[1 - 0.7\, e^{-\left(\frac{150}{70} - \frac{0.3}{0.7}\right)}\right] = 8.74 \text{ mm/day}$$

For t' = 2, using equation (18a) or (18b) the mean evapotranspiration rate for the period (t - 2) is:

$$\bar{E}_{re(t-2)} = \frac{100}{8}\left[1 - 0.7\, e^{-\left(\frac{150}{70} - \frac{0.3}{0.7}\right)}\right] - \frac{30}{8}$$

$$= 7.17 \text{ mm/day}$$

This example shows that when neglecting the first two days the difference in estimated transpiration rate over the irrigation cycle can be considerable. The water volume data that were obtained from soil sampling of irrigated fields must therefore be carefully considered. It is recommended that within the irrigation cycle at least two other soil sampling dates are introduced in order to determine the course of the reduction in transpiration.

It is furthermore well known that evaporation data from very frequently irrigated lysimeters under arid conditions can reach the high values of maximum atmospheric demand. The data derived from water balances of irrigated fields generally tend to be lower. This indicates that high values of evapotranspiration will be reached at irrigated fields only during the first few days directly after irrigation.

Estimation of soil and crop factors

The evapotranspiration from a crop depends on prevailing meteorological conditions, availability of soil moisture and physiological properties of the crop. For excellent crop growth non-stress conditions are required, so an approach has to be given to determine the period after irrigation during which non-stress conditions are present. Studies on water uptake by crops (GARDNER, 1960; RIJTEMA, 1965, 1969; ENDRÖDI and RIJTEMA, 1969) show that the relation between leaf water potential, transpiration and soil physical conditions can be given by the general expression:

$$-\Psi_l = E(r_{pl} + b/k) - \Psi_s \qquad (19)$$

where Ψ_l = the leaf water potential in bar
E = evapotranspiration in $mm.day^{-1}$
r_{pl} = crop resistance for liquid flow from root surface to sub-stomatal cavities in $bar.day.mm^{-1}$
b = geometry and activity factor of the root system in bar
Ψ_s = mean soil water potential in the rootzone in bar
k = capillary conductivity at soil water potential Ψ_s

Non-stress conditions for plant growth can be defined as those conditions under which the water use of the crop is not controlled by stomatal reaction. The data as presented for some crops in table 30 concerning the leaf water potential at which transpiration starts to reduce give the boundary values of leaf water potential (Ψ_l) which can be applied in equation (19).

Table 30. Critical leaf water potentials of some crops at which the transpiration rate starts to reduce

Crop	Leaf water potential in bar	Reference
Cotton	- 13	Ehlig and Gardner, 1964
Birdsfoot trefoil	- 10	Ehlig and Gardner, 1964
Grass	- 10	Rijtema, 1965
Wheat	- 10	Rijtema and Ryhiner, 1966
Sunflower	- 7.5	Ehlig and Gardner, 1964
Pepper	- 3.5	Ehlig and Gardner, 1964
Potatoes	- 3.5	Endrödi and Rijtema, 1969

For the purpose of the present study, with hardly any available data on soil moisture characteristics and capillary conductivity, a generalised approach is made using the mean soil moisture characteristics for different soil types as collected by RIJTEMA (1969b). Expressing the available soil moisture between field capacity and wilting point as volume fraction gives the data presented in table 31.

Table 31. Relationship between soil water potential (Ψ_s) and available soil moisture expressed as volume fraction (θ)

	Soil water potential in bar			
	-0.2	-0.5	-2.5	-16.0
FINE TEXTURED SOILS				
Loam	0.197	0.150	0.069	0
Silt loam	0.246	0.187	0.045	0
Silty clay-loam	0.160	0.120	0.065	0
Silty clay	0.190	0.165	0.095	0
Basin clay	0.177	0.149	0.081	0
Mean value	0.194	0.154	0.071	0
MEDIUM TEXTURED SOILS				
Loamy fine sand	0.142	0.105	0.051	0
Sandy loam	0.134	0.081	0.031	0
Sandy clay-loam	0.137	0.108	0.060	0
Mean value	0.138	0.098	0.047	0
COARSE TEXTURED SOILS				
Medium fine sand	0.057	0.028	0.020	0

The relationship between soil water potential and available soil water fraction for the mean values of the three main soil groups can be approximated by an exponential relationship:

$$\Psi_s = -16.0\ e^{-\alpha\theta} \qquad (20)$$

with values of α equal to 22.55, 33.67 and 75.45 for respectively fine, medium and coarse textured soils.

The relationship of capillary conductivity and soil water potential between field capacity and wilting point can be given by the general expression (RIJTEMA, 1965):

$$k = a(-\Psi_s)^{-1.4} \qquad (21)$$

Substituting eq. (20) in eq. (21) yields:

$$k = a'e^{1.4\alpha\theta} \qquad (21a)$$

where $a' = 16.0^{-1.4}a$

From the data given by RIJTEMA (1969b) the following mean values of a' can be derived:

Fine textured soils	$a' = 4.62 \times 10^{-4}$ mm.day^{-1}
Medium textured soils	$a' = 2.64 \times 10^{-4}$ mm.day^{-1}
Coarse textured soils	$a' = 1.32 \times 10^{-4}$ mm.day^{-1}

Based on data for different crops FEDDES and RIJTEMA (1972) showed that for practical purposes, independent of the type of crop, the geometry factor of the root system (b) can be approximated by:

$$b = 0.01275\ Z^{-1} \qquad (22)$$

where b is the geometry factor in bar and Z the effective rooting depth in cm.

They also did show that the value of r_{pl} increases when the soil moisture conditions become more and more limiting. The main reason for this is the change in water uptake pattern in the root zone of the crop when the soil dries. Although the available information on values of r_{pl} in relation to crops and moisture conditions is still very limited, it is assumed that based on the data given by Feddes and Rijtema a very crude first approximation of the relationship between r_{pl} and soil water potential can be given as:

$$r_{pl} = 0.763\ \ln(-\Psi_s) + 1.493 \qquad (23)$$

where r_{pl} is the crop resistance in bar.day.mm^{-1} and Ψ_s the soil moisture potential in bar.

For wet soil conditions a minimum value of 0.5 bar.day.mm^{-1} is introduced. Substituting eq. (20) in eq. (23) yields:

$$r_{pl} = 3.60 - 0.763\alpha\theta \qquad (23a)$$

The so derived values of r_{pl} are crop resistances per unit soil surface. It is to be expected that when increasing the number of plants per unit soil surface the value of r_{pl} will decrease.

Substituting the relations derived above in eq. (19) gives an equation which relates the leaf water potential to maximum evaporative demand, rooting depth and moisture conditions in the root zone:

$$-\Psi_1 = E\{3.60 - 0.763\alpha\theta + 0.01275\ (a'Z)^{-1}e^{-1.4\alpha\theta}\} + 16\ e^{-\alpha\theta} \qquad (24)$$

Tables of available non-stress soil moisture

With the aid of eq. (24) a crude first approximation can be made of the period with non-stress conditions in an irrigation interval. Substituting in eq. (24) the critical leaf water potentials for the different crops mentioned in table 30, a relationship can be derived between E_{max} and the on rooting depth depending moisture content in the soil at which reduction in transpiration starts.

The calculated amounts of soil moisture which can be extracted from the soil without reduction in transpiration are given in the tables 32 through 34 for the three main soil groups and the different crops for different values of E_{max} and rooting depth (Z). It is assumed that the initial soil moisture potential after irrigation equals -0.1 bar, giving initial soil moisture fractions of 0.225, 0.150 and 0.067 for fine, medium and coarse textured soils respectively. The total amount of available soil moisture M_o equals, under these assumptions for a rooting depth Z of 100 cm, 225, 150 respectively 67 mm. Although the tables have been calculated for two rooting depths only, it is possible by simple interpolation at a given value of E_{max} to derive the data for deviating rooting depths.

The soil moisture contents will generally be above field capacity during the day of irrigation

Table 32. Relation between E_{max} and the amount of available non-stress soil moisture ($(1-a)M_o$ mm) in FINE TEXTURED SOILS at two rooting depths (Z = 100 cm; Z = 50 cm) for different crops. For the practical application of equations (18), (18a) and (18b), the value of a = θ/0.225 has been added

E_{max}	Cotton Ψ_1 = 13				Cereals, alfalfa clover, grass Ψ_1 = 10				Sunflower Ψ_1 = 7.5				Pepper potatoes Ψ_1 = 3.5			
	Z = 100		Z = 50		Z = 100		Z = 50		Z = 100		Z = 50		Z = 100		Z = 50	
	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a
1	202.6	0.10	101.0	0.10	188.0	0.16	93.8	0.17	171.4	0.24	85.5	0.24	123.7	0.45	61.7	0.45
2	187.8	0.16	93.5	0.17	169.8	0.25	84.5	0.25	148.8	0.34	74.2	0.34	93.3	0.59	46.6	0.59
3	171.6	0.24	85.4	0.24	150.4	0.33	74.9	0.33	126.6	0.44	63.1	0.44	73.3	0.67	36.6	0.67
4	155.0	0.31	77.1	0.31	131.8	0.41	65.6	0.42	107.8	0.52	53.7	0.52	60.8	0.73	30.3	0.73
5	139.0	0.38	69.2	0.38	115.7	0.49	57.6	0.49	93.2	0.59	46.5	0.59	52.6	0.77	26.2	0.77
6	124.8	0.45	62.1	0.45	102.5	0.54	51.1	0.55	82.1	0.64	40.9	0.64	46.8	0.79	23.4	0.79
7	112.7	0.50	56.1	0.50	91.9	0.59	45.8	0.59	73.5	0.67	36.7	0.67	42.6	0.81	21.3	0.81
8	102.5	0.54	51.1	0.55	83.5	0.63	41.6	0.63	66.9	0.70	33.4	0.70	39.4	0.82	19.6	0.82
9	94.1	0.58	46.9	0.58	76.6	0.66	38.2	0.66	61.5	0.73	30.7	0.73	36.8	0.84	18.4	0.84
10	87.0	0.61	43.4	0.61	70.9	0.68	35.4	0.69	57.2	0.75	28.5	0.75	34.8	0.85	17.4	0.85
11	81.0	0.64	40.4	0.64	66.1	0.71	33.0	0.71	53.6	0.76	26.7	0.76	33.1	0.85	16.5	0.85
12	75.9	0.66	37.9	0.66	62.1	0.72	31.0	0.72	50.5	0.78	25.2	0.78	31.7	0.86	15.8	0.86
13	71.5	0.68	35.7	0.68	58.7	0.74	29.3	0.74	47.9	0.79	23.9	0.79	30.5	0.86	15.2	0.86
14	67.7	0.70	33.8	0.70	55.7	0.75	27.8	0.75	45.7	0.80	22.8	0.80	29.5	0.87	14.7	0.87
15	64.4	0.71	32.1	0.71	53.2	0.76	26.5	0.76	43.7	0.81	21.8	0.81	28.6	0.87	14.2	0.87
16	61.4	0.72	30.7	0.72	50.9	0.77	25.4	0.77	42.0	0.81	21.0	0.81	27.8	0.88	13.8	0.88
17	58.8	0.74	29.4	0.74	48.9	0.78	24.4	0.78	40.5	0.82	20.2	0.82	27.1	0.88	13.5	0.88
18	56.5	0.75	28.2	0.75	47.1	0.79	23.5	0.79	39.2	0.83	19.5	0.83	26.5	0.88	13.2	0.88
19	54.4	0.76	27.1	0.76	45.4	0.80	22.7	0.80	37.9	0.83	18.9	0.83	25.9	0.88	12.9	0.88
20	52.5	0.77	26.2	0.77	44.0	0.80	21.9	0.80	36.9	0.84	18.4	0.84	25.4	0.89	12.7	0.89
21	50.8	0.77	25.3	0.77	42.7	0.81	21.3	0.81	35.9	0.84	17.9	0.84	24.9	0.89	12.4	0.89
22	49.2	0.78	24.6	0.78	41.5	0.82	20.7	0.82	35.0	0.84	17.4	0.84	24.5	0.89	12.2	0.89
23	47.8	0.79	23.9	0.79	40.4	0.82	20.1	0.82	34.1	0.85	17.0	0.85	24.1	0.89	12.0	0.89

and possibly the next one during the moisture redistribution phase. During this time an unrestricted uptake of water by the crop is possible, so the calculated amounts of available non-stress soil moisture are to be increased by one respectively two times E_{max} in order to take into account the conditions during infiltration and redistribution.

The tables are also of direct importance for the calculation of the relationship between real crop water use and irrigation interval as given in equations (18), (18a) and (18b). The factor (1-a) equals the ratio of the amount of available non-stress soil water over total available water, so for practical application of the above mentioned equations the corresponding values of the factor a have been included in the tables 32 through 34.

It must again be stressed that the given approach to determine the duration of non-stress conditions is very crude and that it will require further experimental verification. In this respect it is recommended that soil moisture measurements are performed several times within an irrigation interval in order to investigate the duration of non-stress conditions.

Table 33. Relation between E_{max} and the amount of available non-stress soil moisture {$(1-a)M_o$ mm} in MEDIUM TEXTURED SOILS at two rooting depths (Z = 100 cm; Z = 50 cm) for different crops. For the practical application of equations (18), (18a) and (18b), the value of a = θ/0.150 has been added

E_{max}	Cotton $\Psi_1 = 13$				Cereals, alfalfa clover, grass $\Psi_1 = 10$				Sunflower $\Psi_1 = 7.5$				Pepper potatoes $\Psi_1 = 3.5$			
	Z = 100		Z = 50		Z = 100		Z = 50		Z = 100		Z = 50		Z = 100		Z = 50	
	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a	$(1-a)M_o$	a
1	134.7	0.10	67.0	0.11	125.0	0.17	62.2	0.17	113.9	0.24	56.7	0.24	82.1	0.45	40.9	0.45
2	124.6	0.17	61.8	0.18	112.7	0.25	55.9	0.25	98.7	0.34	49.1	0.35	61.7	0.59	30.8	0.59
3	113.8	0.24	56.4	0.25	99.7	0.34	49.5	0.34	83.9	0.44	41.7	0.44	48.4	0.68	24.1	0.68
4	102.7	0.32	50.9	0.32	87.3	0.42	43.4	0.42	71.4	0.52	35.5	0.53	40.0	0.73	19.9	0.73
5	92.1	0.39	45.7	0.39	76.6	0.49	38.1	0.49	61.6	0.59	30.7	0.59	34.5	0.77	17.2	0.77
6	82.7	0.45	41.1	0.45	67.8	0.55	33.8	0.55	54.2	0.64	27.0	0.64	30.6	0.80	15.3	0.80
7	74.6	0.50	37.1	0.51	50.8	0.59	30.3	0.60	48.5	0.68	24.2	0.68	27.8	0.81	13.9	0.81
8	67.8	0.55	33.7	0.55	55.1	0.63	27.5	0.63	44.0	0.71	21.9	0.71	25.7	0.83	12.8	0.83
9	62.2	0.59	30.9	0.59	50.5	0.66	25.2	0.66	40.5	0.73	20.2	0.73	24.0	0.84	11.9	0.84
10	57.5	0.62	28.6	0.62	46.7	0.69	23.3	0.69	37.6	0.75	18.7	0.75	22.6	0.85	11.2	0.85
11	53.5	0.64	26.6	0.64	43.6	0.71	21.7	0.71	35.1	0.77	17.5	0.77	21.5	0.86	10.7	0.86
12	50.1	0.67	24.9	0.67	40.9	0.73	20.4	0.73	33.1	0.78	16.5	0.78	20.5	0.86	10.2	0.86
13	47.1	0.69	23.5	0.69	38.6	0.74	19.2	0.74	31.4	0.79	15.6	0.79	19.7	0.87	9.8	0.87
14	44.6	0.70	22.2	0.70	36.6	0.76	18.2	0.76	29.9	0.80	14.9	0.80	19.0	0.87	9.5	0.87
15	42.4	0.72	21.1	0.72	34.9	0.77	17.4	0.77	28.6	0.81	14.2	0.81	18.4	0.88	9.2	0.88
16	40.4	0.73	20.1	0.73	33.4	0.78	16.6	0.78	27.4	0.82	13.7	0.82	17.9	0.88	8.9	0.88
17	38.7	0.74	19.3	0.74	32.0	0.79	15.9	0.79	26.4	0.82	13.2	0.82	17.4	0.88	8.7	0.88
18	37.1	0.75	18.5	0.75	30.8	0.79	15.3	0.80	25.5	0.83	12.7	0.83	17.0	0.89	8.5	0.89
19	35.7	0.76	17.8	0.76	29.7	0.80	14.8	0.80	24.7	0.84	12.3	0.84	16.6	0.89	8.3	0.89
20	34.5	0.77	17.2	0.77	28.7	0.81	14.3	0.81	24.0	0.84	11.9	0.84	16.3	0.89	8.1	0.89
21	33.3	0.78	16.6	0.78	27.9	0.81	13.9	0.81	23.3	0.84	11.6	0.84	16.0	0.89	8.0	0.89
22	33.0	0.78	16.1	0.79	27.1	0.82	13.5	0.82	22.7	0.85	11.3	0.85	15.7	0.90	7.8	0.90
23	31.3	0.79	15.6	0.79	26.3	0.82	13.1	0.82	22.2	0.85	11.0	0.85	15.5	0.90	7.7	0.90

Table 34. Relation between E_{max} and the amount of available non-stress soil moisture {$(1-a)M_0$ mm} in COARSE TEXTURED SOILS at two rooting depths (Z = 100 cm; Z = 50 cm) for different crops. For the practical application of equations (18), (18a) and (18b), the value of a = θ/0.067 has been added

E_{max}	Cotton Ψ_1 = 13				Cereals, alfalfa clover, grass Ψ_1 = 10				Sunflower Ψ_1 = 7.5				Pepper potatoes Ψ_1 = 3.5			
	Z = 100		Z = 50		Z = 100		Z = 50		Z = 100		Z = 50		Z = 100		Z = 50	
	$(1-a)M_0$	a	$(1-a)M_0$	a	$(1-a)M_0$	a	$(1-a)M_0$	a	$(1-a)M_0$	a	$(1-a)M_0$	a	$(1-a)M_0$	a	$(1-a)M_0$	a
1	59.9	0.11	29.7	0.11	55.6	0.17	27.6	0.18	50.7	0.24	25.1	0.25	36.6	0.45	18.2	0.46
2	55.2	0.18	27.2	0.19	50.0	0.25	24.7	0.26	43.9	0.34	21.7	0.35	27.5	0.59	13.7	0.59
3	50.4	0.25	24.8	0.26	44.2	0.34	21.8	0.35	37.3	0.44	18.5	0.45	21.6	0.68	10.7	0.68
4	45.5	0.32	22.4	0.33	38.8	0.42	19.1	0.43	31.8	0.53	15.7	0.53	17.9	0.73	8.9	0.73
5	40.8	0.39	20.1	0.40	34.1	0.49	16.8	0.50	27.4	0.59	13.6	0.59	15.4	0.77	7.7	0.77
6	36.7	0.45	18.1	0.46	30.2	0.55	14.9	0.55	24.2	0.64	12.0	0.64	13.7	0.80	6.8	0.80
7	33.2	0.50	16.4	0.51	27.1	0.60	13.4	0.60	21.6	0.68	10.8	0.68	12.4	0.81	6.2	0.81
8	30.2	0.55	14.9	0.55	24.6	0.63	12.2	0.64	19.7	0.71	9.8	0.71	11.5	0.83	5.7	0.83
9	27.7	0.59	13.7	0.59	22.5	0.66	11.2	0.67	18.1	0.73	8.9	0.73	10.7	0.84	5.3	0.84
10	25.6	0.62	12.7	0.62	20.8	0.69	10.4	0.69	16.8	0.75	8.3	0.75	10.1	0.85	5.0	0.85
11	23.8	0.64	11.8	0.65	19.4	0.71	9.7	0.71	15.7	0.77	7.8	0.77	9.6	0.86	4.8	0.86
12	22.3	0.67	11.1	0.67	18.3	0.73	9.1	0.73	14.8	0.78	7.4	0.78	9.2	0.86	4.6	0.86
13	21.0	0.69	10.5	0.69	17.2	0.74	8.6	0.74	14.0	0.79	6.9	0.79	8.8	0.87	4.4	0.87
14	19.9	0.70	9.9	0.70	16.4	0.76	8.1	0.76	13.4	0.80	6.6	0.80	8.5	0.87	4.2	0.87
15	18.9	0.72	9.4	0.72	15.6	0.77	7.8	0.77	12.8	0.81	6.4	0.81	8.3	0.88	4.1	0.88
16	18.0	0.73	8.9	0.73	14.9	0.78	7.4	0.78	12.3	0.82	6.1	0.82	8.0	0.88	4.0	0.88
17	17.3	0.74	8.6	0.74	14.3	0.79	7.1	0.79	11.8	0.82	5.9	0.82	7.8	0.88	3.9	0.88
18	16.6	0.75	8.2	0.75	13.8	0.79	6.9	0.79	11.4	0.83	5.7	0.83	7.6	0.89	3.8	0.89
19	15.9	0.76	7.9	0.76	13.3	0.80	6.6	0.80	11.1	0.83	5.5	0.84	7.5	0.89	3.7	0.89
20	15.4	0.77	7.7	0.77	12.9	0.81	6.4	0.81	10.7	0.84	5.3	0.84	7.3	0.89	3.6	0.89
21	14.9	0.78	7.4	0.78	12.5	0.81	6.2	0.81	10.4	0.84	5.2	0.84	7.2	0.89	3.6	0.89
22	14.4	0.78	7.2	0.79	12.1	0.82	6.0	0.82	10.2	0.85	5.1	0.85	7.1	0.89	3.5	0.90
23	14.0	0.79	7.0	0.79	11.8	0.82	5.9	0.82	9.9	0.85	4.9	0.85	6.9	0.90	3.5	0.90

RELATIONSHIP BETWEEN WATER USE AND CROP PRODUCTION

For analysis of the production of field crops information on both maximum and actual production per unit of soil surface is a prerequisite. Since dry matter production is the result of net photosynthesis, the production other than of compounds of carbon, hydrogen and oxygen can be ignored as regards quantity. Although for practical purposes the total dry matter production is of much more interest than the daily production rate, it is necessary to analyze the influence of environmental factors in terms of this rate, since factors as light, crop height, soil cover, soil water potential and level of fertilization can vary in a complex way over the growing season.

Effect of light and CO_2-diffusion on dry matter production

Without limiting environmental factors, dry matter production is determined by the amount of light intercepted by the crop and by the diffusion of carbon dioxide from the external air to the chloroplasts of the plant. It has been shown by DE WIT (1965) for standard crop conditions and by RIJTEMA and ENDRÖDI (1970) for actual crop conditions that the dry matter production rate can be estimated by means of a formula which combines solar radiation, crop development and the CO_2-diffusion process. Based on their analysis of daily production rates, RIJTEMA and ENDRÖDI (1970) derived the general expression:

$$P = \alpha \frac{4.9}{r_a + r_s + r_m} s_c P_{st} \qquad (25)$$

where P = daily production rate in kg $CH_2O.ha^{-1}.day^{-1}$

α = efficiency factor ranging for different crops from 0.6 to 0.7

r_a = $0.63\{f(z_0,d)u^{0.75}\}^{-1}$ in $s.cm^{-1}$

r_s = canopy diffusion resistance depending on leaf water potential in $s.cm^{-1}$

r_m = mesophyl resistance equalling 4.4 $s.cm^{-1}$
s_c = soil cover fraction
P_{st} = gross photosynthetic rate for standard crop conditions after DE WIT (1965) in kg $CH_2O.ha^{-1}.day^{-1}$

The values of daily photosynthetic rate under De Wit's standard conditions are given in table 35.

Table 35. Daily totals of light (wave lengths 400 to 700 mμ) on very clear days (H_c) in $cal.cm^{-2}.day^{-1}$, the photosynthetic rate on very clear days (P_c) and overcast days (P_o) in kg $CH_2O.ha^{-1}.day^{-1}$ for a standard crop; r_a = 0.5 $s.cm^{-1}$ (after DE WIT, 1965)

North Lat.		Jan. 15	Feb. 15	Mar. 15	Apr. 15	May 15	Jun. 15	Jul. 15	Aug. 15	Sep. 15	Oct. 15	Nov. 15	Dec. 15
0°	H_c	343	360	369	364	349	337	343	357	368	365	349	337
	P_c	413	424	429	426	417	410	413	422	429	427	418	410
	P_o	219	226	230	228	221	216	218	225	230	228	222	216
10°	H_c	299	332	359	375	377	374	375	377	369	345	311	291
	P_c	376	401	422	437	440	440	440	439	431	411	385	370
	P_o	197	212	225	234	236	235	236	235	230	218	203	193
20°	H_c	249	293	337	375	394	400	399	386	357	313	264	238
	P_c	334	371	407	439	460	468	465	451	425	387	348	325
	P_o	170	193	215	235	246	250	249	242	226	203	178	164
30°	H_c	191	245	303	363	400	417	411	384	333	270	210	179
	P_c	281	333	385	437	471	489	483	456	412	356	299	269
	P_o	137	168	200	232	251	261	258	243	216	182	148	130
40°	H_c	131	190	260	339	396	422	413	369	298	220	151	118
	P_c	219	283	353	427	480	506	497	455	390	314	241	204
	P_o	99	137	178	223	253	268	263	239	200	155	112	91
50°	H_c	73	131	207	304	380	418	405	344	254	163	92	61
	P_c	147	223	310	409	484	522	509	448	358	260	173	130
	P_o	60	100	150	207	251	273	265	230	178	121	73	51
60°	H_c	22	72	149	260	356	408	389	309	201	103	37	14
	P_c	66	151	254	383	487	544	523	436	316	195	94	49
	P_o	19	60	114	187	245	276	265	216	148	82	31	11
70°	H_c	0	20	89	209	331	408	380	269	142	45	2	0
	P_c	0	65	185	350	506	612	575	427	262	114	7	0
	P_o	0	16	74	158	241	291	273	200	112	38	1	0
80°	H_c	0	0	28	162	334	424	393	248	81	3	0	0
	P_c	0	0	94	333	571	663	632	474	195	11	0	0
	P_o	0	0	24	133	257	318	297	196	69	2	0	0
90°	H_c	0	0	0	154	339	428	397	252	40	0	0	0
	P_c	0	0	0	371	588	677	646	497	167	0	0	0
	P_o	0	0	0	131	269	319	302	215	35	0	0	0

The daily production rate for standard conditions can be calculated following the procedure used by De Wit, taking:

$$P_{st} = F.P_o + (1-F)P_c \qquad (26)$$

where P_o = production rate on overcast days
P_c = production rate on very clear days
F = fraction of time the sky is clouded.

The value of F is obtained from $(H_c - H_a)(0.8H_c)^{-1}$ where H_c is the mean radiation on clear days and H_a is the actual mean value equalling $0.5H_{sh}$.

Evapotranspiration and dry matter production

The relationship between evapotranspiration and dry matter production is of particular interest for irrigation practice. Taking the vapour transport equation for transpiration as:

$$E = \frac{\varepsilon_s - e_a}{r_a + r_c} \approx \frac{\varepsilon_a - e_a}{r_a + r_c} \tag{27}$$

this gives as simplified equation over the growing season:

$$E = \frac{\bar{\varepsilon}_a - \bar{e}_a}{\bar{r}_a + \bar{r}_e} t \tag{27a}$$

In the same manner equation (25) would for the growing season become:

$$P = \bar{\alpha} \frac{4.9}{\bar{r}_a + \bar{r}_s + \bar{r}_m} \bar{s}_c \bar{P}_{st} t \tag{25a}$$

where $\bar{\varepsilon}_a$, $\bar{e}_a$, $\bar{r}_a$, $\bar{r}_c$, $\bar{r}_s$, $\bar{\alpha}$, $\bar{s}_c$ and $\bar{P}_{st}$ represent the mean values over the growing season and t the length of the growing season in days.

Solving t from equation (27a) gives:

$$t = \frac{E}{\bar{\varepsilon}_a - \bar{e}_a} (\bar{r}_a + \bar{r}_c) \tag{28}$$

This equation can be substituted into equation (25a) giving:

$$P = \bar{\alpha} \frac{4.9}{\bar{r}_a + \bar{r}_s + \bar{r}_m} \bar{s}_c \bar{P}_{st} (\bar{r}_a + \bar{r}_c) \frac{E}{\bar{\varepsilon}_a - \bar{e}_a} \tag{29}$$

or

$$P = a \bar{P}_{st} \frac{E}{\bar{\varepsilon}_a - \bar{e}_a} \tag{29a}$$

The factor a consists of a combination of factors which operate in a more or less opposite direction, so it can be expected that a is more or less constant for a given crop. Sufficient experimental evidence exists that for practical purposes a can be considered to be constant. In a number of cases it might be convenient to replace the vapour pressure deficit term $\bar{\varepsilon}_a - \bar{e}_a$ by the potential evapotranspiration rate yielding:

$$P = a' \bar{P}_{st} \frac{E}{\bar{E}_{pot}} \tag{30}$$

where P = the total dry matter production over the growing season
a' = a crop dependent constant
$\bar{P}_{st}$ = the mean daily production rate of a standard crop
E = the total actual evapotranspiration over the growing season
$\bar{E}_{pot}$ = the mean daily potential evapotranspiration rate without stress conditions

The ratio $E/\bar{E}_{pot}$ in this equation has the dimension of days, giving the equivalent number of days over the growing season for dry matter production under non-stress conditions. The maximum value of P is determined by $\bar{P}_{st}$ and the ratio of $E/\bar{E}_{pot}$, since E can never exceed the total amount of potential evapotranspiration over the growing season.

Evapotranspiration, fertility level and production

The preceding discussion dealt with the relation between production and transpiration when no other limiting environmental factors were present. If, however, the level of fertilization becomes limiting it determines in particular the constant α, giving the photosynthetic efficiency, resulting in a lower potential production level. Under these conditions the relationship between dry matter production and evapotranspiration is no longer a linear one, but curved. Sufficient experimental evidence exists to give the general shape of the relations. An example is given in Fig. 8. The linear part gives the relation for production and evapotranspiration when no other limitations are present, whereas the branching curves give the maximum production at given fertility levels. It can be seen from the figure that under stress conditions the effects of the fertility level sometimes cannot be determined.

Effect of soil water potential on marketable production

The farmer is generally not interested in total dry matter production, but in the production of those parts of the crop which are of economic interest. As soil water potential can affect to a great extent the distribution of dry matter over the various organs of the plant, a discussion on this aspect with respect to irrigation practice is necessary.

Considering the effect of soil water potential on marketable production two phenomena have to be distinguished. The first one is related to the so-called 'passive' water uptake for transpiration, which determines total dry matter production. The second phenomenon deals with the so-called 'active' water uptake by the plant due to a potential gradient between the root zone of the soil and the osmotic potential in the plant. This aspect is in particular related to cell elongation during nighttime. Generally cell elongation is already reduced when the soil water potential in the root zone is less than -0.5 bars. Particularly during tillering heading, flowering and fruit setting a reduction in cell elongation strongly affects the distribution of dry matter over the different parts of the plant. It must be realized that stress conditions during these physiological stages of plant growth can be detrimental to the economic yield, as it is impossible to reduce this effect in later stages of plant growth. In timing of irrigation this aspect in particular must be taken into account.

REVIEW AND EVALUATION OF EXPERIMENTAL DATA ON COTTON AND CORN

A number of aspects discussed in the preceding chapters will be considered in relation to some experimental data derived from the available literature in Egypt. Because of the limited amount of time available for this purpose, this will be limited to a few examples only and no attempt has been made to cover the entire available information.

C o t t o n

Existing data

Cotton is the crop (or is among the crops) most studied in Egypt with respect to irrigation requirements. The early work (before 1946) was mainly of the survey type, in which water flow measurements at weirs to cotton fields were performed. This was followed by a series of simple experiments with three treatments of the type 'light', 'medium' and 'heavy' irrigation under the traditional fixed irrigation schedule. The treatment producing over a number of years the highest yields was considered to give the 'optimum' water requirement. In the fifties, five water treatments instead of three were adopted and yield - response curves were made. Year-to-year and site-to-site variations were very large and the average values were often considered more representative than the incidental ones.

Systematic studies on irrigation intervals for cotton by the Ministry of Irrigation in collaboration with the Ministry of Agriculture started in 1962. Out of five intervals ranging between 10 and 21 days, in general the 15-day interval was considered the best. In the early sixties, irrigation treatments were based more on the hydrophysical properties of the soils and the appearance of wilting symptoms of the crop. Experiments of the type giving the 'depleted water' plus 5, 10, 15 and 20% were performed as well as irrigation at different intervals in relation to the appearance of wilting. As a result of all these sequential studies, two reports were recently issued (1972) by the Water Studies Section of the Ministry of Irrigation, UAR. The consumptive use and water requirements of some twenty crops are given in cubic meter per feddan (1 feddan = 4200 m^2 or about an acre). Thus for cotton water uses of 2600, 3200 and 4500 m^3/feddan are given for Lower Egypt (Delta), Middle Egypt and Upper Egypt, respectively. In certain soils affected by salinity water needs in general were considered to be 10 to 15% higher.

HAMDI et al. (1965) showed that at Beni Saleh, Sharkia the var. Giza 47 gave with 10 irrigations (four before flowering, four during flowering and two during boll ripening) cotton yields of 1520 kg/acre at a nitrogen level of 16 units per acre. However, the data failed to show yield increase with a higher nitrogen level (24 units/acre) and two additional irrigations (one during flowering and the other during boll ripening), this even produced a drop in yield.

KHALIL et al. (1966) reported a water use of 5500, 6430 and 8100 m^3/ha for Sakha (North Delta), Gimmeza (South Delta) and Sids (Middle Egypt), respectively. EID et al. (1966) calculated according to Blaney and Criddle, the water use of cotton as being 7188, 7476 and 8045 m^3/ha for Lower, Middle and Upper Egypt, respectively.

Lysimeter experiments (above ground concrete-type) gave for cotton in the Alexandria area an evapotranspiration (ET) value, ranging from 7150 to 10 910 m^3/ha. With increasing water table depth (from 40 to 160 cm), total ET, yield and plant height all increased, but the moisture contribution from the water table to the root zone decreased (BARAKAT et al., unpublished).

With a fertilizer level of 200 kg of ammonium sulphate a tendency towards higher yields of seed-cotton (1320 kg/feddan) was obtained at short irrigation intervals (7 days) rather than at 21 and 14-day intervals on soils containing 77.4% silt plus clay at Shebin El Kom. The monthly peak rate of water use was of the order of 10 mm/day and the total consumptive use measured after the first flowering stage reached 4170 m^3/feddan (LABIB KUNANY, 1964).

With irrigation intervals of 13 to 17 days at Giza and Sakha (Delta) a total water use of 710 to 725 mm was measured with a peak rate in July of 7.5 mm/day (over a 10-day period). For Middle Egypt the water use was 730 mm at Sids and 807 mm at Mallawi with a peak rate of 7.9 to 8.3 mm/day for the last part of June. It was concluded that during June and July the existing irrigation rotation of 18 days should be shortened to 12 to 13 days in the Delta and to 10.5 days in Middle Egypt. Finally the gradient in consumptive use for cotton from the coast (Delta) towards Aswan was reflected by figures of 705 mm for the Coast and 815 mm for Aswan (EL SHAL, 1966).

Under 'rather frequent' irrigation of deep clay loam soils moisture determinations down to 90 cm depth gave actual evapotranspirations of 850 mm for a cotton crop at Giza. The peak monthly rate of 8.7 mm/day occurred in July (GIBALI, 1972).

For the South Delta (Bahtim) the total water use of the variety Giza 69 reached 729 mm under a 9-day irrigation frequency with a peak rate of 5.5 mm/day occurring in July during flowering and boll formation. Unfortunately, no soil or yield data are given (EL SEROUGY et al., 1971).

For the cotton var. Asmouni on deep clay loam at Giza maximum values were obtained for almost all growth characteristics at the shortest irrigation interval (8 days) combined with the highest nitrogen level (52.5 kg/feddan), but this resulted in a longer vegetation period and a maximum number of worm-infested bolls. A maximum dry weight per plant was obtained, but the heaviest seed cotton weight (11.1 kentars/feddan) resulted from the 15-day interval, the second heaviest yield followed from the 8-day interval. The seasonal water use reached 5573 m^3/feddan and 4150 m^3/feddan under 8 and 15-day intervals, respectively. Peak rates of 14.2 to 14.8 mm/day (over 8-day periods) were observed in the middle of July during flowering and fruiting (CHAUDRY, 1969).

BADAWI A.Y. (1970) found on two successive years for the Middle Delta (El Gimmeza) a total consumptive use of 3210 and 3530 m^3/feddan for cotton (variety Giza 48). The irrigation amount was equal to the depleted moisture plus 10% determined by soil sampling to 60 cm soil depth. The seed cotton yields were 10 and 13 kentars/feddan. Yields were not significantly different but only slightly lower for water applications corresponding exactly to the depleted moisture as well as to the depleted moisture plus 5%. The lower consumptive use under these treatments was 2860 and 3015 m^3/feddan.

MAHROUS (1971) found for the Sakha region the highest average yields of over three years: 6.92 kentars/feddan at a total water amount of 3000 m^3/feddan. Yield was slightly lower (6.67 kentars/feddan) at the higher irrigation level of 3500 m^3/feddan. However, the presence of a water table (at 110 to 150 cm depth) is mentioned to exist in the heavy clay soils of the experiments, as well as 650 m^3/feddan of additional planting irrigation. Seed index (weight of 100 seeds), boll weight and lint percentage tended to increase with increasing amounts of irrigation while earliness tended to decrease. Lint was coarser at shorter irrigation intervals and fibers were stronger at low irrigation amounts. Separate experiments with six irrigation intervals, ranging from 1 to 6 weeks, showed no significant yield difference of seed cotton between the 1 and 2-week intervals which gave the best results with 12.00 and 12.02 kentars/feddan, respectively.

At a fertilizer level of 200 kg calcium nitrate (16.0%), 200 kg superphosphate (15.5%) and 30 kg potassium sulphate (50%) at Giza (TALHA, 1966), a total water use of 1342 mm (5640 m^3/feddan) was given to

Ashmouny varieties in 14 irrigations applied at a 50% soil moisture depletion, determined with soil sampling down to 80 cm. The corresponding yield was 1910 kg/feddan. By subjecting the cotton plants to a drought period at various growing stages (after seeding, after elongation, after first flowering, during peak flowering, during boll development and during boll opening), the boll development period was found to be the critical stage with minimum seed cotton (1049 kg/feddan) and lint yield obtained under water stress (irrigation at the permanent wilting percentage). Under the non-stress treatment, peak water use of 13.0 mm/day (over ten days) occurred in July. The monthly consumptive use rates were 1.0, 2.2, 3.0, 5.4, 9.3, 12.2, 8.3 and 5.4 mm/day starting February and ending September.

The time of the first post-planting irrigation (between 15 to 60 days) was shown not to affect yield, while flowering irrigation at 15-day intervals (versus 30-day intervals) increased cotton yield at N--levels up to 60 kg N/feddan. No further yield increase was observed at 80 kg N units/feddan (GIRGIS, 1972).

Recent unpublished data of FARRAG et al. (1972) show for two successive years at Mallawi peak water use rates between 10 and 10.5 mm/day in June when plant heights were 58 to 83% of the maximum height.

Maximum evapotranspiration and irrigation interval

Equation (18) describes the relation between real evapotranspiration, maximum evaporative demand, available soil moisture and irrigation interval. With the aid of the tables for freely available soil moisture and maximum evaporative demand, curves for real evapotranspiration and irrigation interval were calculated for cotton on a fine textured soil, assuming an effective rooting depth of 65 cm as well as field capacity to be reached two days after irrigation. These curves are given in fig. 5. The envelope of these curves is described by the hyperbolic function $Et_i = M_o$, provided no additional water supply from the groundwater table or precipitation takes place. The curves show that maximum evapotranspiration will be present during rather short periods. In order to reach a maximum evapotranspiration rate of 10 to 12 mm/day a maximum irrigation interval of about 8 days is required. Data of CHAUDRY (1969), using irrigation

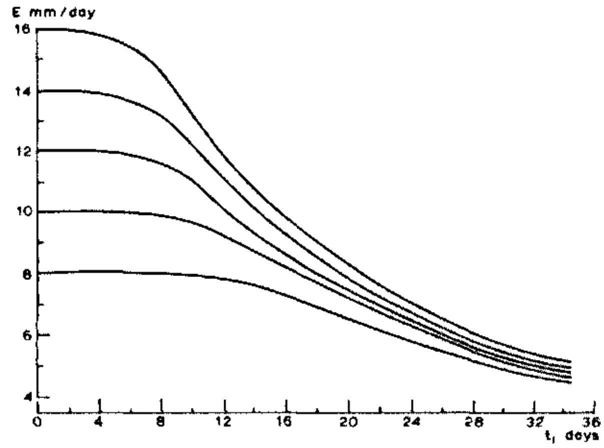


Fig. 5. *Relationship for fine textured soils between* mean monthly maximum evaporative demand (E_{max} = 16, 14, 12, 10 and 8 mm/day respectively), real evapotranspiration (E) and irrigation interval (t_i) calculated with equation (18)

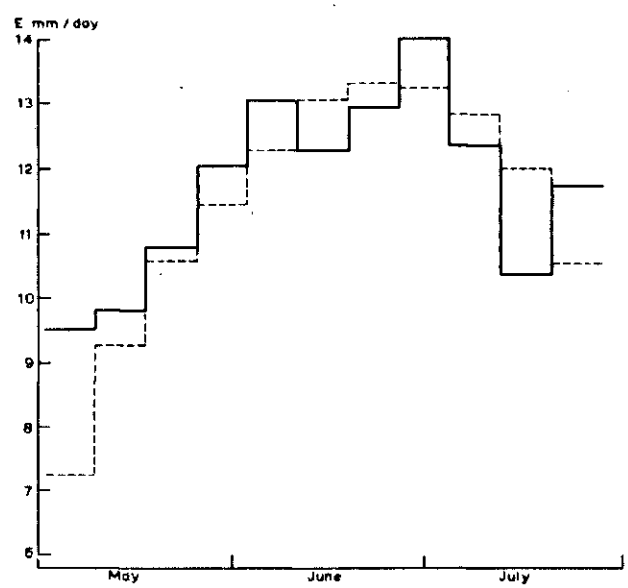


Fig. 6. Evapotranspiration (E) of cotton on a fine textured soil at Giza;

——— mean real evapotranspiration when irrigating with 8-day intervals during 1967 and 1968 (after data of CHAUDRY, 1969);

- - - - - calculated long term mean maximum evaporative demand for the Giza area intervals of 8 days in cotton experiments at Giza are presented in fig. 6 together with the calculated long term mean values for the given irrigation intervals. The general level of the long term mean values coincides very well with the data given by Chaudry, showing that large values can be reached. Since the same author also performed experiments with longer irrigation intervals, the mean evapotranspiration rate was calculated for the different irrigation intervals over May, June and July (fig. 7). As the mean evaporation rate by Chaudry was determined from soil moisture sampling some two days after irrigation and just before the next irrigation, equation (18a) was applied. The calculated values agree with the general trend of the data of Chaudry.

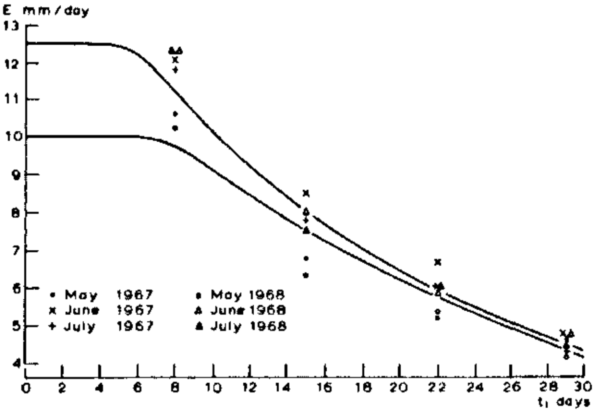


Fig. 7. Relationship between real evapotranspiration (E) of cotton on a fine textured soil and irrigation interval (t_i) as derived from data over 1967 and 1968 by CHAUDRY (1969), as well as according to the calculated real evapotranspiration for the Giza area for two maximum evaporative demands

Data of EL-SHAL (1966) concerning irrigation experiments with cotton at Sakha, Giza, Sids and Mallawi do not show a large variation in peak evapotranspiration values. The irrigation intervals ranged from 13 to 20 days. Water use was determined from soil sampling two days after irrigation and just before irrigation so the data underestimate real evapotranspiration. Considering the family of curves given in fig. 5, it must be concluded that at irrigation intervals of 13 days or more, the mean evapotranspiration rate over the intervals becomes more or less independent of the maximum evaporative demand as the curves approach each other very closely.

The data of TAHA (1966), with irrigation applied at 50% soil moisture depletion derived from soil sampling to 80 cm depth in a clay loam soil, are in agreement with the data which can be calculated when using the tables of non-limited available water in fine textured soils.

The peak water use data of EL SEROUGY et al. (1971) could not be further analyzed as no data of soil type and available moisture were given. The low value of the peak rate of 5.5 mm. day^{-1} under a 9--day irrigation interval seems to be related to experiments on medium textured soils, where the period of non-stress conditions is considerably shorter for the medium textured soils.

The available data clearly show that peak water use in the various experiments is strongly dependent on the length of the irrigation interval. The maximum evaporative demand can only be reached when short irrigation intervals are applied.

Lysimeter data given by BARAKAT et al. (1973) show that when shallow water tables are present, the contribution of capillary rise from the groundwater table to evapotranspiration can be considerable. It ranges from 45% at 40 cm water table depth to 7% in soils with a water table at 160 cm. The consumptive use data given by these authors have a limited value, however, as the lysimeters were placed above ground. Nevertheless they show that a considerable contribution from the water table can be present.

Production

Data of seed cotton production and dry matter present in the stalks were presented by CHAUDRY (1969) for 4 levels of nitrogen application. The nitrogen levels were respectively 0, 53.5, 88.2 and 125.0 kg N per ha. Unfortunately the author did not present the water use data of the separate fertilizer plots, only mean values related to the irrigation interval were available. These data are plotted in fig. 8, giving the relation between dry matter production, evapotranspiration and level of nitrogen fertilization. They show a good agreement with the relation expected from theoretical considerations. Particularly at the short irrigation intervals the water use data are probably overestimated at low nitrogen levels because of the somewhat reduced growth rate whereas

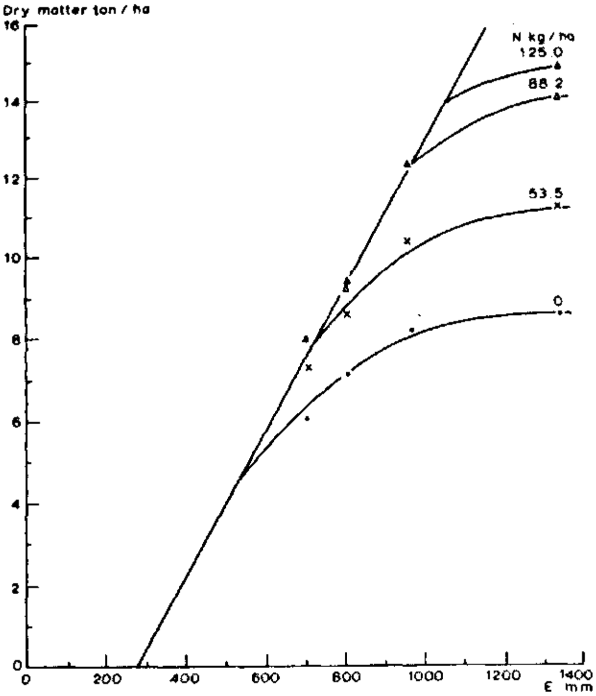


Fig. 8. Relationship between dry matter production of seed cotton and stalks, nitrogen fertilizer level (N) and evapotranspiration (E), after data of CHAUDRY (1969)

they are underestimated at a high N-level. The data show, however, that under severe stress conditions dry matter production is almost independent of the fertilizer level.

As cotton continues growing after flowering, stress conditions after flowering can reduce this vegetative growth resulting in a higher marketable yield. The data of CHAUDRY (1969) presented in table 36 show that the highest yields of seed cotton for the various N-levels were obtained with 15-day irrigation intervals, whereas the highest dry matter production of seeds and stalks were obtained with 8-day irrigation intervals.

Experimental data of TALHA (1966) showed that stress conditions during boll development reduce the cotton yield considerably. Recent unpublished data of FARRAG (1973) show a large reduction in yield with severe stress conditions during flowering, stress conditions during boll opening had only little effect. It is clear from these data that stress conditions during flowering and boll development affects the marketable yield to a great extent. In irrigation practice it is necessary to apply short irrigation intervals during

Table 36. Relationship between water use (irrigation interval) and yield of seed cotton in kg per ha for different fertilizer levels (after CHAUDRY, 1969)

Irrigation interval in days	Nitrogen fertilizer level in kg N per ha			
	0	53.5	88.2	125.0
8	1915	2600	2825	2805
15	2280	3030	3420	3670
22	2210	2600	2890	3005
29	1910	2462	2710	2500

these physiological stages of plant growth, whereas stress conditions at a later stage tend to reduce vegetative growth, resulting in a higher marketable yield.

It can be concluded from the available data that medium stress conditions in the early stages of vegetative growth hardly affects the final yield, but that non-stress conditions must exist, so very short irrigation intervals must be applied, during flowering and boll development giving a peak water use during these stages equal to the maximum evaporative demand. After boll development medium stress conditions can be applied in order to reduce further vegetative growth.

C o r n

Existing data

In the reviewed literature which has appeared in Egypt figures for water use ranging from 430 to 740 mm can be found. Some details are given below and some data are analyzed. Values of 1800, 2300 and 2500 m^3/feddan are given for Lower (Delta), Middle and Upper Egypt respectively (REPORT OF MINISTRY OF IRRIGATION, 1972). These figures, however, are based on a large number of experiments showing large year-to-year and site-to-site variations within the same region.

At Giza (Delta), EL GIBALI (1966) showed that the water requirements over two seasons, for the var. Early American, with six irrigations were 2280 and 2390 m^3/feddan. The fertilizer level was 315 kg calcium ammonium nitrate and 105 kg superphosphate per feddan. Soil moisture extractions of 80 and 20% are reported for the 0 to 30 and 30 to 60 cm soil layers respectively. A peak water rate of 6.7 mm/day occurred over a two-week period in late August. The seasonal water use was between 420 and 450 mm. Better yields were obtained with small plots and furrows (7.8 tons/ha) than with basin irrigation (6.10 tons/ha) with as much as 35% water saving.

For Sakha and Giza (Delta) a total water use of 520 mm was reported by EL SHAL (1966) with a peak rate of 7.0 $mm.day^{-1}$ (over a 10-day period) occurring in October. Soil moisture determination was carried out to 50 cm depth with extrapolation for extraction taking place below.

For the Double-Cross 17A, planted on June 8 and a level of fertilization of 250 kg $(CaNO_3)_2$, 100 kg superphosphate and 30 kg K_2SO_4/feddan, a total water use of 650 mm was obtained at Giza (2725 m^2/feddan). The corresponding grain yield was 3923 kg/feddan. Irrigation was applied at 50% soil moisture depletion in the top 60 cm soil layer. The peak water use rate was between 10.5 and 11.1 mm/day (July 31 to August 3) while the average for August was 8.5 mm/day. Water stress (irrigation at the 15-atmosphere level) affected grain yield at the tasseling stage to the greatest extent; the total crop water use was 560 mm and the yield 1780 kg/feddan. The effect was strong but less marked at the elongation and the silking stages (TALHA, 1966).

For the West Northern coast at Ras El Hekma (225 km west of Alexandria), total water use of 525 mm was observed (AWADALLA, 1970) under a 5-day irrigation interval on a loamy calcareous soil by soil moisture sampling to 45 cm depth. The corresponding grain yield was 669.5 kg/feddan. A great decrease in both water use and yields occurred under the 10-day and 15-day intervals (135.8 and 58.4 kg/feddan for 288 and 235 mm).

For Giza, EL MAGHRABY (1969) obtained the maximum evapotranspiration at July and September (8.0 and 7.6 mm/day) during tasseling and silking stages for early and late planting respectively. The evapotranspiration rates and grain yields decreased progressively as the level of soil moisture deficit increased from 50 to 70, 80, 90 and 100%, but more so at the elongation and tasseling stages. The grain yield decreased as soil moisture deficit exceeded 50%. The decrease in the grain yield was proportional to the decrease in evapotranspiration. Under the 50% soil moisture deficit treatment, the measured water use (sampling down to 60 cm) was between 6840 and 6900 m^3/ha and the grain yields 10.26 to 10.34 tons/ha. The variety used was the Double Cross 17A.

Unpublished data obtained at Sids (Middle Egypt) in 1967 (EL GIBALI and MISEHA) showed corn (U.S. Early variety) seasonal water use (soil moisture sampling to 60 cm depth) of 700 mm under 9-day irrigation intervals. However, no significant difference in yields or water use was obtained under N-levels of 60, 90 and 120 units/feddan although high levels of production (14 tons/ha) are reported.

For Sids (Middle Egypt) total water use of 738 mm and a peak rate of 9 mm/day at the flowering stage was reported by TAWADROS et al. (1969). Seventy and thirty percent soil moisture extraction was allocated to the top and second foot respectively. Irrigation up to the maximum treatment of 3800 m^3/feddan increased corn yield (EL SEROUGY et al., 1969).

For El Gimmeza, Gharbia (Middle Delta), BADAWI (1970) found a seasonal water use of 1952 m^3/feddan (466 mm) for a late summer corn (hybrid double cross 186). Soil moisture sampling was to 60 cm depth. The corresponding yield was 3800 kg/feddan. A peak water use of 11.3 mm/day occurred towards the end of August. The irrigation interval adopted for these silty clay soils was 12 to 15 days. No significant difference in yield was observed for various amounts of water applied, whether equivalent to field capacity (F.C.) or F.C. + 10% or F.C. + 20% (BADAWI, 1970).

Maximum evapotranspiration and irrigation interval

Various authors mentioned peak rates of evapotranspiration during tasseling and silking. A review of the available data on peak water use is given in table 37, as well as the calculated data of maximum evaporative demand.

Based on the soil moisture depletion and evapotranspiration data given by EL MAGHRABY (1969), curves were derived (Fig. 9) for the relation between mean evapotranspiration rate and irrigation interval of early planted corn on fine textured soil at Giza. The curves show a gradual decrease in mean evapotranspiration with increasing irrigation interval. No data were available for shorter intervals, but it seems realistic to assume that already at the 50% soil moisture depletion level stress conditions are present. Under similar conditions (Bekaa area of Lebanon) a significant drop in corn yield was observed within the tensiometer range on clay soils (VINK et al., 1969; ABOUKHALED and SARRAF, 1970). Monthly peak rates

Table 37. Peak evapotranspiration rates of corn given by different authors, as well as calculated maximum evaporative demand

Author	Site	Period of observation	Observed peak rate mm/day	Calculated maximum evaporation mm/day
EL GIBALI (1966)	Giza	End Aug.	6.7	8.6
EL SHAL (1966)	Giza	October	7.0	6.8
TALHA (1966)	Giza Sakha	31/7-3/8	10.5-11.1	10.7
TALHA (1966)	Giza	August	8.5	9.3
BADAWI (1970)	Gimmeza	End Aug.	11.3	10.3
EL MAGHRABY (1969)	Giza	July	8.2	12.1
EL MAGHRABY (1969)	Giza	September	7.2	8.0

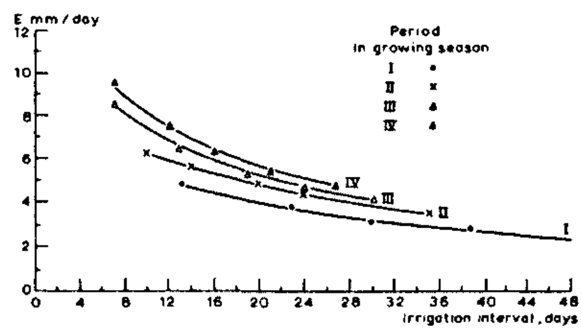


Fig. 9. Relationship between evapotranspiration and irrigation interval of corn on fine textured soil at Giza, after soil moisture depletion data of EL MAGHRABY (1969)

of 11 to 12 mm/day were observed in July and August. This conclusion agrees with the data given by TALHA (1966) presenting peak rates of 10.5 to 11.1 mm/day over very short periods during early August for experiments performed in the same area. Also the data presented by BADAWI (1970) show a peak rate in the same order of magnitude.

The curves in Fig. 9, derived from El Maghraby's data show a similar pattern as those which can be expected when applying equation (18). The period of non-stress conditions seems to be limited to 4 to 5 days after irrigation, when the peak rate is in the order of 10 to 12 mm/day. This is in agreement with data recently obtained from experimental work in Lebanon. Present work in Lebanon tends to show maximum corn yields of 15 to 16 tons/ha on heavy soils with a high nitrogen supply (250 to 300 units/ha) applied with daily or every other day drip irrigation.

Production

The relation between dry matter present in grain and stalks for Giza, as derived from the

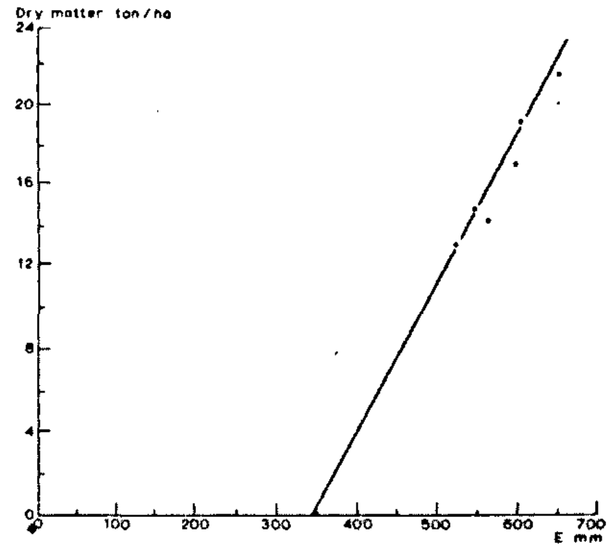


Fig. 10. Relationship between dry matter production (grain and stalks) of corn and evapotranspiration at Giza, after data of TALHA (1966)

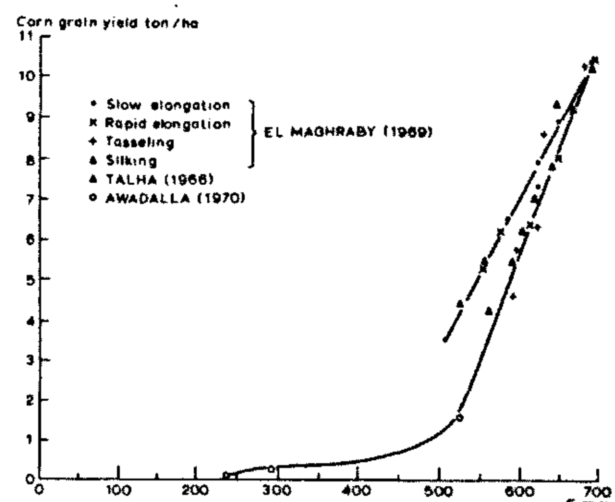


Fig. 11. Relationship between grain yield of corn and evapotranspiration at various stages of growth, after data of the authors mentioned in the figure

data of TALHA (1966) is given in Fig. 10. The data show a linear relationship between dry matter production and evapotranspiration. The reason that the line does not pass originate in the origin of the axes is due to the fact that neither the dry matter of the roots nor that of the stubble was measured, and to evaporation losses from the bare soil in the early stages of growth. It appears from the data of TALHA (1966) and EL MAGHRABY (1966) who applied different levels of stress conditions during various stages of growth, that the distribution of dry matter between stalks and grains is strongly affected by the physiological stage of crop growth. The data of both authors are presented in Fig. 11, resulting in two lines for the relation between grain production and water use. Grain yield is much more affected by stress conditions in the period of tasseling and silking than in other periods. It is remarkable that the data of AWADALLA (1970) based on irrigation experiments on highly calcareous soils show a different relationship. Only the data obtained at a 5-day irrigation interval give a grain production which agrees with both the data of Talha and El Maghraby for stress conditions during tasseling and silking. The other treatments of Awadalla (10 and 15-day irrigation intervals) show that with these irrigation intervals almost only some vegetative growth was possible on this soil. In order to obtain relatively high yields on such types of soils refined irrigation techniques, with very short intervals, are required.

The appearance of two lines for grain yield versus water use at least partly explain the wide variation found in grain production and water use as presented in the reports by the Ministry of Irrigation (ANONYMOUS, 1972). It appears from Fig. 11 that at for instance a total water use of 550 mm of early planted corn at Giza a variation in grain yield can exist ranging from 3 to 5 tons/ha depending on the stress conditions during tasseling and silting, giving a variation in yield of 60%. Unfortunately no sufficiently detailed information on crop water use and grain production was available for Middle and Upper Egypt. The data given in Fig. 11 show, however, that for a high level of grain production non-stress conditions during tasseling and silking are required, resulting in peak rates which are equal to the maximum atmospheric evaporative demand.

REVIEW OF EXPERIMENTAL DATA ON OTHER CROPS

Water use data

Analyses similar to the ones given for cotton and corn have not been executed for other crops, but of some experimental data a review is given.

The water use of b e a n s (Vicia Faba) is given as 900, 1000 and 1400 m^3/feddan for the Delta, Middle Egypt and Upper Egypt, respectively (MINISTRY OF IRRIGATION REPORTS, 1972).

At El Gimmeza (Middle of Delta), on silty clay loam, the variety Giza 2 of Vicia Faba gave the highest yields under irrigation applications equivalent to soil moisture depletion plus 10% (sampling to 60 cm depth). Total water use of the order of 400 mm was observed (1680 m^3/feddan) for the best yield level obtained of 7.65 ardab/feddan. A peak water use rate of 4.3 mm/day occurred in March (BADAWI, 1970).

For the New Valley region a maximum yield per feddan of 1720 kg was obtained with 2770 m^3/feddan. Treatments based on Blaney and Criddle estimates, ranged from 1500 to 5000 m^3/feddan. Consumptive use rates of 5 and 7 mm/day occurred in October and November, and rates between 2.5 and 4.5 for December, January and February. For the lowest yield of 522 kg/feddan, the water use was 1930 m^3/feddan. With the highest water use of 3065 m^3 the yield was 1160 kg. In 1968 the maximum yield of 1543 kg/feddan corresponded to a consumptive use of 2605 m^3/feddan. The lowest yield and the related crop water use were 986 kg/feddan and 2205 m^3/feddan, respectively (REPORTS, DESERT RECLAMATION INSTITUTION, NEW VALLEY, 1967 and 1968).

Under so-called 'frequent' (17 to 18-day intervals) and 'heavy' irrigation treatment (350 m^3/feddan) applied at 50 to 60% soil moisture depletion (60 cm soil depth), the total water use of beans at Sids (Middle Egypt) was 388 mm (1630 m^3/feddan); monthly water uses were 37.1, 73.7, 53.4, 74.9, 100.2 and 49.1 from November till April, successively. Soil moisture extraction of 80% and 20% were reported for the top first and second foot respectively. The highest yield obtained was 13.86 ardab/feddan (about 2.15 tons/ha) with 2.921 tons/feddan of straw. Water use rates of 3.5 mm/day were measured in March. Yield decreased to 12.86 ardab/feddan with 250 m^3/feddan applied at 50 to 60% soil moisture depletion and to

10.54 ardab/feddan for 250 m^3/feddan applied at 80 to 90% depletion (TAWADROS et al., 1969a and 1969b).

MISEHA et al. (1971) showed also for the clay loam soils of Sids a highly significant effect on bean yield of irrigation frequency. Their best yield (10.4 ardab/feddan of grain and 1.581 tons/feddan of straw) resulted from the shortest interval of 15 days, with a water requirement of 1898 m^3/feddan. A slight but not significant yield difference was observed between the two N-levels used (0 and 15 units/feddan). Yield decreased to 5.86 and 4.35 ardab/feddan with 30 and 45-day irrigation intervals respectively. With the 15-day interval, total water use was 395 mm (1650 m^3/ha) with a peak rate of 4.5 to 5.0 mm/day early in March.

EL MOTAZBELLAH et al. (1970) found by irrigating at 30, 45 and 60% available moisture levels seasonal water use values at Sids of 392, 364 and 329 mm, respectively. The corresponding yields were 2862, 1914 and 1575 kg/feddan as green pod or 872, 608 and 472 kg/feddan as dry seed yields.

Adopted water use figures for w h e a t in Egypt range from 260 to 600 mm. In the MINISTRY OF IRRIGATION REPORTS (1972) the wheat consumptive uses for the Delta, Middle and Upper Egypt are 1100, 1300 and 1700 m^3/feddan, respectively.

For the Delta (Sakha), EL SHAL (1966) found water use values between 345 and 385 mm (1450 and 1650 m^3/feddan) with peak rates between 3.0 and 3.9 mm/day for late March and early April. For Middle Egypt (Mallawi) seasonal water use of 370 and 385 mm with peak rates of 3.0 to 3.1 mm/day were observed in late March and early April. The estimated seasonal value for Aswan was 410 mm (1725 m^3/feddan).

For Sakha area (North Delta), ABDEL RASSOUL et al. (1971) used treatments of 4, 5 and 6 irrigations at three levels of nitrogen applications (25, 50 and 75 units/feddan). Giza 155 was seeded in mid-November. They concluded that there was no effect of nitrogen level on wheat water consumption. Their figures even showed that water use would tend to decrease with increasing N-level. Contrary to normal trends, the highest water use value of 420 mm (1760 m^3/feddan) was obtained under the treatments with the lowest nitrogen level versus 356 mm for the highest N-level. The following year, the same tendency was observed, but differences were very small (352 versus 343 mm). Unfortunately, no soil and yield data are available to solve this discrepancy.

For the Middle of the Delta (El Gimmeza), the variety Giza 155 produced on the silty clay soil a highest yield of 12.36 ardab/feddan (4.4 tons/ha) with a total of 2075 m^3/feddan (or 494 mm) with an irrigation treatment based on depleted moisture plus 5%. Peak rates of 5.7 mm/day occurred in April. Wheat consumed between 385 and 495 mm extracting 66.5% from the top 30 cm and the rest from the 30 to 60 cm soil layer (BADAWI, 1970).

At Giza, a total water use of 290 mm was measured (by soil moisture sampling to 60 cm depth). The variety Giza 155 was planted on November 24. Irrigation timing was based on 50% depletion in the top 30 cm. Moisture extractions of 74 and 26% were reported for the top and second foot of soil respectively. The peak rate of 3.1 mm/day (over a 12-day period) occurred in March. Consumptive use dropped to 261 and 238 mm at 75 and 100% moisture depletion. Yields were 1381, 1264 and 984 kg/feddan for the 50, 75 and 100% depletion levels respectively. The corresponding plant heights were 133, 124 and 113 cm, which were partly shortened to 114, 102 and 93 cm by spraying with the growth regulator CCC. The highest yields of the sprayed plants (1505 kg/feddan) resulted from irrigation at 75% moisture depletion. Total nitrogen applications were equivalent to 40 kg/feddan (SEIF EL YAZAL, 1971).

At New Valley, maximum yields of 1421 kg/feddan were obtained (planting 20 October) with a total water application of 3450 m^3/feddan and a seasonal consumptive use of 2560 m^3/feddan (soil moisture sampling to 60 cm depth). The soils were sand to sandy loams. Irrigation treatments were based on Blaney and Criddle estimates, the central treatment was 2268 m^3/feddan. A separate experiment was carried out on irrigation intervals on the clay soils of Kharga Station (REPORTS DESERT RECLAMATION INSTITUTION, 1967 and 1968). Intervals ranged respective of the months between 7 and 12 days for the frequently irrigated treatment and 16 to 21 days for the widely spaced irrigation treatment. The highest yields of 977 kg/feddan were obtained from the frequently irrigated plots as against 653 kg/feddan for the large irrigation intervals.

B a r l e y . The water use of barley is given as 1000, 1200 and 1600 m^3/feddan for the Delta, Middle

Egypt and Upper Egypt respectively (MINISTRY OF IRRIGATION REPORTS, 1972).

In the New Valley area, maximum grain yields of 1300 to 1330 kg/feddan were obtained with a crop water use of 2015 to 2385 m^3/feddan. Two uniform irrigations amounting to 835 m^3/feddan were given before starting soil moisture depletion measurements. The sampling depth in these clay soils, field capacity (FC) 45% and permanent wilting point (PWP) 25%, was limited to 40 cm. Planting and harvest dates were 31/11/1967 and 12/4/1968 respectively. Four irrigation treatments were applied with gifts equivalent to: (a) the depleted amount, (b) depleted plus 25%, (c) depleted plus 50% and (d) depleted plus 75%. A proper timing of water irrigation does not seem to have sufficiently been taken into consideration. A grain yield of 1072 kg/feddan was obtained under irrigation with amounts equivalent to the water depleted. The low yield is considered to be due to soil salinity aspects. An independent irrigation frequency experiment, with the same amount of total water applied (3115 m^3/feddan) showed that the maximum yield of 1480 kg/feddan was obtained for irrigation intervals ranging between 7 and 12 days over the season (NEW VALLEY REPORTS, DESERT RECLAMATION, 1967 and 1968).

In Wadi El Natrun, in the Western desert between Cairo and Alexandria, the highest yield of barley (133 days growing season) was obtained under a seven-day irrigation interval (sandy soils; FC 6.5%, PWP 2.5%) amounting to the total application of 6650 m^3/feddan. However, the highest yield per cubic meter of water corresponded to 2250 m^3/feddan (BATRA, 1967). The irrigation treatments comprised four different doses of water (150, 250, 350 and 450 m^3/feddan) each applied at four different frequencies of irrigation 7, 9, 11 and 13 days).

On the highly calcareous soils of Ras El Hekma, along the Mediterranean coastal littoral 225 km west of Alexandria, the total water use of barley was 395 mm for a maximum yield of 1715 kg/feddan with a 15-day irrigation treatment. The yield decreased to 1430 kg/feddan under a 30-day irrigation frequency with a total water use of 365 mm. The monthly water use rates for the best yield were 4.0, 2.4, 4.5, 2.2 and 2.2 mm/day from November to March inclusive. Peak rates of 6.2 and 7.9 mm/day were measured in November and January (AWADALLAH, 1970).

C l o v e r . The total water use of clover or continuous Berseem (Trifolium Alexandrium L.) is given as 1200, 1700 and 2100 m^3/feddan for the Delta, Middle Egypt and Upper Egypt (MINISTRY OF IRRIGATION REPORTS, 1972).

On the South Tahrir Experimental Farm (sandy to sandy loam soils), the clover crop was grown from 5/12 to 8/4 under weekly irrigation amounting to totals of 4000 to 4800 m^3/feddan (BONIFICA, ITALCONSULT REPORT, 1966).

At El Gimmeza (Middle of the Delta), 3425 m^3/feddan (815 mm) gave a maximum yield of 61.5 tons/feddan of fresh weight per four cuttings. The water application was equivalent to the depleted amounts plus 10%. The soil moisture sampling in these silty clay soils (FC 38%, PWP 20 to 24%, bulk density 1.14) was carried out for 10 cm layers down to 60 cm. The peak water use for this winter crop occurred in May and reached 6.7 mm/day. Water extractions from the 0 to 30 cm and 30 to 60 cm layers were 71.5 and 28.5% respectively (BADAWI, 1970).

In Wadi El Natrun, in the Western desert, for the Egyptian clover El Meskawi maximum production in four cuts was obtained on sandy soils with a total of 3800 m^3/feddan applied at 7 to 9-day irrigation intervals. The economic water requirement and yield was considered to be the level of maximum yield per cubic meter of water at 2700 m^3/feddan (BATRA, 1967).

For the Delta, a total water use of 560 mm and a peak rate of 5 mm/day occurring late in March were reported by EL SHAL (1966). The same author estimated a 10 to 15% increase in water use going from Coast-Delta towards Aswan. BADAWI et al. (1969) found an irrigation requirement of 3480 m^3/feddan (830 mm) for continuous clover in Middle Egypt. Sixty percent of the roots were reported to occur in the top foot of soil.

A l f a l f a . Much less experimental work was found on alfalfa (called locally Berseem Hijazi) than on clover.

Alfalfa root system and water use were studied in sandy soils in tin barrels, but such studies are of limited value for natural field conditions (SAAD ABDEL RAZEK, 1970).

In New Valley, a maximum production of only 24.3 tons (ten cuttings) was obtained with a total water application of 12 685 m^3/feddan. The measured water use was between 6000 and 6470 m^3/feddan. The soils were sandy loam (FC 10 to 12%, PWP 4 to 5%). Peak water use rates of 6.8 to 7.3 mm/day were measured under a 15 to 18-day irrigation interval (NEW VALLEY REPORTS, DESERT RECLAMATION, 1967). The peak rates were low; large water stress and stomatal closure under excessive heat are suspected. This is also reflected in the low yields that were obtained. In South Tahrir Experimental Farm, alfalfa was grown under flood irrigation with a total of 7750 m^3/feddan (BONIFICA, ITALCONSULT REPORT, 1966).

S u g a r c a n e . Only very few experiments were found on sugar cane water use carried out in Mallawi (Middle Egypt) and Mattana (Upper Egypt).

During the period 1964 to 1967, an average area of 133 350 feddans was under sugar cane in Egypt, with a production of 5 million tons of cane, i.e. 546,000 tons of sugar. The crop mainly is grown in Upper Egypt where rainfall is only 3 mm/year. The irrigation season stretches from 1 March to 15 November. At Komombo an irrigation requirement of 14 840 m^3/feddan is given for a production of 71 tons of sugar cane or 9.5 tons of sugar per feddan. GIBALI et al. (1971) found at Mattana Experimental Station that the total water use of the variety Natal Combatore 310 was 1670 and 2000 mm for the first and second season crop respectively. Maximum yields of 56.4 and 65.1 tons/feddan were obtained under the shortest irrigation interval used (10 to 15 days). The yield decreased approximately to 26.0 to 29.6 tons/feddan under less frequent irrigation intervals (25 to 30 days interval). The corresponding water use ranged between 760 and 1330 mm. It was determined by the soil moisture depletion method in 10 cm soil layers down to 60 cm depth.

Evapotranspiration from a sugar cane field in Mallawi Experimental Station was measured by the soil moisture depletion method with soil sampling to a depth of 60 cm every 10 to 15 days (irrigation interval in summer and spring). A total water use of 1165 mm and an irrigation requirement of 1940 mm were reported (GIBALI et al., 1971). A peak water use rate of 7 mm/day occurred in June. Measured values were less than those calculated by Olivier's formula and the Blaney-Criddle method, K coefficients were determined for each growing stage. The total calculated water use was 15 140 m^3/ha for Olivier's formula and 12 140 and 13 420 m^3/ha for Blaney and Criddle with a variable K and a constant K respectively. It is believed that the measured values are too low. Unfortunately, no yield data are given to reflect limiting factors and water stress. More recent unpublished work by GIBALI et al. shows water use rates of 11.0, 12.8 mm/day for August and September.

Unpublished work by FARRAG et al. (1967, 1968 and 1969) shows average figures of approximately 2500, 2060 and 1700 mm for water use under water applications at 30, 50 and 70% depletion levels respectively. These depletion levels were reached on the average every 7, 11 and 18 days. Certain limiting factors are suspected to have occurred and further work is needed since no significant effect on yield was reported.

R i c e . The water use and irrigation requirements of rice are given for Lower Egypt as 7200 and 8000 m^3/feddan respectively (MINISTRY OF IRRIGATION REPORTS, 1972). Comparing transplanting and sowing methods, GIBALI and MAHROUS (1970) found rice total water use of 1120 and 1485 mm respectively. The water use efficiency with the transplanting method was 0.601 kg per cubic meter of water and 0.374 kg per m^3 in the sowing method. Limited experimental work on rice water requirement is available in Egypt and more investigation is necessary.

G r o u n d n u t . On South Tahrir Experimental Farm, groundnut (Arachis hypogea) was sprinkler irrigated on a weekly basis during the growing period of 209 days. The total water applied was 3400 m^3/feddan. By flood irrigation every 7 to 8 days, 4300 m^3/feddan were applied (BONIFICA, ITALCONSULT REPORT, 1966).

In Wadi El Natrun in the Western Desert (between Cairo and Alexandria), using four gifts of water (150, 250, 350 and 450 m^3/feddan) each applied at four different frequencies (6, 8, 10 and 12 days), BATRA (1967) obtained a highest grain yield of groundnut with an 8-day irrigation interval (sandy soils) and a total of 4250 m^3/feddan. The maximum yield per unit water called 'economic yield' was obtained at the level of 2250 m^3/feddan. More work is required on the water use of this crop.

S e s a m e . The water use of sesame (a summer crop) is given as 1700, 2200 and 2300 m^3/feddan for the Delta, Middle Egypt and Upper Egypt respectively (MINISTRY OF IRRIGATION REPORTS, 1972).

On South Tahrir Experimental Farm, sesame was sprinkler irrigated on a weekly basis. The total water given in 16 irrigations (116-day growing period) amounted to 1610 m^3/feddan (BONIFICA, ITALCONSULT REPORT, 1966).

In the sandy soils of Wadi El Natrun, in the Western desert, the highest seed yield of sesame was obtained with a six-day irrigation interval (sandy soils) with total water applied amounting to 5550 m^3/feddan. The 'economic' seed yield or maximum yield per unit of water was obtained with 1950 m^3/feddan (BATRA, 1967). More work is required on the water use of this crop.

F l a x . EL SHARIF (1967) studied in pot and field experiments the effect of 3 levels of soil moisture on phosphorus uptake and dry matter production by four crops including flax. He gave no water use data but showed that a soil moisture level increasing from 50 to 70% of the maximum holding capacity increased dry matter and phosphorus uptake.

The effect of plant density, nitrogenous fertilizer and irrigation on yield and fiber quality of flax was studied at Giza by EL FAROUK (1968). Lengthening the irrigation interval from 21 to 30 and 42 days depressed plant height and decreased seed yields, stem diameter and seed index but the fibers were finer. With increased irrigation interval the technical length of plant decreased from 88.3 to 73.1 cm, the seed yield from 9.93 to 8.97 ardab/feddan and the fiber length from 84.5 to 69.5 cm.

V e g e t a b l e s . The water use of some 12 vegetable crops are tabulated in the REPORTS OF THE MINISTRY OF IRRIGATION (1972). The consumptive use of many vegetable crops is also given in separate reports of the Crop Water Requirement Section, Ministry of Agriculture. Only three crops are selected in this review, namely onions, potatoes and cucumbers.

O n i o n s . The water use of onion is given as 1350 m^3/feddan for the Delta (MINISTRY OF IRRIGATION REPORTS, 1972).

Experiments conducted at Assiut (EL LAKANI, 1971) gave the highest yields of onion bulbs with the wettest moisture regimes of 100% and 80% of field capacity. Increasing the frequency of irrigation increased the diameter of the bulbs and reduced the percentage of soluble solids. Different levels of nitrogen fertilization did not affect the yield of onion in spite of the increase in nitrogen content of the bulbs.

GIBALI et al. (1970) studied the effect of irrigation intervals on nutrient accumulation and oil content of onion seeds.

P o t a t o e s . At Sids Experimental Station (Middle Egypt), the water use of summer potatoes irrigated at 40, 55 and 70% moisture depletion was 500, 460 and 410 mm respectively. The corresponding values for the fall crop were 330, 290 and 250 mm. Soil moisture extraction in both periods from the top and second foot of soil was 78 and 22%. The peak rate of 6.3 mm/day occurred in early May for the summer crop and of 4.0 mm/day in December for the fall crop. The monthly Blaney-Criddle K-factors were also determined (ABDEL RASOUL et al., 1970).

Similar experiments with the variety Alpha based on irrigation at 30, 45 and 60% depletion levels, gave for the summer crop highest yields of 11.6 tons/feddan with an 11-day irrigation interval and 2362 m^3/feddan (565 mm). The yield decreased to 10.7 and 7.7 tons/feddan with 16 and 18-day irrigation intervals. The corresponding water uses were 510 and 385 mm respectively. For the fall crop 5.3, 5.0 and 4.6 tons/feddan used 340, 310 and 270 mm respectively (EL MOTAZBELAH et al., 1970).

At Giza (loamy soil, FC 30.5% and PWP 10.8%), irrigation intervals of 10, 20 and 30 days and 100 and 200 m^3/feddan of water per application were used. The shortest interval of 10 days gave the best vegetative growth, the greatest weight of tubers and the highest yields. The irrigation interval and amount of water for irrigation did not affect the specific gravity, dry matter and starch contents of potato tubers at harvest (MISHRIKI, 1971).

C u c u m b e r s . The water use of cucumber is given for the Delta as 960 m^3/feddan (MINISTRY OF IRRIGATION REPORTS, 1972).

Experiments on the local variety Balady at Giza (clay loam soils) with four irrigation intervals (5, 7, 10 and 14 days) and five nitrogen fertilizer levels (0, 50, 100, 150 and 200 kg ammonium sulphate/feddan) showed the best plant growth (plant height) and yields with the highest N-level and the 5-day irrigation interval. The yield decreased from 22.3 to 19.7, 14.5 and 11.1 tons/ha with the irrigation interval increasing from 5 to 7, 10 and 14 days respectively. Decreasing the N-level had a similar, but somewhat less pronounced, effect. Picking at six days interval produced the highest yields and the largest fruits (EL DEBABY, 1964).

EL MOTAZBELAH et al. (1970) found with irrigation at available moisture levels of 30, 45 and 60% a water use of the Balady variety of 335 (1410 m^3/feddan), 310 and 290 mm respectively. The corresponding yields were 15.30, 12.42 and 12.20 tons/ha and the irrigation intervals 9, 10 and 12 days.

Soil-water relationships

HABIB (1958) studied the factors affecting the field capacity (FC) under Egyptian conditions. He worked on the loam to clay soils with adobe structure at Giza and a water table fluctuating between 1.2 to 2.0 m. He mainly confirmed certain known ideas bringing in some local figures. Short-term and long-term seasonal variations of FC as affected by cultivation practices were shown. A 17 to 18 cm water depth was held by 50 cm deep profiles, but most of it by the ploughed layer. Determination of FC at certain time intervals after irrigation showed a maximum of water held by the profile after 4 hours, followed by a marked decrease in the following 2 hours and equilibrium was attained after 48 hours. Finally, moisture equivalent was found to be equal to FC by volume.

AFIFI (1968) showed certain characteristics of the soils in the coastal region of the Western desert (Ras El Hekma, Mediterranean coastal area). They have a high concentration of $CaCO_3$ (45 to 90%) and the moisture characteristic curves indicate that the major portion of the available water is released before soil moisture tension exceeds one atmosphere. Most of the available water is lost between 0.33 and 1 atmosphere due to uniformity of pore size distribution and to coarse texture. The author compared the permanent wilting point values obtained with the sunflower test with 15 atmosphere pressure values. Due to the presence of salt, the osmotic pressures were subtracted from the 15 atmosphere pressure values to obtain the actual tension at which the plants wilted.

Working with the clay soils of the Kharga oasis, EL DESOUKY (1970) established their moisture characteristic curves and showed that the major portion of the available water is released before soil moisture tension exceeds five atmospheres. At 0.3 atmosphere, the soils lost about 50% of the moisture content retained at saturation. Changes in soil moisture content between 0.3 and 1 atmosphere were small. However, in the surface soil layer (rich in macropores) most of the available water was released rapidly between 1/3 and 1 atmosphere. In sub-surface layers, most of the available water was released between 1 and 5 atmospheres.

RECOMMENDATIONS FOR APPLIED IRRIGATION RESEARCH

Experimental setup

It is strongly recommended that irrigation experiments are performed at a high fertility level and a good population density, with high yielding varieties and good pest control. Under these circumstances all production conditions can be maintained at optimum level, with water as limiting factor. Crop water requirement studies should be carried out by a team of specialists consisting of an agroclimatologist, a crop physiologist and a soil physicist so an integrated approach and interpretation can be made. In the opinion of the authors it is useless to perform irrigation experiments with fixed irrigation intervals throughout the growing season or to apply amounts of irrigation water on a basis of supply to field capacity, field capacity + 10% or field capacity + 20%, unless continuous leaching in connection with salinity control is necessary.

The authors recommend the conducting of different types of irrigation experiments, which can be listed as follows:

1. Experiments with non-stress conditions throughout the growing season in order to check for different crops the given tables of maximum evaporative demand. Timing of the irrigation interval can be based upon these tables, as well as on the soil physical data given for the main soil groups. It is recommended that the amounts of irrigation water are based on the soil moisture characteristics, with a check on the moisture conditions by means of tensiometer readings. It is recommended that the tensiometers at least be installed at 3 depths: 30, 60 and 90 cm respectively.
2. Experiments with fixed levels of

stress conditions throughout the growing season. In these experiments it is recommended that at least one of the treatments is within the tensiometer range. The authors propose the treatments given in table 38, based on soil water potential in the rootzone for the three main soil groups.

Table 38. Proposed treatments in irrigation experiments with fixed levels of stress conditions throughout the growing season (irrigation experiments of type 2)

	Depletion levels in soil water potential (bars)			
Fine textured soils	-0.7	-1.0	-5.0	-16.0
Medium textured soils	-0.6	-1.0	-3.0	-16.0
Coarse textured and calcareous soils	-0.4	-0.7	-1.0	-16.0

3. Experiments based on physiological stages of plant growth. These experiments have to be performed on basis of the application of stress conditions in certain stages of plant growth in order to save water without greatly affecting the economic yield. With the aid of this type of experiments, optimization of crop water use can be studied. The stress conditions, for instance irrigation at 60, 80 and 100% soil moisture depletion, have to be applied outside the so-called physiologically critical stages. Critical stages can be closely identified at high production levels by systematic application of water stress treatments to the various plant development stages and by analysis of the yield responses. For plants with no specific critial stage such as alfalfa, irrigation could be withheld during the months of peak water demand (July and August). This treatment is of practical value since the water saved by inducing dormancy to alfalfa, etc., could be used for crops more sensitive to water shortage during the peak water demand.

Vegetables and other crops grown for fresh weight production are usually very sensitive to water stress conditions. Suggested treatments for potatoes, onions, pepper, etc. is irrigation timing at 0.3, 0.5, 0.75 and 1.0 bar.

Excellent yields and better products were obtained in Lebanon from many vegetable crops by scheduling irrigation on 30 to 50 centibar tensiometer readings in clay and clay loam soils (ABOUKHALED and SARRAF, 1969 to 1971 and SARRAF et al., 1972). Similar trends were obtained in recent work in Egypt (EL LAKANI, 1971).

Whenever salinity conditions are involved, osmotic potential should be taken into account. Leaching requirements must also be viewed as the choice between reduction in yield by leaching of fertilizers and reduction in yield due to increased osmotic potential. Further comments on salinization, soil salinity, water quality and leaching requirement will be given in the chapter on salt affected soils.

Measurements and observations

Soil and crop

Soil moisture measurements should be carried out with a sufficient number of replicates. Most of the work in Egypt reviewed is based on the oven-drying method with soil sampling to 50 or 60 cm depth and two or three replicates per treatment. In many cases this will prove not to be adequate. Large deviations or standard errors are to be expected with such a small number of replicates. Root development depends on the irrigation treatment and therefore sampling to the mentioned limited depth leads to underestimation and errors in the calculated moisture extraction from the various soil layers. Such errors should be assessed by deep sampling, using whenever possible radiation equipment (neutron probes or γ-transmission techniques). Moisture sampling down to 160 cm by a neutron probe did show still significant water extraction by corn below 60 cm (VINK et al., 1969).

Systematic observations of groundwater depth and proper assessment of its contribution to the water use of the crops are essential. Laboratory determinations of soil moisture characteristics on volume basis and of capillary conductivity are required. Tensiometers placed below 60 cm would easily reflect the water status or movement in the deeper soil layers.

Periodic assessment and control of the salinity level in the rootzone is required.

Plant phenology observations are

essential. The planting, germination and harvesting data should be as complete as possible, including fresh weight, final product (sugar for example), total dry matter production.

D a t a   p r e s e n t a t i o n should follow as much as possible a standardized form, set up on a 10-day period basis.

D a t a   i n t e r p r e t a t i o n should integrate the physical and physiological basis as outlined in this report in the analysis of the experimental data on cotton and corn.

Environment

S i t e . The site used for the observations must be representative for the area. The values obtained depend on the exposure of the instruments. The formulae to be used are based on standard measurements, so it is necessary to have exposure conditions which are similar to the standard exposure. This means that the measurements must be made on a plot of level ground, covered with short grass and at least 15 m by 10 m in size. It should be away from the immediate influence of trees, buildings and steep slopes. The The Sakha meteorological station, for instance, does not fulfil these simple requirements.

P r e c i p i t a t i o n . Very important is the height of exposure of the rain gauge. Comparison of measured precipitation data at different exposure heights with the ground rain gauge did give a systematically smaller amount of some 7.5% for an exposure height of 1.5 m and of some 5% for an exposure height of 40 cm. The exact deviations depend on the wind velocity during rain. Therefore it must be recommended that precipitation measurements are performed at zero height, so with ground rain gauges.

R a d i a t i o n   m e a s u r e m e n t s . It is recommended that measurements of global radiation are performed at at least 5 main agrometeorological stations, spread over the country, for instance at Sakha, Giza, Mallawi, Kharga and Aswan. It is recommended to connect the solarimeters with a good integrating recorder system which gives integrated daily radiation values. No published data of measured net radiation could be obtained by the authors. It is recommended that at least at a few locations such measurements are performed in Egypt.

It is recommended that the hours of bright sunshine are noted at all experimental stations. The relations between actual radiation, radiation at the top of the atmosphere and relative duration of bright sunshine to be derived at the main stations can be used at the other locations to calculate actual global radiation.

H u m i d i t y . When only day-time observations of humidity are performed, it is recommended to calculate the actual vapour pressure with the aid of the mean day-time temperature. Calculations of the mean vapour pressure deficit over 24 hours can in that case be obtained by using the mean saturated vapour pressure at the 24-hour mean temperature.

W i n d   v e l o c i t y . The exposure of anemometers requires special attention. Obstacles can exert an influence extending over several times their height, both in up and down-wind direction. A cup anemometer with an integrating counting system will generally give sufficiently accurate information on mean wind velocity, provided the instrument is at least a distance of 10 times the height of an obstruction away from the latter. The actual height of wind velocity measurements should be given. Conversion of the wind velocity at one level to that at the level to be used in the formula must be done with one of the conversion formulae. In most cases a logarithmic wind profile can be assumed. It is recommended that a standard height of 2 m is used.

E v a p o r i m e t e r s . Though Piche evaporimeters are generally used, it must be recommended that at all experimental stations evaporation pans are installed. As the USA Weather Bureau Class A pan is standardised and is in use in various countries in semi-arid and arid regions, it is recommended to use this type of pan for comparison with calculated maximum evaporative demand. It is realised, however, that sunken (BPI) pans generally give more realistic data.

L y s i m e t e r s . As far is known, no realistic lysimeter data on maximum evapotranspiration are available in the country. It is strongly recommended that at 5 main stations (Sakha, Giza, Mallawi, Kharga and Aswan) standardised sunken lysimeters of the drainage type are installed. In this respect it is recommended to use 2 x 2 m^2 metal lysimeters without groundwater table, applying frequent irrigations keep-ing the soil water potential within the tensiometer range. It must be seen to that the buffer areas around the lysimeters are sufficiently large in order to obtain realistic data.

SUMMARY

In the presented analysis of the research on crop water use in Egypt the available data of 24 meteorological stations, located throughout the country, havo been used as well as the recent work published in this field of research. Summarizing, the following comments can be made:

1. Wind measurements were carried out at heights ranging from 2 to 19 meters. Some of the available data were questionable and standardization to measurements for agrometeorological purposes at 2 m height is recommended.
2. For the calculation of crop water use, Egypt has been subdivided into 9 agroclimatological areas namely: Coastal, Central Delta, Desert Delta, Giza, latitude 29° - 27.5° N, latitude 27.5° - 26° N, Dakhla (26° - 25° N), Kharga (26° - 25° N) and Aswan (25° - 24° N).
3. Evaporation measurements from Piche tubes are common, but data from standard pans (Class A, Class B, BPI or Colorado) are very scarce. A greater use of standard pans is recommended especially at sites where crop water requirement studies are being performed.
4. Additional measurements across the country of bright sunshine hour duration and solar radiation are required. Measurements of net radiation at a few sites (Coastal Area, Middle Egypt and Upper Egypt) are recommended.
5. None of the current evapotranspiration formulae so far in use in Egypt, are able to properly reflect the strong evaporation gradient existing between the Coastal Area and Upper Egypt. This gradient in evaporative demand is of great importance for the calculation of the water use of crops in Egypt. A good approach to the calculation of crop water requirements under different agrometeorological conditions can be obtained by means of the presented combined energy balance - vapour transport method.
6. The ratio between Class A pan and Penman evaporation at Giza was found to be in the order of 1.5 to 1.6, which is intermediate between values obtained at Bekaa in Lebanon and Gezira in Sudan.
7. Tables of net radiation and maximum evaporative demand have been prepared for the differentiated agroclimatological zones of Egypt. Maximum water use by full cover crops was calculated by means of the combination method of Penman, as modified by Rijtema to account for the effects of crop roughness in relation to crop height. This is essential when working with crops in arid regions.
8. It is to be realized that for excellent crop growth non-stress water conditions are required. Estimated values of the periods with non-stress conditions within an irrigation interval have been tabulated for Egypt for three main soil groups and for different crops. They require further experimental verification. It must be emphasized that stress conditions during critical stages of plant growth can be detrimental to marketable yield. In this respect irrigation timing in relation to evaporative demand, soil moisture potential and growing stage will remain a major aspect of applied research in crop water use. It is suggested that climatological and plant phenological observations and water use data are standardized on 10-day periods and as such reported on. It is also recommended that soil - water retention curves, salinity aspects and water table levels are part of the report on water use experiments. Such information is essential for the interpretation of the results.
9. It is recognized that Egypt is one of the countries in the Middle East with the longest tradition in irrigation and the largest number of researchers involved in land and water use. It is our opinion that the review and analysis of this work should be carried on and should lead to application to the benefit of Egypt as well as the neighbouring countries. As is mentioned in this Report some research should be reduced while other research should be encouraged. The need for team work and an integrated interpretation has been demonstrated in this Report.
10. It is felt that no real contribution is to be expected from water use experiments based on fixed irrigation intervals with amounts based on Blaney and Criddle or other estimates, or from water

applications equal to field capacity plus 5, 10, 15 and 20%.

11. Plotting total dry matter production against total water use should, from theoretical grounds, result in linear relationships with slopes mainly depending on the region. This has been demonstrated by using experimental data gained in Egypt. The curvilinearity occurring at certain levels of water use, observed for many of the published data, should stimulate the thinking of effects of limiting factors (salt accumulation due to insufficient water supply or nitrogen leaching due to excess water, etc.). It is evident that whenever the level of fertilization is limiting, lower potential production levels are to be expected so the effect of water will become increasingly smaller and even completely masked. This has been observed in the work reviewed.

12. In short, a fairly complete analysis of the obtainable agroclimatological data pertaining to Egypt has been made, with an identification of the gaps in knowledge and with suggestions for improvements. A comprehensive approach to crop water use experiments is recommended. The value of such an approach has been demonstrated by means of data obtained from the reviewed work mentioned in the list of references. Many derived data are given in this Report, mostly in the form of tables and graphs. Finally, a number of suggestions for future work have been made.

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SALT AFFECTED SOILS

BY A. M. BALBA, L.T.KADRY AND A.TAHER

INTRODUCTION

In the soil survey of the areas to be reclaimed by the water of the High Dam carried out in 1960, salinity was a main characteristic of the soils prevailing in an area of about 150 000 ha East of the Delta, 60 000 ha in the middle of the Delta, 40 000 ha West of the Delta and about 40 000 ha in Upper and Middle Egypt, the total area of the thus affected soils amounting to 290 000 ha. In most cases, this phenomenon was attributed to primary salinity. Secondary, salinity as an effect of inefficient irrigation or drainage systems in combination with climatic and anthropic factors is a common feature throughout the arable part of the country. EL GABALY (1959) estimated the area which suffers from salinity, primary or secondary, at about 800 000 ha.

The problem of secondary salinity drew the attention of soil investigators early in this century after perennial irrigation was widely spread over the country. The studies carried out at that time were centered on investigations of the causes which led to soil deterioration in relation to their productivity level at several localities. Later the problem of salinity constituted a major part of soil studies in institutes and research stations.

Because of the complex nature of soil salinity, the investigators had to tackle the problem from various standpoints. The studies made cover different fields, including the soil and plant sciences as well as the engineering and agricultural and economic production facets. The influence of climatic conditions, a major factor in salt accumulation in soils, water use by plants and water and salt balances of soil - plant systems, further increased the complexity of the problem. The relationships between all these aspects are so overlapping that it is very difficult to study one side of the problem without taking into consideration the effect of the others.

Before reviewing the work published in the field of salt affected soils, the authors would like to point out that the subject matter treated in this chapter as well as those treated in the other chapters of this Report are components of a closely knitted soil - water - plant system.

REVIEW OF PUBLISHED WORK

For a better insight in the research connected with salt affected soils the following subjects will be treated subsequently:

Field investigations, soil survey and classification
Soil reclamation and improvement
Water quality, physico-chemical and physical interactions
Crop - water - soil fertility interactions
  Tolerance of crops
  Crop - water interactions
  Crop - soil fertility interactions
Cultural practices

Field investigations, soil survey and classification

Field investigations

The salt affected soils in the Arab Republic of Egypt, in spite of their occurrence in a scattered pattern over the country, mainly predominate in the northern sector. EL GABALY (1959) refers to soil salinity and alkalinity as a major constraint to land productivity in the country and with regard to the distribution of these soils estimates that 60% lies in the northern sector, mainly as a result of sea water intrusion, over-irrigation and inadequacy of the field drainage network; 25% in the Middle Delta, mainly because of high water tables and inadequacy of the field drainage network; 20% in the Southern Delta and Middle Egypt and 25% in Upper (Southern) Egypt where the salinization originates from over-irrigation and waterlogged conditions aggravated by the high evaporative demand of the atmosphere.

EL GABALY (1959) further estimates that 30% of the reduction in soil productivity is to be attributed to soil salinization and that the effect of solving of this problem would be equivalent to 600 000 feddan (1 feddan = 0.42 ha) of additional land area. BALBA (1969) classified the salt affected soils in terms of their profile characteristics as follows:

- the alluvial soils, north of the Delta,
- the alluvial soils of Lake Mariut,
- the alluvial soils in the Nile Valley, i.e. Upper Egypt to South Delta,
- the desert soils,
- the alluvial desertic soils.

and according the main factors in the formation of these salt affected soils:

- a hot dry climate,
- sea intrusion and land submergence,
- secondary salinization in relation with unfavourable water quality, soil physical conditions and low topographic location.

The salt affected soil areas were extensively investigated. EL GABALY (1962) and FARAG et al. (1963) attribute the salinization in the Edco area to unsuitable water quality, inadequacy of the drainage system, high saline water tables as a result of seepage and to improper land levelling and preparation.

EL GABALY et al. (1957) surveyed 18 000 ha south of the Delta and showed that 25.4% of the area was saline. The saline fields were identified by their high groundwater table level. Similar findings were also reported for Tal El Kabeer (ALY, 1964) and North Tahreer (YUNIS, 1967). ARMANIOUS (1970) and ABDEL KADER (1973) described the soils of the Ferhash and Tal El Kabeer areas and established mapping units including vertisols, saline vertisols, fluvisols, saline fluvisols and sodic gleyosols.

In the Burullus Lake - Kafr El Sheikh sector - ZEIN EL ABEDINE et al. (1969) noted that several factors influence the occurrence of soil salinity and alkalinity. The most prominent factors were the topography of the terrain south of Lake Burullus, which declines inland in a southward direction, the heavy-textured soils, the tidal effects of the sea, the high salinity coupled with the high level of the groundwater, the high sodium - calcium and magnesium - calcium ratios in the groundwater solution which in turn are correlated with the comparable ratios in the sea water. These findings were also demonstrated in varying degrees by several other workers: EL BAGHDADY et al. (1969), R.A. MOHAMMED (1965), MUSTAFA (1969), EL NAHAL (1962), EL EKYABI (1963), EL SHABASSY et al. (1969). The role of the rise of groundwater in soil salinization in the Central Delta (R.A. MOHAMMED, 1972) and the regulatory effect on river flow of the High Dam on the salt and water balance in the soils of the Giza area (HAFEZ, 1962) were also subject to investigation. KORKOR (1957) attributed the soil salinization to the aridity of the climate in addition to the above mentioned factors.

Soil survey and classification

VEENENBOS (1971) reported that the soil studies of all cultivated lands of Nile Delta and Valley were finished at the end of 1970. This survey was in effect not performed according to the principles of a soil survey, but was a form of land productivity classification which illustrated actual agricultural productivity in terms of six classes presented on land classification maps of varying scale. The land classification maps were compiled on the basis of a number of factors of variable character, namely physical and chemical properties of the soil profile, development of crops (i.e. productivity) and land drainage conditions. Thus the observations were of a single value nature which lacked the entire correlative complex of all the inherent internal and external soil properties in the form of soil units of a soil classification system or soil mapping units, e.g. soil series, soil associations, soil complexes and their correlations. Otherwise stated, with the method of land classification the soils were not characterized in terms of their macro- and microgeomorphologic origin or other related characteristics.

Soil reclamation and improvement

General

EL GABALY (1970) gave a review of the physical and soil - plant - water relationships of saline, alkaline and waterlogged soils in Iraq, the Syrian Arab Republic and the Arab Republic of Egypt. The salient research findings and the main lines of action presented were:

- the data required and the sequence of field operations to be followed in reclaiming salt affected and alkaline (sodic) and waterlogged soils,
- conservation of soils from salinization and waterlogging,
- the economic aspects of the reclamation of salt affected soils.

BALBA (1969) published a book on the subject-matter with six chapters respectively on: saline and alkali soils, saline and alkaline soils in the world, salts in the soil system, effect of salinity on the plant growth, reclamation of saline and alkaline soils, and land reclamation in the world. Information was presented regarding the main findings of research work on the physico-chemical mechanism operating in the salt affected soil and water systems and its characterization as a means to identify and accelerate the processes of field reclamation, improvement and management of salt affected and waterlogged soils. The existing land reclamation projects of salt affected soils in the Arab Republic of Egypt and other parts of the world were also treated.

Leaching processes

BALBA and his co-workers EL LAITHY, BASSIUNY and SEIF EL BASR (1965, 1968, 1968 and 1972) studied the salt balance in soil columns differing in texture and salt content. They attempted to estimate the amount of water required to remove salts in the field, using the method described by DIELEMAN (1963). BALBA and BASSIUNY (1972) used Na_{22} to trace the movement of NaCl in sand and soil columns. They used the Bryssine equation in calculating the salt concentration in the column after application of water and concluded that the equation was applicable only under specified conditions. BASSIUNY'S work (1972) showed that the GARDNER and BROOKS (1957) approach can be utilized in predicting the depth of water required to leach salts to a particular soil depth. BAGHDADY (1969) showed that the application of higher hydraulic heads decreases the amount of water to reach a certain level of salt concentration. EL WAKEEL (1964) showed that the leaching process in Hamoul (North of Delta) was affected by the quality of the water and the soil profile characteristics.

BALBA and EL LAITHY (1968) noted that when water was limited or when the groundwater was shallow continuous leaching was more effective in removing the salts from soils. RIZK (1964) reached the same conclusion in the Shalma area. However, intermittent leaching was favoured by other workers: EL ATTAR and BAKR (1963) concluded that continuous leaching required larger amounts of water. They also stated that in intermittent leaching the intervals between water applications should be shortened in summer.

BALBA and EL LAITHY (1968), KATTAN et al. (1969) and MASSOUD et al. (1969) concluded that leaching proceeded faster in the presence of gypsum.

Amelioration of sodic soils

SCHOONOVER et al. (1957) showed that leaching alone was not effective in displacing the excess exchangeable Na in sodic soils. BALBA and EL LAITHY (1968) showed that soils should contain a source of calcium, which dissolves when water is applied, in order that leaching is satisfactory. They suggested a test to ascertain whether the soil needs an application of gypsum or that leaching alone will be enough to displace excess exchangeable Na. They also modified the Schoonover method, widely used for the evaluation of gypsum requirement in sodic soils, to make it suitable for this evaluation in saline sodic soils. Again BALBA et al. (1969) verified this point by using Na_{22} and suggesting the evaluation of the gypsum requirement by determining exchangeable Na by means of Na_{22}.

HUSSEIN (1963) used water with a concentration equal to one-third that of sea water to leach the soil, followed by leaching with more diluted water with a SAR value of 5. He showed that the ESP decreased but not enough to consider the soil completely reclaimed.

BALBA and EL LAITHY (1968), KATTAN et al. (1969) and MASSOUD et al. (1969) showed that application of the gypsum requirements before leaching is as effective as application after leaching.

ALI (1964) compared different amendments and showed that chemical materials were more effective than organic matter. Among the chemicals, aluminium sulphate was more effective and penetrating.

HAMDI et al. (1966) used gypsum and water with four different salinity concentrations and sodium - calcium ratios to ameliorate a clay loam and a sandy soil in pot - lysimeters with the result that gypsum applied at the rate of 4 tons per acre was noted to be effective in preventing the harmful effect of saline water of 1000 ppm and 65% sodium on the clay complex of the clay loam soil.

EL SHABASSY et al. (1962, 1970) and MITKEES et al. (1968) determined the quantities of leaching requirement and the qualities of leaching water for an artificially salinized clay loam soil in iron cylinders. It was found that the effectiveness of soil reclamation was increased with an increase of the hydraulic head of the high quality leaching water.

ZEIN EL ABEDINE et al. (1963) studied the changes that had occurred over 60 years in the soil chemical properties of barren versus cultivated soils of the Northern Nile Delta. It was noted that cultivation induced a reduction of salinity in the surface soil, a reduction to 31.5% of the groundwater salinity, and that gypsum application as an amendment was imperative to avoid alkali formation.

Water quality, physico-chemical and physical interactions

Role of irrigation water

BALBA and his co-workers BASSIUNY and SEIF EL NASR (1965, 1970 and 1971) studied the mechanism of salt accumulation with soil columns irrigated with water differing in salt concentration and using Na_{22} labelled water. Using pot experiments BALBA (1960 and 1962) showed the deteriorating effect of irrigation water containing sodium carbonate on soils differing in texture, salinity and $CaCO_3$ content. EL GAMAL (1966) showed that the salt concentration and the SAR value of the soil paste extract increased with an increase in salt concentration and SAR of the irrigation water. The same conclusions were reached by FAHMY (1964), GHAZI (1963), METWALLY (1963) and HUSSEIN (1965). KISHK et al. (1972a) explained the presence of Na_2CO_3 in Tal El Kabeer soils as being due to an excess of (HCO_3^- + $CO_3^=$) and SiO_2 in the Nile water.

HAMDI et al. (1966) when experimenting with a clay loam soil noted that the increase of exchangeable sodium over exchangeable calcium was proportional to their ratio in the leaching solution, regardless of the total soluble salt concentration in the leaching solution.

HAMDI et al. (1968) further noted that irrigating a clay loam soil with water of different salt concentration and increasing sodium to calcium ratio decreased the rate of salt leaching in soil columns. Comparing the effects of different soluble salt concentrations and monovalent - divalent cation and anion ratios in irrigation water on the chemical and physical properties of loamy, clayey and calcareous soils respectively, ABDEL RASHED (1969) showed that the susceptibility of soils to the deleterious effects of high sodium to calcium plus magnesium ratios in irrigation water on soil structure, permeability and level of moisture equivalent was in sequential order of decreasing heaviness: loamy, clayey and calcareous soils respectively.

FATHI (1972) reported that the rate of leaching in saline soils is a function of both the quality of the leaching water and the physical properties of the soil and that a high water table retards the leaching process.

Effect of physical properties

ZEIN EL ABEDINE et al. (1964) studied the effect of soil aggregation on permeability and reported a positive linear relationship between the logarithm of permeability and the structural factor value and between the former and both the degree of aggregation and silt-sized aggregates.

HAMDI et al. (1964) studied the effects of grinding, soaking for different periods and stroking prior to sieving of soil samples on the aggregate size distribution and noted that soaking for 30 minutes gave optimum results. A sharp decrease in aggregation resulted from soaking alkali soils.

ABDALLA et al. (1973) investigated the effects of soil texture and structure on the consistency of soils. It was found that the heavier the soil texture the stronger its consistency was and that the nature and concentration of soluble cations affected soil consistency. Soluble sodium had a reducing effect on hardness, whereas exchangeable sodium had an increasing effect. This effect of exchangeable cations was in descending order: sodium, magnesium, potassium and calcium.

ZEIN EL ABEDINE et al. (1968) studied water permeability in relation to soluble salt content of irrigation water and noted that water soluble salts in soil water effect a change in soil physical properties especially as regards exchangeable bases, stability of aggregates and swelling. These, in turn, influence water conductivity. The higher the ratio of sodium to calcium cations in irrigation water, the lower the permeability coefficient especially in cases of high salt concentrations.

ZEIN EL ABEDINE et al. (1968) reported that swelling and shrinkage of soils depended mainly upon the behaviour of the clay fractions. High clay contents promoted orientation of particles and formation of water stable aggregates. The sand fraction serves as a fairly rigid skeleton preventing visible clay shrinkage at low water contents.

Role of groundwater

BALBA and SOLIMAN (1969) studied the role of water both in the liquid and vapour phase which moved upwards from constant water levels in connection with the salinization of homogeneous and layered soil columns differing in soil texture and length. EL GABALY and NAGUIB (1965) used lysimeters to study the effect of depth and salt concentration of the groundwater on soil salinization. GHAZI (1963) compared the upward movement of water in the field and in lysimeters.

Calculation of depth and spacing of drains was carried out by AMER and EL GABALY (1962) and BATANOUNY (1966).

Chemistry and thermodynamics

The exchange reaction in closed systems was studied by HELMY and EL GABALY (1954) and BALBA and his co-workers ALI BALBA and BASSIUNY (1959, 1962 and 1972). Several mathematical expressions were used to describe the reaction.

The effect of $CO_3^=$, OH^-, $SO_4^=$ and Cl^- on the cation exchange reaction, its thermodynamics and the activity of the adsorbed cations were studied by BALBA and BALBA (1972). It was found that the order of Na-adsorption according to the anion present in similar concentrations was $OH^- > CO_3^= > SO_4^= > Cl^-$ for uni-univalent systems and $CO_3^= > OH^- > SO_4^= > Cl^-$ in the presence of divalent cations.

In flow systems BASSIUNY (1972) used Na_{22} to follow variations in exchangeable Na after application of water or $CaCl_2$ to soil columns. Attempts to apply the equations of BOWER et al. were not successful.

ALI BALBA (1971) studied the effect of anions on the electrical conductivity of clay suspensions and attempted to calculate the contribution of the solid and solution phases to the specific conductivity of the suspension.

Clay mineralogy

EL GABALY and KHADR (1962) made a quantitative study of the clay fraction of Central and Northern Delta soils (alluvium) using cation exchange capacity, X-ray spectroscopic analysis, differential thermal analysis and electron microscopy. It was noted that the dominant clay mineral was montmorillonite followed by kaolinite with a low content of hydrous mica. EL KADY (1966) studied the clay minerals of the Delta using the X-ray diffraction technique and differential thermo-analysis. It was noted that for the clay subfraction 1 to 0.5 µ, the illite clay mineral dominates the clays of the studied samples with variable amounts of other minerals, mainly montmorellonite, kaolinite and hydrous mica in decreasing order of concentration. HEKAL (1968) carried out a mineralogic study of alluvial saline soils in relation to their fertility status and he reported that the dominant clay mineral was abnormal dioctahedral montmorillonite (iron rich similar to nontronite) in association with kaolinite, illite or K-bearing minerals, feldspar and non-crystalline gels. NAGA and MITCHELL (1964) investigated the mineralogy of the clay fraction and reported that montmorillonite was the predominant clay mineral in the Shalma area soils, North Delta.

KISHK et al. (1972) examined the clay fraction of Wadi Al Tumaylat soil (Tal Al Kabeer area) and showed that the dominant clay mineral is a highly swelling iron-rich dioctahedral smectite, possibly a nontronite or a nontronite-montmorillonite mixture. Their results indicated that the average mineralogical composition was: montmorillonite 48 to 56%, kaolinite 15 to 18%, mica 5 to 11%, feldspar 5%, quarts 3 to 5% and free oxides 11 to 16%.

They also stated that in the layers with the highest salt and soda content the X-ray analysis showed the largest amount of X-amorphous oxides and the broadest X-ray diffraction peaks. They concluded that excessive saline and alkaline conditions may cause a degradation of clay minerals releasing more free oxides and resulting in a poorer degree of crystallinity of clay minerals.

Crop-water-soil fertility interactions

Tolerance of crops

The Soil Salinity Laboratory, Soil and Water Research Institute, Alexandria, has since the 1950's been working on the tolerance of crops to saline soils, water quality and fertility. Up to now over 60 research papers have been published on this subject-matter. KADIAH (1962) noted that the four varieties of berseem clover in sand cultures exhibited moderate tolerance to salinized water with a range of 1000 to 4000 ppm total soluble salts. HUSSEIN et al. (1971) worked on two varieties of berseem clover (Miscawi and Higazi) in sand cultures with irrigation solutions of single and mixed soluble salts of sodium, magnesium and calcium cations, and chloride and sulphate anions; the osmotic concentrations ranged from 1.0 to 4.0 atmosphere. It was observed that a reducing effect on yield was exhibited in descending order by magnesium, calcium and sodium salts. It was also noted that the Miscawi variety of berseem was more tolerant than Higazi.

BARAKAT et al. (1971) carried out two lysimeter experiments using a sandy loam soil to determine the relative salt tolerance of five varieties of Egyptian cotton. The range of salinized irrigation water was 180 to 2000 ppm. The descending order of tolerance was reported to be Menoufi, Giza 47, Ashmouni, Giza 45, Karnak. BARAKAT et al. (1970) used pots to determine the salt tolerance of four forage crops: beef builder (fodder rape), sudan grass, sweet sudan grass and sweet sorghum, sown in salinized soil saturation extracts ranging from 200 to 6200 ppm. In general the sequence of tolerance was noted to be in increasing order: fodder rape, sweet sorghum and sudan grass.

BARAKAT et al. (1971a) studied the relative tolerance of 16 varieties and crosses of rice to the salinity of irrigation water. It was reported that grain yield was reduced to two-thirds, one-third and one-tenth of the control by raising the salinity of irrigation water to 1500, 3000 and 6000 ppm respectively. On the average, the cross 201/30/38 exhibited the highest tolerance followed by cross 201/30/37, Giza 159. BARAKAT et al. (1971b) studied the effect of the salinity of irrigation water on germination of 17 rice varieties. Three treatments of saline irrigation waters were applied: 180, 780 and 1380 ppm respectively. The varieties were then grouped in 3 classes relative to their salt tolerance at the germination stage. BARAKAT et al. (1968) worked with pots to determine the salt tolerance of 23 vegetable crops. According to the results, the vegetable crops were classified in terms of their relative tolerance taking as salt index the 75 and 50 per cent relative yield with respect to the control.

HAMDI et al. (1966) studied the effect of saline water on the growth of alfalfa using respectively a sandy and a clay loam soil. Three saline water concentrations were used: 1000, 2000 and 3000 ppm. The reduction in alfalfa yield on respectively the sandy and clay loam soils relative to the sequential increment of the 3 saline waters were respectively 21 and 14%, 36 and 20%, and 68 and 38%.

ABDOU et al. (1971) investigated the effect of high salt concentrations upon the growth of barley in pot cultures with varying cation and anion sources. The saline concentrations in the irrigation waters ranged from 2500 to 10 000 ppm and their effects on the germination, vegetative and grain yield stages of barley growth were recorded. It was found that at the germination stage, barley was sensitive to more than 2.3 atmosphere osmotic potential in the soil solution. As expected, reduction in vegetative and grain yield was proportional to the increase in saline concentration. Magnesium was noted to be the most deleterious cation and chloride exhibited a higher reducing effect on growth as compared to sulphate.

EL GABALY et al. (1971) worked with drum cultures on sugar cane to determine the effect of integrated leaching on the growth and yield of two varieties of cane Co 310 and Co 413. A range of ten increments of salinized soil was used from 0.03 to 1.5% concentrations of soil salinity. The results showed that the two cane varieties grew optimally in a saline soil of 0.4% salinity, provided leaching was carried out. In general, Co 413 was reported to be more tolerant than Co 310.

Crop - water interactions

A comprehensive review and analysis on the irrigated water use of cotton in Egypt has been given by RIJTEMA and ABOUKHALED (see the chapter in this Report). ZEIN EL ABEDINE et al. (1962) used a cotton crop for his comparison of the conventional 18-day irrigation interval as applied by the Ministry of Irrigation with the controlled irrigation amount based on the consumptive use criterion and the time required for the 300 m^3 irrigation water per feddan to be consumed by evapotranspiration. It was reported that the controlled irrigation treatment had several advantages over the conventional irrigation treatment, with respect to savings in water use, improvement of the soil physical condition and a 20 to 25% increment of average cotton yield.

HAMDI et al. (1968) observed from irrigated cotton that irrigating at a 7-day interval increased the average yield and reduced soil salinization as compared to irrigating with 14- and 21-day intervals.

BARAKAT et al. (1970a, 1970b and 1971) used lysimeters to determine the effect of water table depth and restricted drainage on the growth of cotton, 3 rice varieties and flax, alfalfa and maize. Their salient findings were:

- for cotton and a groundwater salinity of 8200 ppm, a maximum yield was obtained at a water table depth of 160 cm. Raising the water table reduced the yield upon which the soil texture became limiting. The sandy clay loam soil produced on the average less yield than the clay loam soil. Calcareous sandy clay loam was intermediate in productivity;
- for rice the Nahda variety gave a maximum yield with a 6-day period of restricted drainage. The yield of the Arabi variety declined progressively at a treatment of 1-day of restricted drainage. The Agami variety was not affected by restricted drainage. Salinity, as well as carbonate and bicarbonate concentrations increased with an increase of restricted drainage periods;
- for flax, alfalfa and maize respectively, the critical depth of water table in terms of salinization and reduced yield was respectively 70, 70 and 130 cm.

Crop - soil fertility interactions

With regard to the effect of salt affected soils on plant growth and response to fertilization, EL GABALY and ABDEL GHANY (1955), EL GABALY and MASSOUD (1956) and EL GABALY and MADKOUR (1965) studied the effect of salt concentration and Na percentage in total soluble salts on the growth of field crops. Their results revealed that good growth of barley, wheat, clover, beans and corn can be obtained with a maximum of soil EC in mmhos and Na percentage of 3.5 and 70, 2.5 and 48, 3.0 and 58, 2.2 and 50, 3.8 and 35 respectively.

BALBA (1962) studied the effect of sodic water on a saline soil in pots planted with cotton. It was noted that saline water decreased cotton growth and yield and that gypsum application did not solve the problem.

BALBA (1960) used $CaCO_3$-rich soil planted with onions to study the effect of water quality on growth and level of cation nutrients in the plants. It was noted that an increase in Na in the irrigation water decreased growth; the tolerance level with respect to the carbonate cation in the irrigation water was 3 meq/l; potassium uptake decreased with an increase of Na, Mg and Ca in the soil extract and the uptake of Ca and Mg decreased with an increase of carbonate cations.

BALBA and EL LAITHY (1968) investigated the cation balance in barley plants as affected by varying leaching levels of a saline soil. It was noted that the content of Na in the plant increased with an increase in soil Na; excessive leaching decreased K-contents in the plant and the ratio (Ca + Mg)/total cations in the plant varied proportionately with the (Ca + Mg)/CEC ratio of the soil.

EL GAMAL (1966) compared the tolerance of barley and berseem plants to saline water and showed that barley was more tolerant than berseem up to 1500 ppm of soluble salt in the water. Dry weight yield of the two crops declined starting from a 3000 ppm soluble salt concentration. This drop in yield increased proportionately with an increase in Na/(Cl + Mg) ratio.

BALBA (1968) showed that increments of NaCl enhanced the fixation of phosphatic fertilizers in a Giza soil. It was also noted that NaCl increased the solubility of $CaCO_3$ as a result of which more phosphate precipitation took place.

AMER et al. (1964) showed that the recovery of fertilizer nitrogen was 58 and 46% for non-saline and saline soils respectively. BALBA and BASSIUNY (1968) used P_{32} to show that water with NaCl or $CaCl_2$ significantly decreased the phosphorus absorption from both fertilizer and soil sources. From recorded field observations, ALI (1964) showed that cotton yield decreased with salinity. He stated that Menoufy cotton was more tolerant than Giza 45 and Karnak cottons with regard to the concentration of total soluble salts, the Cl-concentration and the exchangeable Na-percentage.

KHALIL et al. (1967) showed by a greenhouse experiment that the response of corn to N was reduced due to salinization to 79, 71 and 67% of the non-saline soil at electrical conductivity values of 5, 7 and 9 mmhos/cm of the soil paste extract. They also showed that K-content of corn decreased with salinity.

BARAKAT et al. (1971) employed lysimeters to identify the water and nutrient loss by deep percolation for cotton and maize. It was found that at water table depths of 40 and 70 cm the water losses were 35 and 32 cm respectively, whereas for a water table depth of 160 cm the water loss was 6 cm. Loss of nutrients was proportional to the water losses.

HAMDI et al. (1963) carried out 30 field experiments in Upper and Lower Egypt on the utilization of soil and fertilizer nitrogen by wheat. Two wheat varieties were tested: Hindi (Triticum vulgare) and Baladi (Triticum pyramidale). Calcium nitrate was applied at levels of 0, 100, 200 and 300 kg per feddan respectively. It was noted that the yield of both varieties increased proportionally to the rate of fertilizer application and that the Hindi variety gave higher yields in Upper than in Lower Egypt. The response to nitrogen was higher in the former than in the latter zone. Significant correlations were also obtained between the nitrogen status of soils and experimental crops.

BARAKAT et al. (1970) used pots to investigate the effects of salinized soils and nitrogen fertilization on the grain yield of the Giza 145 variety of wheat. Three levels of saline water: 200, 3000 and 6000 ppm, and two levels of fertilizers: 1.0 and 2.0 gN/pot, were used on clay and loam-textured soils. The yield reducing effect of salinity was greater in coarse than in fine-textured soils. Low levels of nitrogen fertilization gave lower yields.

FATHI et al. (1971) studied the effect of salinized irrigation water on salt accumulation in sandy soils and berseem Higazi growth. It was reported that 3000 ppm in threefold was the level above which salt accumulation was aggravated in sandy soils.

ABDEL SALAM et al. (1963a and 1965b) used pots to experiment on the interaction of saline irrigation water with phosphorus fertilization of alfalfa and barley, and with nitrogen fertilization of corn in calcareous soils. The findings showed that the derivation of phosphorus from the fertilizer was adversely affected by the salinity level in the irrigation solutions and that growth of alfalfa and barley was not affected markedly by the sodium concentration. It was noted that a significant positive interaction was extant between soil salinization and nitrogen application.

EL SHABASSY et al. (1972) noted in a pot experiment to determine the effect of saline irrigation water on growth and phosphorus uptake by soy bean that the phosphorus content in soy bean decreased proportionately with salinization. Decrease in yield and phosphorus content of soy bean was higher in a sandy soil than in calcareous and clayey soils.

Cultural practices

Compaction at ploughing time of layers underlying plough depth was investigated by HANNA and MASRY (1962). Soil moisture was noted to be the dominant factor influencing the extent of desiccation and the hardness of the ploughed layer. Compaction of layers underlying plough and subsoiler depths was detected.

HAMDI et al. (1965) carried out a comparative study of the effect of shallow and deep ploughing on crop yield and soil physical properties. No observable difference was detected between the effect of the native (baladi), chisel and moldboard ploughs on cotton and wheat yield. Chisel ploughing was recommended as being economically advantageous. Deep ploughing was noted to be highly effective to increase maize yield. Improvement of the soil physical conditions was reported to occur after deep ploughing.

ZEIN EL ABEDINE et al. (1968) investigated the effect of the soil physical properties on the drought resistence after chisel ploughing. A linear relationship was noted between clay content, moisture level and specific drought resistance.

BARAKAT et al. (1968) in their study of the effect of depth and spacing of subsoiling on cotton yield in the agriculturally marginal area of the North

Delta reported that 45 cm deep subsoiling was optimal. Close spacing induced an increase in the germination, growth and yield rates of cotton.

ZEIN EL ABEDINE et al. (1970a and 1970b) reported that for cotton and horse bean, seed germination, plant growth, root growth and yield increased in descending order after tillage with rotary, moldboard, chisel and baladi ploughs. It was also reported that chisel ploughs produced smaller sized aggregates than baladi ploughs regardless of the frequency of ploughing.

DISCUSSION

General

Growth, development and yield of crops are determined by their genetic constitution, the prevailing agroclimatic and edaphic conditions with respect to the timely availability of a balanced supply of nutrients, moisture and soil air, and the absence of inhibitory factors such as salinity, waterlogging and unfavourable physical conditions.

In the part on crop water use (RIJTEMA and ABOUKHALED) of this Report it was demonstrated with the aid of agrometeorologic and plant phenological data how to obtain a reliable assessment of the evapotranspiration requirements of crops grown under the irrigated arid and semi-arid environments in the country. It is known that climatic factors have a direct effect on photosynthetic activity, plant metabolism and water use efficiency. It was shown by Rijtema and Aboukhaled that to determine the 'real evapotranspiration' criterion for crops, resort should be taken to a modified combination method based on Penman's established formula (RIJTEMA, 1965 and 1969). Thus in the equations account is taken of weighted effects of net radiation, mean annual temperature and change in vapour pressure per unit change in temperature, as well as of the vapour transport term, so important in arid regions. The evaporative demand is high in arid environments. Plant roughness and height, per cent soil cover and water availability all were integrated in the analysis. Based on an analysis of the available and derived agrometeorologic data, it was noted by Rijtema and Aboukhaled that agrometeorologically, the Arab Republic of Egypt can be subdivided into 9 distinct agroclimatic areas.

Maximum yield can be obtained when the evaporative demand determined for each of the 9 agroclimatic zones is met, taking into account the crop growing stage. For a crop, optimum growth, development and yield response is dependent upon the sustained existence of non-stress conditions within the foci of metabolic activities and in particular in the leaf stomata. Stated otherwise, the level of leaf water potential of the particular crop is continuously to be higher than the level of the maximum evaporative demand of the agroclimatic (i.e. atmospheric) environment. This in turn implies that adequate amounts of moisture and nutrients are readily available to the plant roots throughout their entire growing period. Hence, it is important for a proper application of the agroclimatologic findings, that the extent of limiting factors as water stress conditions, waterlogging, soil salinity and unfavourable soil physical or fertility status, is known and that adequate solutions are found to curb their influence. Only then the crops can respond optimally and give high yields.

Stated in other terms, it is essential that for each of the 9 agroclimatic areas the criteria are determined for a sound assessment of drainage, reclamation, improvement and management of salt affected soils and of soils afflicted with other crop growth inhibitory factors.

Field investigations, soil survey and classification

It can be generally stated that the investigations and survey of salt affected soils carried out in Egypt, in spite of their extensive character, have invariably been dictated by the need to seek solutions to local problems or by policy decisions of the Government to determine the potential of the limitations of land productivity of the cultivated floodplain in the valley and delta of the River Nile.

In his evaluation of the land classification work in the country, VEENENBOS (1971) expressed the crucial need to carry out a systematic soil survey of the entire Nile delta and valley, in which all the correlative external and internal factors related to the geomorphologic origin and edaphologic constitution of the soil groups would be characterized in terms of their associations and mapping units. Once a systematic soil survey and classification is carried out with use of aerial photo-analysis and interpretation, concurrently with the application of applied research programmes on alternative systems of land use in representative areas on the agroclimatologic areas of the country (c.f. RIJTEMA and ABOUKHALED in this Report), this would lead to a more rational evaluation of the land use potentials of the different soils in terms of their intrinsic multi-value qualities.

Soil reclamation and improvement

The experience and progress achieved in Egypt in the field of applied research on land reclamation and improvement of salt affected soils are impressive when seen from the viewpoint of short-term research. The main limitation of this research effort is, howver, its lack of wide coverage with the objective to determine criteria for every phase of field operations regarding reclamation and improvement of the different soils. In this respect, it is thought that when subprogrammes were to be formulated for each of the representative centres of research institutions and experimental areas in such a manner that the elements of the sub-programme are interlinked in a unified research programme, then a significant progress could be achieved.

The research work under review in the field of land reclamation was directed to one main point, namely the use of chemical amendments, especially gypsum, in the desodization process. The effectiveness of gypsum was demonstrated and widely accepted. Methods to estimate the amount of gypsum required for reclamation and the suitable time for its application still need further work.

Other points of importance in the reclamation process of the salt affected soils that were not well-covered in the research work reviewed are:

- the leaching process especially under lysimeter and field conditions. A method to evaluate the amount of water required to remove salts to a specified soil depth is still to be found,
- the determination of suitable spacings and depths of open drains, tile or mole drains for the varying waterlogged soil conditions,
- the technology of dealing with impermeable sub-soil layers which are a common feature of the salt affected soils of the North Delta region.

The present authors stress that for an effective progress in the field of land reclamation and improvement it is essential that the applied research programme is comprehensive in its coverage and its representation of inter-disciplinary fields, as agricultural and mechanical engineering, agronomy, soil and water science, crop breeding and physiology, agroclimatology, agricultural production and economics. Meaningful results in applied research can only be achieved through inter-disciplinary team work.

Water quality, physico-chemical and physical interactions

The relevant findings in the fields of water quality and physico-chemical and physical interactions of salt affected soils determine to a large extent the successful performance of land reclamation and improvement activities. Of predominant importance in this respect is the need of formulating standardized research programms for application in each of the representative experimental station and pilot areas in each of the agroclimatologic areas of the country. The primary objective of this research programme should be the determination of criteria for each of the main physical and physico-chemical properties of the representative soils, these to be used in the design and construction of irrigation and drainage networks and reclamation, improvement and management of salt affected soils. It will be needless to mention in this respect that each agroclimatologic area has its own typical soil and water resource problems which necessitate its own course of specific line of problem solving. Other points to be mentioned are:

- the work reviewed in the area of physico-chemical reactions is very limited and it needs to be extended, especially regarding flow systems, and use should be made of mathematical relationships expressing the exchange, movement and dynamics of cations and anions upon application of water,
- the effect of salts on the clay minerals is another phase of basic research which was only recently attempted and which deserves more attention,
- secondary salinization received considerable attention in the field, as well as in the laboratory. However, studies on techniques for the utilization of saline water where fresh water is not sufficiently available, are limited.

Crop - water - soil fertility interactions

Irrigation agriculture in the arid and semi-arid zones of the country will not attain sustained optimum land productivity conditions unless a proper combination of factors of the crop - water - soil fertility relationships is used. This phase of crop - water - soil fertility management follows in sequential order a sound maintenance of salt and water balances by means of proper installation of field irrigation and drainage networks, coupled with a timely application of land preparation and cultural practice measures in accordance with the needs of the prevailing soils.

It was noted that in this field, research dealing with salt balance was very limited and did not include growing plants. Several centres of research studied the effect of salinity on plant growth and the response to fertilization. In this regard, the present authors emphasize the importance of studies about the effect of salts on physiological and biochemical processes in plants. Also studies on techniques which might be adopted to increase the production of salt affected soils were not sufficiently numerous.

It was also noted that a need exists to carry out a comprehensive soil fertility test and demonstration survey, which should be closely coordinated with regular pilot area work. This line of action, to be based on a soil mapping unit characterization, has to cover field experimentation, demonstration, soil testing and correlation with yield and soil properties; soil and water management and conservation; irrigation, drainage and pest control; economics and improvement of fertilizer distribution and training facilities. Coordination of this line of action in the pilot experimental and development areas will have to take place.

RECOMMENDATIONS

General

The review of the applied research work on land and water has revealed the evidence of constraints in certain facets of the work. The most significant constraint at the national level resides in the lack of cooperative and coordinative relations that link the operational programmes of the centres of applied research on land and water in a common action programme.

Effective land and water development planning and programming is to be based on a sound systematic evaluation of the soil and water resources followed by field investigations on soil - crop - water relationships in pilot experimental areas. These areas are to be located within larger scale pilot development areas, where integrated multi-disciplinary operations to assess the economic and marketing feasibilities of alternative systems of land use are to be implemented. This does not mean that the land and water use planning and programming phase has to wait for the outcome of pilot development area operations, but that current plans and programmes for land and water use have to be executed as scheduled by the country's agricultural development plan, subject to improvement modifications when relevant results are obtained from the pilot development areas.

In assessing, reclaiming and utilizing problem soils at a country level, the first phase for these field operations has to include proper taxonomic and geomorphologic characterization and identification of these soils in accordance with acceptable standards of soil survey, the determination of their physical, chemical and fertility limitations and the setting of criteria in terms of their land use capabilities for alternative cropping systems through their application in pilot development areas. As more relevant technical and production-economic findings accrue from the pilot development areas, these findings will contribute to a further improving and refining of the local classification system for land evaluation.

For the determination of the criteria of problem-soil characterization and utilization, it is necessary that in each representative agroclimatologic zone in the country, standard methods of field procedures and experimental layouts are applied for their reclamation, improvement and management. This standardized approach will make it possible to attain immediate comparative assessments of the soil and water use criteria under the varying environmental conditions prevailing in the country.

In both the programming and implementation phases of these applied research field operations, it will be necessary that the subject-matter specialists attached to each of the Ministries of Agriculture, Land Reclamation, Irrigation and to the Universities, form teams down to the level of field operations. Clearly defined organizational procedures reporting have to be set for each research worker participating in the team work, as well per discipline as per phase of the applied research programme at the country level. Adequate budgetary allocations and authorizations for expenditure have to be issued within the framework of the total estimated cost of execution of the applied research programme.

Investigations

The field investigations on salt affected soils, their reclamation and improvement, the soil - crop - water relationships and their interactions for which criteria have to be determined at the country level from pilot experimental areas selected in each of the nine agroclimatologic zones are in the following paragraphs.

Soil reclamation and improvement

- Characterization and classification of saline, saline-sodic and sodic soils.
- Hydrologic survey of the experimental area and a field irrigation and drainage requirement survey.
- Land levelling in connection with the leaching and post leaching (i.e. soil and irrigation management) phases.
- Design of field irrigation and drainage networks. Checking of the applicability of empirical field drainage formulae and salt and water balance formulae through evaluating the measure of correspondence between calculated and actually determined field parameters.
- Intermittent versus continuous leaching; time of application; water quality and quantity; ESP, SAR; infiltration rate and hydraulic conductivity; monitoring water table movement; depth and quality in relation to the salt balance and crop response.

Water quality, physico-chemical and physical interactions

- Quality of water, infiltration rate, hydraulic conductivity interaction.

Crop - water - soil fertility interactions

- Standardization of methods of soil, water and crop analysis.
- Effect of magnesium cations in relation to soil physical and chemical properties.
- Soil - crop - water testing and analysis criteria.
- Determination of quick tests based on sound calibration with actual field conditions and responses.

Tolerance of crops

- Restricted to new strains of the high value crops.
- Effect of fluctuating groundwater level and water quality.
- Effect of fertilizer level - tolerance interaction.
- Role of high magnesium cation levels in soils in relation to crop tolerance.

Crop - water interactions

- Effect of fluctuating groundwater levels and water quality and their interaction with fertilizer levels.
- Crop testing relative to field experiments.

Crop - soil fertility interactions

- Wide range of single and combined fertilizer element effects.
- Fertilizer level in connection with saline and sodic soil conditions.
- Crop testing in relation to soil fertilization and soil problem conditions, e.g. salinity, sodicity, calcium content and other physical and chemical inhibitory conditions.

Cultural practices

- Effect of varying depth of sub-soiling.
- Effect of harrowing versus conventional methods.
- Agricultural production-economics of land preparation and cultural practices.
- Determination of the optimum cultural practices for the various soil physical conditions, particularly with reference to soil texture, structure, consistence and the timing, based on the soil moisture status, of cultural practices.

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DRAINAGE

BY A. ARAR AND B.G. BISHAY

ROLE OF AGRICULTURAL DRAINAGE IN EGYPT

G e n e r a l

Egypt is among the most densely populated countries in the world. On a cultivated area of about 7 million feddan (1 feddan = 4200 m^2), it has to support more than 34 million inhabitants and provide employment for over 50% of its population. The situation is further aggravated by a continuous growth in population which is not concurrent with a proportional increase of cultivated area. At the start of the century, the total cultivated area was estimated at 5.4 million feddan and the population was 12 million, whereas in 1970 the cultivated area was 7 million feddan and the population 34 million. Thus the increase in cultivated area amounted to 30%, while the increase in population during the same period was about 180%.

This clearly is a crucial problem and all efforts should be made to devise plans to secure a balanced growth of agricultural production in such a way that it matches population growth. Consequently agricultural programmes are given a high priority in the Government's development planning, with particular emphasis on an increase of food production to reduce imports and to increase crop exports. This can be achieved by one or both of the following means:

The first consists of the expansion of agricultural land with the provision that adequate water resources are available. For Egypt this solution has several drawbacks of which some are that:

- most of the lands available for reclamation are of sandy nature and situated in desert areas, which implies high irrigation water requirements,
- irrigation projects in such areas are very costly as they require the construction of pumping stations, much land levelling and lining of canals. Furthermore, such new areas require the settlement of new farmers which involves high investments in the form of housing, roads and other domestic services. The overall investments involved amount to about £.E. 600 per feddan, the equivalent of about US $ 3500 per ha. Thus, the increase of agricultural land is very expensive and anyhow limited by the available water resources.

The second solution is the raising of agricultural produce coming from the now cultivated areas. Most of these areas have been under perennial irrigation with multiple cropping since the early part of the century. This has caused a rise of the water table and an aggravation of the soil salinization problem. The excessive salinization of the land at many locations in Upper Egypt and the continuously decreasing yields of areas which were productive before the conversion from basin to perennial irrigation drew the attention to this unforeseen hazard that would suppress the advantage gained from multiple cropping. Consequently, adequate drainage facilities are to be provided to lower the water table and to control soil salinity, thus achieving increases in yield of the major crops. D r a i n a g e w a s f o u n d t o b e t h e m o s t e f f i c i e n t s o l u t i o n t o a m e l i o r a t e t h e l a n d f o r a g r i c u l t u r a l p r o d u c t i o n , w h i c h h a s b e e n e x h a u s t e d t h r o u g h c e n t u r i e s o f i n t e n s i v e c u l t i v a t i o n .

E x t e n t o f s o i l s a l i n i t y a n d w a t e r l o g g i n g

On basis of a soil survey carried out by the Land and Water Research Institute of the Ministry of Agriculture the present cultivated soils of the country roughly can be divided into three groups, according to the effect of waterlogging and salinity on crop production. The first group consists of Class 3 and 4. It comprises about 60% of the total area, with a yield below the country average, and it is considered to be moderately to severely affected. The second group covers 33% of the area and is classified as Class 2, with a yield at yield country average. This group is slightly to moderately affected. Finally, only 7% of the total irrigated area gives yields not noticeably affected by these limiting factors.

Moderate to high salinity as such affects about 30% of the total area, while waterlogging to varying degrees is affecting about 93% of the irrigated areas in the Delta and the Nile Valley.

Drainage, productivity and economy

It was recognized early from results of observation plots and experiments since 1938 carried out in different parts of the country that drainage alone increases soil productivity by 25 to 50%. A joint committee from the Ministry of Irrigation and the Ministry of Agriculture reviewed the available research data up to 1968 with regard to the effect of drainage on crop yield and found that the percentage of yield increase as a result of drainage was about 27, 32 and 35 for wheat, maize and cotton respectively.

The present gross value of agricultural production in the Arab Republic of Egypt is estimated to be about US $ 2560 million. The total value of agricultural exports is about US $ 700 million in hard currency, which is used for development including that of agriculture. In this way raising the standard of living and creating employment.

Based on the above mentioned percentages of yield increase it can be stated that the annual increase in agricultural production due to drainage alone would amount to about US $ 768 million. The agricultural exports will be raised by the same ratio and increase the economic and social benefits. In terms of area, a 30% increase in yield due to drainage amounts to an equivalent increase in cultivated area of 0.8 million ha. If drainage is combined with leaching, application of gypsum and subsoiling, the total equivalent increase would be about 1.3 million ha. From an agricultural point of view, this is more than what the High Aswan Dam could achieve. Use of covered collectors and field drains would save about 15% of the area as compared to open drainage.

In view of the fact that the proposed extension of agricultural land to a maximum of 4.0 million ha by the turn of the century can hardly keep pace with the population increase, the importance of conservation of land resources, soil reclamation and intensive use of all available lands is to be realized. One is to start with adequate drainage systems. The use of high yielding varieties, breeding of new strains resistant to diseases and of a short life cycle are other important factors to consider. For this reason the Government of Egypt has given top priority to irrigation and drainage projects in the coming 10-year plan. It is planned to spend the amount of about £.E. 450 million (US $ 1035 million) on irrigation and drainage projects alone. The share of drainage is estimated at about £.E. 300 million (about US $ 700).

Present and planned drainage

Before 1960 only 50 000 feddan were provided with tiles in the whole country at a total investment of about £.E. 2.1 million. During the country's five--year plan (1960-1965) about 250 000 feddan were provided with tile drains at a cost of about £.E. 8 million, giving an average ameliorated area of 50 000 feddan per year. By the end of 1972 the total area tiled amounted to about 675 000 feddan. In the coming five years (1973-1978) it is planned to install covered drains in about 770 000 feddan in the Delta alone. Other plans exist for Upper and Middle Egypt.

Drainage research began in 1938 at 15 experimental stations with the purpose to investigate the effect of tile drainage systems on agricultural productivity and the chemical composition of soils in relation to salinity. The results obtained from these experiments in this respect can be summarized as follows:

- soluble salts were removed from the soil at a rate of 2.82 tons of sodium chloride and 1 ton of sodium sulphate per acre per year,
- water application was reduced by about 17% and drainage requirement was found to be 20% of irrigation water requirement,
- increase in yield was 40% as a mean of 3 years from the date of execution,
- tile drains save about 15% of the cultivated area, otherwise occupied by open field drains,
- water levels in the main drainage channels were to be lowered from the previous level of 1.5 m to 2.5

m below land surface, this allowing a field drainage depth of 1.25 m,
- average investment for the tile drainage system was about £.E. 35 per acre and £.E. 0.275 per meter. This includes unforeseen expenses, profit and compensation payments.

As far as drainage and soil amelioration projects are concerned, there are three main projects:

- the Tile Drainage Project of the Delta (Lower Egypt) of about 4.5 million feddan,
- the Tile Drainage Project of the Nile Valley (Upper and Middle Egypt), 2.3 million feddan,
- the National Project for Land Improvement and Soil Conservation. This will be complementary to the above-mentioned two projects. Its main activities will be devoted to the soils seriously affected by salinity, sodicity, waterlogging and hard pan in the north-west, north and north-east of the Delta. The total area to be ameliorated is about 1.5 million feddan during a period of 5 years.

To be able to implement the above mentioned important projects, the Government of the Arab Republic of Egypt has established two semi-autonomous bodies, which are attached to the Minister of Irrigation. These are The Nile Delta Drainage Authority and The Authority for Tile Drainage in Middle and Upper Egypt, which are responsible for planning and execution of drainage works in the Delta area, and Upper and Middle Egypt respectively. Steps now are being taken to merge these two authorities. It is planned to establish another authority in the Ministry of Agriculture to be responsible for the third project mentioned above.

The Government of the Arab Republic of Egypt had requested the IBRD for credit facilities to help finance the hard currency component of these projects. It has already obtained a loan of US $ 26 million for the first project and negotiations are held for a loan of US $ 36 million for the Tile Drainage Project in the Nile Valley and US $ 14 million for the National Project for Land Improvement and Soil Conservation. As mentioned above, the total Government allocation for drainage alone in its coming 10-year plan is estimated at about £.E. 300 million. This is an enormous investment and every effort should be made to have the necessary data, based on field studies and investigations, to save time and money and to accomplish the planned targets in time. In this context the importance of a systematic drainage research to answer the questions involved hardly can be exaggerated.

The importance of time and the necessity to achieve the anticipated high construction rate of 240 000 feddan per year of tile drainage, made it necessary to use precise methods for planning and scheduling the tile drainage network. A study was carried out in 1971 by M. AMER and S. ABDEL DAYEM on the use of the Critical Path Method (CPM) in planning and scheduling the different tasks of tile drainage execution. The latter includes investigations, design, preparing of specifications, bidding review and awarding contracts and the construction of the tile drainage system. A computer programme for the solution of the problem with the CPM was made. This can be used for planning and scheduling all tasks connected with the drainage systems according calendar dates starting from the beginning of the work.

REVIEW OF PUBLISHED WORK

General

When compared with irrigation the studies on drainage in the country are of recent origin and still rather limited. The publications that are available in this field of research are listed as references to this part of the Report. As will be clear from the to be given review, the work done has been dictated by the need to seek solutions to small local problems. The only exception is the work carried out by the UNDP/FAO Pilot Project for Drainage of Irrigated Land in the Arab Republic of Egypt (NEDECO and ILACO, 1966). To simplify matters this report will be reviewed separately; the review of the other publications is grouped under the first four of the following headings:

Drain spacing
Siltation of drain lines
Water table depth and salinization
Drainage and crop yield

Drain spacing

AMER and EL GABALY (1960) studied in the field the suitability of the use of the Glover equation (non-steady state condition) for the design of field drainage systems. The main conclusion of this work, which was carried out at the Kafr Khadr Tile Drainage Experiment Field, is that the Glover equation adequately characterizes the relation between the rate of drop of water table and tile spacing and that it may prove valuable for drainage design in Egypt.

EL SHAZLY and DAWOOD (1965) did work on practical drainage requirements in part of the Abis project. The project area originally was a lake with very permeable top layer of about 2.3 m overlying an impermeable layer. Field experiments were conducted to determine the soil hydrological properties through measurement of drainage flow as related to water head. It was found that the Donnan formula is suitable for determining depth and spacing of field drains when using the correct parameters.

BATANOUNY (1966) worked on the drainage problems of sandy soils in the Ferhash project, where at least the top 4 m of the soil consist mainly of sand. The hydrological properties of the soil profile, including the via field measurements attained soil permeability, were related with studies on the discharge - head relationship of field drains. Applying the Dupuit--Farchheinar equation which is similar to the Donnan equation, it was possible to estimate the depth of the impermeable layer and also the depth and spacing of field drains taking a drainage discharge of 4 mm/day and assuming a reasonable depth of the dewatering zone.

HAMDI, METWALLY and GUINDI (1968) studied the hydraulic conductivity of soils in relation to drainage design. It was observed that no relationship existed between hydraulic conductivity, textural fractions and aggregation index. Hence, the dependence of drain spacing on soil texture is not reliable. It was recommended that measurements of soil permeability for drainage network design are made in situ.

KHAFAGI, ZEIN EL ABEDINE and SHAHIN (1963) gave a theoretical treatment of the problem of depth and spacing of field drains under different hydrological conditions, using different kinds of drainage formulae. Data obtained from field drainage experiments at Kafr Khidr and from the Cairo University Farm in Giza were used to verify the formulae to determine the spacing between tile drains as affected by water head and depth of drains and to estimate the design drain discharge. Some of the conclusions are:

- the optimum depth of field drains under Egyptian conditions is more than 1.2 m and less than 1.8 m,
- although small diameters of drain pipes are sufficient from a hydraulic point of view, it is recommended not to use pipes smaller than 10 cm inside diameter, as smaller pipes will become clogged with sediments.

Siltation of drain lines

AMER (1969) carried out field investigations and gave an analysis of siltation of tile drains in the Delta 5 years after construction. The tile lines had slopes differing from 0.06% to 0.04% and the soil was a silty clay. An empirical equation was derived which can predict siltation in similar areas in the Delta and in Upper Egypt. The analysis also showed that a minimum slope of 0.1% and a maximum slope of 0.25% are satisfactory for design purposes. The paper recommended, however, to use a gravel filter when these slopes are used to prevent siltation, especially in the early stages of construction.

Water table depth and salinization

AMER and EL GABALY (1962) found a relationship between water table depth and salt accumulation in the first 15 cm of the soil profile according to the equation:

$$S^{-1} = 0.156 - 7.643\ W^{-1}$$

where S = salt content of the soil saturated extract in meq/l
W = depth of groundwater in cm

They concluded that with a 99% confidence level the water table should be kept at least 90 cm below the soil surface in order to keep the total cation concentration in the soil saturation extract in the Delta below 20 meq/l.

Drainage and crop yield

NICOLA and AMER (1969) reviewed the studies carried out by various government agencies on the effect of sub-surface drainage on productivity of crops in the Delta area. Their review can be summarized as follows.

Y. HALIM (1954) reported that the results of 10 years study (1942-1952) over an area of 18 500 feddan in the Southern Delta showed an average yield increase due to tile drainage of 47% for maize and of 48% for wheat.

A joint research between the MINISTRY OF IRRIGATION and the FACULTY OF IRRIGATION, ALEXANDRIA UNIVERSITY was carried out from 1949 to 1957. The increase in yield after 2 years of tile drainage was 6%, 85% and 47% for cotton, maize and wheat respectively without use of fertilizers. With use of fertilizers the increase was 10%, 92% and 73% in the same sequence.

From the work carried out by the DRAINAGE RESEARCH BUREAU for 5 years (1963-1968) at three sites on the effect of drainage on wheat yield an increase in yield following drainage was reported ranging from 20 to 26% as an average of four years of data.

A joint committee from the MINISTRIES OF IRRIGATION and of AGRICULTURE was formed in 1964 and 1968 to evaluate the effect of drainage on crop yield. After reviewing all the work available, they reported that the average increase in yield of cotton, maize and wheat was 35%, 32% and 27% respectively.

UNDP/FAO Pilot Project for Drainage of Irrigated Land in the UAR (SF 4/5 UAR/1)

The main objectives of the project are to test and demonstrate the drainage methods and practices by executing pilot projects in some selected areas in the Nile Valley. Five sites in separate areas with different soil characteristics were chosen. The following data were obtained (NEDECO and ILACO, 1966) mainly from the results of the research work carried out in the El Embabe, Bilbeis and Sindabis pilot areas. Next to hydrologic and soil investigations, a comparison between effectiveness and cost of various tile drainage types, an economic analysis of comparative costs and benefits of various types of drainage systems under various soil conditions, and the execution by mechanical means using tile-trenching machines were included in these studies.

Design drain discharge

Potential evapotranspiration calculated according to Penman varies from less than 2 mm/day in winter to about 7 mm/day in summer with a yearly average of 4.6 mm/day. The high evaporation in summer is sufficient to lower the groundwater table without a drainage system. Therefore the greatest need for drainage occurs in the winter period. Summer crops will benefit indirectly from drainage by a decrease in soil salinity.

Additional to evapotranspiration, natural drainage has an important influence on the lowering of the groundwater table. The rate of natural drainage was determined for each area by means of a salt balance method. Based on the results of these calculations and on information regarding the piezometric levels of the deep groundwater, a simplified method was proposed. With this method, the rate of natural drainage was quantitatively estimated for the whole area, taking the elevation of the land surface in account.

From collector and lateral discharges, measured in the Embabe, Bilbeis and Sindabis pilot areas, it appeared that a discharge of 4 mm/day (17 m^3/feddan/day) is very rarely, if ever, exceeded for the laterals. This means that tiles of 5 cm inside diameter are quite sufficient for the laterals, even if they have a spacing of 60 m. For the calculation of the diameters of the collectors, a design discharge of 2 mm/day (8 m^3/feddan/day) is recommended. This value should be doubled when rice is grown. The high discharge of the main drains is for a large part - about two-thirds - caused by tail-water from the irrigation system. Therefore, the same design discharge is recommended for the main as for the collector drains.

Taking into account the results of the various investigations the following values of the drainage factor were recommended for the calculation of field drain spacing:

Location	mm/day	m^3/feddan/day
South of contour 12	0.50	2
12 - 8	0.75	3
8 - 5	1.00	4
5 - 3	1.25	5
North of contour 3	1.50	6

Should the areas to be drained be located near high level irrigation canals or river branches and consequently be subjected to considerable seepage influences, then the above mentioned discharges should be slightly increased.

Water table depth

The depth of the dewatering zone for drainage design was assumed to be 1.0 m for the non-rice growing areas and 0.8 m for the areas in which rice is grown.

From detailed piezometer observations on the fluctuation of the groundwater table it appeared that generally after each irrigation during the flood season and in the winter period, the groundwater table rises to surface level. In summer the soil profile is very dry and after irrigation the groundwater table does not reach a level higher than about 0.5 m below surface and it drops very fast to a basis level which in the southern part of the Delta, is usually below drain level. Observations in the selected plots of the pilot areas indicate that the criteria of dewatering to 1 m or 0.8 m below soil surface in about 5 days are nearly always met with the constructed drainage system.

Salt balance

A rate of percolation of 1.0 mm per day, of which part is discharged by the drainage system and part flows vertically to the aquifer, is about 20% of the average irrigation rate. By means of a salt balance it was demonstrated that this results in a sufficiently low salinity level of the soil moisture. The minimum soil salinity which can be obtained depends on soil structure and leaching efficiency and will vary from 1 to 2 mmhos/cm.

The chemical composition of the Nile water was discussed in view of its suitability for irrigation purposes. It appears that the soils irrigated over a long period with this water have a rather low salt content, with the exception of some areas near the Mediterranean coast. But even in the Southern Delta, a rather considerable average yield increase can be expected from drainage in consequence of a decrease in salt content. About one year after drainage, a considerable desalinization of the soil of the root zone was observed in the Embabe and Bilbeis areas, as the average ECE decreased from 3.7 to 1.6 mmhos/cm and from 5.9 to 3.2 mmhos/cm respectively.

The alkalinity hazard in cultivated and irrigated soils is very low. A saline soil may have a high percentage of exchangeable sodium, but this is lowered after a drainage system has been constructed. A deteriorated soil structure due to alkalinity has not been observed in the cultivated areas. For the average case of drainage of a slightly saline soil, no special dressings with amendments such as gypsum are required. The need for such dressings for the more saline soils in the northern coastal zone is doubted and should be further investigated.

Drainage of rice fields

The groundwater flow conditions for drained rice fields were rather extensively discussed although no excessive water losses because of the drainage system were measured in the rice areas of the pilot areas. The average rate of drainage appeared to be less than about 1 mm per day and therefore equal to or lower than the discharge of the surface drainage system. It does not appear necessary or desirable to provide the drainage system in rice areas with extra structures to be able to close the drains. It is recommended to maintain a dewatering zone of 0.8 m in these areas, so a drain spacing of about 20% wider than that in non-rice areas, and to study the advantages of more intensive puddling practices. Further, it should be studied how the surface drainage system can be abolished after construction of tile drainage. It is doubted whether the surface drainage system has any real advantage for rice growing, but if so, its function is taken over by the tile system.

Effective porosity

The storage coefficient or specific yield for a groundwater table which drops from the surface to about drain level has been checked by moisture depletion measurements and by means of moisture stress curves determined in the laboratory. It appeared that the value of 5% storage originally adopted is too large and that a more correct figure is about 3.5%. Nevertheless, part of the pore volume might be occupied by a varying percentage of entrapped air.

Vertical versus horizontal drainage systems

The possibility of making instead of a horizontal tile drainage system a vertical drainage system consisting of wells through the semipervious clay layer was briefly discussed. This method makes use of a possible positive potential difference between phreatic water and deep groundwater and consists essentially of a perforation of a semipervious layer, thus increasing its permeability and downward flow. But it appeared that the required well density is that great that the costs are prohibitively high.

Studies on the feasibility of the use of vertical drainage in the Delta were executed in 1949 at Kafr-Ramada, Qalubia Province. A similar experiment was carried out at another site in the Delta in 1958. The results of both experiments were not in favour of the use of vertical drainage. Also two pumping tests were performed in Upper Egypt. These experiments, however, did not provide the necessary and definite conclusion to use vertical drainage as a means to lower the subsoil water. More investigations and experiments are needed for other Delta areas and for Middle and Upper Egypt so that sufficient knowledge can be gained and the potentialities of wells for drainage or irrigation purposes can be estimated.

Economics of drainage

The average increase in yield for the various crops, to be expected after drainage, are not known accurately. Because of the strongly varying conditions in the different parts of the cultivated area, they are difficult to determine. Moreover, the yields of crops vary heavily from year to year as a result of meteorological conditions and plagues. It is no wonder that the data on yield increase due to drainage vary greatly: cotton 0 to 50%, wheat 20 to 32%, maize 17 to 48%. Measurements of wheat yields in the pilot areas indicate that in the first one or two years after drainage, a yield increase of about 10% can be expected to occur. This percentage may increase to 20% after some years. Although for some better agricultural areas the latter percentage is high, for many other areas with comparatively low yields, a higher increase can be expected for wheat. Although the yield increase for other crops has not been measured, it is reasonable to assume the achievement of similar increases.

Drainage gives many indirect benefits of an agro--economic and a socio-economic nature, as the available labour on the land is more efficiently used and the higher production increases the volume to be marketed and processed. The increased export value of the produce or the decreased import requirement of certain foodstuffs is of national economic importance. It is almost impossible to express the value of the indirect benefits quantitatively within the scope of the project. No allowance is made in the used cost - benefit appraisal for indirect benefits.

A basic rule in judging project investments from the economic point of view is that their benefits should at least compensate the costs. Therefore, a detailed economic project evaluation is a first requirement. Owing to the limited length of the observation period, no definite figure could be given for the exact financial return to be expected from drainage. Some interesting conclusions can be already drawn, however.

A cost - benefit appraisal has been made, assuming a depreciation period of the drainage system of 35 years and a rate of interest of 5%. The ratio of annual cost to annual benefits, based on an average yield increase of 10%, is calculated at 1 : 2.77. For an increase in yield of 20%, the ratio becomes 1 : 3.5. The first ratio is already satisfactory, the second is very good. It can be calculated that the money invested for an average yield increase of 10% will earn an interest of nearly 20%. These figures demonstrate that it is right that drainage projects have a high priority among investment projects.

The average investment for a drainage system is rather accurately estimated at £.E. 35 per feddan, including the payment of damages to the farmers for crop injury and of about 20% for contingencies and contractor profit. This price is based on mechanical construction of the laterals. When giving continuous attention to the improvement of working methods, it is to be expected that a slight decrease in cost still is feasible. This may, however, be partly or fully nullified by the rising trend in wages and machinery prices.

Suitable drainage formulae

The steady state formulae of Hooghoudt and Ernst for the calculation of the drain spacing are discussed. The formulae are compared with the Dupuit or Donnan formula. Also non-steady state flow is discussed and some formulae are mentioned. They are, however, not recommended for routine use, as the parameters are too difficult to determine, while they do not represent any advantage over the steady state formulae. By means of the Hooghoudt method for the more homogeneous profiles and the Ernst formulae for the layered profile, a rather satisfactory means of calculating the drain spacing has been obtained, provided the criteria are well chosen.

CURRENT RESEARCH

The D e l t a D r a i n a g e A u t h o r i t y is continuing the collecting of field data from three experimental fields which were originally established by the UNDP/FAO Pilot Project for Drainage in the Delta at Bilbeis, Embabe and Sandabies (1962-1963). No reports have been issued on this work after the report published in 1966 by NEDECO and ILACO as the collected field data are still unprocessed.

The D e l t a D r a i n a g e A u t h o r i t y has also established an experimental field at Zankalon to study the water requirements of crops and the drainage requirement. Daily observations are made of drain discharges as well as of water table levels. No reports so far have been issued on this work.

The D e l t a D r a i n a g e A u t h o r i t y investigates several covered field drains which have been constructed several years ago with and without gravel envelope, to appraise the effect of gravel around the tile lines. It is said that the outcome of this study is negative with regard to the use of a gravel filter in the heavy clay soils of the Delta. However, no official report has been issued on this work as yet.

The L a n d a n d W a t e r R e s e a r c h I n s t i t u t e of the Ministry of Agriculture had established a tile drainage experiment at Sakha Agricultural Research Station. The experiment is located on a low permeable, saline-sodic, heavy clay soil. The experiment concerns the interaction of drain spacings and the use of soil amendments (gypsum) during reclamation, and the salt and water balances in this type of soil. Envelope material is not used around the tiles, but a comparison is made between the results with and without application of gypsum in the soil layer surrounding the tiles. Daily measurement of water table levels and drain discharge is carried out. The experiment started in March 1972 with two crops, maize and barley. In the summer of 1973, rice will be planted. Analysis of soil samples is being carried out regularly. So far, however, in this experiment no provision is made for the measurement of amounts of irrigation water. It is recommended to do this as soon as possible to have information on crop water requirements and water balances. No reports were written on the results of this experiment up to May, 1973.

The T i l e D r a i n a g e a n d G r o u n d w a t e r B u r e a u of the Ministry of Irrigation initiated an investigation in Upper and Middle Egypt with a view to assess the need for artificial drainage and to establish design criteria. A feasibility study for the whole area was carried out as also an intensive research in six pilot experimental areas of about 1000 feddan each scattered in the Nile Valley starting in Minia Province in the north and ending in Aswan Province in the south. The studies include among other things, groundwater hydrology and field exploration for drainage. Two pumping tests were performed in Upper Egypt to study the feasibility of the use of vertical drainage. More pumping tests are needed, however, in the different locations of the Nile Valley to have sufficient information available for the possible use of wells for irrigation or drainage purposes. One of the purposes of this study is to define the correlation between the piezometric heads of the deep groundwater and the heads of water in the overlying clay. This to estimate the amount of natural vertical drainage, as well as a possible effect resulting from a variation of piezometric pressures of the groundwater in the aquifer.

DISCUSSION

In Egypt drainage is needed as a control of the rise in the water table resulting from water conveyance losses and over-irrigation, thus preventing waterlogging and salinization. When saline land is reclaimed, adequate drainage facilities are a prerequisite to leach excess salts out of the root zone, to desalinize the groundwater and to prevent resalinization. In recent years the importance of adequate drainage is increasingly appreciated. Areas which could not be utilized for farming owing to an excess or a lack of water are now being brought into cultivation by means of drainage and irrigation works. Consequently there has been a very considerable increase in the requests by farmers for assistance in the design and construction of field drainage systems. In such designs a very important consideration is the calculation of a proper spacing of parallel relief drains. To this purpose numerous drainage formulae have been developed over the years. In order to use such formulae two entirely different sets of data are required, viz. the drainage criteria and the soil physical properties in relation to the prevailing hydrologic conditions.

By 'drainage criteria' or 'drainage requirements' is here meant the permissable minimum depth of the groundwater and the corresponding projected discharge. In the case of formulae based on the steady state flow conditions the soil physical data required are the hydraulic conductivity and the depth to an impermeable layer, whereas in the case of non-steady flow formulae it is also necessary to know the drainable pore space.

The importance of an adequate drainage formula to plan the proper drain spacing is often overrated. A chain is only as strong as its weakest link. The weak link in the calculation of drain spacing is not the formula itself but the data substituted in it, viz. the drainage criteria and soil hydrological data. Since soil hydrological data may vary extensively within a short distance, their accuracy is very often doubtful. It should therefore be realized that in practice the use of drainage formulae can never result in more than what may be termed a 'calculated estimate', viz. a drain spacing which very probably will be approximately correct. In contrast to the facts obtained in chemistry or physics, of many results of agro-hydrological calculations it can be said that from science to fiction is but one step. But on the other hand, the importance of the formula should not be underrated. They not only must be employed in the calculations, but they emphasize the importance of the various factors involved and their interrelationships under the varying field conditions.

In the past both steady and non-steady state formulae were used in Egypt to calculate drain spacings. However, due to the difficulty to obtain an accurate estimate of the effective porosity (i.e. drainable pore space) of the soil profile which ranges from 2 to 5%, it was decided, without affecting too much the accuracy of the calculations, to depend mainly on the use of the steady state formula (i.e. Hooghoudt) in estimating drain spacings. In this respect, the following parameters were adopted:

- The soil permeability is measured by means of the auger hole method, it varies from 0.1 to 0.8 m/day and the depth of the impermeable layer is more than 10 m.
- The minimum depth of the dewatering zone is taken to be 0.5 m which corresponds to a drainage norm discharge of 1.0 mm/day. As indicated in the review, this discharge will slightly vary according to local conditions, elevation of the soil surface and the type of crop. A norm discharge of 3 mm/day is used for collectors when non-rice crops are grown and this is increased to 4 mm/day for rice areas. For pumping stations a norm discharge of 7 mm/day is adopted.
- The depth of the field drains varies from 1.25 m to 1.50 m with an average of 1.35 m.

The calculated drain spacing in the Delta ranges between 10 to 60 m. However, in practice, the field drains are mainly constructed at spacings of 40 m in the heavy soils and about 60 m in lighter soils. This is based on general judgement and on the fact that the above mentioned parameters are not believed to be final. A detailed systematic drainage research is required to find for the various agroclimatological areas of the country the real values of these parameters under different hydrological and soil conditions as well as cropping patterns. In this connection it can be stated that under Egyptian conditions, although irrigation is the main factor which determines the amount of excess water to be discharged by the drainage system, as yet no simple recipe can be given with which the design discharge rate directly can be derived from the characterization of a critical irrigation and from the available groundwater storage. This because the answers to the following problems have not yet been found:

- the characterization of the irrigation requirement,
- the available groundwater storage capacity which can be utilized to store a certain amount of the irrigation water before excess water conditions occur. This storage capacity is undefined because the initial groundwater level at the time of irrigation as well as the maximum permissible groundwater level over a certain period of time, i.e. one, two or more days, are not sufficiently known,

- the discharge rate of the drainage systems. This rate cannot be introduced as a constant rate because it is a function of the actual height of the groundwater level over the drains, i.e. of the amount of irrigation water not yet discharged but stored in the groundwater. This storage is not stable, it fluctuates.

Although much is known about the many factors involved in realizing optimum drainage conditions, the agronomist and the soil physicist are not yet able to present the drainage engineer with specifications needed for the determination of drainage criteria. Not much work, if any, has been done on this aspect in Egypt. The drainage criteria stand for a chosen combination of required drain discharge and groundwater level control with the object of preventing the occurrence of excess water under the prevailing set of hydrologic and agricultural conditions. These conditions on which the drainage criteria should be based are in effect complex functions and they should be formulated taking the following steps:

- the establishment of the relation between plant growth and moisture conditions in the root zone, in order to define the concept 'economic optimum moisture regime' (see the preceding parts of this Report),
- the determination of the relation between moisture conditions in the root zone and groundwater regime (level and fluctuations),
- the expressing of the required control of the groundwater regime under the prevailing hydrologic conditions of irrigation and natural groundwater flow in terms of a single value which can be treated mathematically by means of the available drainage formulae.

When compared with irrigation, the drainage studies in the country are of a recent origin and rather limited. Research in drainage only started in 1938. As a rule, most of this work was dictated by the need to seek solutions to local problems. The work carried out by the UNDP/FAO Pilot Project for Drainage of Irrigated Land in the UAR (SF 4/5 UAR/1), as reported by NEDECO and ILACO (1966), is one of the exceptions to this rule. Notwithstanding this, the experience and progress achieved to this date in the fields of drainage research and execution are rather impressive although several gaps in our knowledge are still to be filled.

As mentioned above, the most important task is the formulation of the drainage criteria for the major crops grown in soils of the main soil groups in the various agroclimatologic areas of the country.

Limited studies on the use of vertical drainage were carried out both in the Delta and the Nile Valley. However, more intensive investigations and experiments are still to be carried out in order to determine the feasibility of vertical drainage, particularly in Upper Egypt.

It should be stated here that gravel cannot be considered to be a filter material in clay soils, finer materials as sand should be used if it is proved that filter materials are needed in these soils. In spite of this expensive gravel envelopes are being used in the construction of field drains in the country. At present it is estimated that the cost of this gravel envelope amounts to about 20% of the total cost of field drainage. In view of the large scale in which drainage work in the country is being planned, it is very important to know if gravel or any other kind of material is needed as filter in the major soil groups in the country. An evaluation of the use of gravel as envelope material could be carried out immediately by investigating already executed drainage schemes with and without gravel envelope in the country. In addition it would be very useful to initiate as soon as possible field tests to compare different types of drainage materials, including the envelope material, and different methods of drainage installation, including trenching and trenchless drainage machines.

Some drainage experiments have been carried out separate from irrigation. Under such conditions the studies will be incomplete. It is strongly recommended that experiments on drainage should always include measurements of irrigation water, to be able to estimate the water balance (inflow and outflow method). With little additional effort it will be possible to set up a salt balance in these experiments.

As mentioned in the Section 'Current Research', several drainage studies are being carried out in the country. It became apparent, however, that although field data are collected, they are kept in file for a long time without compilation and processing. Research efforts will be of no value unless the data are compiled and reported in a proper manner. Furthermore, it seems that some reports written on aspects of the drainage studies are for use within the own limited organization only which proved to be not available when needed. In view of this, there is a large need to collect all these fragmented but important information and to publish them in a comprehensive report.

RECOMMENDATIONS

It has been indicated before that the increase of agricultural production in Egypt to keep pace with the increasing population could be achieved by two methods, i.e. expansion of the cultivated area and increased produce from the existing area. Under Egyptian conditions increasing the produce from the now cultivated lands is cheaper and quicker as compared to area increase. Drainage was found to be the most important step to ameliorate soils which have been exhausted through centuries of intensive cultivation and hence to increase productivity. Drainage is also needed in the areas which have been converted from basin irrigation to perennial irrigation, as well as in newly reclaimed areas to avoid waterlogging and soil salinization.

Experience with drainage in the Delta during the last thirty years or so has shown that well drained areas achieve an increase of production of about 30%. In view of this the Government of Egypt is giving drainage top priority in its agricultural planning. In its coming 10-year plan the Government has allocated about £.E. 300 million for drainage alone. This is an enormous investment and it is essential that, to avoid bottlenecks, the necessary drainage criteria needed for design and execution of the drainage programme should be made available in time. The importance of systematic drainage research to provide the data required for estimating depth and spacing of field drains, i.e. hydrological soil characteristics and drainage criteria, can hardly be exaggerated.

There is another important point which should be mentioned with regard to the implementation of the planned large scale drainage programme and that is the need for proper planning and scheduling the different operations involved. Harmonization and streamlining of different activities to avoid setbacks and bottlenecks are very important. It is very important for example to synchronize the construction of the pumping stations with that of the open main drainage system and the covered field drainage system, so each can start functioning as soon as it is constructed. This will save time and money and ensure a proper functioning of the system. Work has been initiated in this respect by AMER and ABDEL DAYEM (1971) by the use of the Critical Path Method (CPM) in planning tile drainage work. This work should be refined and be expanded upon.

When compared with irrigation, the drainage studies in the country are of a recent origin and rather limited. Research in drainage started in 1938. The experience and progress achieved to this date in the field of drainage research and extension are rather impressive. However, the review of drainage research has revealed the existence of several gaps which need to be filled. With this in mind the following lines of action in the field of drainage investigations and research are recommended. Some of these actions have to be carried out at a country level in pilot experimental areas selected on major soil groups and in each of the nine agroclimatologic zones, as defined in the part on Crop Water Use in this Report:

Drainage criteria

Experiments are needed to determine the optimum groundwater regime for the production of various crops as well as for the economy of irrigation water on different soil types and to establish the corresponding drainage discharge which is required to control this groundwater regime under the prevailing hydrologic conditions of irrigation and natural groundwater flow. Experiments with a wide range of drainage intensities have to be initiated to this purpose.

Vertical versus horizontal drainage systems

The feasibility of vertical drainage as opposed to horizontal drainage is to be further investigated in some parts of the Delta and in Upper Egypt from both the physical and the economical point of view.

Reports on current research

As mentioned before, several drainage experiments are being conducted in the country. Data are collected on the amount of irrigation water, on drain discharges, on salinity of soils and groundwater and on the level of water tables. Some of these data are reported for use within the own limited organization only. These reports are usually misplaced and difficult to consult. Most of the data, however, are being kept in file without being processed and reported on for several years. Very valuable information could be obtained on the various drainage aspects, particularly on the hydrologic properties of the soil profile, from these experiments in combination with drainage discharges and salt and water balances. It is strongly recommended that the compilation and processing of the data of these experiments is carried out as soon as possible. Top priority should be given to the issue of a comprehensive report on the results of such work.

Testing of drainage materials and construction methods

In view of the large scale drainage programme which is planned in the country, attention is to be given to finding the best possible drainage material and the most economic method of drainage construction. At present concrete tiles are used laid in trenches by hand or machine. A gravel envelope is used which costs about 20% of the total investment, while nobody is sure if it is really required. An evaluation of the use of the gravel envelope immediately should be carried out on already executed drainage systems with and without gravel envelope in different parts of the country.

In addition it is strongly recommended to initiate as soon as possible field tests to compare different types of drainage material, including tiles and envelope material, as well as different methods of drainage installation, including trenching and trenchless drainage machines. In such a programme the means and methods for maintenance of covered drainage systems also should be included.

Miscellaneous

- The effect of the new surface and sub-surface water regime after the completion of the High Dam on the drainage conditions in the Nile Valley and in the Delta needs to be followed up.
- The future needs of newly reclaimed areas for drainage are to be ascertained. The Western Nubaria project is a good example of this. As a result of large water losses from canals of different elevation and of field irrigation losses, the problem of waterlogging and salinization of soils as well as salinization of the irrigation water in low level canals requires immediate action.
- The problems of drainage in rice and sugar cane areas require special studies. This should include not only the drainage requirement of these areas, but also the problems associated with the construction and operation of drainage systems under the prevailing conditions.
- In view of the existence in different parts of the country of large areas which have been provided with tile drainage it is opportune to initiate systematic studies on the evaluation of field drainage of different soils under various cropping systems.

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