DRAINAGE RESEARCH INSTITUTE
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Egypt

REUSE OF DRAINAGE WATER PROJECT

Analysis of Water Management in the Eastern Nile Delta

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Wageningen
The Netherlands

Reuse Report 30
(Main Report)

Wageningen/Cairo, 1991

ANALYSIS OF WATER MANAGEMENT IN THE EASTERN NILE DELTA

READING GUIDE

In the underlying report the simulation results of some alternative water management scenarios for the Eastern Nile Delta will be presented. The report also includes short descriptions of the SIWARE package, input data, and the calibration and validation procedures applied. More detailed information can be obtained from the basic reports in the Reuse modelling series as enumerated on the next page.

This report will be preceded by an extensive summary and, where relevant, conclusions drawn from the subjects as treated in the various chapters.

In chapter 1 an introduction to some of the current the water management problems in the Nile Delta in Egypt will be presented. The objectives and completed activities of the 'Reuse of Drainage Water Project', as well as the future possible activities of this project will be discussed.

In chapter 2 a short explanation of the simulation model package 'SIWARE' will be given. The majority of the relevant physical and functional relationships which are combined in the model will be discussed.

In chapter 3 attention will be paid to the important required input data which have been used for the simulation of the water management in the Eastern Nile Delta. The accuracy and reliability of these data will be discussed, as well as the reasons for calibration of some of these data.

In chapter 4 the simulation results for the year 1986, which has been used for the model input parameter calibration, will be compared with the results of the monitoring network. The model performance will be further illustrated by confronting the simulation results of the complete period 1984-1988 with the measured data. Attention will be paid to the analysis of the water management system and its performance during 1986. Furthermore, the crop response simulated by the model will be compared with experimental data and results from both the international and the Egyptian relevant literature.

In chapter 5 the simulation results for a number of alternative water management scenarios will be discussed. The scenarios considered take into account effects of changes in the cropping pattern, changes in the crop water duty of rice, extension of the agricultural area in the Eastern Nile Delta, and changes in the irrigation behaviour of farmers.

REUSE OF DRAINAGE WATER PROJECT

ANALYSIS OF WATER MANAGEMENT IN THE EASTERN NILE DELTA

FINAL REPORT REUSE MODEL

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REUSE REPORT 30 (1991)

ABSTRACT

Abdel Gawad, S.T., M.A. Abdel Khalek, D. Boels, D.E. El Quosy, C.W.J. Roest, P.E. Rijtema and M.F.R. Smit, 1991. Analysis of Water Management in the Eastern Nile Delta. Final Report Reuse Model, Report 30, Reuse of Drainage Water Project. 245 pp., 100 figures, 44 tables, 28 ref.

The regional water management in the Eastern Nile Delta of Egypt (756,000 ha) has been analyzed for the years 1984 through 1988 using the SIWARE model package. This versatile package has been compiled for integrated agricultural water management under arid and semi-arid conditions. It comprises 4 sub-models: DESIGN for dimensioning irrigation canals and allocating water to the main intakes; WDUTY for calculating the farmers' water requirements; WATDIS for distributing irrigation water; and REUSE for on-farm water and salt management, and reuse and disposal of drainage water. The modelled processes in SIWARE warrant reliable simulations of irrigation and drainage flows and salt loads, confirmed by the model calibration and validation. Three alternative water management scenarios have been evaluated, leading to the following conclusions: reducing the rice water allocation duty rather than reducing the rice acreage is a better proposition to save on irrigation water; saved irrigation water can be used profitably in reclaimed desert areas for winter crops; and unofficial reuse of drainage water by farmers should not be prohibited.

Keywords: regional water management, Eastern Nile Delta, Egypt, SIWARE model package, integrated agricultural water management under arid and semi-arid conditions, on-farm water and salt management, reuse of drainage water, model calibration and validation, evaluation of alternative water management scenarios.

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The Winand Staring Centre (SC) is continuing the research of the Institute for Land and Water Management Research (ICW); the Institute for Pesticide Research, Environmental Division (IOB); the Research Institute for Forestry and Landscape Planning, Landscape Planning Division (LB); and the Soil Survey Institute (STIBOKA).

Project nr. 382.1

RECOMMENDATIONS

Irrigation water is becoming more and more a scarce commodity in Egypt with the continuously increasing demand for food crops. Since the use of Nile water, Egypt's main resource, is reaching its limits, a more efficient exploitation of this water becomes imperative.

In order to provide the Ministry of Public Works and Water Resources with information regarding reusable drainage water in the Nile Delta, a monitoring network and a mathematical simulation model have been developed simultaneously. The monitoring programme includes drain discharges, salinities and the chemical composition of the drainage water at a comprehensive number of locations throughout the Nile Delta. All measured data have been reported in a series of yearbooks. The SIWARE[1] integrated water management model package provides a quantitative estimation of alternative water management measures in irrigated agriculture under arid and semi-arid conditions.

One of the merits of the SIWARE simulation model is its ability to provide intelligent estimates of the future conditions in the modelled system brought about by changes in the system's input parameters. The real consequences of such changes on the short and the long term, however, can only be verified through field surveys and measurements.

1. **It is therefore strongly recommended to maintain the present measurement network along with its frequent data collection.**

The application of the SIWARE model package on the Eastern Nile Delta has proven its accuracy and validity. Further verification of the model approach can only be obtained by simulations for other areas where different agricultural and hydrological conditions prevail. Expanding the modelled area also contributes to a more accurate prediction of the aggregated effects of alternative water management scenarios on a national scale.

2. **It is therefore recommended to apply the SIWARE model package on the Middle and Western Nile Delta.**

The analysis of the water management during 1986 revealed a significant discrepancy between the calculated crop water requirements and the fixed crop allocation duties used by the Ministry of Public Works and Water Resources. Investigations into these deviations, which are mainly caused by the spatial variability of the crop water requirements, may lead to a higher efficiency in the irrigation water distribution and savings on irrigation water.

3. **It is therefore recommended to analyze the spatial variability of the crop water requirements through literature and field research in order to determine the validity of the spatially distributed values simulated with the SIWARE model package.**

Three clusters of different water management strategies have been simulated and analyzed. All identified strategies were aimed at water savings, either through conversions in the cropping pattern, or through improvements in the irrigation water distribution, or by resorting to reductions in the Nile water supply to the old lands.

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[1] SIWARE stands for SImulation of Water Management in the Arab Republic of Egypt

All performed cropping pattern simulations, except those for extreme water savings, indicated that reducing the allocation water duty of rice rather than substituting part of the rice area with maize is a better proposition to save on irrigation water. This finding was supported by a financial and an economical analysis using price levels of 1979/1980.

4. **It is therefore recommended, in case of water shortages, to consider a reduction in the allocation water duty of rice rather than replacing rice by maize in the southern part of the Nile Delta as was implemented in 1988.**

5. **It is also recommended to repeat the financial and economical evaluation of the various cropping pattern strategies with more up-to-date price levels and figures concerning governmental pricing policy, and to include cash crops like vegetables and trees in this evaluation.**

The strategies handling the extension of the old lands with reclaimed desert areas showed that water saved in the old lands can be profitably used in the new areas. Despite a total Nile water supply limited to the very low amount of 1988, the simulated productivity of the winter crops was good. Summer crops performed less well.

6. **It is recommended to collect crop yield and price data for reclaimed areas on which a sound cost-benefit analysis can be based, justifying the investments for such areas.**

SIWARE model simulations indicated that banning small diesel pumps used by farmers for lifting water directly from the irrigation canals offers some relief with respect to the irrigation water distribution. Major improvements, however, could not be established because these effects will be primarily noticeable on a 3 times lower scale as employed in the model simulations.

7. **It is therefore recommended to apply the SIWARE model package on an equal scale as currently used for the calculation units (approximately 15,000 feddan[1]) in order to determine the non-uniformity in the water distribution within these units.**

The same strategy cluster also showed that banning these diesel pumps for the unofficial reuse of drainage water will lead to negative effects on crop yields caused by local and temporal water shortages.

8. **It is therefore recommended not to prohibit the unofficial reuse of drainage water by farmers under the presently prevailing conditions in the Eastern Nile Delta.**

In none of the strategies studied, Nile water savings by extending the official reuse of drainage water has been considered. The precarious situation of Egypt's water resources requires the engagement of such a task with utmost priority.

9. **It is therefore recommended to investigate the prospects of expanding the official reuse of drainage water quantities and to predict the effects on the water management in the Delta.**

10. **It is also recommended to balance various water saving strategies against each other to pinpoint the optimum strategy with the least adverse effects.**

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[1] or 6,300 hectares

The 'Reuse of Drainage Water Project' is a joint activity of the technical agencies:

the Drainage Research Institute (DRI), Delta Barrages, Egypt, and
The Winand Staring Centre (SC), Wageningen, the Netherlands.

The project is funded by the Ministry of Public Works and Water Resources of Egypt and by the Ministry of Foreign Affairs of the Netherlands in the framework of the joint programme of Technical Cooperation between Egypt and the Netherlands.

During the first phase of the project the Advisory Panel for Land Drainage has acted as a Steering Committee. During the last phase a separate Steering Committee has been appointed consisting of:

D.E. El Quosy	(Drainage Research Institute)
E.H. Imam	(Cairo University)
M.Q. Nadar	(Ministry of Public Works and Water Resources)
P.E. Rijtema	(The Winand Staring Centre)
J.W. Wesseling	(Delft Hydraulic Laboratory).

The results of studies as carried out in the 'Reuse of Drainage Water Project' have been presented in preliminary reports and in a final report. As such the contents of the preliminary reports can vary strongly, from a simple presentation of data to a discussion of research results with tentative conclusions.

All opinions, conclusions and recommendations in the reports are those of the cooperating Institutes, and not of the Ministry of Public Works and Water Resources of Egypt, or the Ministry of Foreign Affairs of the Netherlands.

The Winand Staring Centre (SC) is continuing the research of:

ICW	Institute for Land and Water Management Research
IOB	Institute for Pesticide Research, Environmental Division
LB	Research Institute for Forestry and Landscape Planning, Landscape Planning Division
STIBOKA	Soil Survey Institute

OTHER REPORTS IN THE REUSE (MODELLING) SERIES

report number	title
23	Formulation of the Water Distribution Model WATDIS, P.E. Rijtema, M.F.R. Smit, D. Boels, S.T. Abdel Gawad, D.E. El Quosy, Reuse of Drainage Water Project, 1991.
24	Formulation of the On-Farm Irrigation and Drainage Water Model FAIDS, C.W.J. Roest, P.E. Rijtema, M.A. Abdel Khalek, D. Boels, S.T. Abdel Gawad, D.E. El Quosy, Reuse of Drainage Water Project, 1991.
25	Formulation of the Regional Drainage Water Model REUSE, D. Boels, M.A. Abdel Khalek, C.W.J. Roest, D.E. El Quosy, M.F.R. Smit, Reuse of Drainage Water Project, 1991
26	User's Guide for the program package WATDIS V1.0, M.F.R. Smit, S.T. Abdel Gawad, Reuse of Drainage Water Project, 1991.
27	User's Guide for the program package SIWARE V1.0, D. Boels, M.A. Abdel Khalek, M.F.R. Smit, S.T. Abdel Gawad, Reuse of Drainage Water Project, 1991.
28	Comparison between two approaches for Irrigation Water Supply in the Eastern Nile Delta of Egypt, M.F.R. Smit, D. Boels, D.E. El Quosy, S.T. Abdel Gawad, M.A. Abdel Khalek, Reuse of Drainage Water Project, 1991.

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SUMMARY

THE PROJECT

The total acreage of Egypt amounts to roughly one million km^2, but the majority of the Egyptian inhabitants is concentrated on 4-5% of this area only. Expansion of agriculture by reclaiming new lands will be the first priority measure in Egypt to overcome the presently prevailing food balance crisis, caused by the rapidly growing population.

Reuse of drainage water appears to be one of the most promising, fast, and economic means to increase the Egyptian water budget and to improve the efficiency of water use.

In order to provide the Ministry of Public Works and Water Resources with the necessary information regarding the available drainage water, which potentially can be reused for irrigation purposes, the 'Reuse of Drainage Water Project' has been initiated. The project consists of three main activities:

- to establish a monitoring network in the main drainage canal system in the Nile Delta to provide information on drainage water with respect to quantity, quality and location, for the present situation;
- to predict future changes of quantity and quality of the drainage water as a result of changing water management through model simulations;
- to train Egyptian counterpart staff in the techniques to obtain the above mentioned information.

The monitoring network covers the complete Nile Delta. The accuracy of the measurement results of this monitoring network has improved steadily since the start in 1980, and from 1984 onwards the results are reliable or fairly reliable.

At present an amount of about 14 billion[1] m^3 (1984) to 12 billion m^3 (1988) of drainage water flows annually to the Mediterranean Sea and coastal lakes. The salinity ranges between 1,000 and 7,000 $g{\cdot}m^{-3}$, but around 75% (1984) to 70% (1988) of this quantity has a salinity of less than 3,000 $g{\cdot}m^{-3}$. An amount of 3 billion m^3 (1984) to 2.4 billion m^3 (1988) of drainage water is reused annually in the southern part of the Nile Delta by mixing, in most cases, with fresh Nile water in the larger irrigation canals.

So far, the model simulations have been performed for the Eastern Nile Delta only. Consequently, the analysis of the present water management, as well as the alternative water management scenarios discussed in this report, concern the Eastern Nile Delta only. It has been envisaged that during the next phase of the project model simulations will be carried out for the Middle and Western Nile Delta.

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[1] one billion m^3 equals 10^9 m^3

THE MODEL

In order to predict future changes of drainage water quantity and salinity, as a result of changed conditions in the water management, agronomic changes, or changes in the hydraulic conditions, the SIWARE model has been developed. SIWARE is the abbreviation of SImulation of Water management in the Arabic Republic of Egypt. In this simulation model for the Nile Delta all relevant physical and other functional relationships have been combined. This has been done in a simplified and schematized way, which is inherent to regional modelling with the present knowledge and technical facilities.

The following subsystems can be distinguished in the water management in the Nile Delta, and consequently in the simulation model:

- the water allocation to the intakes of the highest order irrigation command canals, which is treated in the model 'DESIGN';
- the estimation of the water requirement at farm level, taking into account the hydrological and climatic conditions and the soil moisture and salinity status of the soil, which is treated in the model 'WDUTY';
- the water distribution from the intakes of the command canals to the agricultural fields within the command areas, including the operational losses to drainage canals and to the aquifer, which is treated in the model 'WATDIS';
- the water losses from the Nile Delta to the atmosphere through evaporation and transpiration, to the aquifer through leakage and seepage, and to the Mediterranean Sea and Coastal Lakes through the drainage system, which is treated in the model 'REUSE';
- the drainage water collecting and transporting system, which is the source for reuse of drainage water either through reuse pump stations, or through abstraction by farmers' pumps (unofficial reuse), is included in the model 'REUSE'.

Two types of processes are simulated in the SIWARE model:

- physical processes, such as: the water flow through the irrigation canals and control structures; the flow of water and salt to the (sub)surface drains; the evapotranspiration and related increase in soil salinity and osmotic pressure; decrease in soil moisture, etc.;
- human behaviour processes, such as: decisions related to the allocation of irrigation water among the irrigation command areas and the determination of target water levels at control structures in the irrigation system (decision maker); the simulation of the height of the gate openings of control structures (gate operator); the abstraction pattern during the day for field irrigation of agricultural crops and decisions related to the distribution of the limited available irrigation water among the fields crops (farmer), etc.

The water allocation to the main intake canals in the Nile Delta is based on the official Ministry of Public Works and Water Resources water requirements of the agricultural crops grown in the command area, the local groundwater use, the intended official reuse of drainage water, the occurrence of rainfall (since 1988), the industrial and domestic water requirements, and a percentage of the allocation for conveyance and operational losses.

The hydraulics of each irrigation canal can be characterized by a stage-discharge relation. Given the water requirement for each month, the target waterlevels in the irrigation system can be determined for each point in the system where control structures with movable gates or movable crests are situated.

The farmers' demand for irrigation water depends on the initial soil moisture conditions in the field, on the local hydrological conditions, and on the local climatic conditions (evaporative demand). Farmers will try to maximize the quantity of irrigation water given to the crops in order to leach as much accumulated salts from the crop root zone as possible. This intended irrigation quantity is limited, of course, by the hazard of crop damage due to oxygen shortage in the root zone under prolonged ponding.

In the water distribution model the water distribution, as intended by the Ministry of Public Works and Water Resources, is confronted with the water needs of the individual farmers. The realized water distribution within the Nile Delta depends on the water allocation and distribution strategy of the Ministry of Public Works and Water Resources and on the farmers' behaviour. Farmers may influence the water distribution to a certain extent with respect to the total quantity they consider necessary, and through their daily abstraction pattern (day versus night irrigation).

The actual water distribution is also influenced by the operation of the irrigation system by gate operators, who act as an intermediary between the Ministry objectives (intended water distribution) and farmers' objectives (irrigation during day time and farmers' water requirements).

Farmers use sakkias (water-wheels) and diesel pumps to lift the water from the lowest order irrigation canals to irrigate their fields. Water supply to these lowest order irrigation canals normally takes place through submerged movable gates. Two times daily, during irrigation-on periods, the height of the gate openings are adjusted according to the target waterlevel downstream of the canal inlet. If farmers withdraw more water than their official share, the gate opening is enlarged, thus rewarding such behaviour. Obviously the reverse holds if farmers withdraw less than their official share.

The main purpose of the regional drainage model REUSE is:

- organization of input and output for the module FAIDS, where the on-farm water management is simulated;
- distribution of irrigation water supplied to the agricultural areas among the different field crops;
- simulation of crop succession after the harvest, at the onset of the next growing season;
- simulation of unofficial reuse of drainage water by farmers;
- simulation of the irrigation water salinity after mixing with drainage water by reuse pump stations;
- taking care of the simulation sequence of the agricultural areas distinguished in relation to official and unofficial reuse of drainage water;
- calculation of time-lags in the drainage system;
- preparation of output for presentation.

THE INPUT DATA

The data required for performing model simulations can be classified in four categories:

- time invariant input data, also called model parameters, such as soil permeability, soil anisotropy factor, etc.;
- time dependent input data, such as total water supply, cropping pattern, meteorological data, etc.;
- model variables which have to be initialized, such as soil moisture contents, soil salinity, groundwater depth, etc.;
- field measurements for the comparison of simulated model output in order to calibrate some of the time invariant model parameters.

Any simulation model is a simplified reproduction of the complex reality. Although it is the objective of the modeller to include all relevant relationships in the model, implicit assumptions made during the modelling process will limit the equivalence between the simulation model and reality. For the actual model simulations in a certain defined study area, such as the Eastern Nile Delta, not only the processes are schematized. Also the area itself and the associated relevant input data have to be schematized. The reasons for subdividing the area into smaller units and schematization of the input data are not only related to limited computing facilities, but frequently also with insufficient knowledge about the detailed spatial and temporal variability of the required input data.

For the subdivision of the Eastern Nile Delta into calculation units, the boundaries of the administrative Irrigation Districts have been respected. Since the simulation model follows both the hierarchy of the irrigation and drainage canal system, these districts have been split up into smaller units. Finally, the (schematized) calculation units have been defined in such a way that its irrigation water originates exclusively from one canal, and its drainage water flows exclusively to one drainage canal. The resulting number of calculation units in the Eastern Nile Delta is 88.

Correct cropping pattern data are of vital importance for the simulation of the water management. Cropping pattern data are also important for the allocation of the available irrigation water over the intakes of the main irrigation canals. In order to reduce the amount of calculations required in the on-farm water management model the number of crops considered has been reduced from the 28 crops distinguished by the Ministry of Public Works and Water Resources to the 9 major field crops.

For the water allocation model DESIGN the planned cropping pattern, as negotiated between the Ministry of Agriculture and the Ministry of Public Works and Water Resources, should have been used. For the crop water requirement model WDUTY, and for the regional agricultural and drainage model REUSE, the actual realized cropping pattern, should have been used as input. This aspect has been neglected, and the same cropping pattern has been used for the three models.

For the initial model soil moisture and salinity input data, equilibrium conditions have been assumed. These initial conditions have been generated by running the SIWARE model for a sufficiently long period with the same irrigation water allocation, climatic, and soil use input data. The year 1986 has been selected for calculating the initial input data, because both the cropping pattern and the irrigation water supply are both more or less equal to the long term historical average. The same year has been used for the calibration of model input parameters.

For the simulations with the SIWARE model a number of simplifying assumptions with respect to the subdivision of the study area into calculation units have been made. The input data have been schematized with respect to spatial and temporal variability. The most important simplifying assumptions are:

- rotation of irrigation water supply takes place below the level of the distinguished calculation units;
- the gate operation procedures are considered valid for all gates in the complete study area;
- the irrigation water uptake pattern is considered uniform for the complete study area;
- the irrigation intervals are considered identical for the complete study area;
- the seasonal distribution of the groundwater abstraction in the calculation units is assumed constant with time;
- the climatic input data are based on long term observations, and differences between individual years are not considered;
- the same cropping pattern is used both for simulating the water allocation and for the crop water requirement and regional drainage water simulations;
- only the nine major field crops are considered;
- uniformity is assumed within the schematized calculation units with respect to soil and hydrological characteristics;
- uniformity is assumed with respect to growing period of the crops in the study area;
- crop development input data, such as rooting depth, relative soil cover, crop height, etc., are assumed uniform within the calculation unit;
- the feedback of saline soil conditions to crop development data is not considered;
- unofficial reuse of drainage water is applied uniformly within each calculation unit.

THE MODEL CALIBRATION

The collection of sufficiently accurate and representative field data as model input for the Eastern Nile Delta has proven to be a too large effort to be implemented within the framework of the project. Instead, model input data calibration has been used in order to improve the accuracy of the model results. During this procedure the measured output has been used as a yardstick for changing the input data between certain ranges. The input data values which gave the best results were selected. Accurate model results for the circumstances for which the data have been calibrated does not automatically mean that the simulation results are reliable. Therefore it is always necessary to use an additional set of measured output data for different circumstances in order to prove the validity of the used input data and the model approach.

Model input parameter estimation (calibration) and checking (validation) has been performed at the three levels for which measurement data are available:

- at canal command level for checking the water allocation procedures;
- at irrigation branch canal level for checking the water distribution within the

irrigation canal command;
- at drainage catchment level for checking the integrated result of irrigation water supply, hydraulic and operational relations in the irrigation canal network, field water distribution, evapotranspiration, drainage and salt accumulation relations, and official and unofficial reuse of drainage water.

The input data which are required for performing model simulations with the SIWARE model package can be subdivided into three categories, which are fundamentally of a different nature:

- input data which define the water management strategy, such as cropping pattern, water allocation duties, and water supply data (time dependent input data);
- model input parameters which determine the system's behaviour (time invariant input data);
- initial input data for moisture and salinity conditions of each soil layer for each crop in each calculation unit considered.

Of these input data, only the system behaviour model input data are subject to calibration. For this model input data calibration one year (1986) of field observations of drain discharge and salinity has been selected. For this selection the following two considerations have played an important role:

- the drainage water discharge and salinity observations of 1986 are sufficiently accurate;
- 1986 is a more or less average hydrological year with respect to cropping pattern and water supply.

Comparison of the water allocation and distribution simulated with the SIWARE model with field observations can be done only for the main canal intakes and the main side branches of the irrigation canals. Below the level of side branches in the irrigation canal system no data are available for checking the model performance with respect to the water distribution. The next level of comparison of model results with field observations is the drainage catchment for which discharge and salinity data have been collected by the Drainage Research Institute.

The accuracy of the model simulation results has been determined for each location in the Drainage Research Institute observation network by calculating the 'average monthly deviation' parameter. This parameter has been defined as the average of the absolute differences between the monthly simulated and observed values expressed as a percentage. Because deviations tend to average out when the results of small individual catchments are combined, the 'average monthly deviation' parameter should have lower values for composite catchments and for the complete study area, compared to the individual drainage catchments.

THE MODEL VALIDATION

Accurate simulation results for 1986 with model parameter values, which have been calibrated for the same period, does not prove that the simulation model represents the complex reality sufficiently well. It also does not prove that the model parameter values used are representative for the actual values in the physical reality. Since more parameters are calibrated simultaneously, it is very well conceivable that a different combination of parameter values will produce a similar quality of output data.

Although accurate model results are desirable, it is more important that the simulation model has a good predictive value. Determining the predicting capabilities of a simulation model should always be done for different circumstances than those used for model parameter calibration. This procedure is called validation. The drainage water discharge and salinity observation period from 1984 till 1988 covers a substantial range of variation in water supply to the Eastern Nile Delta and has been used for the validation of the input parameter values (in combination with the SIWARE model of course).

A simulation model can be considered reliable if the predicted trend in drainage water discharge and salinity complies with the observed trend. In order to judge this reliability, the 'predictive value' parameter has been defined as the average deviation of the simulated yearly totals from the observed trend, divided by the range of the observations, expressed as a percentage. A high 'predictive value' means that the simulated yearly change in discharge complies with the change in the observed discharge.

The 'predictive value' of the SIWARE model, established in this way, should be considered as a conservative estimate of the real predictive value of the model. In some cases both the observed and simulated values do not change much during the validation period. Although the agreement between simulations and observations is good in such cases, a low 'predictive value' is calculated.

A predictive value above 50% means that more than 50% of the observed variations are explained by the model simulations and that the SIWARE model can be considered as reasonably validated. With a predictive value above 75% the model can be considered as sufficiently validated.

THE ANALYSIS OF WATER MANAGEMENT IN 1986

The average irrigation water supply to the Eastern Nile Delta in 1986 was around 6 $mm \cdot day^{-1}$. The drain discharges, measured by the Drainage Research Institute, range from roughly 1 $mm \cdot day^{-1}$ in the southern part of the Eastern Nile Delta to as high as 8 $mm \cdot day^{-1}$ in the north. The explanation of these differences in drain discharges has always been difficult. The SIWARE model simulation results with respect to drain discharges and salinities agree quite well with the observations. Consequently, the simulation results may be used to explain the magnitude of the different water and salt balance components as well as the regional differences which have been observed in the monitoring programme.

The discharges and salinities of the drainage water are the composite result of the processes taking place during water distribution, crop evapotranspiration, soil moisture and salinity processes, etc. Given the fact that the magnitude of both discharges and salinities is simulated correctly, one can assume that also the crop reaction to water supply and salinity conditions as simulated by the SIWARE model is correct. The simulated crop response has been compared with data from the international literature on relationships between soil salinity and crop yield, as well as with field research results from Egypt.

By the schematization of the study area into calculation units for the SIWARE model simulations, about 80 artificial experimental fields have been created (for each of the crops considered). The relative evapotranspiration (relative to the optimum), which is simulated by the SIWARE model, is generally accepted to be correlated with total dry matter production, and thus with crop yield. Consequently, the reduction of the actual evapotranspiration rate may be used as an indicator of crop yield depression due to water stress conditions and/or high soil salinities.

Evapotranspiration is generally considered to be linearly correlated to the total dry matter production of the agricultural crops. The crop yield, which is of course the main interest to farmers, may react differently to water stress conditions than the total dry matter production. For crops like berseem for instance, soil moisture stress conditions may promote additional root growth at the expense of shoot production, resulting in a larger crop yield decrease than the decrease in actual evapotranspiration. For some grain crops it is known that moisture stress conditions reduce the straw production first, and that the grain yield is affected to a lesser extent. A further complication of the relation between moisture stress and crop yield is the occurrence of growth sensitive periods, such as the flowering period.

It has been assumed that the crop yield decrease caused by soil salinity, reported in the international literature and the evapotranspiration reduction simulated by SIWARE are consistent with each other. It has been assumed also that evapotranspiration reductions due to soil moisture and salinity stress result in comparable crop yield decreases. This means that toxic effects of specific ions have not been considered in the analysis. Based on these assumptions, on the data from the international literature, and on the SIWARE model results on relative evapotranspiration, relations between the seasonal relative crop evapotranspiration and crop yield have been derived for the Eastern Nile Delta.

The SIWARE model simulation results on the seasonal average irrigation water salinity and soil salinity have been examined in order to find the relation between both. The relation found was clear, although the scatter in the data appeared to be considerable. Most probably this scatter can be attributed to differences in hydrological conditions, but also to differences in the quantities of water supply. In an attempt to explain (at least part of) the scatter, the seasonal leaching fraction has been calculated for each of the calculation units distinguished for the model analysis. This fraction has been defined as the amount of irrigation applied (including unofficial reuse and groundwater use) during the growing season diminished with the seasonal amount of actual evapotranspiration.

For estimating the influence of the seasonal leaching fraction on the relation between irrigation water salinity and soil salinity, the simulation results per distinguished crop have been classified into three clusters of more or less equal size. One cluster with the lowest leaching fractions, one with the medium, and one with the highest leaching fractions. In this context, a high leaching fraction may be associated with a sufficient water supply and good internal (soil profile) drainage conditions. A low leaching fraction may be due to either an insufficient water supply, or to bad internal drainage conditions (for instance due to low soil permeability or seepage conditions), or it may be due to a combination of both. For each cluster, and for each crop, the average ratio between the soil salinity and the irrigation water salinity has been determined.

Based on the model simulation results and the comparison with international and Egyptian literature on crop response, the following irrigation water salinity classification for average leaching conditions in the Eastern Nile Delta has been made:

salinity below 400 g·m^{-3}: no problems;
salinity from 400 - 800 g·m^{-3}: increasing problems with vegetables and maize;
salinity from 800 - 1,200 g·m^{-3}: serious problems with vegetables and maize; increasing problems with rice;
salinity above 1,200 g·m^{-3}: cultivation of vegetables and maize is not recommended; serious problems with rice; increasing problems with berseem and wheat; no problems with cotton.

THE WATER MANAGEMENT STRATEGIES

Three clusters of water management scenarios have been analyzed with the SIWARE model. They are the following:

- water saving strategies by replacing rice in the cropping pattern by maize and/or reducing the rice allocation duty;
- extension of agricultural area in the Eastern deserts in yearly increments of 44,000 feddans[1], starting with the 1988 water management and cropping pattern situation;
- improvement of the local water management situation by prohibiting the use of movable irrigation pumps and/or prohibiting the unofficial reuse of drainage water by farmers.

For each of the strategies studied the SIWARE model package has been used in first instance to estimate the amount of available official reuse of drainage water. In the DESIGN sub-model the allocation of irrigation water, differentiated for the irrigation command areas, is simulated. During run-time a message file is created by the REUSE sub-model in which differences between assumed and realized quantities of drainage water for reuse are reported. By updating the reuse quantities for the water allocation and running the model again, consistent water management strategies have been obtained.

In practice not all simulated drainage water available for reuse is actually reused. Generally reuse pump stations are constructed in a small branch of the main drain from where they withdraw the drainage water. In this way the main drain itself functions as a by-pass for emergency situations, and excess water which is not reused will continue in the main drain. Reuse of drainage water data of 1986 have been used to estimate the fraction of the simulated available drainage water which is actually lifted by the official reuse pump stations. These correction factors are differentiated for the winter, spring/autumn and the winter period, and have been used for all the strategies.

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[1] one feddan equals approximately 4200 m^2

In addition to the effects of the strategies on the official reuse, also the effects on the evapotranspiration and crop yields have been considered. A distinction can be made between the short (1 year) and the long term effects (50 years), caused by a salinization or desalinization of the top soil. When supported by sufficient data, a financial and an economical evaluation have been added.

For each of the three clusters of water management strategies as specified above, a reference situation has been defined. In order to facilitate the interpretation and comparison of strategies within each cluster, the initial conditions with respect to soil moisture and soil salinity for the three reference strategies have been obtained by running the SIWARE model for a period of 50 years. Since this reference situation is different for each cluster of strategies, the results of a certain strategy from one cluster cannot be compared to the results of a strategy from another cluster.

THE RICE AREA AND ALLOCATION DUTY STRATEGIES

The rice crop is known to have large water requirements of about 2 to 3 times higher than for other summer crops. Savings of irrigation water can thus be realized by exchanging the rice in the crop rotation by other summer crops. An alternative method of saving on Nile water supply to the Eastern Nile Delta is to reduce the allocation water requirement of the rice crop. The philosophy behind reducing this allocation water requirement is that farmers may be forced to use the available water more efficiently, thereby reducing the losses of irrigation water. By combining both water saving measures in different degrees, 23 water management scenarios have been defined. All 23 strategies have been evaluated with the SIWARE model package, both for the short term (1 year) and for the long term effects (50 years). The net Nile water savings range from zero for the reference strategy till about 24% for the most far reaching scenarios.

The reference strategy for the rice area and allocation duty strategies has been defined by comparing the cropping patterns of 1984 and 1988 and taking the maximum percentage of rice occurring in each calculation unit as the reference. The water supply to the Eastern Nile Delta for this reference strategy has been taken equal to the allocation requirements for this specific cropping pattern.

Because of the high rice water requirements of almost 2 to 3 times those of other summer crops, the Egyptian farmer is not allowed to grow any quantity of rice he wants. The Ministry of Public Works and Water Resources has divided the Eastern Nile Delta in so-called rice zones. In the southern part of the Eastern Nile Delta (rice zone 5) the growing of rice is forbidden, because leaching of salts is not necessary here. In the most northern part (rice zone 1) it is allowed to plant 50% of the area with rice, because leaching of accumulated salts is a prerequisite in this area which is dominated by saline seepage from the aquifer.

In the discussions with the Steering Committee reducing the rice allocation water duties from the present 8,800 $m^3 \cdot feddan^{-1}$ till about 6,000 $m^3 \cdot feddan^{-1}$ was considered realistic. Further reduction below 6,000 $m^3 \cdot feddan^{-1}$ was felt to contradict the existing evidence of the high water requirements of the rice crop. Some recent field studies, conducted on both experimental and farmers' fields, indicate that a lower actual water use than 6,000 $m^3 \cdot feddan^{-1}$ for the rice crop may occur.

In the simulations the lowest allocation water duty considered for rice is 2,700 $m^3 \cdot feddan^{-1}$. For this extreme, the gross water savings are equal to the gross water savings obtained by removing all rice from the cropping pattern in the complete Eastern Nile Delta. Both options (removal of all rice and an allocation duty for rice equal to that of maize) are considered unrealistic from a practical point of view.

The overall effect of the 23 rice area and allocation duty strategies has been considered in terms of the composite effect in the evapotranspiration. Since in the different strategies the rice areas and maize areas are different, the total evapotranspiration simulated by the SIWARE model for the complete cropping pattern has been corrected for the difference in evapotranspiration of the rice and the maize crop (43 $mm \cdot year^{-1}$). This correction has been weighted with the change in the fraction of the Eastern Nile Delta which is grown with rice. For the reference strategy the percentage of rice in the cropping pattern equals 27.45%. Consequently, the maximum correction (increase) in the simulated evapotranspiration of the cropping pattern is 12 mm. This is about 1% of the reference strategy evapotranspiration.

Assuming that the production costs remain constant when the water supply is reduced, the financial consequences (for the farmer) as well as the economic consequences (for the country) can be estimated. In this analysis it has been assumed that the water which is saved by the distinguished strategies can be used in the next year for crop production. This means that the economic (or financial) return of the saved irrigation water is the same for both years. In other words: the saved water increases the total area irrigated, not during the year considered however, but during the next year. Savings of 10% of Nile water, results than in securing the irrigation water for an additional 10/0.90 = 11.1% of the area for the next year. The total benefits of such a water saving of 10% is than the extra income of this 11.1% additional area, reduced with the income losses of the present 100% area (losses due to water savings), diminished with the cost of production of the 111.1% of the area cultivated.

The financial and economic analyses have been performed using production and price levels of 1979/1980 as found in the literature. The vegetable and tree crops have not been considered in the analysis, due to the absence of relevant data.

THE EXTENSION OF AGRICULTURAL AREA STRATEGIES

Horizontal expansion of the agricultural area in the Eastern Desert is foreseen in the planning of the Ministry of Public Works and Water Resources in the near future. The extension anticipated is about 350,000 feddan, to be executed at a pace of 44,000 feddan per year. This would increase the present gross agricultural area in the Eastern Nile Delta of about 1.8 million feddan with more than 19%. The practical question of the Ministry of Public Works and Water Resources in this respect is the following: which allocation of irrigation water has to be applied when, starting from the cropping pattern and water supply of 1988, the irrigation water for an additional area adjacent to the Eastern Nile Delta of 44,000 $feddan \cdot year^{-1}$ has to be made available. At the same time also an answer should be provided concerning the reductions in the amount of drainage water available for reuse in the old lands.

Only 7 to 8% of the total reclaimable area will be supplied with groundwater, whereas the remaining lands will be fed with Nile water. Since the total yearly amount of Nile water available for irrigation is not likely to be raised until the year 2000, the supply of the reclaimed areas will largely go on the account of the supply to the old lands in the Nile Delta and Valley. Reuse of drainage water, withdrawal of groundwater, storage reservoirs, an improved water distribution, and other irrigation methods are expected to offset water shortages.

A number of simulations with the SIWARE package have been carried out, including a long term run (50 years) for the maximum extension with 350,000 feddan. In order to approach the irrigation efficiency of the drip and sprinkler irrigation applied in the desert areas as closely as possible, relative small plot sizes have been chosen in the reclaimed areas for the model simulations. As to the soil productivity, simulations have been based on the assumption of similar soil fertility levels for reclaimed soils as for deltaic clay soils. The soil moisture retention, however, has been adjusted in accordance with the actual soil texture.

Considering the model input data, the actual cropping pattern in the reclaimed areas has been obtained by extrapolating figures available for existing reclaimed desert areas (Ismaileya District). It has also been assumed that each extension will follow a similar pattern. In the reference simulation part of the desert area is already cultivated. For the extensions of 44,000 feddan per year these areas are filled with crops first, completely fallow desert areas are followed later.

The effects on the different irrigation and drainage water balance components have been studied with the emphasis on the irrigation water allocation to the main intakes along the river Nile and the official reuse of drainage water. Also the short and long term crop reaction have been analyzed, using the evapotranspiration of the different crops as a standard of comparison. The relative increase of the latter output variable has been plotted against the relative increase of the total area cultivated with a certain crop, thus giving a crop performance indicator.

THE IMPROVEMENT OF LOCAL WATER MANAGEMENT STRATEGIES

A considerable discrepancy exists between the water duties used by the Ministry of Public Works and Water Resources for the water allocation, target level control and gate opening procedures, and the agricultural, spatially variable water requirements of the farmers. The control in the traditional irrigation water management in the Nile Delta was very tight. Farmers were obliged to use sakkias for irrigating their fields. The supply pipes to the sumps from which sakkias were taking their water had a limited diameter and were under the control of the Ministry of Public Works and Water Resources. Consequently, farmers were forced to irrigate during night hours as well. The introduction of small capacity, movable diesel pumps has created a surplus in uptake capacity, and farmers near the intake gates of distributary canals or meskaas are no longer compelled to irrigate during the night. As a result, farmers at the downstream end of meskaas sometimes have to use drainage water, because farmers upstream take more than their equal share.

Using the SIWARE model package, the consequences of changes in the local water management conditions have been evaluated. The effects on the different irrigation and drainage water balance components as a result of eliminating the diesel pumps and/or prohibiting the unofficial reuse of drainage water by farmers have been studied. Finally, the short (1 year) and long term (50 years) reaction of the 9 different crops as distinguished in the model have been analyzed using the evapotranspiration as an indicator.

The conclusions should be interpreted cautiously, because the areas of the schematized calculation units are on the average three times larger than those of the agricultural units served in reality by a distributary canal. The non-uniformity in the water distribution, as a result of the use of diesel pumps, will be mainly concentrated within the calculation units. Since the area served by a distributary canal is much higher, and the irrigation water distribution within such a unit has been assumed uniform in the model simulations, it will be clear that the effects of eliminating diesel pumps cannot be predicted very accurately. Model application on a single calculation unit is a more appropriate way to quantify these effects. The model simulations carried out so far will only provide the effects on the inter-calculation unit scale.

THE MODEL CALIBRATION

Calibration of model input parameters can be justified by the limited knowledge about these model input parameters, the uncertainty about the exact values, and the effects of spatial variability within assumedly uniform agricultural areas.

Through the calibration of model input parameters, which show spatial variability within subareas, it has been attempted to establish their representative average value. The reliability of such calibrated model parameters remains questionable, however. Since more than one parameter is calibrated simultaneously, it is conceivable that a different combination of parameter values produces a similar model performance, i.e. similar simulation results.

By the selection of the year 1986 for calibration of model parameters and the estimation of initial soil moisture and salinity data, an implicit assumption has been made. This assumption concerns soil salinity equilibrium conditions for the calibration year 1986, meaning that in the model simulations for 1986 no salinization or desalinization takes place.

The water allocation and water distribution simulated with the SIWARE model for 1986, after calibration of the model parameters, show a fair agreement with the observed values. This agreement could be confirmed for the six main canal intakes and for seven side branches only, because no additional data for checking the water distribution were available for the Eastern Nile Delta.

Small deviations of about 10% in the water supply to a certain area correspond to deviations of about 25% in the simulated drainage water discharge from that area. This means that the REUSE model is very sensitive for the simulated water supply to the agricultural areas. A good performance of the SIWARE model with respect to drain discharges consequently implies a good performance of the simulated water distribution by the WATDIS model, which is included in the SIWARE package.

The Steering Committee for the Reuse of Drainage Water Project has defined the accuracy criteria for drain discharge and salinity for individual catchments, composite catchments, and for the complete study area. The SIWARE model simulation results of 1986 for the complete study area and for the composite catchments comply to this quality criteria, both for drainage discharge and salinity. For the results of the individual catchments the Steering Committee criteria have been met in 99% of the study area as far as discharge is concerned and in 97% of the study area for salinity. This good performance has been reached after the calibration of a number of relevant model parameters.

THE MODEL VALIDATION

The drain discharge and salinity data of the monitoring programme of the Drainage Research Institute for the period 1984 - 1988 offer good opportunities for model validation. The Nile water supply to the Eastern Nile Delta in 1988 was 16% lower than that in 1984, the drainage discharge was 21% lower, and the salinity of the discharge was 32% higher. Compared to the year 1986, the Nile water supply to the Eastern Nile Delta in 1988 reduced with 11%, the drainage discharge with 15%, and the salinity of the drainage water increased with 20%. The official reuse of drainage water reduced with 30%, and its salinity increased with 23%.

CONCLUSIONS

THE MODEL

The SIWARE simulation model provides answers on the effects of water management measures in irrigated agriculture under arid and semi-arid conditions. It should be realized, however, that these answers are just an intelligent estimate of the effects. The real effects may be observed in the measurement network, be it, after the measures have been implemented. The importance of the continuation of the monitoring network can, therefore, not be stressed enough.

Through the cascade effect, consequences of water management measures, which are taken in an upstream area, will trickle down gradually until they reach the most downstream area. Due to this complexity it becomes impossible to predict the reaction of the system, and its feedback through reuse of drainage water, when a number of water management measures are taken simultaneously and when they are spatially distributed. The proper procedure for predicting changes in such a complex situation is to formulate all relevant physical and functional relationships and to combine them into a simulation model. Such a model provides the ability to estimate effects of changes in the irrigation water management, cropping pattern, and cultivated area (reclamation).

THE INPUT DATA

The number of crops considered in the model analysis has been reduced from the 28 crops distinguished by the Ministry of Public Works and Water Resources for the water allocation to the 9 main field crops only. The effect of this simplification on the total required water allocation for the Eastern Nile Delta appeared to be acceptably small.

The drainage water discharge and salinity simulated by the SIWARE model turned out to be more sensitive to changes of certain model parameters than to others. The following relative sensitivity has been observed:

- the crop characteristics: growing period, irrigation frequency, ponding period, and irrigation priority appeared to be the most sensitive type of general model input parameters;
- the factors governing the (human influenced) processes of water abstraction by farmers and target level control by the Ministry of Public Works and Water Resources were the next sensitive model input parameters;
- the physical model input parameters appeared to be the least sensitive, when compared to both the crop and human behaviour related model parameters.

The accuracy and reliability of model simulation results are determined by a number of factors, such as:

- the quality of the model formulation, including the schematization of the processes considered;
- the quality and representativity of the areal schematization used;
- the quality and reliability of the model input parameters;
- the quality of the input data.

The water allocation and distribution appear to be predicted very well by the SIWARE model for the validation period 1984/1988. Deviations between simulated and observed values are systematic, indicating that the simulated trends are correct.

On drainage catchment level the simulations of both the yearly discharge and the average salinity show the same trend as the observations during the validation period. Generally, the agreement between both the simulations and measurements is excellent when considering the year totals.

On Eastern Nile Delta level the SIWARE model has been sufficiently validated for both drain discharge and salinity by using the data of the period 1984/1988. Of the observed variation in the yearly discharges 93% is explained by the model, and 79% of the observed salinity is explained by the model.

On drainage catchment level the model is validated for discharge for 90% of the study area (predictive value above 50%). Of this 90%, 70% has a predictive value higher than 75% and can be called sufficiently validated. For salinity the results are less good. On catchment level the SIWARE model is validated for 80% of the study area for chloride concentration, and validated sufficiently for 40% of this area.

THE ANALYSIS OF WATER MANAGEMENT IN 1986

Based on the SIWARE model simulation results and the agreement with the observed drainage discharges and salinities, the following conclusions can be drawn with respect to the water management in the study area during 1986:

- On Eastern Nile Delta level, the water management system can be classified as rather efficient: 62% of the irrigation water (Nile supply) is used for crop evapotranspiration;
- The composite effect of the losses (conveyance losses, tail-end losses, and municipal water consumption) and gains (official reuse of drainage water) of the main irrigation system renders it very efficient: the total Irrigation District water supply in the Eastern Nile Delta is a mere 3% lower than the total Nile water supply;
- Consequently, also on Irrigation District level the water management can be classified as rather efficient: 63% of the water supply is used for crop evapotranspiration;
- The composite effect of the losses (conveyance and spillway losses) and gains (groundwater use and unofficial reuse of drainage water) of the irrigation canal system within the Irrigation Districts in the Eastern Nile Delta renders it very efficient: the crop water supply is only 10% lower than the water supply through the irrigation network;
- Also the on-farm irrigation water management system can be classified as rather efficient: 70% of the water supplied to the fields by farmers is actually used for crop evapotranspiration;
- Despite the fact that spillway losses at Irrigation District level are not excessive (23% of the water supply), these losses constitute a considerable component (43%) of the drainage water produced in these districts.

Considering the agreement between the simulated and measured chloride concentrations of the drainage water in the Eastern Nile Delta, the following conclusions can be drawn concerning the salt balance:

- On Eastern Nile Delta level, the chloride supply through Nile water is about 496 million kg·year^{-1} and the discharge to the sea 1,842 million kg·year^{-1}, which is 3.7 times the Nile supply. Both components are balanced by losses and gains of salt to and from the aquifer. Since soil salinity equilibrium has been assumed for the calibration year 1986, it must be concluded that a desalinization of the aquifer (deeper than roughly 5 to 10 meter) is taking place;
- Although unofficial reuse of drainage water is only 8% of the total Irrigation District water supply, it forms about 33% of the Irrigation District chloride supply;
- Although only 15% of the crop water supply is coming from groundwater use and unofficial reuse of drainage water, the chloride contribution of these water balance components is about 46% of the total crop chloride supply through irrigation;
- For the water balance, seepage is a relatively unimportant component (10% of the crop water supply). For the chloride balance, however, seepage contributes for about 58% to the total crop chloride drainage.

Considering the spatial distribution of the simulated water and salt balance components in the Eastern Nile Delta, the following conclusions can be drafted:

- Unofficial reuse of drainage water constitutes only 11% of the total crop water supply. On some locations in the northern part of the study area, however, drainage water is easily available because it has been lifted by drainage pump stations. Here the magnitude of unofficial reuse of drainage water may approach the irrigation water uptake by farmers from the irrigation system;
- The same holds true for the seepage flux, which on the average is only 10% of the total water balance. In the northern part of the study area, along the Nile branch and the Manzala Lake, seepage may be in the same order of magnitude as the irrigation uptake by farmers;
- The chloride supply through unofficial reuse of drainage water is about 28% of the total crop chloride supply through irrigation. In the north-eastern part of the study area the chloride supply through unofficial reuse is frequently in the same order of magnitude, or even higher, than the chloride supply through irrigation uptake;
- The chloride supply through seepage is concentrated in the northern part of the study area. Here, this source of chloride supply is dominant over the other sources, and the drainage water salinity is mainly determined by the seepage quantity and salinity;
- The chloride supply through groundwater use, which is moderate on the average (18% of the crop chloride supply through irrigation), is absent in the northern part of the study area. In the south the chloride supply through groundwater use approaches the same magnitude as the chloride supply through irrigation uptake, because the quantity of groundwater use is high here. In the middle part of the study area the same holds true, because here the salinity of the groundwater use is relatively high;
- Although the two main components of the drainage water (crop drainage and spillway losses) are in the same order of magnitude, the relative importance of the spillway losses in the north is much less than in the southern part of the study area. In the south the spillway losses component is frequently larger than the crop drainage component.

The simulated agricultural crop water requirements are relatively high in the southern part of the study area and in the fringes along the Eastern Desert. This is most probably due to climatic differences as well as soil property influences (light textured soils).

Crops which receive only light irrigations, such as wheat and cotton, have a larger seepage contribution in the salt balance, compared to crops which are irrigated more frequently and more heavily such as rice, berseem, and vegetables. Consequently, wheat and cotton are crops which cause soil salinization in a crop rotation, while rice takes care of the indispensable removal of the accumulated salts.

Although in the SIWARE model simulations a soil salinity equilibrium has been assumed for the calibration year 1986, the model results suggest that the assumed equilibrium is a very dynamic one. For the individual field crops, such as rice, the salt discharge may be up to 300% higher than the total salt supply to the soil profile. For other crops, such as wheat, the salt discharge may be as low as 25% of the total salt supply to the soil profile. The lowest simulated value of salt discharge for cotton is a mere 10% of the salt supply.

The correlation between the simulated salt discharges of the main field crops (average of three calculation units in the neighbourhood of the Mashtul Pilot Area) and those reported for this research area is remarkably good for rice, maize, and long berseem. For cotton, short berseem, and wheat the agreement is less, but the simulated ranges approach the measured values closely.

THE CROP RESPONSE TO WATER MANAGEMENT IN 1986

The SIWARE model simulation results of relative crop evapotranspiration related to soil salinity have been compared with available Egyptian field research results relating crop yield with soil salinity. Considering this comparison, the following two observations can be made:

- the SIWARE simulation results show a similar scatter of data as the reported field researches;
- the crop yield reductions measured in the field tend to appear at lower soil salinities than the evapotranspiration reduction simulated with the SIWARE model.

The scatter in the relation between the relative evapotranspiration and the soil salinity in the SIWARE model results is partly caused by variations in the relative water supply to crops. The seasonal leaching fraction, which is defined as the ratio of the crop water supply diminished with the crop evapotranspiration over the crop water supply, was found to explain this scatter. Depending on these seasonal leaching fractions, which varies for all crops between roughly 0% and 65%, the same irrigation water salinity may cause soil salinity differences up to 60%.

For all crops, except cotton and rice, the crop yield reduction as a result of soil salinity reported in the international literature, starts at lower soil salinities than the evapotranspiration reduction in the SIWARE model simulations. For all crops the decrease of relative crop yield per unit increase in soil salinity reported in the international literature is higher than the reduction in the relative evapotranspiration simulated with the SIWARE model. These differences are caused by the fact that the relative evapotranspiration is related to total dry matter production rather than crop yield.

By combining both the results from the international literature on crop yield reaction to soil salinity and the SIWARE simulation results on evapotranspiration reaction to soil salinity and water supply, the relation between relative evapotranspiration and relative crop yield has been deduced. Supporting evidence for these relations has been found in the Egyptian literature for both cotton and maize. For both crops the derived relations agree very well with available experimental results.

The above mentioned relationship for the cropping pattern of 1986 in the study area indicates that the crop yield reduction is less than proportional for reductions in the water supply up to 15%. Reductions larger than this 15% result in a reduction of the crop yield of roughly 1.2% per additional per cent of supply reduction. Consequently, the optimum (economic) water supply (disregarding the seasonal distribution of the water supply) most probably will be in between the agricultural demand and 85% of this quantity.

During 1986 the total crop water supply (including unofficial reuse of drainage water and groundwater use) was 1,750 mm·year^{-1}, which is about 5% lower than the agricultural demand of 1,840 mm·year^{-1}. Disregarding spatial and seasonal variations in both the water supply and agricultural water requirements, this means that the on-farm water management system during 1986 has been operated very close to the optimum.

From the analysis of the SIWARE model simulation results it becomes clear that farmers tend to apply more leaching than 50% of the crop evapotranspiration if the irrigation water salinity is above 400 g·m^{-3}. Most probably they do this to counteract the salinization effect of the higher irrigation water salinity.

For the lowest class of leaching conditions, as found in the study area for the cotton crop, a groundwater (seepage) contribution of 19% to the crop evapotranspiration is realized. Also for the wheat crop this phenomenon is observed, be it to a lesser extent.

Based on the model simulation results and the comparison with international and Egyptian literature on crop response, the following irrigation water salinity classification for average leaching conditions in the Eastern Nile Delta has been made:

salinity below 400 g·m^{-3}: no problems;
salinity from 400 - 800 g·m^{-3}: increasing problems with vegetables and maize;
salinity from 800 - 1,200 g·m^{-3}: serious problems with vegetables and maize; increasing problems with rice;
salinity above 1,200 g·m^{-3}: cultivation of vegetables and maize is not recommended; serious problems with rice; increasing problems with berseem and wheat; no problems with cotton.

Good drainage conditions and an adequate water supply increase the prospects for reuse of drainage water. In the range of a relative crop production between 75 and 100% the irrigation water salinity may be increased with roughly 50% on the condition that the drainage circumstances are improved and the water supply is adequate. This conclusion is valid for irrigation water salinities below 800 $g{\cdot}m^{-3}$ with average leaching conditions, and corresponds to irrigation water salinities of 1,200 $g{\cdot}m^{-3}$ with high leaching conditions.

Based on the SIWARE model simulations for 1986, an impression is obtained about the potential crop yield increase due to improvement of the drainage conditions in relation to the irrigation water salinities. The model gives in this case only the minimum potential increase, because the relative evapotranspiration in the model has been defined based on the present drainage depth. For those crops for which these drainage depths are limiting the root development, a lowering of the drainage depth also increases the potential crop yield. This increase in potential crop yield is not included in the analysis of the water management for 1986. The minimum potential crop yield increases that can be expected due to improvement of drainage conditions range from about 6% for an irrigation salinity of about 400 $g{\cdot}m^{-3}$ to roughly 26% for an irrigation water salinity of 1,200 $g{\cdot}m^{-3}$.

THE RICE AREA AND ALLOCATION DUTY STRATEGIES

The monthly distribution of the water allocation duties for the rice area and allocation duty strategies follows the observed monthly distribution of actual water use found in the Egyptian literature better than that of the official allocation duty.

Reducing the rice area results in a reduction of the official reuse of drainage water. The effect of replacing rice by maize in the southern part of the Eastern Nile Delta on the reduction of the official reuse of drainage water is larger than replacing rice by maize in the northern part. The reason for this is that the reuse pump stations are mainly located in the southern part of the Nile Delta. Taking rice out of cultivation in areas outside the catchments of the reuse pump stations does not influence their discharge.

Due to the reduction of the official reuse of drainage water, the net water savings are less than the reduction in the total water allocation. Water savings by reducing the allocation duty of rice is more efficient than through the reduction of the rice area. When reducing the allocation duty, the reduction is effective for about 90% due to the associated reduction in reuse of drainage water. When reducing the rice area, the reduction is effective for 85% only.

The strategy with the variable allocation duty has a higher official reuse of drainage water for the same gross water requirement than any other strategy with a comparable gross water requirement. The highest allocation duty is used in the southern part of the Eastern Nile Delta were the majority of the drainage water is reused, and the lowest duty in the northern part were almost no drainage water is reused.

The savings of irrigation water by reducing the rice area and allocation duty strategies are compensated by reductions in the irrigation water losses. Reducing the rice area results in a reduction of these losses with about 40%. Savings of irrigation water by reducing the allocation duty of rice are compensated by reductions in the irrigation water losses of 70% and 45% for the first two reductions of 1,400 $m^3 \cdot feddan^{-1}$. For the next two reductions the compensations are 30% and 25% respectively. Saving irrigation water by reducing the rice allocation duty until 6,000 $m^3 \cdot feddan^{-1}$ is therefore superior to reducing the rice area to reach comparable savings. This superiority is caused by the larger reduction in irrigation water losses, resulting in a much smaller reduction in irrigation water uptake by farmers.

Reducing the rice area results in a reduction of the unofficial reuse of drainage water. The reduction is about 6% of the reduction in the Nile water supply. By reducing the allocation duty the unofficial reuse of drainage water is increased with about 5% for the first two reductions of 1,400 $m^3 \cdot feddan^{-1}$ considered. Reducing the allocation duty for rice below 6,000 $m^3 \cdot feddan^{-1}$, however, results in a drop in the unofficial reuse of 4% for the first additional reduction and 23% for the second. Apparently, at this level of water savings the reductions in the water supply have increased the irrigation efficiency to such an extent that the availability of drainage water for unofficial reuse becomes a limitation.

The effect of the water saving rice area and allocation duty strategies on the drainage water quantity is more than proportional. Saving on Nile water by reducing the rice area results in a reduction of the drainage water of 1.4% for each per cent reduction in Nile water supply to the Eastern Nile Delta. Reducing the allocation duty of rice results in a 2.1% decrease of drainage water discharge for each per cent reduction of Nile water supply. Reducing the allocation duty as a water saving measure therefore has a larger influence on the system efficiency than replacing rice by maize.

Due to the changes in the different water balance components in the Eastern Nile Delta upon changing the water management strategies, the crop water supply changes differently to changes in the Nile water supply.

A reduction of the gross water requirements with 1,000 million m^3 results in a reduction of the net crop water supply of 60% of the net savings on Nile water supply to the Eastern Nile Delta if rice is replaced by maize. Reducing the allocation duty to reach comparable savings results in a reduction of the crop water supply of 11% of the net water savings only.

Reducing the gross water requirements with an additional 1,000 million m^3, the net crop water supply reduces with 62% of the net Nile water savings if rice is replaced by maize, and 33% by reducing the allocation duty of rice.

If the gross water requirements are reduced with 3,000 million m^3, the difference between both approaches is less. Reducing the rice area results in a reduction in the crop water supply of 62% of the net Nile water savings, and reducing the allocation duty leads to a reduction of 53%.

These remarkable results can be ascribed to the flexibility in the water management system in the Eastern Nile Delta. Apparently, saving irrigation water by reducing the allocation duty of rice makes a better use of this flexibility than the alternative method of replacing rice by maize. The largest differences between both approaches to save on irrigation water are observed for allocation duties until 6,000 $m^3 \cdot feddan^{-1}$. Below this value the model simulations still indicate an advantage of reducing the rice allocation duty above replacing rice by maize, but the differences between both approaches are small.

The distribution of the crop water supply over the different crops, which are simultaneously in the field, is the responsibility of the farmer. He will give the crop which he considers the most important the largest share of the (limited) available water. Consequently, a lower allocation duty for the rice crop not only affects the rice production, but also that of the other summer crops in the field.

The allocation duty of the rice crop can safely be reduced from the present figure of 8,800 till 6,000 $m^3 \cdot feddan^{-1}$ without seriously affecting the average evapotranspiration or the linearly correlated productivity[1]. For the allocation duty of 4,600 $m^3 \cdot feddan^{-1}$, however, the rice evapotranspiration falls substantially. Comparable water savings can be obtained by reducing the rice area till 210,000 feddan. The effect on the average evapotranspiration of rice is more or less the same for this strategy.

The effect of reducing the rice area and maintaining the allocation duty of rice on the relative evapotranspiration, or productivity, of maize is small for the first two reductions until 375,000 feddan. Further reduction of the rice area by replacing rice by maize results in a sharper decrease in the average evapotranspiration of the maize crop. Maize is quite sensitive to high soil salinity and produces less good in the northern part of the Eastern Nile Delta.

Reduction of the allocation duty of rice has a smaller negative effect on the evapotranspiration of the maize crop compared to reducing the rice area. For water savings up to about 10% the minimum adverse effect on the maize evapotranspiration is obtained by reducing the allocation duty of rice until 6,000 $m^3 \cdot feddan^{-1}$. Larger water savings, while maintaining the evapotranspiration of the maize crop at its maximum attainable level, are obtained by prohibiting the growing of rice in the first two rice zones (4 and 5). Reduction of the rice area below this 375,000 feddan is not recommended from the viewpoint of maintaining the maize evapotranspiration. The growing of rice in the most northern belt only (rice area 1) is in all cases unfavourable for the average maize crop yield.

The reaction of the cotton crop to reductions in the rice areas and rice allocation duties if quite different from that of rice and maize. Reducing the rice area results in only minimal reductions of the relative evapotranspiration of the cotton crop. At 24% water savings (without rice) the relative evapotranspiration goes down with only 4%. Maintaining the maximum rice area and reducing the allocation duty, however, results in large losses in relative evapotranspiration, which is caused by the low priority of cotton when farmers distribute the available water over their crops.

It can be concluded that reducing the rice area as well as reducing the rice allocation duty affects the actual evapotranspiration of all summer crops. The effect of reducing the rice area on the actual evapotranspiration rates of the summer crops, except for cotton, are larger compared to reducing the rice allocation duties to reach comparable savings.

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[1] both the evapotranspiration and productivity are defined per unit area

On the long term (after a few years) also the winter crops are affected by the water saving measures due to an increased soil salinity status, caused during summer time. The evapotranspiration rates of winter crops show a gradual decrease with time.

Assuming economic returns of the crops grown in the Eastern Nile Delta proportional to their actual evapotranspiration, the composite reaction of the cropping pattern in terms of actual evapotranspiration can be used as a yardstick for the selection of alternative water management strategies. For net Nile water savings up to 15% of that of the reference strategy the maximum crop evapotranspiration is secured by reducing the rice allocation duty from 8,800 $m^3 \cdot feddan^{-1}$ till 6,000 $m^3 \cdot feddan^{-1}$ and leaving the rice area intact at 510,000 feddan. Water savings from 15 till 20% are best obtained by reducing the rice area from 510,000 feddan till 375,000 feddan, accompanied by a further reduction of the rice allocation duty till 4,600 $m^3 \cdot feddan^{-1}$. Water savings larger than 20% should then be realized by abandoning the cultivation of rice.

The substitution of rice by maize in the northern part of the Eastern Nile Delta results in larger total production losses of both maize and rice than in the southern part. In the north, these losses are not completely compensated by the increase in the total maize production, due to the higher soil and irrigation water salinities in this part of the study area. The removal of rice from the cropping pattern in the southern part of the Eastern Nile Delta hardly causes production losses. This is valid for all rice water allocation duties considered, and supports the official rule of the Ministry of Public Works and Water Resources that in this area (rice zone 5) the growing of rice is not allowed.

Generally, a water saving strategy can be classified as attractive if the water savings are larger than the losses in income due to decreases in crop production. This is only true, of course, if the saved water can be used in other areas (land reclamation) or during other periods (storing for later use) successfully. In other words, the benefits should be larger than the costs. Applying this criterion to the total production of maize and rice together leads to the conclusion that the rice area should not be reduced below the 309,000 feddan. In rice zones 1 and 2 (north) the exchange of rice by maize is therefore not recommended.

The effects on the average farmers' income of water saving measures are more advantageous when water savings are realized through reducing the rice allocation duty rather than replacing rice by maize. However, in case of serious water shortages endangering the crop production of the coming period, none of the strategies studied has a negative effect on the farmers' income during the first year of introducing these strategies when the future effects are taken into account in the financial analysis. On the long term, after 50 years, the soil salinity build-up causes lower crop yields, and 6 of the 23 strategies studied have an adverse effect on the farmers' income. In order to secure the farmers' income, maintaining the rice area at 510,000 feddan, and reducing the allocation duty of rice, appears to be the best method to save water in case of a serious water shortage, both on the short (1 year) and on the long term (50 years).

The negative effects on the national income of water saving measures are larger when these water savings are realized through replacing rice by maize rather than reducing the allocation duty of rice. Reducing the rice area, while maintaining the rice allocation duty at the present figure of 8,800 $m^3 \cdot feddan^{-1}$, has a negative effect on the national income, even when the positive effects of the saved water for the next years are taken into account. This renders 7 of the 23 strategies studied economically unattractive on the short term (1 year). On the long term (50 years) an additional 2 (total 9 of the 23) strategies are economically unattractive. Reducing the allocation duty of rice, on the other hand, appears to be the better method to save on Nile water in case of a water shortage for safeguarding the national income both on the short (1 year) and long term (50 years).

Both the financial and economical analyses presented here point out that water savings by reducing the rice allocation duty is better for the farmers' income and for the national income on the short as well as on the long term, using the price levels of 1979/1980. The difference between both analyses indicates also the sensitivity of the strategy appraisal for the prices used. It is therefore recommended that the analysis is repeated with more up-to-date figures.

The financial and economical analyses of the SIWARE model simulation results for the long term effects (50 years) reveal that the superiority of the water saving measure of reducing the allocation duty over reducing the rice area is more pronounced after 50 years, compared to the first year of introducing such measures.

The results presented are valid only for the condition that saving of water is absolutely necessary in order to assure minimal reductions in the agricultural activities for the next years. If the water availability is sufficient, saving of water serves no purpose.

The general conclusion concerning the strategy appraisal is that reducing the rice allocation duty is preferred above reducing the rice area as a water saving measure. Lowering the rice allocation duty to the lowest value studied (2,700 $m^3 \cdot feddan^{-1}$), however, results both on the short and on the long term in an unacceptably unequal distribution of crop yield reductions. Farmers at the tail-ends of the irrigation system receive less than their equal share of the irrigation water in this case, and are suffering more than proportional with respect to their crop production and thus income. Reduction of the rice allocation duty below 4,600 $m^3 \cdot feddan^{-1}$ should therefore not be recommended as a good water management measure to save on water.

During 1988 the Ministry of Public Works and Water Resources has saved on the use of Nile water in the Eastern Nile Delta by reducing the rice area till 375,000 feddan, thereby saving approximately 925 million m^3 of Nile water. This strategy has resulted in a reduction of the rice production of about 35% and an increase in maize production of about 25%. The same net savings on irrigation water could also have been obtained by maintaining the original rice area of 510,000 feddan and by reducing the allocation duty to 7,000 $m^3 \cdot feddan^{-1}$. In this case the rice production would not have suffered from any loss, whereas the maize production would have been decreased by a mere 5%.

The water management strategy followed by the Ministry of Public Works and Water Resources in 1988 has resulted in a decrease in farmers' income of about 5% and a decrease in the national income of about 9%. Both figures could have been reduced to roughly 1%, if the rice allocation duty would have been reduced to about 7,000 $m^3 \cdot feddan^{-1}$. For either case comparable savings on Nile water for the Eastern Nile Delta would have been realized. It is therefore recommended that in the future, in cases of water shortages, the reduction of the allocation duty for rice will be considered as a good alternative instead of replacing the rice crop by maize.

THE EXTENSION OF THE AGRICULTURAL AREA STRATEGIES

Eight consecutive extension strategies have been simulated with the SIWARE model package. Each extension comprised a gross area of 44,000 feddan per annum located in the desert eastwards of the Eastern Nile Delta. The maximum reclaimed area therefore amounted to 350,000 feddan, which is about 19% of the existing cultivated area of roughly 1.8 million feddan used in the model simulations for 1988.

An implicit condition for these strategies was that no extra irrigation water could be diverted to the reclaimed areas, so that the water requirements in these areas should be satisfied on the account of the allocation to the old lands in the Eastern Nile Delta.

As a consequence of the above mentioned condition, the annual Nile water allocation to the existing cultivated areas decreases by approximately 10% for the maximum extension of 350,000 feddan. This percentage includes the fall of the official reuse in the old lands of 28%, causing a relatively higher share of the Nile water supply to be diverted to this area. The non-linear reaction of the official reuse on reductions in the supply is noticeable in the allocation to the main canals intakes from the fourth extension onwards (176,000 feddan). Evidently, the annual allocation to Ismaileya canal, supplying the reclaimed areas, will go up by 10% for the maximum extension of 350,000 feddan.

The annual farmers' uptake from the irrigation canals increases with 4% for the extension of the area with 350,000 feddan. The net agricultural area, however, increased with more than 17%, clearly showing the adverse effects for the individual farmers in the old lands.

The irrigation system losses fall by 18% for the strategy with an extension of 350,000 feddan as a result of a more efficiently operated irrigation system.

Lowered rates of crop drainage together with lower spillway losses from the irrigation system cause lower discharges within the drainage canal system. This directly affects the reuse quantities. The official reuse of drainage water is pressed considerably, and goes down with 28% for the maximum extension with 350,000 feddan. The unofficial reuse on the other hand decreases with only 3% under similar conditions, underlining its importance to keep the crop water supply on an acceptable level. As a consequence of the lower irrigation water losses and crop drainage, the simulated total discharge at the drainage canal outfalls drops substantially with 17% for the maximum extension.

All crops cultivated in the old lands also occur in the reclaimed desert areas, except rice. The total evapotranspiration of almost all the individual crops show an increase for each extension taken into production. The best performance, expressed in terms of a relative increase in seasonal evapotranspiration related to the relative areal expansion, is obtained with the winter crops.

Notably long berseem overtakes its 19% areal expansion by an increase of 21% in evapotranspiration for the maximum extension with 350,000 feddan, and short berseem reacts in a similar way with 9 and 10% respectively. Also wheat performs quite well considering its 15% raise in evapotranspiration compared to a 16% higher cultivated area. Most probably the higher evaporative demand in the desert areas causes higher transpiration rates, apparently hardly being limited by water or salinity stress for these crops.

Summer crops generally perform less well. In all cases their relative increase in evapotranspiration falls short of their relative areal expansion. Among them, maize shows the best performance with a 21% higher total evapotranspiration compared to a 26% higher cropped area for the maximum extension with 350,000 feddan. The production of rice, with its unchanged area, goes down as a result of a 5% drop in the evapotranspiration.

In most cases irrigation water shortages occurring during summertime can be hold accountable for the low response in evapotranspiration of the summer crops. Holding on a fixed allotment of irrigation water for the Eastern Nile Delta, the potential of supplementing this quantity with drainage water should be investigated (higher official reuse).

Serious problems are faced with the vegetables in the reclaimed desert areas. High initial soil salinities of around 5.7 $mmho \cdot cm^{-1}$ impede plant growth, and a major part of the accumulated salts should be flushed first from the top soil.

Despite a substantial fall of the average soil salinity till around 3 $mmho \cdot cm^{-1}$ in most reclaimed areas, the evapotranspiration of summer vegetables in the total area does not exceed a 3% increase for the maximum extension of 350,000 feddan. In fact, this situation is even more critical since the cultivated area with summer vegetables has been enlarged with not less than 32%. Clearly, the reclaimed areas are unable to offset production losses for the vegetables in the old lands caused by water shortages and a salinization of the top soil. Notwithstanding an intensive leaching of the soil in the reclaimed areas, salinity problems will continue to afflict the production of these salt sensitive crops.

At first sight it seems recommendable to exclude the vegetables from the cropping pattern in the reclaimed desert areas. However, the application of more sophisticated methods as for instance sprinkler or drip irrigation may lift the vegetable production considerably. Such equipment offers a much higher leaching efficiency, and may even be a prerequisite for growing vegetables. In fact, sprinkler irrigation is already used in these areas on a large scale.

Generally, it can be concluded that crop production in the old lands will decline as a direct result of the fixed Nile water allotment for the total area, leading to water and/or salinity stress conditions for the crops. Production in the reclaimed areas should compensate for these losses and should yield a reasonable extra quantity in order to be economically attractive.

It appears from the model simulations that an expansion of the arable land may indeed raise the country's crop production. The simulations show an 11% higher aggregated (all crops) evapotranspiration after the last extension has been taken into production, i.e. after 8 years. Confronting the 11% with the 17% expansion of the total cropped area, the conclusion can be drawn that the reclaimed areas perform quite well. The more so because the aggregated evapotranspiration in the old lands goes down with more than 5%, which can be largely compensated by an increase in evapotranspiration in the reclaimed desert areas.

The simulations also reveal that the aggregated evapotranspiration can be maintained during a period of 50 years, despite a small increase in average soil salinity, mainly concentrated in the old lands. It should be denoted, however, that the conclusions regarding the evapotranspiration do not account for the difference in productivity between the deltaic clay soils and the desert soils. Commonly, the soil productivity is split up into soil moisture retention and soil fertility. The latter characteristic has been assumed at a similar level as for the old lands.

THE LOCAL WATER MANAGEMENT STRATEGIES

Two (local) water management strategies have been simulated with the SIWARE package. The first concerned a complete elimination of the small diesel pumps used by farmers, which implies that the irrigation water will again be lifted from the canals with the traditional sakkia (water-wheel). Moreover, the elimination of diesel pumps will also re-introduce continuous irrigation (24 hours) uptake by farmers during irrigation-on periods. When farmers do no longer have motorized pumps at their disposal, they also lack the means to withdraw water from the drainage canals in substantial amounts (unofficial reuse). The second strategy only considered a prohibition to use the pumps for lifting water from the irrigation canals.

The idea behind these strategies is to confront and evaluate the current Nile water supply and cropping pattern with the past situation, where the lifting capacity of the irrigation tools was more in accordance with the supply and the distribution under the control of the Ministry of Public Works and Water Resources.

The two simulations show a better match between the farmers' uptake from the irrigation canals and both the farmers' water requirements and the allocation water duty used by the Ministry of Public Works and Water Resources. Consequently, the farmers' uptake is higher during the major part of the year, and increases annually with 0.3% for the strategy without diesel pumps and unofficial reuse, and 1.3% for the strategy without diesel pumps only, when compared to the 1988 reference situation. This confirms the expectation that replacing the diesel pumps by sakkias will lead to more balanced distribution pattern.

Considering the farmers' uptake during the summer months June, July and August, however, both strategies show a drop, most notably for the strategy without diesel pumps and unofficial reuse. For the latter strategy this can be explained satisfactorily by the lower rice crop water requirements as a result of the improved salinity of the irrigation water (absence of the unofficial reuse component). For the strategy without diesel pumps only, the reason can be sought in the water allocation and distribution procedure, which is based on the Ministry of Public Works and Water Resources (MPWWR) allocation crop water duties. Together with the 1988 cropping pattern, where rice is cultivated in a northerly belt and where maize is grown in the southern and central part of the Eastern Nile Delta, the differences between the MPWWR duties and the actual calculated farmers' crop water requirements prevent a more optimum irrigation water distribution. In the maize areas, located upstream of the rice areas, the MPWWR duty is lower than the farmers' requirements, resulting in a lower allocation on main canal level than what is considered necessary for the crops locally in the model calculations. Thus, despite their favourable location, but lacking pumps necessary for extra lifting head, these farmers are not in the position to meet their demand completely. Farmers downstream cultivating rice, however, are provided with excessive amounts of irrigation water due to a higher MPWWR duty compared to their requirements. Simulations using the cropping pattern of 1986 most probably would have produced better results, although it must be commented that during the summer season the whole agricultural system is operated very efficiently and further improvements will be difficult to realize. Still, additional investigations into the aforementioned differences, and some modifications in the MPWWR rice duty as discussed previously, may lead to a higher farmers' uptake during the summer season for the strategy without diesel pumps only.

Total yearly irrigation system losses to the drainage canals and the groundwater aquifer fall by 2.4% for the strategy without diesel pumps and unofficial reuse, and by 13.3% for the strategy without diesel pumps only. These reductions are the result of a higher farmers' uptake, a higher potable and industrial water withdrawal, and a lower official reuse contribution to the total irrigation water supply in case of the latter strategy. Remarkably, the absence of the diesel pumps also results in a shift in the irrigation water losses from the spillways in the agricultural calculation units internally to the spillways at the tail-ends of the irrigation command canals. This phenomenon is typically caused by the smoother irrigation water abstraction pattern during the day of the sakkias in the calculation units.

The official and unofficial reuse from the drainage canals are also affected by differences in the quantity and location of the irrigation water losses. The total yearly reuse goes down with 61% for the strategy without diesel pumps and unofficial reuse, and with 11% for the strategy without diesel pumps only.

The crop water supply is the composite result of farmers' uptake, groundwater abstraction, and unofficial reuse. The total yearly crop water supply falls by 12% for the strategy without diesel pumps and unofficial reuse, implying that the absence of unofficial reuse cannot be compensated by a higher farmers' uptake. For the strategy without diesel pumps the lower amount of official reuse added to the Nile water supply is compensated by a higher farmers' uptake from the irrigation canals.

Both strategies benefit from the different mixing ratio of the less saline irrigation water and the more saline unofficial reuse. The average salinity of the crop water supply goes down from 445 $g{\cdot}m^3$ for the reference simulation to 365 for the strategy without diesel pumps and unofficial reuse, and to 440 $g{\cdot}m^3$ for the strategy without diesel pumps only. Most crops will not be impeded in their growth by these salinities as verified before, though small problems may be encountered with maize and vegetables.

Effects of changes in the crop water supply and the accompanying salinity are reflected in the evapotranspiration. Seasonal values show a decrease for the strategy without diesel pumps and unofficial reuse. All crops are affected with reductions varying between 1% (rice) and 7% (cotton). The same strategy comes up with a drop of 4% for the aggregated cropping pattern, whereas the strategy without diesel pumps remains at the reference value of 100%. The latter strategy also shows somewhat higher evapotranspiration values for half the winter crops, and somewhat lower values for half the summer crops. It appears that this crop reaction follows the seasonal crop water supply rather accurately, which on its turn seems to correspond with the irrigation priority ranking of the crops as assumed in the model simulations.

Changes in the water management express themselves on the long term in a salinization or desalinization of the soil. Simulations for the Eastern Nile Delta indicate a drop in the average soil salinity from 3.51 mmho·cm^{-1} to 3.28 mmho·cm^{-1} (-12%) for the strategy without diesel pumps and unofficial reuse after a period of 50 years. This is caused by the much lower salinity of the crop water supply. For the long term strategy without diesel pumps only, the result is close to the reference soil salinity, i.e. 3.50 mmho·cm^{-1} (-2%).

The effects after 50 years in terms of evapotranspiration show that the strategy without diesel pumps and unofficial reuse can still not compete with the reference simulation, despite improved soil salinity conditions. Although half the crops, with the emphasis on the summer crops and rice in particular, are able to increase their evapotranspiration when compared to the short term values, they still fall short of the reference values. Also the evapotranspiration of the aggregated cropping pattern cannot approach the reference value with a drop of 3%.

Evapotranspiration rates for the long term strategy without diesel pumps cannot recover from the lower water supply to the summer crops (notably maize and cotton). The more so because the irrigation water salinity, and thus the soil salinity, hardly shows improvements for this strategy. Also the winter crops remain unaffected on the long term, and therefore the aggregated evapotranspiration value stays equal to the reference value.

Analyzing the spatial variability of the aggregated relative evapotranspiration over the study area reveals a somewhat more even distribution for the strategy without diesel pumps only, when compared to the reference run. Especially improvements of the lowest, locally occurring, evapotranspiration values will be socially more acceptable for farmers. Also the strategy without diesel pumps and unofficial reuse shows a significant lower standard deviation, which is however fully counteracted by a much lower average aggregated relative evapotranspiration value.

Finally, it can be concluded that the strategy without unofficial reuse and diesel pumps does not offer an alternative for the present situation. When crop yields should be maintained at the current level or when authorities aim for an increase, the simulations made clear that this lies outside physical reality for both the short and the long term. Therefore a combined elimination of diesel pumps and unofficial reuse cannot be considered as a realistic alternative and the unofficial reuse should remain permitted.

The strategy in which the diesel pumps have been eliminated for lifting water from the irrigation canals, but where the unofficial reuse remains permitted, presents itself as an alternative which could be considered. However, peak demands occurring in summer are difficult to meet with the available amounts of irrigation water and the reduced uptake capacity of the farmers.

Improvements in the water distribution for the strategy without diesel pumps in the summer cannot be established on the inter-calculation unit scale, given the specific cropping pattern of 1988 and the Ministry of Public Works and Water Resources allocation water duties. An optimum distribution, in relation to significant lower spillway losses, can only be obtained after further examination of these two factors. Nevertheless, improvements are certainly to be anticipated on the intra-calculation unit scale. A further down-grading of the current scale, however, will meet serious problems with input data and hardware facilities. Model application on a single calculation unit is a more appropriate way to quantify these effects.

Since all performed strategies were aimed at improving the irrigation water distribution by eliminating the diesel pumps for lifting water from the irrigation canals, it should be denoted that such a policy will have negative effects on the amount of reuse.

By itself, it is highly preferable to pursue improvements in the irrigation system, removing the need to draw on large amounts of drainage water with rather high salinities. However, simulation results show that such improvements are accompanied by a shift in the release of excess irrigation water from the agricultural calculation units internally to the tail-ends of the irrigation command canals. As a consequence not only less drainage water will be generated, but also less drainage water will be available for reuse because of the downstream location of these tail-ends.

The relation between the irrigation water distribution and the reuse of drainage water is a critical one when on farm level the reduction in unofficial reuse is not counteracted by at least a similar increase in farmers' uptake from the irrigation canals. This clearly appears to be the case for the strategy without diesel pumps and unofficial reuse.

Taking away the flexibility in the agricultural system by eliminating the unofficial reuse should not only be discouraged, but also single-sided improvements in the irrigation system by banning the diesel pumps as irrigation tools should be accompanied by further measures to minimize spillway losses. Therefore investigations into the disparities between the water duties used by the Ministry of Public Works and Water Resources, when allocating and distributing the irrigation water, and the calculated farmers' crop water requirements should provide the knowledge to arrive at substantial lower spillway losses to offset the reduced amounts of reuse. Also a more uniform cropping pattern (maize versus rice) is likely to cut down spillway losses.

The implementation of strategies prohibiting the use of diesel pumps will meet formidable obstacles. The use of diesel pumps is widely spread nowadays. Since the unofficial reuse remains necessary to maintain or even increase present evapotranspiration rates, they are also needed to provide enough lifting head for withdrawing water from the deeper excavated drainage canals.

The unlimited access of the diesel pumps to the irrigation canals on the other hand should be prevented. Therefore farmers should be persuaded to lift their irrigation water from the original sakkia sump, which is connected with the canal by means of a fixed diameter pipe. In this way both the lifting head and the uptake capacity can be limited, and shortages occurring in the irrigation system will be spread more uniformly over the whole area. In case the water requirements can still not be met, farmers should have the possibility to turn to the drainage canals. However, implementation of such a practice will require enforcement by a rigid control system.

1. INTRODUCTION

"IF I WERE TO RULE A COUNTRY LIKE EGYPT, NOT EVEN ONE DROP OF WATER WOULD BE ALLOWED TO FLOW TO THE MEDITERRANEAN SEA",

Napoleon Bonaparte has been quoted to say during the French occupation of Egypt (1798-1801). Obviously this remark made by Bonaparte illustrates that he was not aware of the concept of the salt balance, but also illustrates the desperate need of the country to use the available water resources to the maximum possible degree.

1.1. General introduction

The total acreage of Egypt amounts to roughly one million km², but the majority of the Egyptian inhabitants is concentrated on 4-5% of this area only. In the Nile Valley, a narrow strip bordering the river Nile from Aswan to Cairo, and in the Nile Delta fertile agricultural land does exist and irrigation water is available.

The population of Egypt has been growing at a high rate from 22 million in the year 1947 to more than double, roughly 55 million in the year 1987, reducing the per capita share of agricultural land from 1,150 m² in 1947 to the extremely low level of 450 m² in 1987. Obviously, this per capita area is not sufficient for the countries required production of food and fibre as well as for the extension of the required infrastructure for housing and transportation.

In view of the above situation the countries bill of importation of foodstuff is rapidly growing. For slowing down this growth, vertical as well as horizontal expansion of agricultural production is a must. Crop yields in Egypt are already high according to international standards and a further increase will be a relatively slow process. Consequently horizontal expansion of agriculture by reclaiming new lands will be the first priority measure to overcome the presently prevailing food balance crisis. Additional to land reclamation, the introduction of early maturing varieties of the crops grown in Egypt may also increase the total agricultural production due to a higher cropping intensity.

However, both reclamation of 'new' desert land as well as an increase of cropping intensity by the introduction of short age varieties requires additional quantities of irrigation water.

The Egyptian water budget is confined to the countries share of Nile water which is fixed according to international agreements with the Nile River basin countries at 55,500 million m³ per year. Added to this are minor quantities gained by exploiting groundwater from the reservoirs of the upper part of the Nile Valley, the Western Desert, the Eastern Desert and in the Sinai Peninsula. Small quantities of precipitation do fall on the north-western and north-eastern coasts which modestly add to the water budget. All these quantities are hardly adequate to meet the existing demand for agriculture, domestic use, electricity generation, industry and inland navigation.

A number of measures are being taken or studied at present to improve the efficiency of water use and to exploit new water resources. These include the following:

- increasing the irrigation efficiency both on farm level as well as on larger scale;
- reducing the acreage of crops that consume much water such as rice and sugar cane;
- reducing the amount of fresh water lost to the sea by providing the appropriate storage during periods of low water demand;
- improving the drainage characteristics of the Nile catchment and its tributaries from its source in the south of Africa.

The above measures, although effective on the long term, will take several years for implementation and many years may pass before obtaining significant results.

Reuse of drainage water appears to be one of the most promising, fast, and economic means of increasing the Egyptian water budget and improving the efficiency of water use. At present an amount of about 14,000 million m^3 (1984) to 12,000 million m^3 (1988) of drainage water flows annually unused to the Mediterranean Sea and the coastal lakes. The salinity ranges between 1,000 and 7,000 $g.m^{-3}$ but about 75% (1984) to 70% (1988) of this quantity has a salinity of less than 3,000 $g.m^{-3}$.

Reuse of drainage water is not a new practice in Egypt. After the construction of the Aswan High Dam the Egyptian designer was clever enough to return all drainage flows in the upper and middle part of the Nile Valley to the river's main course. Due to this practice the salinity of the Nile water changes from some 200 $g.m^{-3}$ upstream of the High Dam to approximately 280 $g.m^{-3}$ upstream of the Delta Barrages, the inlet gate of the cultivated areas in the Nile Delta. Moreover, an amount of 3,000 million m^3 (1984) to 2,400 million m^3 (1988) of drainage water is reused annually in the southern part of the Nile Delta by blending, in most cases, with fresh Nile water in the larger irrigation canals.

Reuse of drainage water, however, has its limitations and drawbacks. Technical limitations such as the quantity of drainage water, salinity of drainage water, seasonal variation, the location of availability and surface elevation of this location restricts to some extent where, when and how much of this water can be used.

1.2. National water management planning

The target of the land reclamation plans of the Ministry of Public Works and Water Resources and the Ministry of Land Reclamation has been set at 2.8 million acres of new land by the year 2000. In the plans the water supply for 0.4 million acres is foreseen by exploiting groundwater and for 1.2 million acres by reducing the conveyance losses of the Nile catchment in the Sudd, southern Sudan. The remaining 1.2 million acres depend on rationalization of water use in the 8 million acres presently irrigated. This should be achieved by improving the irrigation methods, by changing the cropping patterns as well as by the reuse of drainage water.

Depending on the location of the areas to be reclaimed, and the locations where drainage water is available in suitable quantities with suitable salinities, drainage water may be directly used with or without mixing with fresh irrigation water in the areas which will be reclaimed. Such projects where drainage water from the Nile Delta will be transported to the reclamation area are at present under implementation: the Salam Canal Project for the reclamation of 0.8 million acres in the Eastern Nile Delta and in the Sinai, and the Umum Reuse Project for the reclamation of 0.4 million acres in the Western Nile Delta. In both cases blending of the drainage water with fresh Nile water is absolutely required and also planned by the Ministry of Public Works and Water Resources.

If drainage water cannot be transported in an economic way to the intended land reclamation areas, the irrigation water for these new areas can be made available by diverting fresh irrigation water to such new areas, thereby decreasing the supply to the old lands and increasing the reuse of drainage water in the existing agricultural area. Although reuse of drainage water can be considered as a fast and economic solution for the future water shortage due to reclamation projects it still needs investments in infrastructure such as pump stations and transport canals. Generally the time span between planning and realization of these projects takes several years.

The prolonged drought period of the past eight years in Africa has affected the discharge of the river Nile upstream of the Aswan High Dam. During this period the live storage of the dam has been sufficient to supplement the Nile discharge to the normal water duty required for agriculture, industry and domestic use. However, if the drought period will persist for a number of years, the live storage may be exhausted and an acute water crisis may develop. Under these conditions a water shortage of 10%, or even 20%, could be acute and only water management measures which can be implemented on a very short notice, requiring a low level of investments can be used to minimize the damage of such a shortage in terms of agricultural production.

In the light of the above situation, the potential of a variety of such measures which can be swiftly implemented in case of an acute water shortage, will be outlined in this report. Also the long term effects of diverting fresh Nile water to land reclamation projects on the account of the water budget of the old lands, will be studied in this report.

1.3. Reuse of Drainage Water Project

For the planning and implementation of reuse of drainage water projects by the Ministry of Public Works and Water Resources a good knowledge of the spatial distribution of available drain water, its salinity and the seasonal variation is important. Knowledge of the present situation, however, is not sufficient for planning purposes. Information on the expected changes in the drainage water as a result of changing water management and changing agronomic conditions are equally important.

In order to provide the Ministry of Public Works and Water Resources with the required information the 'Reuse of Drainage Water Project' has been operational since 1983. The objectives of this project are threefold:

- provide information on the drainage water in the Nile Delta in Egypt with respect to quantity, quality and location for the present situation;
- provide the above mentioned information and expected future changes as a result of changing water management;
- to train the Egyptian counterpart staff in the techniques to obtain the above mentioned information.

The procedures followed to reach the mentioned objectives have been as follows:

- The implementation of a comprehensive measurement network with about 100 observation points in the drainage system of the Nile Delta. At these observation points the discharge and the salinity are continuously monitored and every three weeks the chemical composition of the drainage water is determined by sampling. The measurement results are published on a yearly basis in the so-called hydrological and chemical yearbooks.
- The formulation, programming and testing of a model package for the simulation of the water management in the Nile Delta.
- The simulation of a number of alternative water management strategies for the Eastern Nile Delta.
- For all activities mentioned a close cooperation between the Dutch and the Egyptian colleagues has been established and in performing the job both parties have gained from the experience of the other party. For special subjects training courses have been organized, some in the Netherlands given by the Dutch colleagues for their Egyptian counterparts and some have been given in Egypt by the Egyptian colleagues for other Drainage Research Institute staff members.

1.4. Outlook to the future

So far the Reuse of Drainage Water Project has concentrated its activities with respect to the water management simulation on the Eastern Nile Delta and on short term effects of a few 'swift' water management measures. For the extension of the simulations to the other Delta Areas (Middle Delta and Western Delta), these areas have to be schematized into calculation units, the appropriate input data have to be collected and entered into the computer system and calibrated against the observation results of the monitoring network.

Depending on the amount of manpower available, both from Egyptian and from Netherlands side, this will take some 12 to 18 months.

For the evaluation of long term effects of water management measures a continuous dialogue between the planning department of the Ministry of Public Works and Water Resources and the modelling team should be realized in the future. Based on existing or future water management plans the effects can be estimated with the simulation model. Based on the acceptability of the simulation results with respect to total agricultural production and the distribution over the Nile Delta, water management plans can be adapted and alternatives formulated.

The importance of the continuation of the monitoring network cannot be stressed enough. The simulation model provides answers on the effects of water management measures before these measures are actually implemented. It should be realized, however, that these answers are just an intelligent estimate of the effects, and that the real effects may be observed in the measurement network, be it, after the measures have been implemented. Continuation of the observations in the measurement network will thus provide clues for the validity of the model, improvement of the schematization used and possibly the need to collect better input data. Application of the simulation model to other areas, such as the Fayum depression will not give major technical problems provided that the required input data are available.

2. SIMULATION MODEL

The fundamental limitation in the planning of future reuse of drainage water for irrigation lies in the uncertainty of future changes in quantity and salinity of drainage water as a result of changes in water management in the corresponding catchment. Also the uncertainty of the consequences in terms of agricultural production in the area receiving this (mixed) drainage water limits this planning. The prediction of changes for complex situations such as the water management in the Nile Delta in Egypt seems to be very difficult under these circumstances. In this chapter the formulation of all relevant physical and other functional relationships combined in a simulation model for the estimation of effects of changes in the irrigation water management, cropping pattern and crop characteristics will be discussed.

2.1. Introduction

Quantity, salinity as well as the seasonal distribution of drainage water are influenced by water management and agronomic factors in the catchment such as: water supply; irrigation water salinity; cropping pattern; crop characteristics; drainage conditions; drainage water availability for unofficial reuse; the control of irrigation water losses; etc. A number of these factors will be discussed below.

Water supply

Changes in the water supply, be it in the total quantity, or in the seasonal distribution of the supply in a certain area will affect the amount of drainage water. Generally, the relation between supply and drainage is non-linear which means that an increase of the supply during a certain period of say 10% will not automatically result in an increase of the drainage water with 10%, but possibly with a lower percentage. The increase of the drainage water as a result of the increase of supply depends on the ratio of the actual demand for irrigation water at field level and the actual supply. If the area already receives sufficient water the complete increase of supply will disappear in the drainage system. A complicating factor is that, depending on the seasonal variation in the ratio between the demand for water and the supply, also the degree of non-linearity changes from period to period.

Irrigation water salinity

Changes in the irrigation water salinity, be it in the total level or in the seasonal variation will have an immediate effect on the drainage water salinity, caused by the unavoidable operational and spillway losses to the drains. On the long term salinization of the soil profile will take place and the leaching water will gradually increase the drainage water salinity. Also the drainage rates will be influenced by the irrigation water salinity. This concerns both the effects of an increased water requirement for leaching on one hand as well as the effects of lower actual crop evapotranspiration rates caused by the increased osmotic pressure in the root zone.

Cropping pattern

Each of the crops grown in the Nile Delta in Egypt can be characterized, from a water management point of view, by planting date, harvesting date, consumptive water use (including distribution in time), rooting depth, number of irrigations and intervals between irrigations, leaching requirements, salt resistance, etc. As a consequence each crop has its own demand for irrigation water and its own drain discharge distribution, given the hydrological conditions under which the crop is grown. It is well known that a crop like cotton receives only light irrigations, especially after flowering and that only minimal leaching of the soil profile takes place. A crop like rice is grown under ponding conditions and has a high demand for water, a high consumptive use and a high drain discharge. Changes in the cropping pattern, be it accompanied by the corresponding change in water supply due to the changed total demand for water or not, will result definitely in changes in the drainage water quantity and salinity and the seasonal distribution of both.

Changes in crop varieties

The introduction of early maturing varieties of crops, or the introduction of high yielding varieties which are more sensitive to moisture stress conditions and/or salt resistance may result in a higher required irrigation frequency and a higher leaching requirement. As a consequence the demand for water changes and, whether the supply changes according to the changed demand or not, also the drainage discharge and salinity and the seasonal distribution will change.

Drainage conditions

The installation of a subsurface drainage system in agricultural lands has a number of effects. First the water table is lowered and as a consequence the rooting depth of agricultural crops may increase. Second, seepage from the aquifer, if present, will increase. Third, due to the improved internal drainage conditions, desalinization may be effectuated, increasing the potential evapotranspiration due to reduced osmotic effects. If there is an ample water supply to the area, this may result in an increase of actual evapotranspiration, a decrease of direct irrigation water losses, an increase of leaching and, in most cases, a decrease in the total drainage of the catchment. On short term the drainage water salinity will increase significantly, due to the desalinization process; on the long term the drainage water salinity most probably will still be higher due to both increased seepage and increased actual evapotranspiration.

Availability of drainage water for unofficial reuse

Egyptian farmers in the Nile Delta are masters in the organization of the water required for irrigating their crops. In the field ingenious constructions can be found connecting the tail-ends of meskaas with tubes crossing the drainage canals so that tail-end losses may be used in the adjacent distributary areas. Generally, shortage of irrigation water, which occurs during one or more short periods during the year, will be concentrated at the tail-ends of the distributary canals and at the tail-ends of the branching meskaas. Near these tail-ends, drainage canals are located, and in case of (temporary) water shortage farmers use movable diesel pumps to lift water from the drain to use it for irrigation of their crops. If, in upstream drainage catchments, the drainage water will be used for irrigation purposes, less drainage water will be available in the downstream catchment for unofficial reuse by farmers. The effect will be that during periods of water shortage the catchment drainage will diminish and that the seasonal distribution of the drainage water will change.

Control of irrigation water losses

The irrigation water supply to a canal command area is continuous and no significant changes in flow magnitude during day and night can be detected. The majority of the farmers irrigate their field during the day. As a consequence the waterlevel in the irrigation distribution canal system rises during night hours. Depending on the storage capacity in the system and on the average supply during late night and early morning, tail-end spillways may start spilling fresh irrigation water directly into the drains. If these direct irrigation losses are reduced by increasing the overnight storage capacity of the irrigation system or by an improved operation of the irrigation system, the drainage water discharges and salinities will be affected. If the supply to the agricultural areas is reduced in accordance with the decrease in direct irrigation losses, the discharge will decrease with the same amount and the salinity will increase. The reaction of the system to changes in the irrigation water control may show variation over the year. Consequently, it may be expected that also the seasonal variation in the drainage water will change.

It is already difficult to give a qualitative description of the effects of the individual water management measures given above. A number of measures can be taken simultaneously, spatially distributed in many different combinations. Some of these measures will have long term effects, appearing after several years have elapsed. Taking into account the cascade effect through which consequences of measures taken in an upstream area will trickle down gradually until it reaches the most downstream area, it must be realized how complex the system reacts to a number of water management measures which are taken simultaneously.

The proper procedure for predicting changes in such a complex situation is to formulate all relevant physical and functional relationships and combine them in a simulation model for the estimation of effects of changes in the irrigation water management, cropping pattern and crop characteristics.

2.2. The SIWARE model

For the prediction of future changes as a result of changed conditions in the water management, agronomic changes or changes in the hydraulic conditions the SIWARE model (SImulation of Water management in the Arabic Republic of Egypt) has been developed. In this simulation model for the Nile Delta all relevant physical and functional relationships have been combined, be it in a simplified and schematized way.

To facilitate the calculation process, the Eastern Nile Delta has been schematized into a number of subareas. These subareas, also referred to as calculation units, should be uniform with respect to soil, hydrological, climatic, and water supply conditions. Within the calculation units each crop is represented by one typical (average) field plot. Through a special algorithm the drainage quantity and salinity output of all typical field plot with different crops is combined and transformed to the aggregated total calculation unit drainage output.

Following the pathway of the irrigation water from the Nile Delta Barrages, where it enters the Nile Delta to the points, where it leaves the area, a number of different subsystems can be distinguished (fig 1):

- the water allocation to the intakes of the major irrigation command canals, which is treated in the model 'DESIGN';
- the estimation of the water requirement at farm level, taking into account the hydrological and climatic circumstances, as well as the moisture and salinity status of the soil, is treated in the model 'WDUTY';
- the water distribution within the irrigation command areas resulting in a supply to the agricultural fields and operational losses to the drainage system is treated in the model 'WATDIS';
- the water losses from the Nile Delta to the atmosphere through evaporation and transpiration, to the aquifer through leakage and seepage, and to the Mediterranean Sea and Coastal Lakes through the drainage system are treated in the model 'REUSE'.

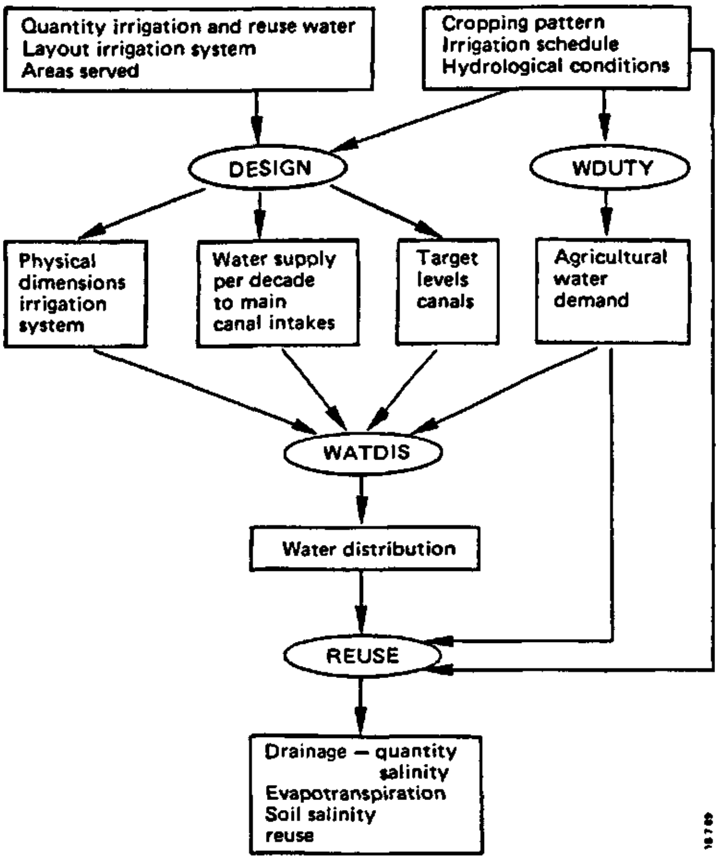

Fig 1. Schematization of the SIWARE simulation model, its sub-models, and required in- and output.

In the following paragraphs the different subsystems will be discussed. Attention will be focussed on the two types of processes which are simulated:

- physical processes, such as: the water flow through the irrigation canals and control structures; the flow of water and salt to the (sub)surface drains; the evapotranspiration and related increase in soil salinity and osmotic pressure; etc;
- human behavior processes, such as: decisions related to the allocation of irrigation water among the irrigation command areas and the determination of target waterlevels at control structures in the irrigation system (decision maker); the simulation of the height of the gate openings of control structures (gate operator); the abstraction pattern during the day for field irrigation of agricultural crops and decisions related to the distribution of the limited available irrigation water among the fields crops (farmer); etc.

2.3. Water allocation

The water allocation in the Nile Delta by the Ministry of Public Works and Water Resources is based on the administrative subdivision of the Nile Delta. The smallest administrative unit distinguished by the Ministry is the Irrigation District. The size of such a district varies from roughly 13,000 feddan to 75,000 feddan (one feddan equals about 0.42 ha). The Irrigation Districts are clustered in Irrigation Directorates with sizes ranging from 150,000 feddan to more than 600,000 feddan. A complicating factor is that the administrative boundaries of both Irrigation Districts and Irrigation Directorates do not necessarily coincide with the irrigation canal command boundaries.

Based on years of experience and supported by research of the Water Research Center, the Ministry of Public Works and Water Resources is well aware of the water requirements of the agricultural crops grown in the Nile Delta and the seasonal distribution of these requirements. In cooperation with the Ministry of Agriculture the cropping pattern per irrigation district is decided and the total water duty for these districts is determined on a monthly basis. These monthly water duties per district are corrected (reduced) for the local groundwater use. By summing up these requirements per Irrigation Directorate and per irrigation canal command area and correction (reduction) for the intended official reuse of drainage water, the net monthly agricultural requirement per canal command area is determined. Since 1988 also the occurrence of rainfall in the northern part of the Nile Delta during the winter period is taken into account. Next, the net agricultural requirement is augmented with the industrial and domestic water requirements, and, after allowing for conveyance and operational losses, the total gross water requirement per irrigation canal command area is determined.

The hydraulics of each irrigation canal can be characterized by a stage-discharge relation. Given the water requirement for each month the target waterlevel to be maintained in the irrigation system can be determined for each point in the system where control structures with movable gates or weirs with movable crests are situated.

For the simulation of the water allocation in the Nile Delta with the model DESIGN (fig 1) the same procedure is followed. Based on the cropping pattern, which is an input, the monthly water requirement for each crop, the groundwater use per irrigation district, the intended reuse of drainage water, the domestic and industrial use, the precipitation, and an allowance for conveyance and operational losses, the target waterlevels to be maintained by the gate operators of the Ministry of Public Works and Water Resources are calculated. These target levels are an input for the water distribution simulation model.

In addition to the input data mentioned above, an enormous amount of input data concerning irrigation canal and control structure dimensions should be available for the calculation of the target levels to be maintained. In order to reduce the amount of input data the design criteria relating the characteristics of the canal cross section to the area served have been used. The same procedure is followed for the dimensions of the control structures such as weirs, head regulators and intakes.

The simulation of human behavior processes takes place at two different levels in the model DESIGN. The decision maker intends to distribute the available irrigation water in a certain way, taking into account the cropping pattern, the crop water duties and the official reuse of drainage water. Physically, the intended or desired water distribution is translated into target levels to be maintained upstream and downstream of control and inlet structures. The second human behavior process treated in the model DESIGN concerns decisions related to the water allocation during periods of unforeseen excess of shortage of irrigation water.

The intended amount of drainage water to be reused by reuse pump stations is part of the irrigation water allocation and distribution strategy of the Ministry of Public Works and Water Resources. As such, the reuse of drainage water can be considered as input data. Later on, during the model simulation with the regional drainage model REUSE (fig 1), it is checked whether the quantities defined in the water allocation strategy are available at the specified locations. If this is not the case, the water allocation policy has to be redefined, with the new estimation of drainage water, available for reuse.

2.4. Agricultural water requirement

The water distribution within the Nile Delta depends on the operation of the irrigation system by the Ministry of Public Works and Water Resources, and on the other hand on the farmers behavior with respect to the amounts of water they consider necessary for irrigating their crops. These quantities may deviate considerably from the official water requirement figures used by the Ministry of Public Works and Water Resources for the official water allocation strategy.

The farmers demand for irrigation water depends on the initial moisture conditions in the field. Farmers will try to maximize the quantity of irrigation water given to the crops in order to leach as much accumulated salts from the crop root zone as possible. This intended leaching quantity is limited, of course, by the hazard of crop damage due to oxygen shortage in the root zone under prolonged ponding.

Another important difference between the official water requirement and the farmers demand is the spatial differences in hydrological conditions. In the southern part of the Nile Delta leakage conditions prevail and soil permeability is high. Under these conditions farmers require more water for field irrigation than in the northern part of the Nile Delta where soil permeability is lower and seepage conditions are dominant. Also differences in climatic conditions (evaporative demand) can play an important role.

Since the farmers demand for irrigation water influences the water distribution, this demand is calculated with the model WDUTY, before the water distribution is simulated (fig 1). For each calculation unit in the Eastern Nile Delta and for each irrigation turn of each crop, the quantity of water the farmer will use under the condition of unlimited supply of irrigation water, is calculated. In this procedure the hydrological conditions for each calculation unit are taken into account. The initial moisture conditions prior to each irrigation are simulated using the evapotranspiration and drainage modules developed for the REUSE model.

2.5. Water distribution

As has been mentioned before, the water distribution within the Nile Delta depends on the water allocation and distribution strategy of the Ministry of Public Works and Water Resources, on the operation of the irrigation system by gate operators, but also on the farmers behavior. Farmers behavior with respect to irrigating their crops may deviate from the official water requirement as used by the Ministry of Public Works and Water Resources for the water allocation and distribution strategy. Since the farmers demand for irrigation water may influence the water distribution, this demand has to be calculated before the simulation of the water distribution.

Farmers use sakkias (water wheels) and diesel pumps to lift the water from the lowest order irrigation canals to irrigate their fields. Water supply to these lowest order irrigation canals normally takes place through submerged movable gates. Two times daily, during irrigation-on periods, the height of the gate openings are adjusted according to the target waterlevel downstream of the canal inlet. If farmers withdraw more water than their official share, the gate opening is enlarged, and when farmers withdraw less, the gate opening is decreased.

Generally, farmers tend to irrigate their crops during day-time, and only when abstraction by farmers in the upstream areas exceeds their equal share of the irrigation water, farmers downstream will be forced to irrigate at night. The distribution of the abstraction pattern over the day depends on the season. In winter time days are relatively short and farmers operate the irrigation tools (sakkias and diesel pumps) during less hours than in summer.

After calculating both the target waterlevels to be maintained in the irrigation system (DESIGN) and the farmers water demand (WDUTY), the distribution of irrigation water to the calculation units in the Nile Delta can be simulated with the water distribution model WATDIS (fig 1).

The main purpose of the water distribution model is to simulate the water movement from the main intakes at Delta Barrages through the hierarchical network of irrigation canals to the lowest order canals in the system. From this (distributary) canal, water is lifted by farmers for the irrigation of individual fields.

The following two main types of processes are simulated with the water distribution model:

- hydraulic processes, for the simulation of water flow through the main irrigation canals, via control structures to the lowest order canals and over spillways to the drainage system;
- human behavior processes, such as maintaining the target waterlevels in the irrigation system and the simulation of the height of the gate openings of control structures (gate operator) and the abstraction pattern during day and night for field irrigation of agricultural crops (farmer).

For the simulation of hydraulic processes the main irrigation canals are divided into compartments of reasonable length. Water is transported from one compartment to the other with the difference in waterlevels between compartments as the driving force. The resistance against flow is a function of the average waterlevel and the cross section dimensions and is calculated with the formula of Chezy. Water passing head regulators, weirs, inlet structures and spillways is calculated with the appropriate hydraulic equations.

The input to the irrigation system consists of: the intake discharge into the main canals at the Nile Delta Barrages; the lifting of water from the Nile branches to these canals by irrigation pump stations; and the discharge of reuse pump stations lifting drainage water. A special algorithm in the regional drainage simulation model is used to calculate the change in irrigation water salinity if drainage water is blended with fresh Nile water.

The simulation of human behavior processes takes place at three different levels. The decision maker intends to distribute the available irrigation water in a certain pre-conceived way, taking into account the cropping pattern, the crop water duties, the official reuse of drainage water and the occurrence of excess or shortage of irrigation water. In the water distribution model the intended or desired water distribution is an input in terms of target levels to be maintained upstream and/or downstream of control and inlet structures. These target levels have been calculated in the model DESIGN, assuming continuous irrigation supply to the canals, and continuous irrigation uptake by the farmers.

The gate operator regulates the flow through inlet points, over weirs and through head regulators twice a day. His task is to maintain the levels prescribed by the decision maker as good as possible. Through a special algorithm in the model the adjustment in the gate openings performed by the gate operator are simulated taking into account both the upstream as well as the downstream target waterlevel for the structures in the main irrigation system. For the intakes of the lowest level canals gate adjustments are based on the downstream target level only.

Farmers will always try to receive the quantity of irrigation water they consider necessary for field irrigation of crops. Generally, they prefer to irrigate during day time, and only when abstraction by farmers in the upstream areas exceeds their equal share of the irrigation water, farmers downstream are forced to irrigate at night. In the water distribution model farmers behavior is introduced in two ways: by the farmers demand for irrigation water; and by the daily irrigation uptake pattern.

The farmers demand for irrigation water for each time step has been calculated in the model WDUTY and is an input for the water distribution model.

The distribution of the abstraction pattern over the day depends on the season. In winter time, days are relatively short, and farmers operate the irrigation tools (sakkias and diesel pumps) during less hours than in summer time. In the water distribution model the abstraction pattern (farmers behavior) is defined through an input file for the different seasons. During each day farmers are assumed to stop irrigation when they have satisfied their need for that specific day.

2.6. Regional drainage simulation

The next step in the simulation sequence is the application of the regional simulation model REUSE for calculation of evapotranspiration, drainage and drainage water salinity (fig 1).

The calculation unit considered in the regional irrigation and drainage model corresponds with the area supplied with water by the lowest order irrigation canal in the water distribution model.

The main purpose of the regional drainage model REUSE is:

- organization of input and output for the module FAIDS where the on-farm water management is simulated;
- distribution of irrigation water supplied to the calculation unit among the different field crops;
- simulation of crop succession after crop harvesting, at the onset of the next growing season;
- simulation of unofficial reuse of drainage water by farmers;
- simulation of the irrigation water salinity after mixing with drainage water by reuse pump stations;
- taking care of the simulation sequence of the calculation units in relation to official and unofficial reuse of drainage water;
- calculation of time lags in the drainage system;
- preparation of output for presentation.

Reuse of drainage water can take place on three different levels. On the highest level reuse of drainage water takes place by the reuse pump stations and the quantity to be reused is part of the irrigation water allocation and distribution strategy of the Ministry of Public Works and Water Resources. The regional drainage model checks whether the quantities defined in the water allocation strategy are available at the specified locations. If the simulated quantity of drainage water is insufficient (during certain time periods) the model gives a warning and the water allocation and distribution strategy has to be redefined. If the simulated quantity of drainage water is sufficient to meet the required discharge specified in the water distribution strategy, this quantity is subtracted from the specified drainage canal section and added to the irrigation canal section with the simulated drainage water salinity. Using a special algorithm, the salinity of the irrigation water downstream of the mixing location is then calculated.

The second level at which reuse of drainage water is simulated in the regional drainage model takes place if farmers do not receive sufficient irrigation water, according to their (farmer's) demand. This phenomenon is considered in each calculation unit separately for each distinguished time step. Under these circumstances, farmers try to reuse available drainage water until their demand is satisfied. Drainage water, generated in upstream areas, and passing through or along the catchment under consideration may be used (within some limits) for irrigation. In the regional drainage model these limitations are formulated and they restrict the maximum amount of drainage water which can be used in two ways. First, only a fraction of the drainage water passing by or passing through can be utilized. Second, only part of the catchment has access to this external drainage water.

Generally, the fraction of the area which has access to the drainage water, is located at the downstream end of the distributary canals, and is also the fraction of the area which suffers first from insufficient water in case of a shortage. In the model the most restrictive of both limitations is evaluated and determines the maximum amount of unofficial external reuse of drainage water which can take place.

The required amount of unofficial external reuse of drainage water is determined as the deficit resulting from the irrigation supply, simulated with the water distribution model WATDIS, and the farmer's demand, simulated with the water requirement model WDUTY.

The actual amount of unofficial external reuse is evaluated in the regional drainage model REUSE as the minimum of the required and the potentially available amount of drainage water. Next, this quantity of drainage water is subtracted from the pertinent drainage canal section and added, with its pertaining salinity to the agricultural water supply.

The procedure described above indicates that it is necessary for the simulations to proceed according to the upstream-downstream sequence of calculation units following the drainage system layout. This simulation sequence is included in the regional drainage model.

The third level of reuse of drainage water recognized in the regional drainage model may take place when, despite unofficial external reuse of drainage water, the crop water demand is not yet satisfied. In this case, farmers will start to use also drainage water from the smaller internal drains within their catchment. Contrary to the situation for the estimation of external unofficial reuse, which is based on the aggregated crop water demand, for the internal unofficial reuse decisions are taken at crop level. In order to do so, it is necessary to estimate beforehand, how much drainage water will be available. In the REUSE model, a conservative estimate is made of the total quantity of drainage water which is expected. Only a fraction of this quantity is considered to be practically available for reuse. A second restriction to the unofficial internal reuse of drainage water considered, is that only a fraction of the total area has access to these minor drains.

Once the total irrigation water supply including unofficial external reuse of drainage water has been calculated, the farmers behavior with respect to the allocation of the available water over the different crops, which are simultaneously in the field and which require irrigation water, is simulated. Based on the agricultural demand for water for each crop and the available supply, the highest priority crop receives larger amounts than the lower priority crops. The priority is mainly based on the relative drought and salt resistance of the crops. Crops like wheat and cotton have a low priority and berseem and vegetables have a high irrigation priority. The allocation of irrigation water to the different crops is simulated in a separate algorithm. Part of the total supply is allocated proportional to the agricultural demand and the remaining quantity according to relative priority.

After allocating the total supply to the crops, the regional drainage model collects for each irrigation interval for each crop the initial moisture and salinity conditions and simulation control is passed to the on-farm water management model FAIDS.

2.7. On-farm water management

The on-farm water management model FAIDS is called by the regional drainage model REUSE for each irrigation interval for each crop in each of the calculation units. This model simulates for one time step and one crop the irrigation water application, evapotranspiration, drainage and salinity changes in the soil. Five separate modules are distinguished:

- on-farm irrigation module;
- redistribution of salts in the root zone module;
- evapotranspiration module;
- drainage module;
- salinity module.

Following is a brief explanation of each of the modules:

On-farm irrigation module IRREFF

On-farm irrigation starts with lifting the water from a meskaa, which is the smallest type of irrigation canal, by means of a sakkia (water wheel) or a diesel pump. Diesel pumps are growing in number, replacing the traditional sakkias. The water is spread over the field and some of this water evaporates, some of the water runs off from the tail-end of the plot due to poor land leveling and some is lost by leakage from the merwaa, which is the small field channel between sakkia and field plot. The majority of the water infiltrates into the soil, of which a part will be converted into evapotranspiration through abstraction by plant roots and another part will pass through the soil and will be collected by field drains. The remaining water, if any, will replenish the deep aquifer, depending on local hydrological conditions.

Simulation of on-farm irrigation is carried out by using an advance function considering the hydraulic process as a flow through an open channel of infinite width compared to the water depth. Both the advance function, as well as the total infiltration of water, is determined to a large extent by the cracking characteristics of the Egyptian clay soils in the Nile Delta. The loss of water through the soil cracks to the drainage system during ponding of the field plots is taken into account. The time period during which this rapid drainage occurs is calculated based on the swelling speed of the Egyptian clay soils. The capacity of the sakkia or diesel pump, the basic infiltration rate, the plot characteristics, the soil drainable porosity and the initial soil moisture deficit and groundwater depth are taken into consideration in the analysis.

The output of the IRREFF module consists of the updated content of the soil moisture store, the updated groundwater depth, the volume of water lost from the field tail-end (surface drainage), the volume of water lost by leakage from the merwaa field irrigation channel, and the volume of water lost to the drainage system by rapid drainage through cracks.

Redistribution of salts in the root zone module REDIS

During field irrigation, water is flowing into the soil cracks. Due to the hydraulic gradient and the high permeability of the cracked top soil, water is also flowing through the cracks to the field drains. The majority of the crop roots develop along these cracks and salt accumulation due to transpiration can be observed on the crack walls. The water flowing into, and through the cracks causes these salts to go into solution. Infiltration of water into the soil takes place at the ponding soil surface and at the crack walls. At the soil surface the infiltrating water has the irrigation water salinity, at the crack walls the salinity of the infiltrating water includes (part of) the accumulated salts which went into solution from the crack walls.

In the simulation model this process has been formulated in a simplified way. For the vertical water fluxes through the soil elements a leaching efficiency of 100% is assumed, and for the vertical water flow through the cracks a leaching efficiency of 0% (no leaching). Consequently, the initial irrigation water salinity is assigned to the horizontal fluxes from the cracks into the soil elements. For the simulation of the salt removal with the rapid drainage through the cracks a certain leaching efficiency is assumed. This leaching efficiency is dependent on the size of the cracks: if no cracks have developed the leaching efficiency is assumed 100% (in this case rapid drainage is zero, however) and if cracks are maximal the leaching efficiency has a very low value (large rapid drainage flux). In this way the infiltrating water into the defined soil layers always has the irrigation water salinity and leaching is only considered through the soil elements. In each distinguished soil layer complete mixing of the inflowing water with the soil moisture is considered. The outflowing concentration equals at each moment of time the soil moisture salinity.

The output of the REDIS module consists of the updated salinity in each distinguished soil layer above drain level, the updated salinity of the drainable water reservoir, i.e. the soil water stored in the drainable porosity, and the quantities of salts lost through tail-end losses of the merwaa, surface drainage, and rapid drainage through soil cracks.

For the salinity calculations the chloride ion has been selected because this element is not retained in the soil by adsorption processes nor is it involved in precipitation reactions. Based on the analysis of about 4,000 water samples a good empirical relationship between chloride concentration and total salinity has been established.

Evapotranspiration module EVA

After field irrigation the soil is at or near field capacity. Under these conditions, generally, evapotranspiration rates will be potential. Upon depletion of the soil moisture the actual evapotranspiration rate may be reduced based on the soil moisture potential as well as on the osmotic potential of accumulated salts. In this process of reduction characteristic plant factors play an important role.

In the simulations in the EVA module the Rijtema approach has been used. Evapotranspiration is considered potential, until in the plant the critical leaf water suction is reached. At this suction the plant stomata start to close and reduction starts. In the model this critical leaf water potential is translated into a fraction of the total available soil moisture, resulting in the quantity which is easily available for transpiration, i.e. available before reduction starts. Since each crop has its own characteristic critical leaf water potential, this fraction is different for each distinguished crop. The module EVA accounts for the osmotic potential and also takes the capillary flux into the root zone into account.

Since the climatic conditions in the Nile Delta in Egypt do not change much from year to year, long term average climatic input data have been used. Based on the crop development data such as crop height and relative soil cover for the different stages in the growing season the maximum rates are calculated. For the capillary flux ten different soil types are considered.

Evapotranspiration of rice fields is simulated by balancing the standing water layer depth, taking into account open water evaporation from the free water surface based on relative soil cover as well as abstraction by the plant roots.

The output of the EVA module is the simulated volume of actual evapotranspiration, the volume of capillary supply to the root zone and the updated soil moisture volume.

Drainage module DRAGE

After field irrigation, drainage takes place both to the drainage system, and to the deep aquifer.

For the simulation of drainage the resistance against flow to the drainage system is based on the theory of Ernst and discharge is simulated by a linear relation between water table depth above the drains and discharge. Discharge to and from the aquifer is simulated in a similar way. In this case the resistance against flow is based on the thickness of the clay cap and the vertical hydraulic permeability. The difference between water table depth and the piezometric head in the aquifer is the driving force for discharge to (leakage) and from (seepage) the aquifer. For the calculation of the discharges from the soil the capillary flux, calculated in the evapotranspiration module is taken into account.

The output of DRAGE consists of the volumes of water drained through the saturated soil to the drainage system, the volumes lost to, or gained from the aquifer, and the updated water table depth.

Salinity module SAMIA

In the salinity module two separate processes are simulated. It updates the soil salinity of the saturated subsoil, based on the volumes of drain discharge and seepage/leakage flows. In each soil layer complete mixing of the incoming water fluxes with the soil moisture is assumed. Outgoing fluxes to other layers, to the drainage system, and/or to the aquifer have the instantaneous salinity of this soil moisture.

The second process simulated by the salinity module SAMIA is the updating of the soil salinity in the unsaturated zone above drain level caused by capillary fluxes and actual evapotranspiration. Plant root abstraction of soil water is assumed uniform in the plant's root zone and, based on the resulting moisture balance of the distinguished soil layers, the updated salinities are calculated.

The output of the salinity module SAMIA consists of the drainage water salinity, the leakage flux salinity and the updated salinity of both the saturated and unsaturated soil layers.

3. INPUT DATA

3.1. Introduction

The data required for performing model simulations can be classified in four categories:

- time invariant input data, also called model parameters, such as soil permeability, soil anisotropy factor, etc;
- time dependent input data, such as total water supply, cropping pattern, meteorological data, etc.
- model variables which have to be initialized, such as soil moisture contents, soil salinity, groundwater depth, etc.
- field measurements for the comparison of simulated model output; in order to calibrate some of the time invariant model parameters.

In the description of the data needed for the model simulations, given in this chapter, no distinction is made concerning the models (DESIGN, WDUTY, WATDIS, and REUSE) for which these data are required. The large amount of data which is required for the simulation with the SIWARE model has been collected from several sources, amongst others:

Egyptian Public Authority for Drainage Projects:

- the hydraulic permeability of the soil;
- the drainage conditions (drain distance; drain depth) in subsurface drained areas. In the areas not yet provided with a subsurface drainage system these data are based on incidental field observations.

Groundwater Research Institute:

- the vertical hydraulic resistance against leakage to and seepage from the aquifer. These data are based on clay cap thickness data and vertical hydraulic permeability, which, in turn, is based on field investigations and water and salt balance studies;
- the piezometric head in the aquifer;
- the salinity of the deep groundwater from the monitoring programme of about 100 deep observation wells, distributed in the Nile Delta;
- the groundwater use for irrigation in the distinguished irrigation districts is based on an inventory of irrigation wells, performed by the Groundwater Research Institute.

Water Distribution and Irrigation Research Institute:

- the climatic conditions, based on long term meteorological observations in Egypt.

Soil and Water Research Institute:

- the soil conditions. The classification used in the model is based on soil texture. For the clay soils a relation has been found between the swelling and shrink-

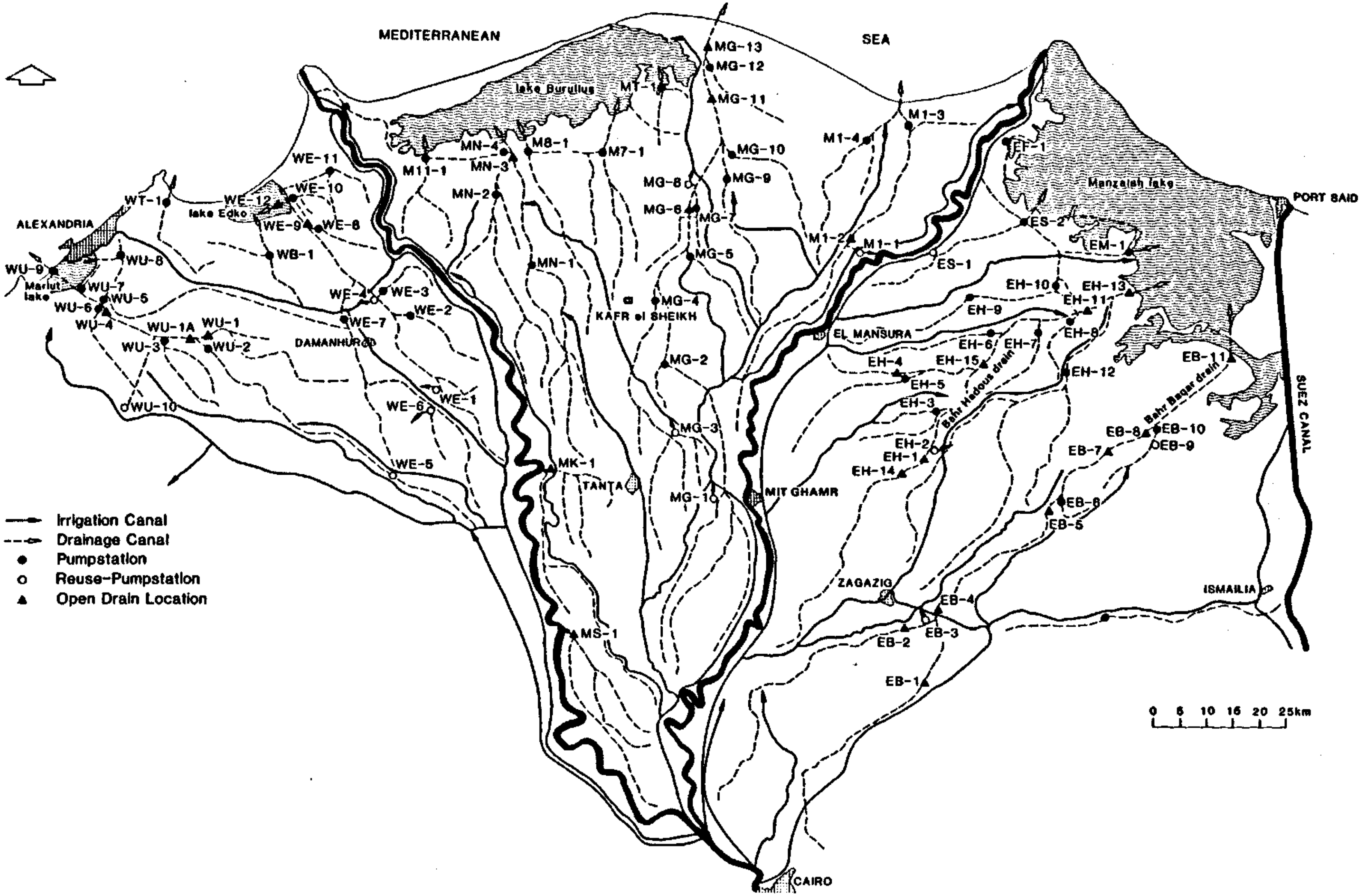

Fig 2. Nile Delta of Egypt with the locations of the observation points of the measurement programme of discharges and salinities of drainage catchments.

ing behaviour of the soil, and the clay content.

Ministry of Agriculture:

- the cropping pattern per agricultural district (markaz) for the period 1984-1987;
- data on crop development, recommended irrigation intervals, etc. have been obtained from pamphlets of the Agricultural Extension Service of this Ministry.

Ministry of Public Works and Water Resources:

- the design criteria of the irrigation system;
- the irrigation system layout and type and location of control structures;
- the administrative irrigation district boundaries;
- the monthly crop water allocation duties;
- the realized total water allocation to the six main irrigation command canals for the period 1984-1988;
- the cropping pattern per irrigation district for 1988;
- the non-agricultural water requirements in the Eastern Nile Delta.

Drainage Research Institute:

- the layout of the main drainage system and drainage catchment boundaries;
- the realized quantities and salinities of officially reused drainage water for the period 1984-1988 (through reuse pump stations);
- the observed drain discharges and salinities in the Eastern Nile Delta for the period 1984-1988.

The initial values of model variables, such as moisture conditions and salinities per calculation unit, per crop, and per soil layer cannot be found in, or estimated from previous studies and/or inventories. This type of input data has been generated with the SIWARE model itself, by running it for a considerable number of years and updating the initial conditions after each simulated year.

3.2. General description Eastern Nile Delta

The Nile Delta in Egypt can be subdivided into three hydrological independent regions: the Eastern Nile Delta; the Middle Nile Delta; and the Western Nile Delta (fig 2). The hydrological boundary between these regions are the two Nile branches: the Rosetta branch between the Western and Middle Delta; and the Damietta branch between the Middle and Eastern Nile Delta.

Because the Delta regions are more or less hydrological independent, in first instance only one area, the Eastern Nile Delta, has been selected for testing the model. Also for the analysis of alternative water management strategies only the Eastern Nile Delta has been considered so far. The Eastern Delta (fig 2) covers the agricultural area east of the Damietta Nile Branch from Cairo in the south till the Manzala Lake in the north. In the east the Eastern Desert forms the boundary of the agricultural area.

The water supply to the Eastern Delta is through three main irrigation command canals and three minor (small) command canals. Five of these canals branch from the Nile upstream of the Delta Barrages at the bifurcation of the two Nile branches (fig 2). The Ismaileya Canal starts in Cairo, and supplies irrigation water to part of the Eastern Nile Delta, but also transports irrigation water to the Ismaileya and Salheya Irrigation Directorates. The second main command canal is the Rayah Tawfiki, which takes water at the Delta Barrages. The third main command canal is the Mansureya Canal which supplies the northern part of the Eastern Delta with water. It takes water from the Damietta Nile Branch near Mit Ghamr (fig 2).

The area served by the Ismaileya Canal downstream of Salheya head regulator, where it leaves the Eastern Nile Delta is taken into account in the water allocation and water distribution simulations, but not in the reuse model. In the underlying report the Eastern Nile Delta is defined as the complete area served with irrigation water. The Eastern Nile Delta with the exception of the area served by Ismaileya Canal downstream of Salheya head regulator will be referred to as the 'study area'.

Almost all drainage water in the study area is disposed in the Manzala Lake, which is in open connection with the Mediterranean Sea. The majority of the area is drained by two main drainage catchments: the Bahr Baqar catchment and the Bahr Hadus catchment (fig 2). The drainage water in the Bahr Baqar catchment is seriously polluted by the sewage water discharged from part of Cairo city. This sewage water is transported through the Bilbeis Drain to the Bahr Baqar near Zagazig.

The topography in the study area is sloping gently from the south to the north. The land elevation near Cairo is about 30 meter above mean sea level. In the northern part of the Delta the land level is at or even below mean sea level.

The geohydrological profile in the Eastern Nile Delta is characterized by a clay cap overlying a coarse textured aquifer of considerable thickness. The extend of this clay cap varies. In the fringes near the Eastern Desert the clay cap thickness is limited, and on some locations absent. In the central part of the Eastern Nile Delta the clay layers may extend to 30 meter depth. The clay content of the top soil also varies within the study area. The heaviest type of clay soils are found in the northern part; in the fringes of the Delta in the south-east also lighter textured soils are found.

With the exception of a narrow strip along the Ismaileya Canal, leakage conditions are dominant in the southern part of the Eastern Nile Delta, and recharge of the aquifer takes place. In the northern part seepage conditions prevail. Although generally the seepage flux is of limited magnitude, locally seepage may be important due to the irregular thickness of the clay cap. Due to the high salinity of the deep groundwater in the northern part of the Nile Delta the salt load introduced by the seepage flux may be considerable, and cannot be neglected.

The climatological conditions in the Eastern Nile Delta are fairly constant over the years. The rainfall varies from some 150 mm annually in the north till about 30 mm in the south. In the southern and south-eastern part of the Eastern Nile Delta the relative humidity of the air is somewhat lower, and the temperature higher, due to desert influences. In the northern part of the Eastern Nile Delta the temperature is lower, and the average wind speed higher. For the model simulations three climatological regions have been distinguished according to Rijtema and Abu Khaled (1967).

3.3. Schematization Eastern Delta

Any simulation model, such as SIWARE, is a simplified reproduction of the complex reality. Although it is the objective of the modeler to include all relevant relationships in his model, implicit assumptions, made during the modelling process, limit the equivalence between the simulation model and reality. For the actual model simulations in a certain defined study area, such as the Eastern Nile Delta, it is not only the processes which are schematized, however. Also the area itself, and the associated relevant input data have to be schematized. The reasons for schematization of the area and the input data are generally related to limited computing facilities on one hand, but frequently also with insufficient knowledge about the detailed spatial and temporal variability of the required input parameters. Sometimes input data have to be lumped, due to insufficient knowledge about such model input parameters.

Before simulations with the SIWARE model can be performed, the irrigation system hierarchy, the drainage system hierarchy, and the connecting links between both, have to be determined in terms of input data. The links between the irrigation canal system and the drain canal system which can be distinguished are the following:

- spillway losses from the tail-ends of main irrigation canals directly to the drainage system;
- the unit areas (calculation units or subareas) which receive irrigation water from the irrigation canal system and produce drainage water and spillway losses at the tail-ends of distributary canals and meskaas;
- reuse pump stations which lift drainage water from the drainage canal system into irrigation canals.

The lowest level of irrigation canals considered in the analysis, is the distributary canal which receives water through an inlet gate, operated under supervision of the Ministry of Public Works and Water Resources. Such a distributary canal may have several lateral canals, called meskaas. Generally, no control structures are present at the branching locations of these meskaas. The agricultural area served by such a distributary canal can consequently be considered as an unit area. The average area served by a distributary canal in the Eastern Nile Delta is about 6,000 feddans. Strict schematization of the Eastern Nile Delta according to this criterion would then result in roughly 300 calculation units.

For the management and operation of the irrigation system and water distribution in the Eastern Nile Delta, the Ministry of Public Works and Water Resources has subdivided this area into 5 administrative units, the so-called Irrigation Directorates: Qalyubeya Directorate (373,000 feddans); Sharkia Directorate (499,000 feddans); Dakhaleya Directorate (613,000 feddans); Salheya Directorate (213,000 feddans); and Ismaileya Directorate (151,000 feddans). These Directorates are further subdivided into Irrigation Districts ranging in number from 4 (Salheya and Ismaileya Directorates) to 14 (Dakhaleya Directorate). The average size of an Irrigation District is about 48,000 feddans, and consequently contains on the average 8 distributary canals, each serving an average of 6,000 feddans. The irrigation water supply to these unit areas is rotational, and consists of 7 days on and 14 days off in winter; 7 days on and 7 days off in summer for non-rice areas; and 4 days on and 4 days off in summer for areas where rice is included in the cropping pattern.

For the subdivision of the Eastern Nile Delta into calculation units the boundaries of the administrative Irrigation Districts have been respected. Since the simulation models follow both the irrigation system hierarchy and the drainage system hierarchy, these districts have been split up into smaller units. The (schematized) unit areas have been defined in such a way that its irrigation water originates exclusively from one canal, and its drainage water flows exclusively to one drainage canal. The number of calculation units in the existing ('old') agricultural area in the Eastern Nile Delta is 82 (fig 3). An additional 11 calculation units are located outside the study area in the Eastern Desert. This additional area is supplied with water through the irrigation system (Ismaileya Canal), but measurements in the drainage water have not been considered in the drainage monitoring programme of the Drainage Research Institute. In the model simulations, the water allocation and distribution will be considered for the complete Eastern Nile Delta, including these additional calculation units. The simulated drainage water discharge and other (spatially distributed) model results, however, are restricted to the study area (fig 3).

Due to the fact, that on the average 2 to 3 distributary areas have been combined in the calculation units, the rotational supply to these units is not considered in the water distribution model. The consequences of this assumption in terms of dimensions of the inlet structures, the distributary canals and spillways have been accounted for, however. Both the inlet gate and the spillway have been dimensioned in the model on half the capacity of the dimensions based on rotational supply. Also the storage capacity of the distribution canals has been reduced with a factor two.

The hierarchy of the irrigation canal system and the locations in the Eastern Nile Delta, where the calculation units receive their irrigation water from the system is given in figure 4. The layout of the canals, including the head regulators for water-level control is based on information collected at the Regional Offices of the Ministry of Public Works and Water Resources. The locations where reuse of drainage water by pump stations takes place is included in this schematization. The calculation of the water supply to the calculation units in the Eastern Nile Delta follows the irrigation canal system hierarchy. After simulating the first order canals, the second order canals are treated, and finally the third order canals are simulated.

In the model the irrigation command areas are indeed considered as command areas, which is sometimes a simplification of reality. The command areas of Rayah Tawfiki and Ismaileya Canal are interconnected through Abu El Akhdar Canal, which branches from Bahr Mois and discharges into Wadi Canal (fig 4). The possibility to use Abu El Akhdar Canal for the transport of water to Wadi Canal is considered in the model approach, but only for a certain percentage of the demand

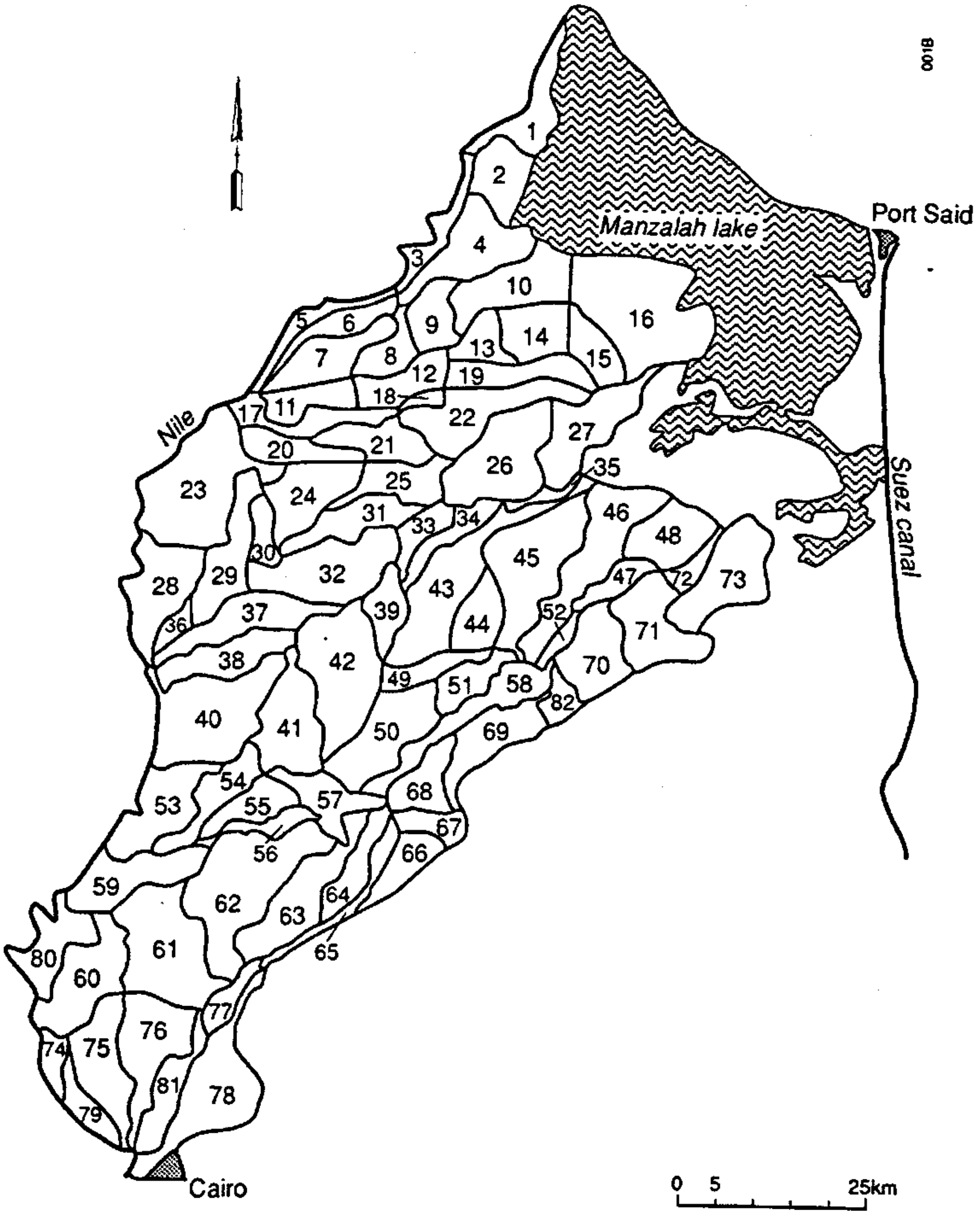

Fig 3. Calculation units distinguished in the study area. The 11 additional calculation units in the Eastern Desert are not included.

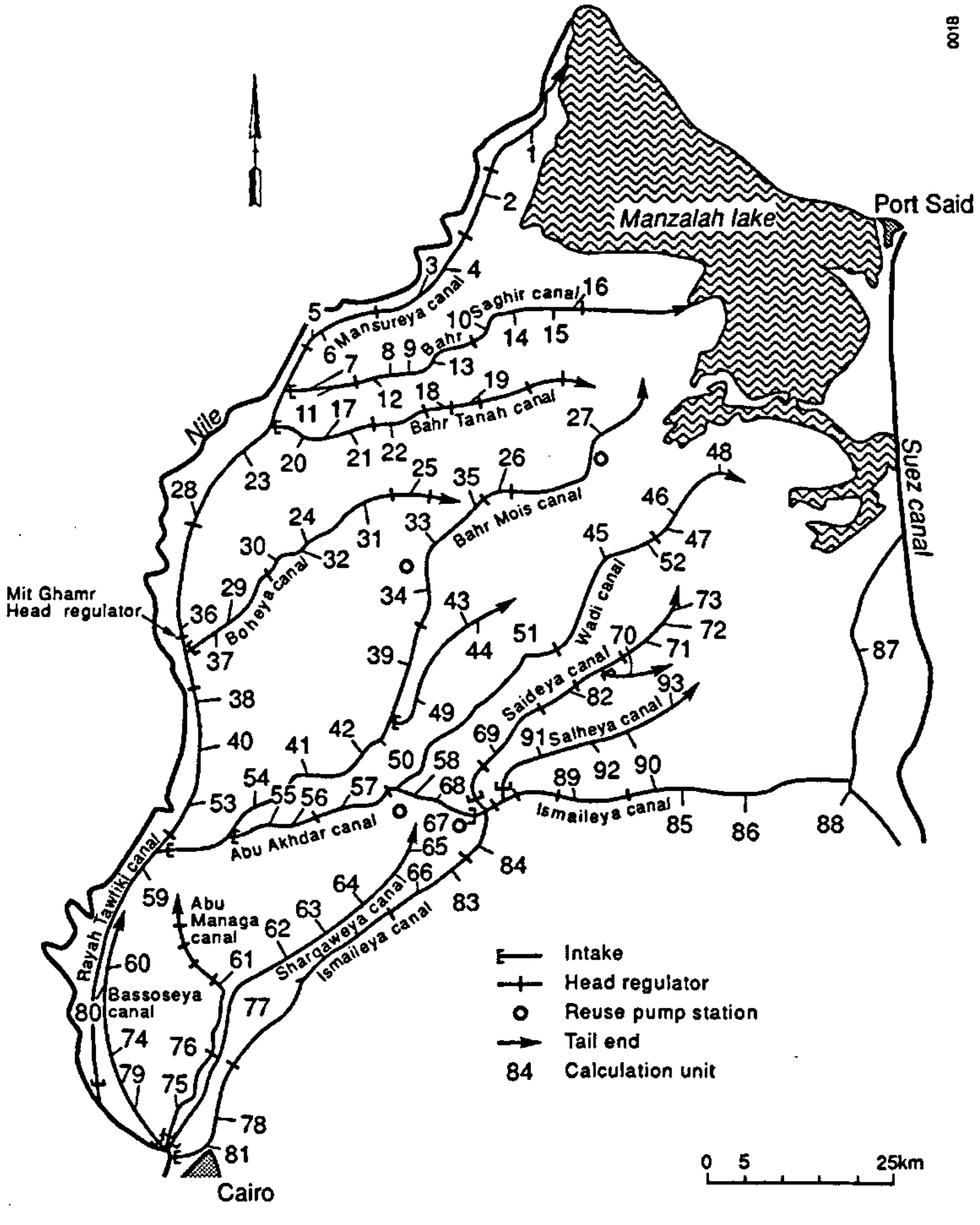

Fig 4. *Schematization of the irrigation canal system hierarchy in the Eastern Nile Delta. The calculation units numbered 83 till 93 are included in the irrigation system, but are outside the study area.*

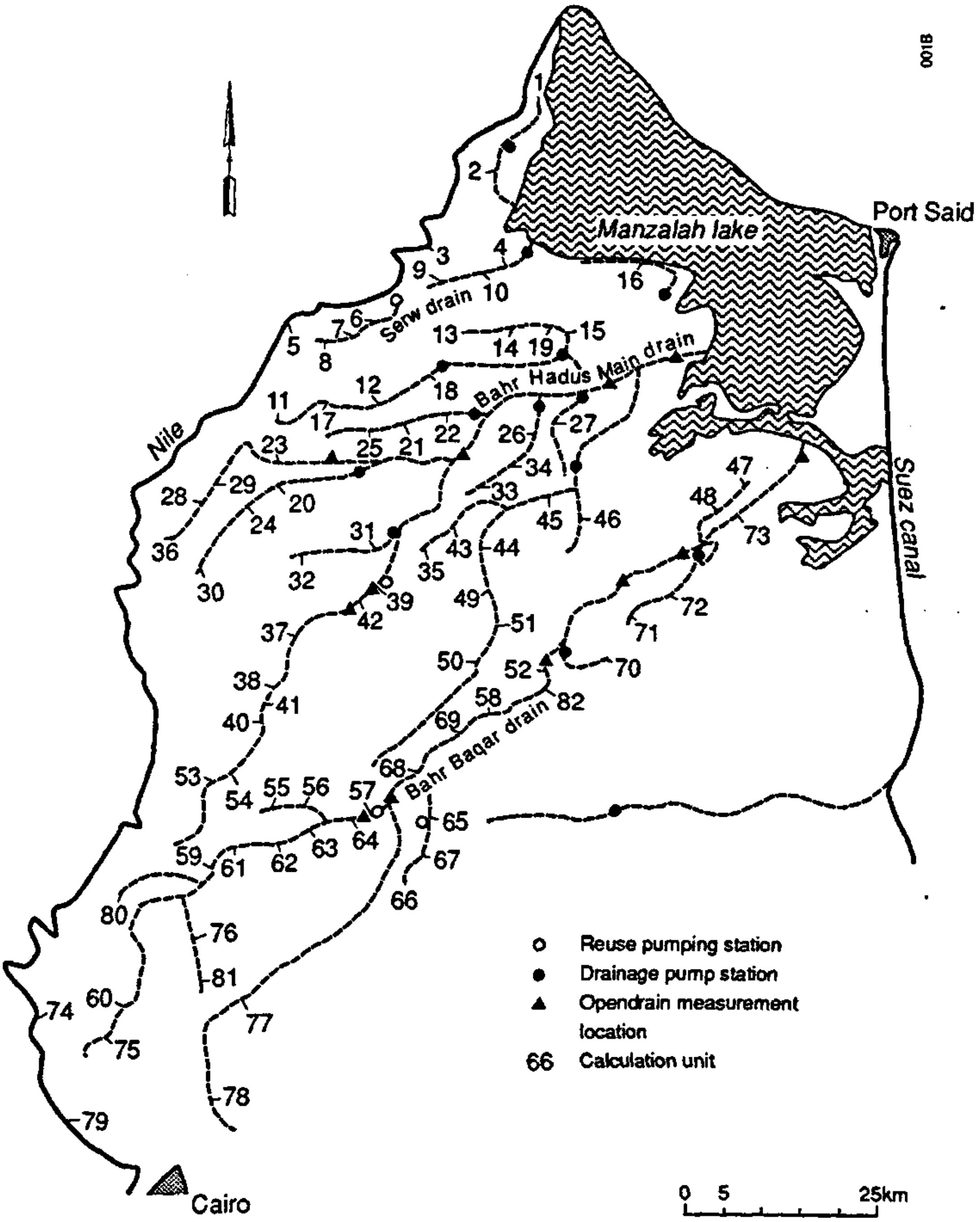

Fig 5. Schematization of the drainage canal system hierarchy in the study area. The 11 calculation units in the Eastern Desert are not included in the drainage system schematization.

of the downstream part of the Wadi command area. This percentage is time invariable and has been fixed at 40%, so in the model Abu El Akhdar Canal serves 40% of the Wadi catchment, the whole year round. This does not reflect reality. Also the command areas of Tawfiky Rayah and Mansureya Canal are interconnected, through the Mit Ghamr head regulator. During winter time considerable quantities of water are transported through Tawfiky Rayah and Mit Ghamr head regulator to the Mansureya Canal. This is not considered in the model. Mit Ghamr head regulator is considered in the model as tail-end, where the losses, in this case, do not flow to the drainage system however, but to another canal instead.

The hierarchy of the drainage canal system determines the simulation sequence of the regional irrigation and drainage model, REUSE. Drainage water generated in upstream calculation units may be available for unofficial reuse in downstream calculation units (fig 5). The model therefore always starts calculations at the upstream ends of the drainage system. At the confluence of two drains, the simulations for the tributary branch have to be finished first, before simulations can proceed further downstream.

At official reuse locations a special section in the drainage canal has been defined, from which the pump station lifts the water into the irrigation canal system. Each time the drainage water simulation of such a section is completed, the normal simulation procedure is interrupted. Using a special algorithm the irrigation water salinity downstream of the mixing point is recalculated before on-farm water management simulation proceeds. The quantity of drainage water, simulated for such reuse sections, is compared with the quantities, defined in the water allocation procedure. If deviations of more than 5% occur, this is reported to a special message file.

3.4. Cropping pattern

Correct cropping pattern data are of vital importance for the simulation of the water management. Different crops have different characteristics such as rooting depth, soil cover, crop height, growing season, etc. This has a direct effect on the required irrigation water quantity; the irrigation frequency; and on the amount of evapotranspiration, which is the most significant term in the water balance. In the Eastern Nile Delta about 28 different crops are distinguished by the Ministry of Public Works and Water Resources for the water allocation procedure. The majority of the agricultural land, roughly 86%, is occupied by the nine major field crops, however. The remaining additional 19 minor crops occupy roughly 14% of the area only.

Cropping pattern data are also important for the allocation of the available irrigation water among the different irrigation canals. In order to reduce the amount of calculations required in the on-farm water management model, the number of crops considered, has been reduced to nine crops only. The water allocation procedure to the main canal intakes should not be affected by this procedure. Therefore, the water allocation duty of the Ministry of Public Works and Water Resources (table 1) has been used as the yardstick for simplifying the cropping pattern. The simplification of the cropping pattern is given in table 2. The effect of this simplification on the total allocation requirement for the Eastern Nile Delta for 1988 is small (fig 6).

Table 1. Allocation water duties used by the Ministry of Public Works and Water Resources for the 9 major crops (mm.month^{-1}).

	crop								
month	long bers	wheat	short bers	winter veget	decid trees	maize	rice	cotton	summer veget
Jan	81	41	-	69	48	-	-	-	-
Feb	81	41	-	70	47	-	-	83	-
March	161	83	-	139	81	-	-	77	-
April	180	78	-	-	129	-	-	72	168
May	50	-	-	-	130	-	43	99	189
June	-	-	-	-	147	81	537	156	159
July	-	-	-	-	146	155	424	180	31
Aug	-	-	-	-	140	146	626	90	-
Sept	-	-	-	-	117	168	465	-	-
Oct	13	-	68	127	93	90	-	-	-
Nov	72	42	141	168	57	-	-	-	-
Dec	90	96	183	189	47	-	-	-	-

Table 2. Minor crops in the Eastern Nile Delta which have been considered as main field crops in the SIWARE model simulations

main field crops considered		minor crops considered as main field crops
long berseem	-	other winter crops
wheat	-	broad beans; barley; flax; onions; garlic; sugar beet
winter vegetables	-	helba; tirmis; hummus; lentils
short berseem	-	
deciduous trees	-	sugar cane; looff
maize	-	peanuts; soya beans; summer onions; other summer crops
rice	-	
cotton	-	
summer vegetables	-	
not considered	-	nili maize; nili vegetables

After simplifying the cropping pattern, the data have been scrutinized (and corrected) for inconsistencies. The effect of this consistency analysis on the water allocation is larger than the effect of simplifying the cropping pattern (fig 6).

The cropping pattern data for the period 1984 till 1987 for the agricultural districts (markaz) have been obtained from the Ministry of Agriculture. These data have been translated to the cropping pattern for the calculation units by superimposing the markaz boundaries on the calculation unit boundaries (fig 3) and assuming uniformity within the agricultural markaz. For 1988 the cropping pattern data have been obtained from the Ministry of Public Works and Water Resources

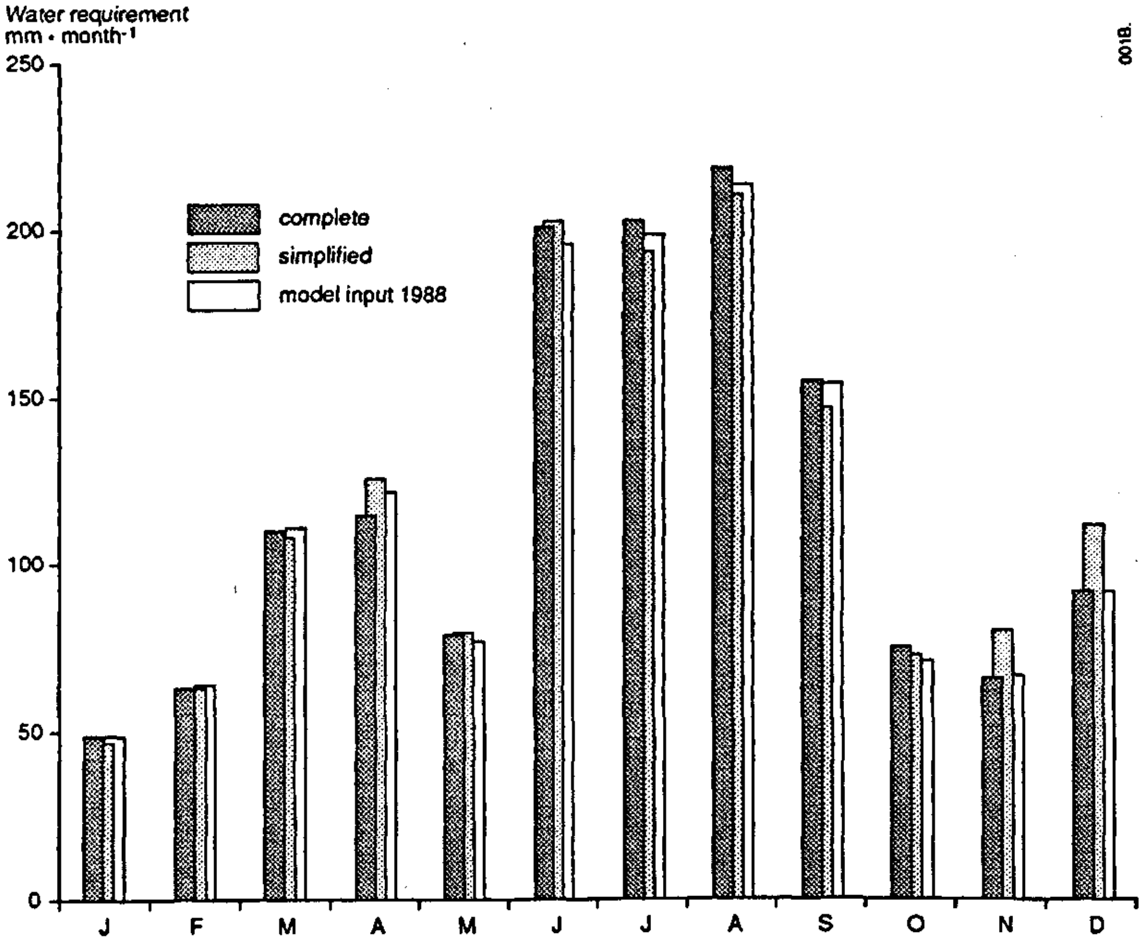

Fig 6. Water allocation requirement Eastern Nile Delta for the cropping pattern of 1988 (complete cropping pattern, data Ministry of Public Works and Water Resources); for the simplified cropping pattern (simplified according to table 1); and for the cropping pattern actually used for the simulations (after correction).

for each distinguished Irrigation District. In this case no interpolation was necessary. The winter cropping pattern and the spatial distribution of the two main winter crops, long berseem (32%) and wheat (29%) for the study area during 1986 is given in fig (7). Long berseem appears to be dominant in the northern part of the Eastern Nile Delta, but also in the fringe along the Eastern Desert, and in the southern tip fairly large quantities of long berseem are found. The wheat crop is found more or less complementary to the long berseem crop: small quantities in the south and the north; and a large quantity in the central part of the Eastern Nile Delta (fig 7). The summer cropping pattern and the spatial distribution of the two main summer crops, maize (31%) and rice (28%) for the study area during 1986 is given in fig (8). Maize appears to be dominant in the southern part of the Eastern Nile Delta, and the quantity of maize in the cropping pattern drops sharply to the north, where the soil salinity is higher. Rice is absent in the most southern part of the Eastern Nile Delta. Moving northwards the share of rice in the summer cropping pattern is increasing, but in the utmost northern part of the eastern Nile Delta its share is slightly lower again (fig 8).

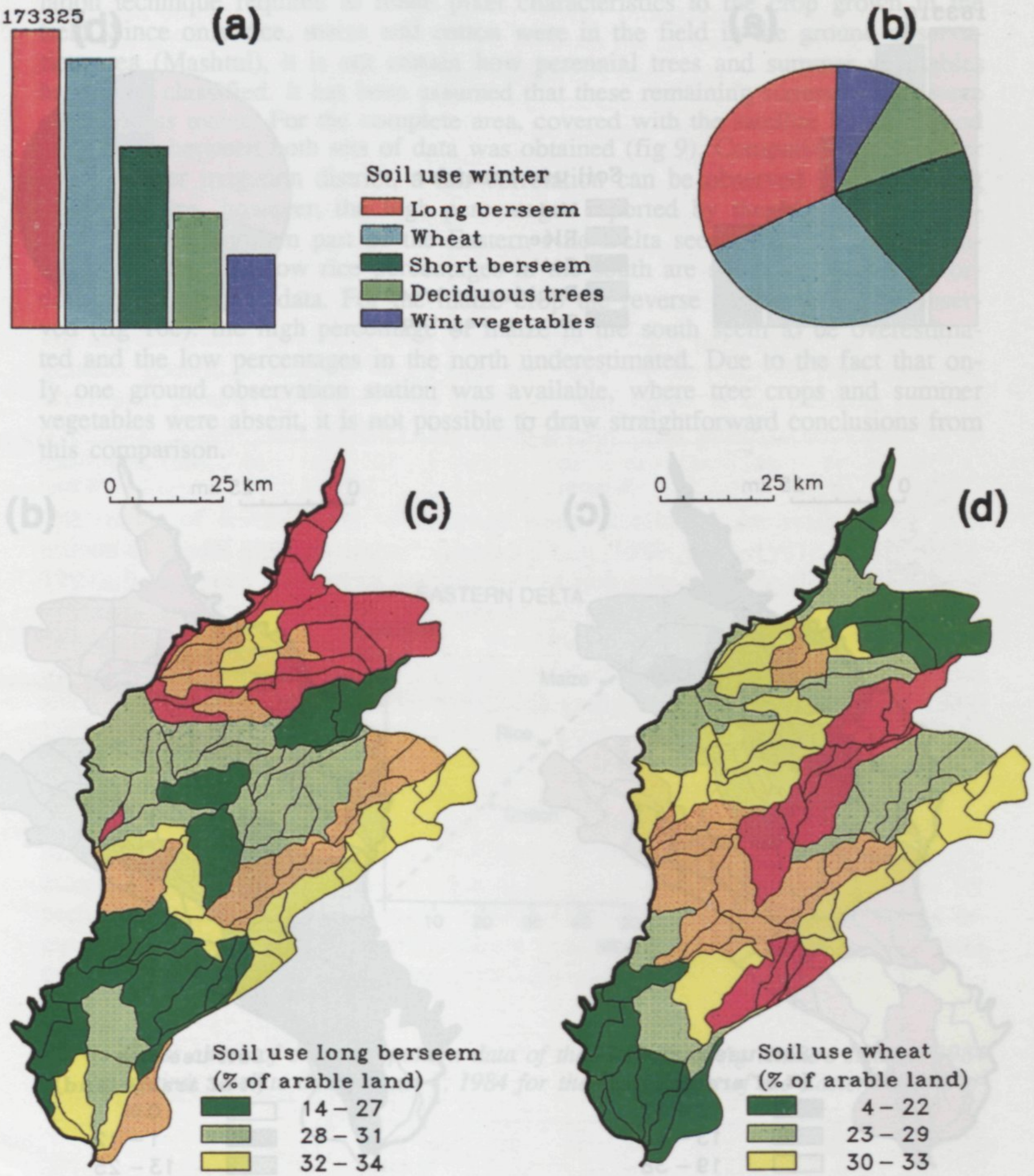

Fig 7. Cropping pattern Eastern Nile Delta study area winter 1986 (%).

a - total net acreage winter crops (ha); b - average occurrence winter crops (%);
c - spatial distribution long berseem; d - spatial distributions wheat crop

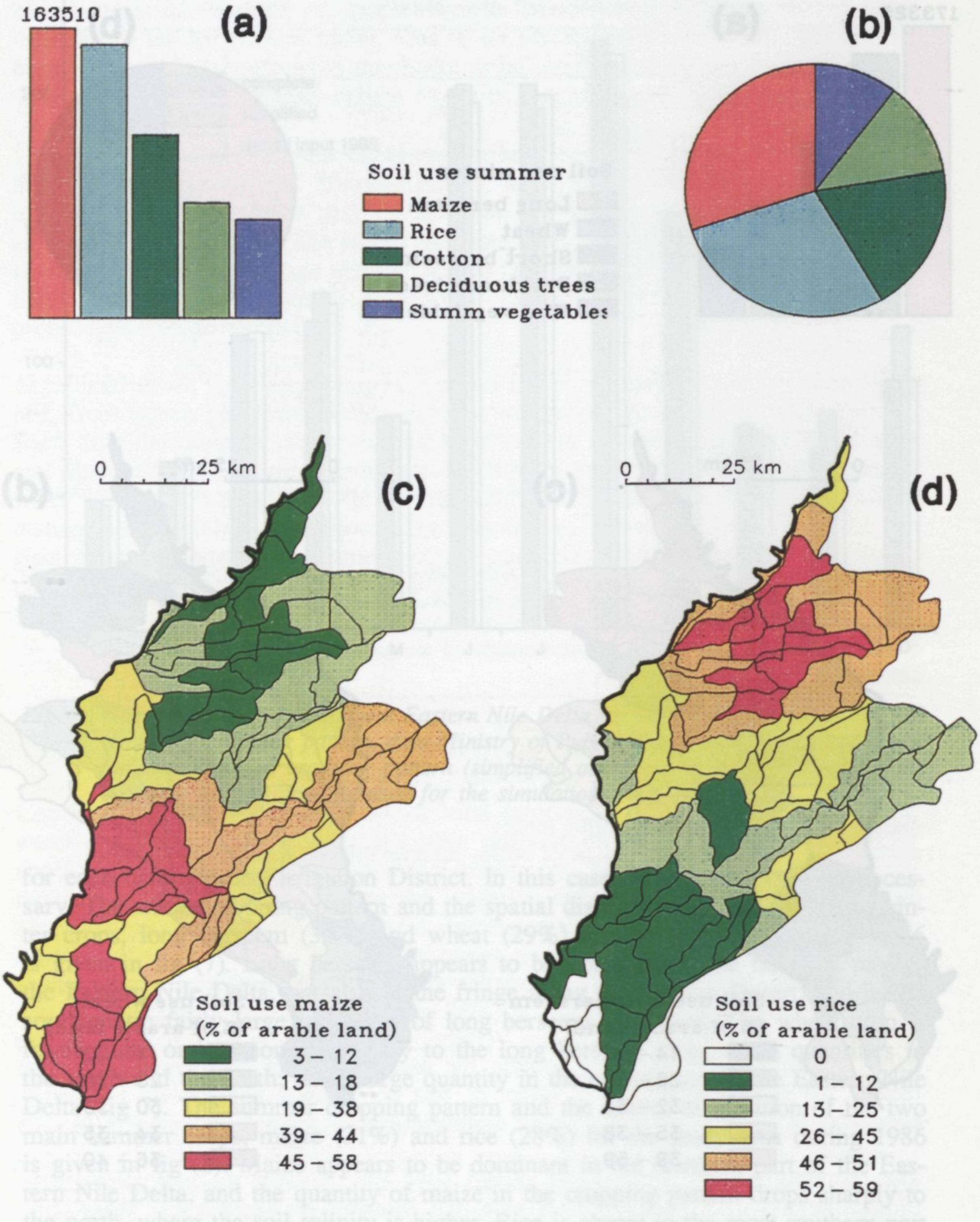

Fig 8. Cropping pattern Eastern Nile Delta study area summer 1986 (%).

a - total net acreage summer crops (ha); b - average occurrence summer crops (%);
c - spatial distribution maize crop; d - spatial distribution rice crop

In order to check the cropping pattern data, the digital information of one image of the Landsat Thematic Mapper, covering the middle part of the Eastern Nile Delta (about 65%) has been used. This picture was taken on august 4, 1984, and could obviously only be used for the summer crops. The cropping pattern data of the Mashtul Pilot Area (Abdel Dayem et al, 1985) have been used for the correlation technique required to relate pixel characteristics to the crop grown in the field. Since only rice, maize and cotton were in the field in the ground observation area (Mashtul), it is not certain how perennial trees and summer vegetables have been classified. It has been assumed that these remaining summer crops were classified as maize. For the complete area, covered with the satellite image a good correlation between both sets of data was obtained (fig 9). Comparing the data per crop and per irrigation district, a fair correlation can be observed for cotton (fig 10a). For rice, however, the high percentages reported by the Ministry of Agriculture in the northern part of the Eastern Nile Delta seem to be an overestimation (fig 10b). The low rice percentages in the south are somewhat higher according to the satellite data. For the maize crop the reverse tendency can be observed (fig 10c): the high percentage of maize in the south seem to be overestimated and the low percentages in the north underestimated. Due to the fact that only one ground observation station was available, where tree crops and summer vegetables were absent, it is not possible to draw straightforward conclusions from this comparison.

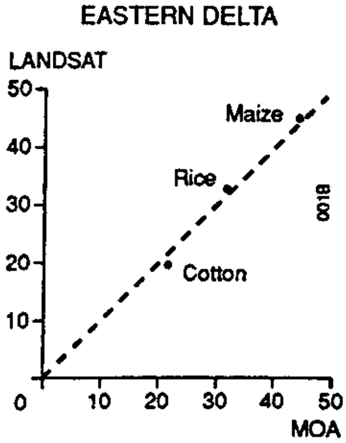

Fig 9. Cross check of cropping pattern data of the Ministry of Agriculture summer 1984 against satellite data august 4, 1984 for the central part of the Eastern Nile Delta.

The analysis of the satellite data resulted in an additional aspect of required input data. The major infrastructure, such as villages, main roads and railways, as well as barren lands, has also been classified from the satellite picture. Minor infrastructure such as small farm roads, ditches, small houses, etc are not detected by the Landsat scanner because the pixel size is about 20 by 20 meter. Estimating this area occupied by minor infrastructure at 10%, the net cropped area per irrigation district can be obtained (fig 12b).

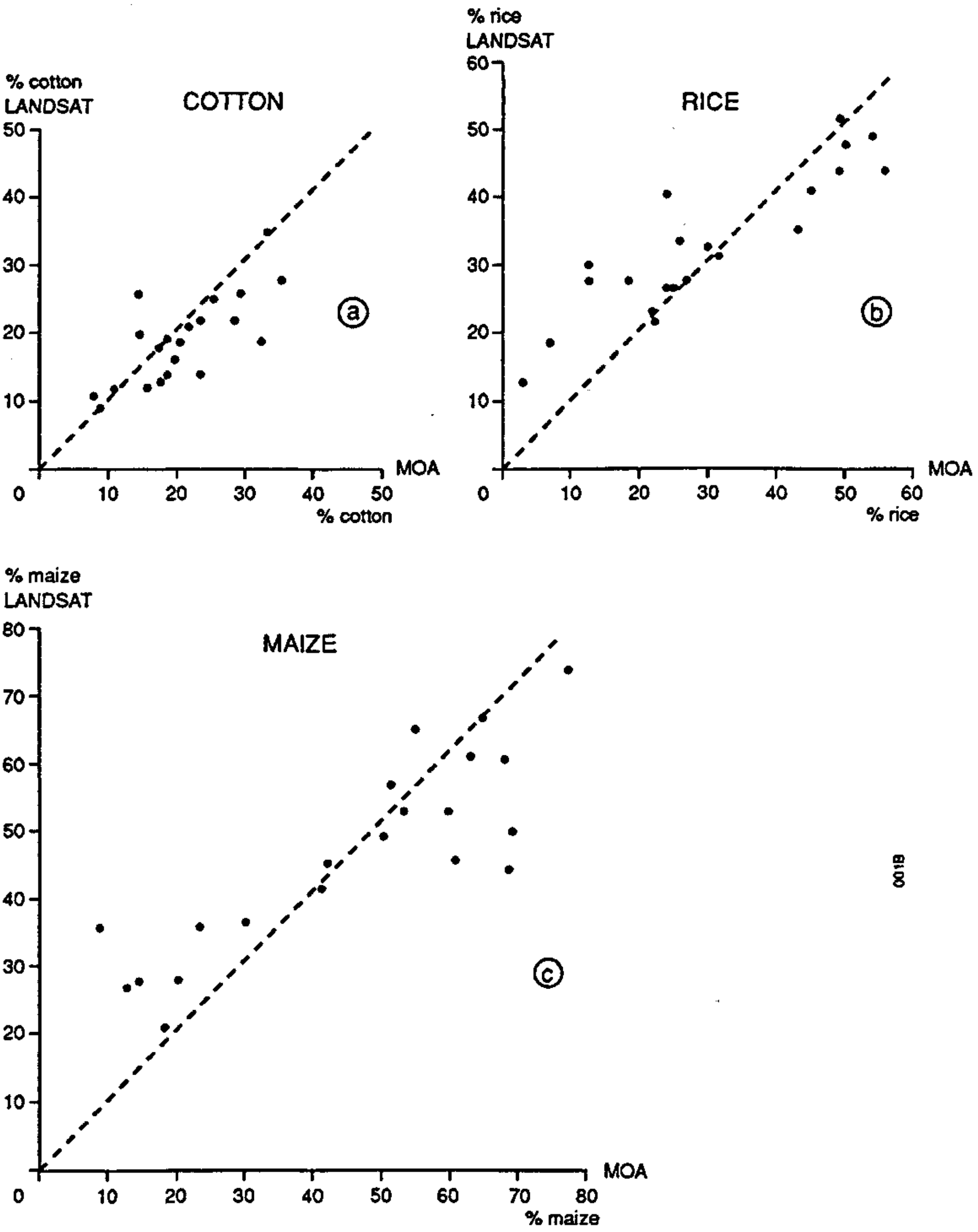

Fig 10. Comparison of the cropping pattern reported by the Ministry of Agriculture per irrigation district summer 1984 with the results of the Landsat thematic mapper august 4, 1984.

a - cotton; b -rice; c -maize (other crops)

3.5. Calibrated model parameters

Theoretically, for performing model simulations with a physically based simulation model it is sufficient to collect the pertinent input data and to analyze the simulated output. For regional (physically based) simulation models, this procedure is not sufficient. Generally, deviations between the measured and calculated output are observed and adjusting model parameters may improve simulation results. The limited knowledge about certain model parameters, the uncertainty about the exact value, and the spatial variability of parameters within the assumed uniform calculation units justify the adjustment of model parameters (calibration). Many processes considered in the SIWARE model are, as is frequently the case in nature, non-linear. So, even if the spatial variability of a certain model input parameter is known, averaging of such a parameter does not necessarily produce the correct simulation result.

For the calibration procedure two types of model input parameters can be distinguished: general parameters, which have one value for the complete study area; and distributed parameters, which may have different values in the different calculation units. Within each category of parameters the most sensitive ones have to be calibrated first.

The results of several years of drainage water monitoring are available for calibration of model input parameters (Project Team, 1984, 1986, 1987, 1988a, 1988b, 1989). It has been decided to use the data of one year only for the calibration of model parameters, and to use the data of the remaining years for model validation, i.e. to check whether the model simulations show the same trend as the observations. The monitoring programme started in 1980, and has been continued since. The measurement methods have been gradually refined, until around 1984/1985 the required degree of precision and accuracy was obtained (Roest and El Quosy, 1989). It has been impossible to collect the required initial input data (soil moisture and salinity data) from the field, or from the existing literature. By running the model for a sufficiently long period with the same soil use, climatic and irrigation input data, equilibrium conditions are generated. These equilibrium conditions have been used as initial input data. The year 1986 has been selected for performing the calibration of model input parameters and calculating the initial input data because both the cropping pattern and the irrigation water supply are both more or less equal to the long term historical average.

3.5.1. General model parameters

The most sensitive type of general model input parameters appeared to be the crop characteristics: growing period, irrigation frequency, ponding period and irrigation priority. For the first estimate of these data the extension pamphlets of the Ministry of Agriculture have been used. These pamphlets recommend the best planting/sowing dates, irrigation frequencies, and agronomic measures such as fertilizer use etc. In reality planting and sowing takes place during a certain period, during which the area occupied by a certain crop increases gradually. These periods are subject to calibration procedures. The same holds true for the irrigation frequency and number of irrigations which are given to the different crops. The simulated output appeared to be very sensitive for small changes in the irrigation pattern of individual crops and changes in the planting date of crops. The final results of the crop model input parameters are given in table 3.

Table 3. Calibrated growing period and irrigation pattern of the main crops in the study area.

main crop	planting period	number of full irrigations	harvesting date
long bers	15 oct - 10 dec	7	1 june
wheat	15 nov - 1 jan	4	1 june
short bers	1 oct - 15 oct	5	15 march
wint veg	15 oct - 1 nov	11	15 may
trees	1 jan - 1 jan	17	-
maize	1 may - 20 may	8	1 oct (*)
rice	15 may - 1 jul	18	15 nov (**)
cotton	15 mar - 1 apr	9	1 dec
summ veg	15 apr - 1 may	19	20 oct

* long growing season may be explained by the occurrence of nili maize

** for rice: 1 pre-irrigation for nurseries (10% of rice area); 4 nursery irrigations (15 may - 1 june); 7 pre-transplanting irrigations (1 june - 1 july).

In the model simulations, the harvesting date of the crops mentioned in table 3 does not have to be realized. Based on the crop succession preference (table 4), the planting date of the succeeding crop determines the actual simulated harvesting date. Since planting of crops is considered diffusely, this means that in the model simulations also harvesting is frequently considered during a certain time period. These aspects are taken into account in the simulation models, and the growing periods are adapted accordingly.

Table 4. Calibrated crop succession preference for the main crops in the study area. The second preference for preceding and succeeding crop is given between brackets.

preceding crops		crop	succeeding crops	
rice	(maize)	long bers	maize	(summer veg)
cotton	(rice)	wheat	rice	(maize)
summer veg	(maize)	winter veg	summer veg	(cotton)
maize	(rice)	short bers	cotton	(summer veg)
wheat	(long bers)	rice	long bers	(short bers)
short bers	(winter veg)	cotton	wheat	(winter veg)
long bers	(winter veg)	maize	short bers	(long bers)
winter veg	(long bers)	summer veg	winter veg	(short bers)

Other important crop parameters are crop development: rooting depth, soil cover, crop height and maximum ponding period (table 5). These parameters affect the evaporative demand of the crop canopy to a great extent, and are consequently important for the crop water requirements. In the models the rooting depth of the crops given in table (5) may be limited by the drain depth. The maximum rooting depth, considered in the model, is restricted to 25 centimeter less than the local drainage depth. The maximum ponding period indicates the period during which the crop withstands anaerobic conditions in the root zone without serious damage. Generally, summer crops are more sensitive to ponding than winter crops.

Table 5. Calibrated crop development characteristics and maximum ponding period for the main crops in the study area. The date, at which the maximum value is reached, is given between brackets.

main crop	max crop height (cm)	max soil cover (%)	max root depth (cm)	max ponding period (hours)
long berseem	20 (10 dec)	70 (1 jan)	30 (1 jan)	12/6
wheat	120 (1 may)	100 (1 apr)	40 (1 feb)	7
short berseem	40 (15 apr)	100 (1 feb)	30 (20 nov)	12
wint veget	30 (1 jan)	75 (1 jun)	30 (10 dec)	5
trees	300 -	80 -	125 -	6
maize	120 (15 jul)	100 (15 jul)	70 (1 aug)	8
rice	110 (1 sep)	100 (15 jul)	30 (10 jul)	-
cotton	120 (15 aug)	100 (1 jul)	75 (15 aug)	5
summ veget	30 (1 jun)	75 (1 jun)	30 (20 may)	5

The distribution of available irrigation water on farm level among the different crops in the field is a decision made by the farmer. Although crop water requirements will be of prime importance in his decisions, other considerations may also play an important role. If the supply of irrigation water is not sufficient to cover the crop water requirements of all crops, the farmer may decide to give less water to those crops which are not very sensitive to moisture stress, such as cotton, or to crops that are less profitable. In the simulation model a certain percentage of the supply is assumed to be distributed proportional to the crop water requirements. This percentage has been calibrated at 75%. The remaining 25% of the irrigation supply is given to the crops, according to the irrigation priority sequence (table 6).

Table 6. Calibrated irrigation priority ranking of the main crops in the study area.

priority	summer period	winter period
highest	rice	trees
high	vegetables	vegetables
medium	maize	long berseem
low	trees	short berseem
lowest	cotton	wheat

In the Nile Delta in Egypt the water distribution in the main irrigation system is based on waterlevel control. Water is delivered to the farm on a rotational basis at a certain, more or less, fixed level which is below land surface. Farmers are used to withdraw water from the meskaas with sakkias, which are water wheels drafted by farm animals. Supply pipes connect the meskaa with a sump, from which these sakkias lift the water into the field channels, called merwaas. The dimensions of these supply pipes are under control of the Ministry of Public Works and Water Resources. Due to the fairly constant waterlevel in the meskaa, farmers were used in the past to irrigate during the day as well as during the night. At present small movable pump units are also used for irrigation, thereby creating an additional irrigation capacity at farm level. Due to this overcapacity, farmers close to the irrigation canal intakes are no longer compelled to irrigate during the night. Depending on the frequency of gate adjustments by gate operators, the actual water distribution may deviate from the distribution intended by the Ministry of Public Works and Water Resources, due to these practices.

The factors governing these (human influenced) processes of water abstraction by farmers and target level control by the Ministry of Public Works and Water Resources appeared to be the next sensitive model input parameters to be calibrated.

The capacity of sakkias varies from location to location. Values varying from 0.015 to 0.030 $m^3.sec^{-1}$ are common in the Eastern Nile Delta. For reasons of simplicity the sakkia capacity has been set at 0.025 $m^3.s^{-1}$ at design waterlevel and the pump capacity at 0.050 $m^3.s^{-1}$. Because rotation of water supply is not considered in the SIWARE model, the actual irrigation capacity in rice areas during the summer period is higher (waterlevels above design level). The number of sakkias has been calibrated at one sakkia per 73 feddan (based on continuous supply), and the number of pumps at one pump per 292 feddan. Since these values are based on continuous supply, this means in reality one sakkia of 0.025 $m^3.s^{-1}$ per 25 - 35 feddans.

In order to ensure a proper water distribution between different irrigation canals, employees from the Ministry of Public Works and Water Resources adjust the gate openings of the water distribution structures in the irrigation canal network a number of times during the day. For the number of gate adjustments and for the time during the day that they take place (on the basis of deviations of the preset target levels), the winter period, the summer period, and two periods in between have been considered. It turned out that good results were obtained for the water distribution when in summer (june, july, and august) the gates were adjusted five times daily and during all remaining seasons three times.

The number of irrigation tools that is simultaneously in operation varies during the day. Generally, the maximum is found in the morning and in the afternoon. Due to the overcapacity of the irrigation tools, during night time only a limited number of tools are in operation. Because the day length varies with the seasons, the irrigation intensity uptake pattern (fraction of the total number of irrigation tools simultaneously in operation) has been calibrated for the winter, summer, and spring/autumn periods separately (table 7). The values given are the maximum intensities; during the model simulations they may be adjusted based on the difference between the daily demand and the amount already supplied during that day. Whenever in a certain calculation unit the required daily water duty is reached, irrigation uptake stops, and starts the next day again as soon as the maximum irrigation intensity (table 7) changes from night level to day level.

The simulation of the water allocation requirement for the main canal command intakes in the model DESIGN follows the same procedure as used by the Ministry

Table 7. Calibrated irrigation intensity uptake pattern (fraction of the total number of irrigation tools simultaneously in operation) for the different seasons in the study area.

winter = january, february, march, april, november and december
spring/autumn = april, may, september and october
summer = june, july and august

time during the day (hours)	maximum irrigation intensity (-)		
	winter	spring/autumn	summer
0 - 5	0.1	0.2	0.4
5 - 7	0.1	0.2	0.8
7 - 8	0.5	0.5	1.0
8 - 12	1.0	1.0	1.0
12 - 14	0.8	0.8	0.8
14 - 16	0.8	1.0	1.0
16 - 17	0.5	1.0	1.0
17 - 19	0.2	0.5	0.8
19 - 24	0.2	0.2	0.8

of Public Works and Water Resources. By comparing the total supply to the Eastern Nile Delta for 1986 with the total allocation requirement for this year, deviations are noticed during some periods (fig 11). During the summer period (peak demand) the supply is generally less than the allocation requirement. Possible explanations for this phenomenon are: the storage in the river Nile from Assuan to the Delta Barrages increases in order to transport the higher discharge (higher waterlevels); the seepage losses from the Nile to the aquifer increase due to higher waterlevel; and the agricultural area in Upper and Middle Egypt uses slightly more water than intended. Deviations during periods with low demand for water (in spring and autumn) generally means that the supply is higher than the allocation requirement (fig 11). The main reason for this is the minimum waterlevel which must be maintained in the Nile for shipping purposes and for the protection of barrages.

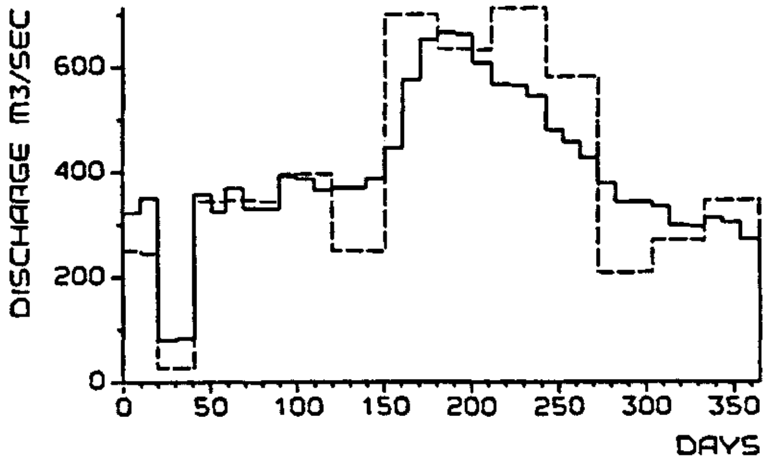

Fig 11. Comparison of the total water allocation requirement (excluding the groundwater use) for the Eastern Delta in 1986, and the total supply (including the official reuse of drainage water) per period of 10 days.

— observed — simulated

No information could be obtained from the Ministry of Public Works and Water Resources on the procedures followed in dealing with these deviations i.e. how these shortages and excesses of water were allocated over the main canal command intakes during 1986. For this reason three alternative procedures, called 'allocation rules' in this report, have been formulated in the allocation model DESIGN. They are the following:

1. allocate an excess as well as a shortage proportional to the area served;
2. allocate an excess as well as a shortage proportional to the allocation requirement;
3. - during the growing season of rice:
     * allocate a shortage proportional to the area of rice;
     * allocate an excess proportional to the allocation requirement;
   - during other periods:
     * allocate an excess proportional to the area of rice;
     * allocate a shortage proportional to the allocation requirement.

By applying these three rules and comparing the allocation reported by the Ministry of Public Works and Water Resources with the simulated water allocation the allocation rule with the best fit has been selected. It turned out that the best fit between reported and simulated water allocation for 1986 was obtained with allocation rule number 3. An average deviation in the monthly water allocation, weighted with the total discharge, of 23% was obtained with allocation rule 1; 18% with allocation rule 2; and 13% with allocation rule 3. There is some logic in this rule: the allocation water duty of the rice crop is high compared to that of other crops (table 1). As a consequence reductions in the water allocation of areas with much rice will not be felt as seriously compared to areas with little or no rice. Since rice is dominant in the northern part of the Nile Delta, where seepage conditions prevail and soil salinity is generally high, any excess water outside the rice growing season can be used there for extra leaching of the soil.

In the water distribution model WATDIS, and in the regional drainage model REUSE, the calculation unit is considered uniform. Irrigation uptake by farmers in WATDIS stops, as soon as the crop water requirement is reached. The water distribution within the calculation unit is not explicitly taken into account. Generally, farmers located near the gate inlet of the distributary canals have easier access to the irrigation water and tend to waste some. This implies that farmers at the end of the distributary canals and meskaas may have a shortage of water, although on the average the supply may be sufficient for the crop water requirements. Farmers at the end of the system generally have access to drainage water from upstream areas, and use this water to supplement the canal water supply. This is taken into account in the regional drainage water model REUSE. In order to account for the unequal water distribution within the calculation unit, an over-irrigation factor has been defined in REUSE. The farmer's decision to (unofficially) reuse drainage water is based on the crop water requirement multiplied with this factor. Based on calibration runs with the SIWARE model the over-irrigation factor has been set at 1.25.

The majority of the general (uniform) model input parameters, discussed so far were mainly crop and human behaviour related model parameters. The model output appeared to be more sensitive for these model input parameters than for the physical model input parameters. The two important physical model parameters which have been extensively calibrated are discussed below.

The clay soil in the Nile Delta has been formed during centuries of flooding by the Nile, depositing yearly thin clay layers on the soil. Alluvial soils, deposited in layers, generally have a different hydraulic permeability in horizontal direction than in vertical direction. This phenomenon is called anisotropy and the ratio between horizontal and vertical hydraulic permeability is called the anisotropy factor. This factor for the clay layers below drain depth has been calibrated at 15.

Rice is grown under ponded conditions. The flow of water from ponded fields to drains, be it covered (subsurface) or open drains is essentially different from drainage of non-ponded fields. In the latter case all drainage water will flow through the soil. Under ponded conditions, however, water flows over the surface will be dominant midway between drains. Close to the drains the majority of leaching will take place. Farmers are aware of these unequal field losses, and frequently construct small dikes, parallel to field drains. In the salinity sub-model SAMIA, this phenomenon is taken into account by defining a fraction of the drainage water which leaches the layers above drain level only. This fraction has been calibrated at 0.10.

3.5.2. Distributed model parameters

Distributed model input parameters may have different values for the distinguished calculation units. A distinction can be made between hydrological input parameters, mainly influencing the water balance, and water quality input parameters which mainly determine the salt balance. The hydrological parameters have been calibrated first, and the water quality parameters next. For the calibration of the distributed model parameters, restrictions have been made with respect to the degree to which the initial estimation of such a parameter may be varied. Not the absolute values have been calibrated, but the spatial distribution of these parameters.

A number of the most important calibrated distributed model input parameters will be discussed below. They are:

- the percentage of the area within each calculation unit that has access to the drainage water for (unofficial) reuse in irrigation;
- the clay cap thickness;
- the aquifer piezometric head;
- the radial resistance against flow to field drains;
- the salinity of the local groundwater use for irrigation;
- the salinity of the deep aquifer.

One of the important parameters to be calibrated is the percentage of the calculation unit that has access to the drainage water for use in irrigation (fig 12a). The justification for calibration of this model input parameter is insufficient knowledge. The initial estimate has been based on the intensity of the drainage system, taking the fact into account that lifting of drainage water by drainage pump stations increases the accessibility of this water for farmers. The calibrated percentage is generally higher in the north than in the south (fig 12a). In the northern part of the Eastern Nile Delta drainage water is lifted to the main drains by drainage pump stations, and one some locations this lifted drainage water can even be used by gravity.

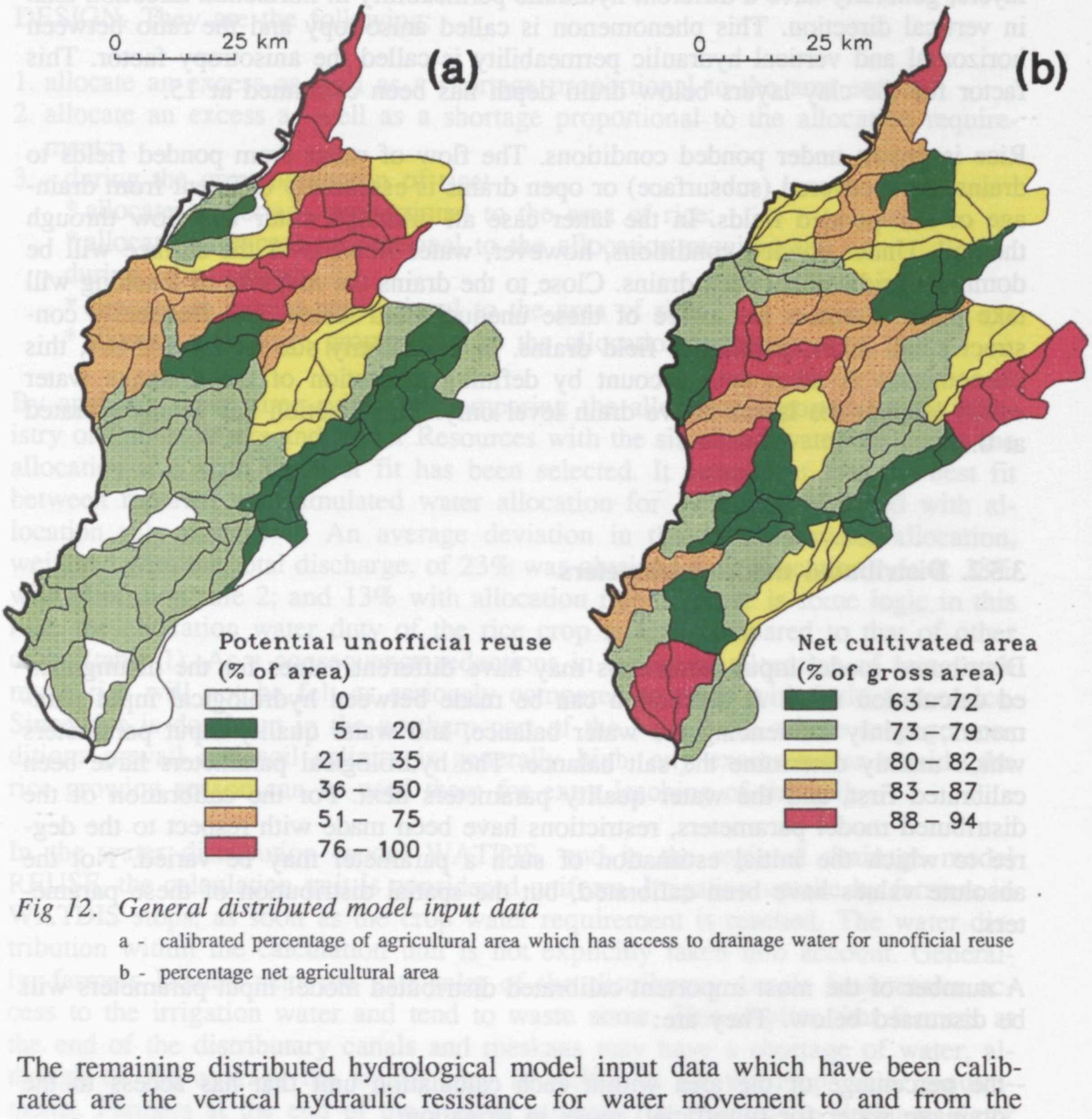

Fig 12. General distributed model input data

a - calibrated percentage of agricultural area which has access to drainage water for unofficial reuse

b - percentage net agricultural area

The remaining distributed hydrological model input data which have been calibrated are the vertical hydraulic resistance for water movement to and from the aquifer, and the piezometric head in this aquifer. The justification for the calibration of these parameters is the spatial variability on a small scale (within the calculation unit), and the limited number of observations, on which the maps with these data have been based. The piezometric head in the aquifer in the Eastern Nile Delta, for instance, is based on about 23 observation wells, which is insufficiently detailed for the 82 calculation units distinguished in the study area. For the calibration procedure, use has been made of the available drainage catchment discharges (fig 2) on monthly basis for the hydrological year 1986. Not only the total discharge has been considered, but also the seasonal distribution of the discharge. The average monthly deviation between simulated and observed discharges and salinities has been used as a measure for the model performance. This parameter is obtained by adding the absolute values of the difference between the monthly simulated and observed quantities, dividing by 12, and dividing by the yearly average value.

The calibrated values for the hydraulic resistance against vertical flow (seepage/leakage) varies between 325 days in the desert fringes and 4,650 days in the central northern part of the study area. The vertical hydraulic resistance has been modified by changing the clay cap thickness input parameter. The calibrated thickness of the clay cap varies between 2 and 23 meter. Since the clay cap thickness also influences the hydraulic resistance against flow to the drainage system, this parameter is also affected by these changes. The relation between groundwater depth and drain discharge is also influenced by the drain entrance resistance. This calibrated parameter has values ranging from 1 to 6 day.m^{-1}. A value of 1 indicates a good functioning subsurface drainage system, and a value of 6 is representative for a surface drainage system in an unripened clay soil, or a saline clay soil with a high percentage of sodium on the adsorption complex. The resulting drainage resistances, calculated according to Ernst (1962), range from 40 days in well-drained areas to 360 days in areas which are in need of subsurface drainage.

In the southern part of the study area the calibrated aquifer pressure is far below soil surface, with the exception of a fringe along the Ismaileya Canal (fig 13a). Moving to the north the aquifer pressure increases progressively, which is partly due to the corrections applied to account for the higher density of the saline groundwater in the northern part of the study area.

After calibration of the spatially distributed hydrological model parameters, two water quality model input parameters have been used to calibrate the drainage discharge salinity: the salinity of the deep groundwater; and the salinity of the groundwater used for irrigation. Due to spatial variability, both values do not necessarily have the same value for a certain calculation unit. Groundwater abstraction will most probably be concentrated on locations (and abstraction depths) within the calculation unit, where the salinity is relatively good. The salinity of the deep groundwater must be representative for the seepage fluxes which may be dominant in other parts of the unit area. Changes in the salinity of the groundwater (both for the aquifer and for the abstraction) will have consequences for the salinity of other discharges considered in the model simulations. Upon changing a parameter and after a certain time lag (several years of simulation) the effect of such a change may trickle down to affect the reuse of drainage water salinities (both official and unofficial reuse), simulated in the model. Consequently, the calibration of these parameters is very (computer) time consuming.

Sometimes the calibration procedures, described above, resulted in unrealistic values. In such situations the model parameters determining the discharge have been readjusted. This implies that the goodness of fit of the discharges and the salinities of the simulations and the observations had to be compromised. This was the case, for instance, with the calibrated seepage rates for the catchments of Lower Serw (ES02) and Erad (EH10) drainage pump stations (fig 2). Together with high seepage rates an unrealistic low salinity of the deep groundwater was necessary to fit the simulated drainage water salinity of these catchments with measured data. Through changes in the clay cap thickness and aquifer pressure these simulated seepage rates have been decreased again. In the catchment of Lower Serw the high pumped drainage water discharge can be explained by the seepage

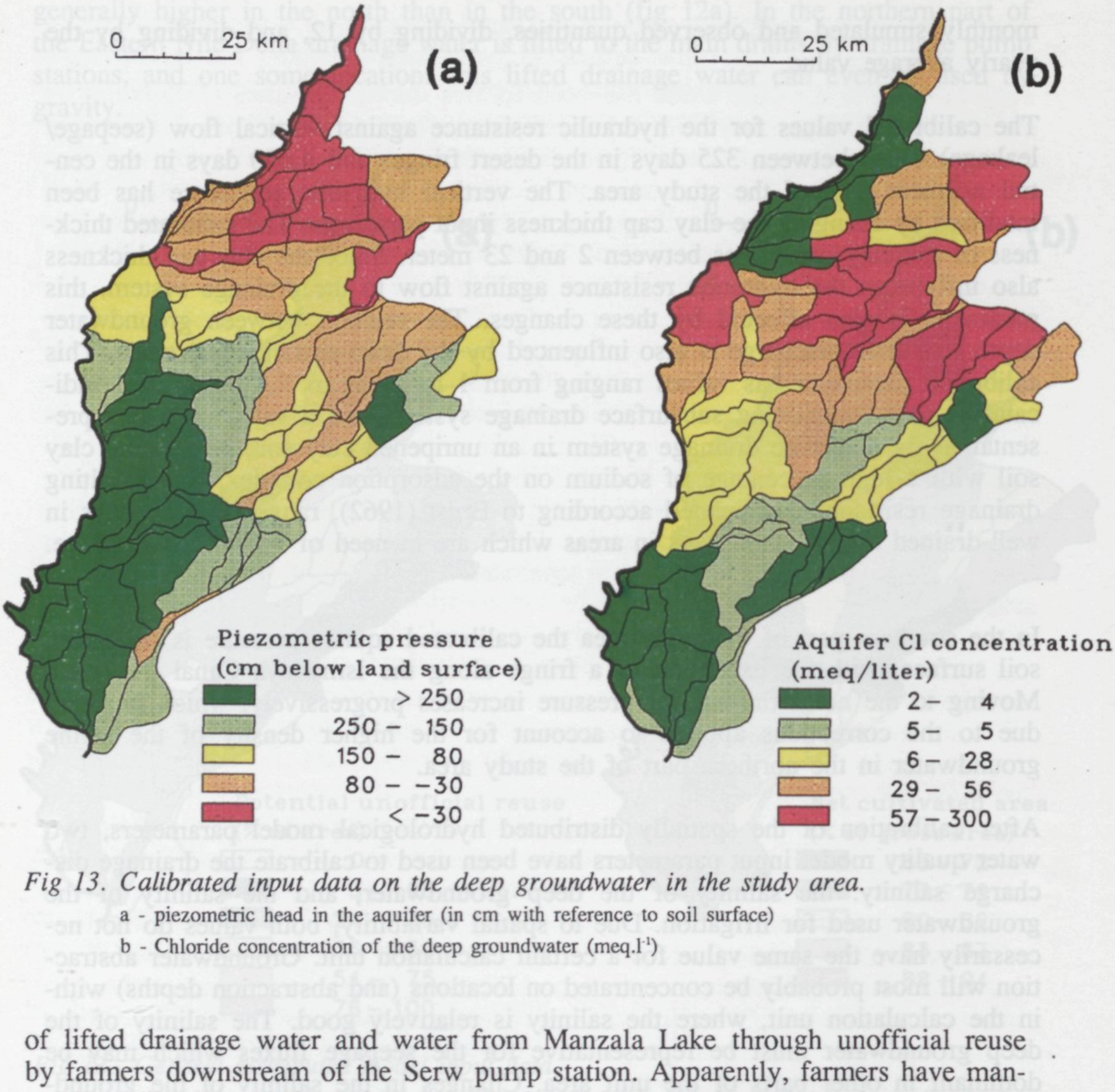

Fig 13. Calibrated input data on the deep groundwater in the study area.

a - piezometric head in the aquifer (in cm with reference to soil surface)

b - Chloride concentration of the deep groundwater (meq.l^{-1})

of lifted drainage water and water from Manzala Lake through unofficial reuse by farmers downstream of the Serw pump station. Apparently, farmers have managed to discharge their drainage water from these newly reclaimed areas to the Lower Serw catchment. In the catchment of Erad drainage pump station the lifted drainage water is flowing directly alongside deeply excavated so-called ganabeya drainage canals from which the water is lifted by this pump station. Farmers have constructed pipes crossing these ganabeya canals, and are able to irrigate by gravity using the lifted drainage water. Losses from these pipes and direct seepage through the subsoil from the lifted water to the ganabeyas is responsible for the observed high drainage discharges of Erad pump station. These aspects are not included in the model formulation, and consequently deviations in the simulated discharges for these two catchments have been accepted.

Generally, the calibrated salinity of the deep groundwater increases from the south to the north (fig 13 b), with an exception for a fringe along the Damietta Nile Branch in the north. An earthen dam at the downstream end of this Nile Branch prevents discharge of this water to the Mediterranean Sea, causing relatively high waterlevels. Based on the analysis of the local situation (Boels et al, 1990) the conclusion can be drawn that seepage through shallow good permeable soil layers to the adjacent agricultural areas at low elevation may be considerable, and of relatively good quality.

The calibrated salinity of the groundwater used in the study area generally increases from the south to the north (fig 14b). In the northern part of the Eastern Nile Delta no groundwater abstraction takes place, most probably due to the high salinity.

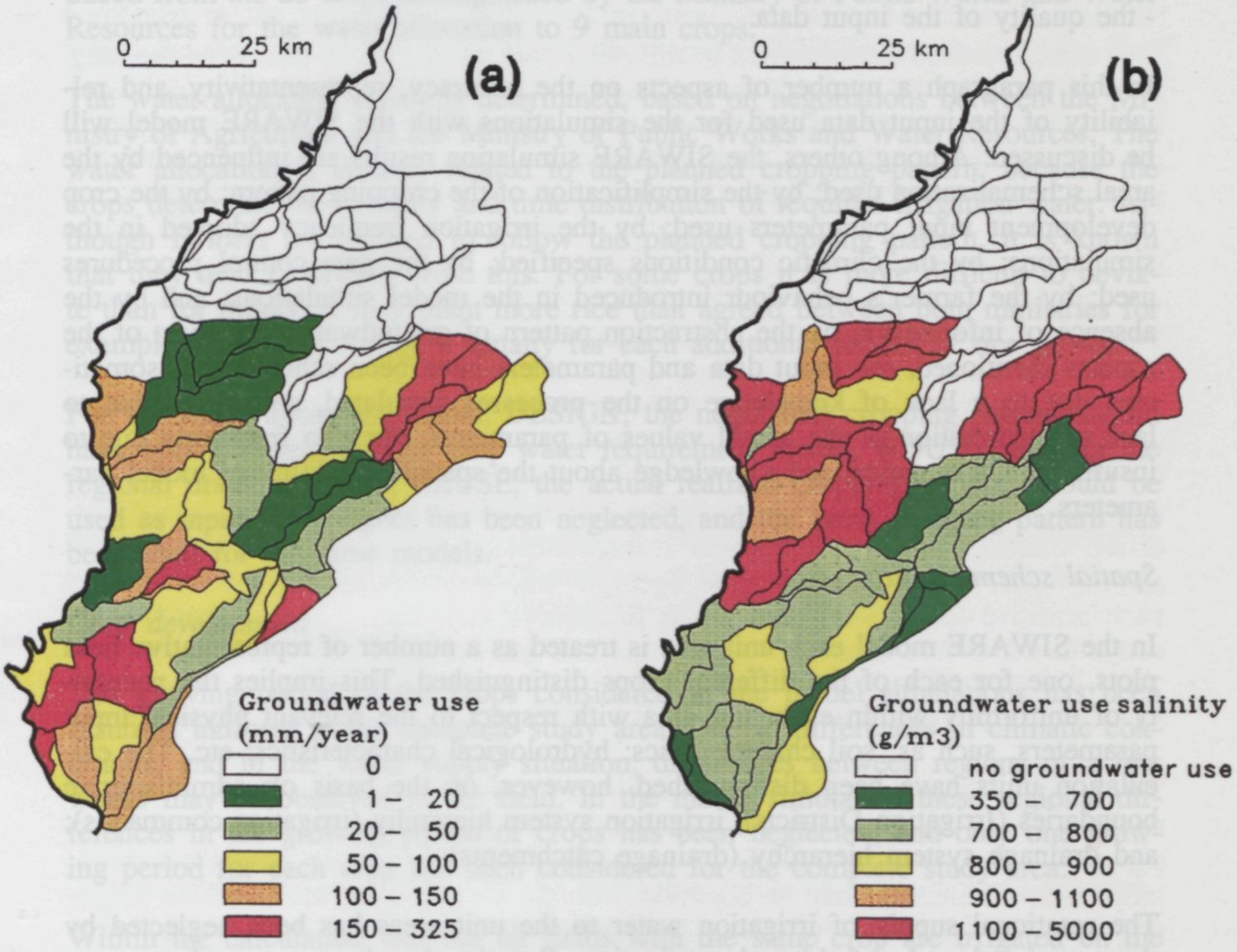

Fig 14. Groundwater use data Eastern Nile Delta

a - groundwater abstraction (mm.y^{-1}) b - calibrated groundwater abstraction salinity (g.m^{-3})

3.6. Discussion

Within the framework of the Reuse of Drainage Water Project, and the constraints imposed during the project implementation, the results presented in the underlying report give the best possible approach to the analysis of the water management of the Eastern Nile Delta. It is important, however, to be aware of the limitations associated with the simulation techniques used. To this purpose a discussion of the input data used for the SIWARE model simulations is given here with the objective to increase awareness of the importance of good information on the required input data.

The accuracy and reliability of model simulation results are determined by a number of factors, such as:

- the quality of the model formulation, including the schematization of the processes considered;
- the quality and representativity of the areal schematization used;
- the quality and reliability of the model input parameters;
- the quality of the input data.

In this paragraph a number of aspects on the accuracy, representativity, and reliability of the input data used for the simulations with the SIWARE model will be discussed. Among others, the SIWARE simulation results are influenced by the areal schematization used; by the simplification of the cropping pattern; by the crop development input parameters used; by the irrigation frequency adopted in the simulations; by the climatic conditions specified; by the gate control procedures used; by the farmer's behaviour introduced in the model simulations; and by the absence of information on the abstraction pattern of groundwater. For most of the aspects mentioned, the input data and parameters have been schematized, sometimes due to a lack of knowledge on the processes simulated, sometimes due to lack of information of the actual values of parameters, but also frequently due to insufficient information and knowledge about the spatial variability of model parameters.

Spatial schematization

In the SIWARE model each unit area is treated as a number of representative field plots, one for each of the different crops distinguished. This implies the necessity of uniformity within each unit area with respect to the relevant physical input parameters, such as: soil characteristics; hydrological characteristics; etc. The calculation units have been distinguished, however, on the basis of: administrative boundaries (Irrigation Districts); irrigation system hierarchy (irrigation commands); and drainage system hierarchy (drainage catchments).

The rotational supply of irrigation water to the unit areas has been neglected by the associated scale of this schematization. Rotation has been assumed to occur within the boundaries of the schematized calculation units. This has certain consequences for a number of input parameters, in order to counteract the effects of this simplification. To account for this, the dimensions of the inlet gates of the distributary canals and the effective storage capacity of these canals have been adapted.

Unofficial reuse of drainage water occurs locally, and takes mainly place in the area served by the most downstream reach of the distributary and meskaa canals. In the SIWARE model, this drainage water is applied uniformly to the complete calculation unit. This is a simplification of reality.

For several hydrological parameters, such as vertical resistance and hydraulic permeability, it is known that the spatial variability in an assumed uniform area may be considerable. Through calibration of those input parameters it has been attempted to establish their representative average value. It should be kept in mind, however, that such a calibrated parameter value is just the representative average for use in the model analysis and has no other operational value. Moreover, since more than one parameter is calibrated, it is very well conceivable that a different combination of parameter values produces a similar quality of output data.

Cropping pattern

The number of crops considered in the SIWARE model simulations has been reduced from the 28 crops distinguished by the Ministry of Public Works and Water Resources for the water allocation to 9 main crops.

The water allocation policy is determined, based on negotiations between the Ministry of Agriculture and the Ministry of Public Works and Water Resources. The water allocation is directly related to the planned cropping pattern, because the crops determine the quantity and time distribution of required irrigation water. Although farmers are obliged to follow the planned cropping pattern, it is known that they tend to deviate from this. For some crops it is more difficult to deviate than for others. If they plant more rice than agreed between both ministries for example, they have to pay a penalty for each additional feddan of rice grown.

For the water allocation model, DESIGN, the negotiated cropping pattern should have been be used. For the crop water requirement model, WDUTY, and for the regional drainage model, REUSE, the actual realized cropping pattern, should be used as input. This aspect has been neglected, and the same cropping pattern has been used for the three models.

Crop development

The growing period of the crops considered in the model simulations has been assumed uniform in the complete study area. Due to differences in climatic conditions, and in the water supply situation, differences between regions of a few weeks may be observed in the field. In the model simulation these regional differences in the growing period of crops has been neglected, and only one growing period for each crop has been considered for the complete study area.

Within the calculation unit not all fields with the same crop are irrigated on the same day. In the model simulations this phenomenon is taken into account as far as the irrigation water input and simulated drainage water is concerned. The same should consequently have been done with the crop development input data such as rooting depth, relative soil cover, crop height, etc. This has not been taken into account in the model simulations.

Under saline soil conditions crop growth is retarded, and crop height as well as soil cover are affected. In the model simulations the resulting feedback to the crop evaporative demand has been neglected.

Crop irrigation intervals

In the SIWARE model simulations the irrigation intervals have been fixed for the complete study area. The possibilities for farmers to irrigate their fields more frequently are limited, because the water is supplied on a rotational basis. Under saline conditions, however, farmers will certainly try to practice shorter intervals in order to achieve sufficient leaching without crop damage due to prolonged ponding. Also, in areas with a restricted drain depth, which may impede root growth, a higher irrigation frequency may be used by farmers, to offset the limited soil water availability. Finally, on sandy soils in the desert regions, the evaporative demand and the limited available soil moisture storage may also promote farmers to practice shorter irrigation intervals. These aspects have not been considered in the SIWARE model simulations.

Climate

The climatic zones distinguished in the Nile Delta of Egypt are based on the long term observations of about 12 meteorological stations. As a consequence the exact boundaries between these climatic zones are arbitrary. Since the long term average climatic data have been used, differences between individual years are averaged out. This has consequences for the simulation results.

Gate operation procedures

The gate operation procedures have been calibrated as an uniform procedure, which has been assumed valid for all gates in the complete study area. It is easily conceivable, that the larger gates in the main canal system are adjusted more frequently and accurately than the smaller inlet gates to the unit areas. Depending on the size of the area served by a certain distributary canal, and in relation to the crops grown, the ratio between discharge and storage capacity of such a canal may differ. Canals with a relatively low storage capacity are more liable to spill irrigation water. In practice, the gate operator will probably pay more attention to such sensitive inlet gates, than to the insensitive ones with a larger storage capacity. In the SIWARE model simulations this has not been taken into account.

Farmer's behaviour

The irrigation water uptake pattern has been considered uniform for the complete study area. Farmers in calculation units, suffering (temporarily) from water shortages, will most probably deviate from this uptake pattern. Also within the calculation unit differences may be common. For the allocation of the available irrigation water at farm level to the different crops a priority ranking has been defined. This irrigation priority, does not change with time, and neglects the occurrence of stress sensitive periods during the growing season of crops.

Groundwater use

Due to lack of information on the seasonal distribution of the groundwater abstraction in the different Irrigation Districts, the abstraction has been assumed constant with time. Most probably, farmers will use more groundwater during the peak demand period.

4. COMPARISON SIMULATION RESULTS WITH OBSERVATIONS

4.1. Introduction

A large number of physical and functional relationships have been formulated and combined in the water distribution and regional irrigation and drainage models, which are the different components of the regional SIWARE model package. For a correct validation of these models, field data on input and output of each of the relations included in the models should be collected. By comparing the observed and the simulated output of each relation the model validity can be proven. A complete coverage of all relations considered requires, however, an enormous research effort and is beyond the scope of this project.

The collection of sufficiently accurate and representative field data for model input for the Eastern Nile Delta alone, has proven to be a too large effort to be implemented within the framework of the project. Model input data calibration has been used instead in order to obtain more accurate model results. During this procedure the measured output is used as a yardstick for changing the input data between certain ranges. The values giving the best results are then finally selected. Accurate results for the circumstances for which the data have been calibrated, do not automatically mean that the simulation results are also reliable. Therefore, it is always necessary to use an additional set of measured output data for different circumstances in order to prove the validity of the model approach.

Model input parameter estimation (calibration) and checking (validation) has been performed at the four levels for which measurement data are available:

- at canal command level for the water allocation procedures (model DESIGN);
- at irrigation branch canal level for the water distribution within the irrigation canal command (model WATDIS);
- at drainage catchment level for the integrated result of hydraulic and operational relations in the irrigation canal network, irrigation water supply, farmers behaviour, field water distribution, evapotranspiration, drainage and salt accumulation relations including official and unofficial reuse of drainage water (model REUSE);
- at composite catchment level, based on the measurement locations of the Drainage Research Institute (model REUSE).

For the first two levels of comparison the observations of the Ministry of Public Works and Water Resources have been used. These observations cover the complete Eastern Nile Delta. The drainage water discharge and salinities have been monitored by the Drainage Research Institute on drainage catchment scale. These observations are restricted to the major part of the study area (fig 3).

4.2. Calibration year 1986

The input data which are required for performing model simulations with the SIWARE model package can be subdivided into three types which are fundamentally of a different nature:

- input data which define the water management strategy, such as cropping pattern, allocation water duties and water supply data;
- model input parameters which determine the system's physical behaviour;
- initial input data for moisture and salinity conditions of each soil layer for each crop in each calculation unit considered.

Of these input data only the system behaviour model input data are subject to calibration. This means that the values of such model input parameters are changed in order to fit the model simulation results with the field observations. The justification and methodology of model input parameter calibration has been treated in the previous chapter.

The main model input parameters which have been calibrated are the following (clustered in sequence of importance):

- crop characteristics such as: growing period, irrigation frequency, ponding period, and irrigation priority;
- crop development: rooting depth, relative soil cover, and crop height;
- farmer's irrigation tool capacity and daily irrigation water uptake pattern;
- allocation of water excesses and shortages over the main canal intakes;
- over-irrigation factor to account for the unequal water distribution within the calculation unit;
- anisotropy of the clay cap;
- distributed model input parameters:
  *percentage of the calculation unit which has access to the drainage water;
  *clay cap thickness;
  *aquifer piezometric head;
  *radial field drain resistance;
  *salinity groundwater use;
  *aquifer salinity.

Estimation of the initial status of soil moisture conditions and salinity from the literature or by field observations is virtually impossible (88 calculation units with 5 winter crops and 20 soil layers per crop results in about 40,000 initial salinity data for the start of the model simulations). As an alternative a historical run with the SIWARE model using the actual cropping patterns and water supply data for this period can be used. The required cropping pattern and water supply data for such a period are not easily available however. In the present approach, a year with a more or less long term average water supply and cropping pattern has been selected. This year (1986) has been used for both the model input data calibration and, by running the SIWARE model for a sufficient number of years, the estimation of initial soil moisture and salinity data.

For the model input data calibration one year of field observations has been selected. Two main considerations have played an important role in this selection:

- the field observations of the hydrological year used for the model input data calibration with which the simulations have to be compared should be sufficiently accurate and reliable;
- the hydrological year in question must have a cropping pattern and a water supply which does not deviate much from the long term historical average.

Following this procedure, it has been implicitly assumed that equilibrium conditions prevail for the calibration year 1986. This implies that no soil salinization or desalinization takes place during 1986 in the model simulations.

4.2.1. Water allocation and distribution

The water allocation algorithm in the model DESIGN deals with assigning the available Nile water at the Delta Barrages to the canal commands. The following aspects are taken into account: the official Ministry of Public Works and Water Resources water allocation duties per crop per month; the official reuse of drainage water per command area; the groundwater use per command area; the domestic and industrial water requirements per canal command; and the distribution of shortages or excesses of Nile water supply at Delta Barrage level over the different canal commands distinguished. Using the water allocation rule where both shortages in the summer period as well as excesses in the autumn, winter and spring periods are distributed proportional to the area of rice grown in the command area appeared to give best results (figs 15 and 16).

During summer time the simulated water allocation to the Ismaileya canal command seems to be underestimated (fig 15a). During the same period the calculated allocation to Rayah Tawfiki is higher than the quantities reported by the Ministry of Public Works and Water Resources (fig 15b). During this period large quantities of irrigation water destined for the Ismaileya command area are transported to this area through the connection between Tawfiki canal and Wadi canal (fig 4). In the schematization of the irrigation canal network this connection between both canal commands has been taken into account for the water allocation, but the percentage of the command area located in the Ismaileya area served by this connection, the Akhdar canal (fig 4) is considered as a constant fraction. By adding both the simulated and the reported water allocation to both canal commands together, the deviation during the summer period becomes negligible (fig 15d).

During winter time the simulated water allocation to the Tawfiki command area seems to be underestimated (fig 15b). During the same period the calculated allocation to Mansureya canal is higher than the quantities reported by the Ministry of Public Works and Water Resources (fig 15c). During this period large quantities of water are transported through the Rayah Tawfiky to the Mansureya canal. For this purpose the Mit Ghamr head regulator at the tail-end of Rayah Tawfiky is used (fig 4). In the schematization of the irrigation canal network this connection has not been taken into account as a feeder of Mansureya canal, but as a tail-end of Rayah Tawfiki. By adding both the simulated and the reported water allocations to both canal intakes together, the deviation during the winter period becomes acceptably small (fig 15e).

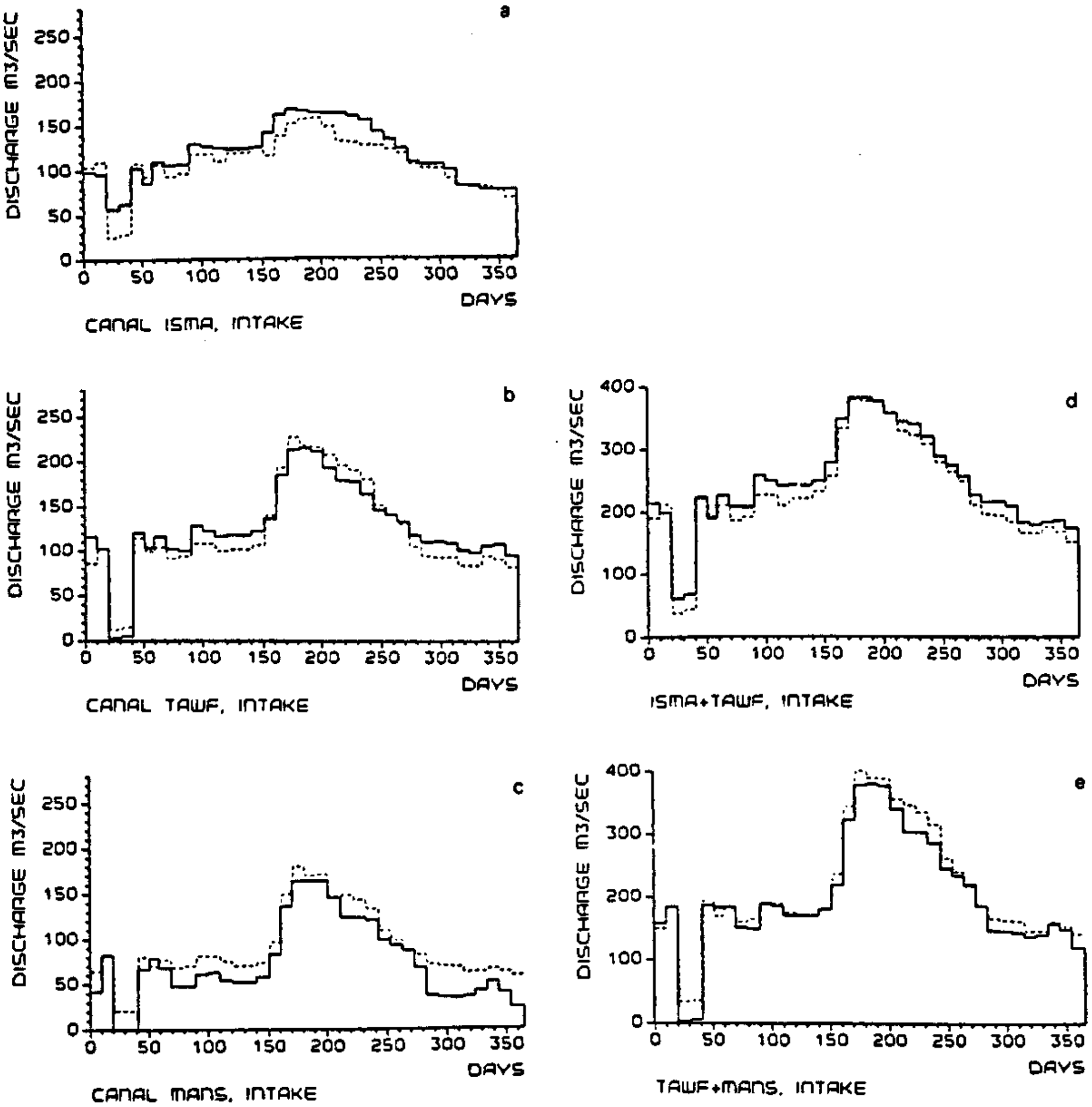

Fig 15. Simulated and realized water allocation to the three major irrigation command areas in the Eastern Nile Delta during 1986.

a - Intake Ismaileya Canal
b - Intake Rayah Tawfiki
c - Intake Mansureya Canal
d - Sum of Ismaileya and Tawfiki intakes
e - Sum of Tawfiki and Mansureya intakes
— observations;
--- simulations

For the three small irrigation command areas in the southern part of the Eastern Nile Delta (fig 16), the deviations between the simulated water allocation and the values reported by the Ministry of Public Works and water Resources are relatively large. The reasons are most probably the inaccuracies in the spatial schematization of these command areas and in the uncertainty about seasonal distribution of the groundwater use. Groundwater abstraction has been considered constant during the year in the model simulations and is relatively high and thus relatively important in this part of the Eastern Nile Delta. By summing both the simulated and reported allocations to these three minor command areas together, it can be seen (fig 16d) that the total deviations for this part of the Eastern Nile Delta is within acceptable limits.

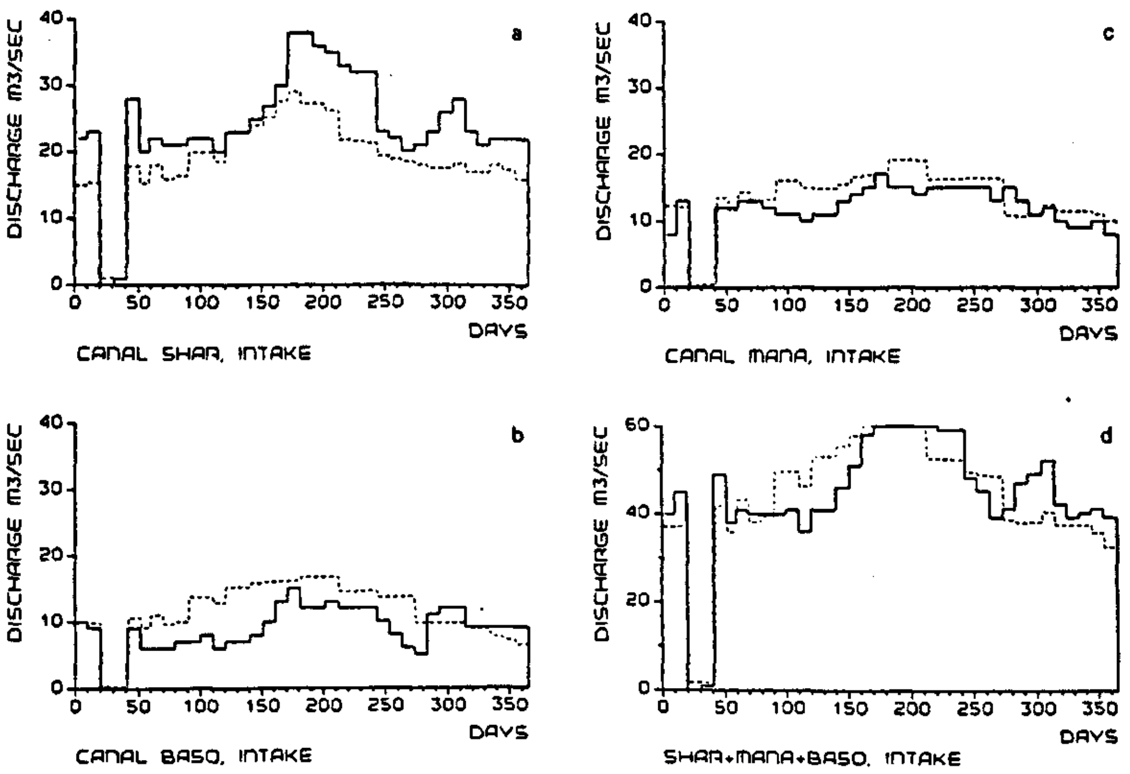

Fig 16. Simulated and realized water allocation to the three minor irrigation command areas in the Eastern Nile Delta during 1986.

a - Intake Sharqaweya Canal
b - Intake Managa Canal
c - Intake Bassoseya Canal
d - Sum of the three small commands
* observations;
— simulations

The results of the water distribution simulations generally show a fair agreement with the reported values by the Ministry of Public Works and Water Resources. For the two main branch canals of Ismaleya Canal (figs 17a and 17b), Wadi Canal and Saidia Canal, the results for Saidia are satisfactory. For Wadi Canal the simulated summer discharges are higher, and the winter discharges lower than those reported by the Ministry. These deviations can be largely explained by the practice to use the Akhdar Canal as an additional feeder of Wadi Canal. Akhdar Canal is a side branch of Bahr Mois Canal which is supplied through the Rayah Tawfiki Canal (fig 4). In the model simulations the supply of Nile water through the Akhdar Canal is assumed to be a fixed yearly percentage of the net water requirements of Wadi Canal downstream of the tail-end of Akhdar Canal.

For the side branches of the other two main irrigation canal commands, Rayah Tawfiki and Mansouria Canal (fig 17) the deviations between the simulated and reported discharges are relatively small.

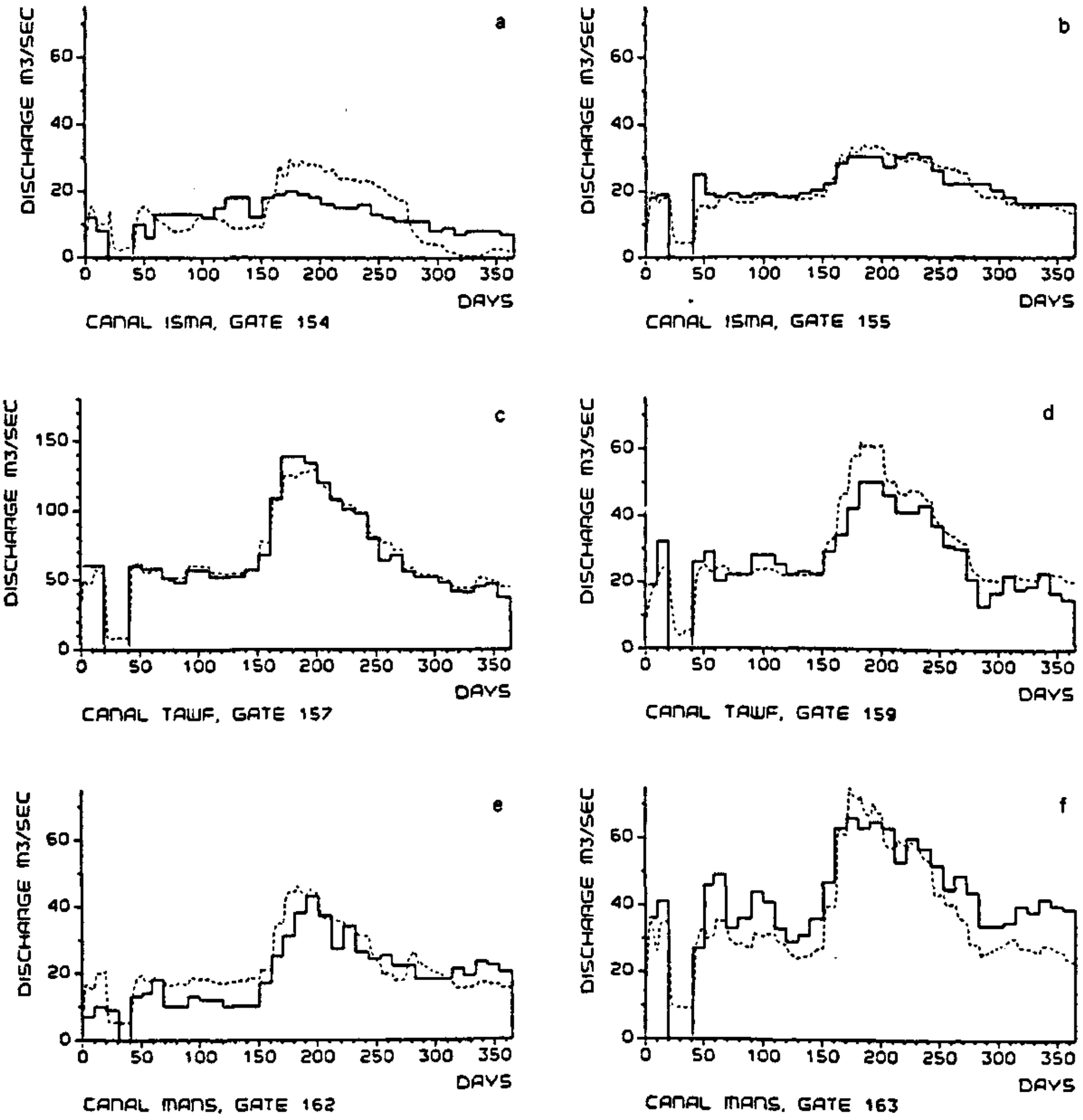

Fig 17. Measured and simulated discharges through the inlet gates of the six important side branches in the Eastern Nile Delta during 1986.

a - Wadi Canal	b - Saidia Canal	(both Ismaleya command)
d - Bahr Mois Canal	d - Bouhia Canal	(both Tawfiki command)
e - Bahr Tanah Canal	f - Bahr Saghir Canal	(both Mansureya command)
¯measured;	— simulated	

4.2.2. Drain water discharge and salinity

Below the level of side branches in the irrigation canal system no data are available for checking the model performance with respect to the water distribution. The next level for which checking can be done is the drainage catchments. The required discharge and salinity data have been collected by the Drainage Research Institute. The total drainage to the Mediterranean Sea and to the coastal lakes has been estimated at only 43% of the total Nile water supply to the Eastern Delta in 1986. This means that model performance is judged on 43% of the water balance only. A 10% deviation in the simulated water supply therefore corresponds roughly with a 23% deviation in the drainage discharge. In other words: the REUSE model is very sensitive for the simulated water distribution, and a good performance of the SIWARE model with respect to drain discharges indicates also a good performance of the simulated water distribution.

Before starting the calibration of input parameters, the criteria with respect to the required accuracy of the simulations have been determined by the Steering Committee (table 8). The parameter used for the comparison of the simulations with measurements is the average monthly deviation. This is the average of the differences between monthly measured and simulated values, expressed as a percentage. Because deviations tend to average out when the results of small individual catchments are combined, the criterium is more strict for composite catchments and for the complete study area.

Table 8. Pre-set model performance criterium: average monthly deviation allowed.

	discharge	salinity
single catchments	30%	50%
composite catchments	20%	30%
complete study area	10%	20%

For all single catchments the model performance has been sorted according to decreasing average monthly deviation (fig 18). Both for discharge and salinity the model performance on single catchment scale (average monthly deviation) is satisfactory for 99% of the area covered by single catchments. The model performance criterium characterizes the deviations relative to the observed values. Comparing the deviations of Farasqur and Main Qassabi catchments (18% and 17% for discharge; 16% and 27% for chloride concentration) with those of Saada catchment (50% for discharge and 59% for chloride concentration) clarifies this point (fig 19). On this scale (smallest drainage catchments) the regional differences in the magnitude of the drainage quantity is remarkable: from 5 to 10 mm.day^{-1} in the north (Farasqur and Main Qassabi) to 1 to 2 mm.day^{-1} in the south (Saada).

For the larger single catchments the regional differences are much less (fig 20) and discharges generally range between 1 and 3 mm.day^{-1}. It should be noted, however, that the larger single catchments are not located in the north, but in the southern and middle part of the Eastern Nile Delta. The same holds true for the composite catchments (fig 21).

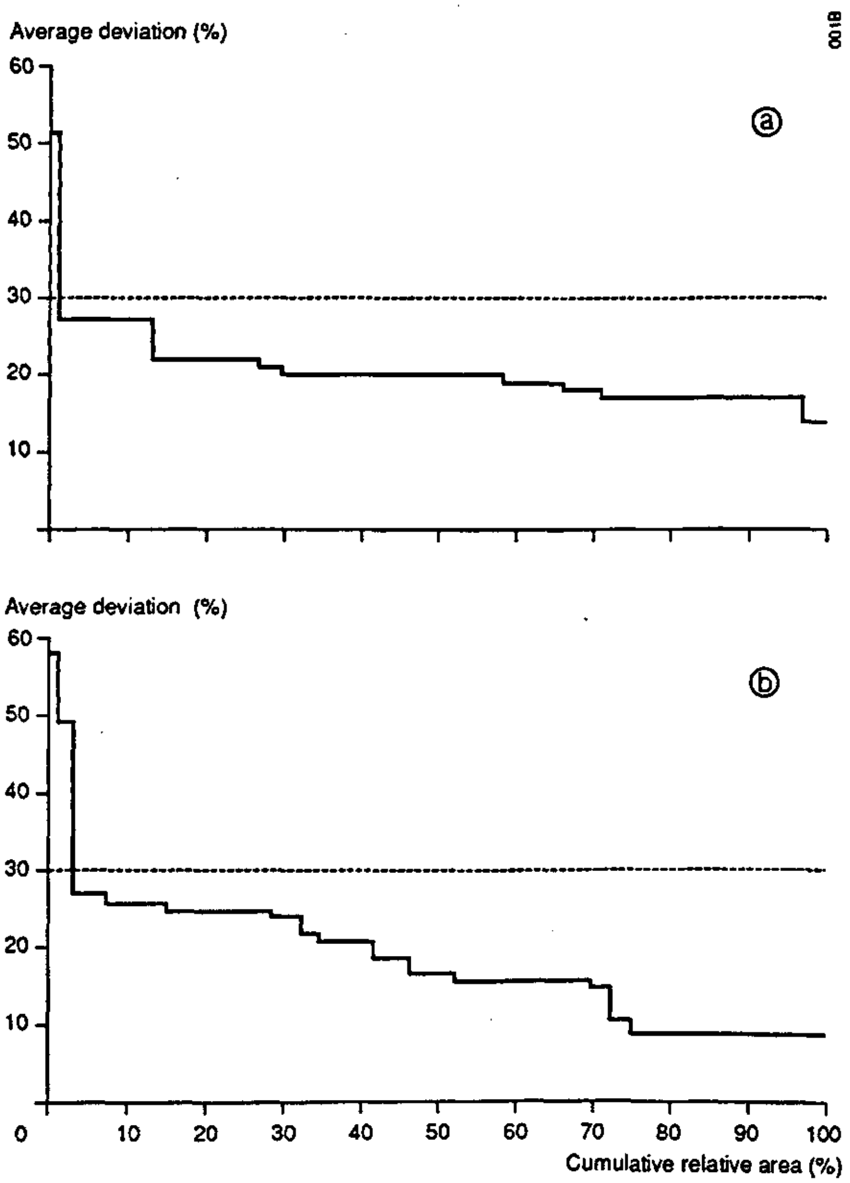

Fig 18. Model performance on single catchment scale; relation between the average monthly deviation and the percentage of the area covered with higher deviations.
a - discharge b - chloride concentration

The discharge of the total study area simulated with the SIWARE model agrees quite good with the observations for 1986 (fig 22a). The average monthly deviation between simulations and observations complies with the criterium set by the Steering Committee (table 8). The same is true for the salinity expressed as chloride concentration in the drainage water (fig 22b). On this scale the model performance (deviation 8%) obviously excels the criterium for salinity (20% deviation permitted; table 8). The resulting simulated salt (chloride) load from the study area consequently also fits the observations sufficiently good (fig 22c).

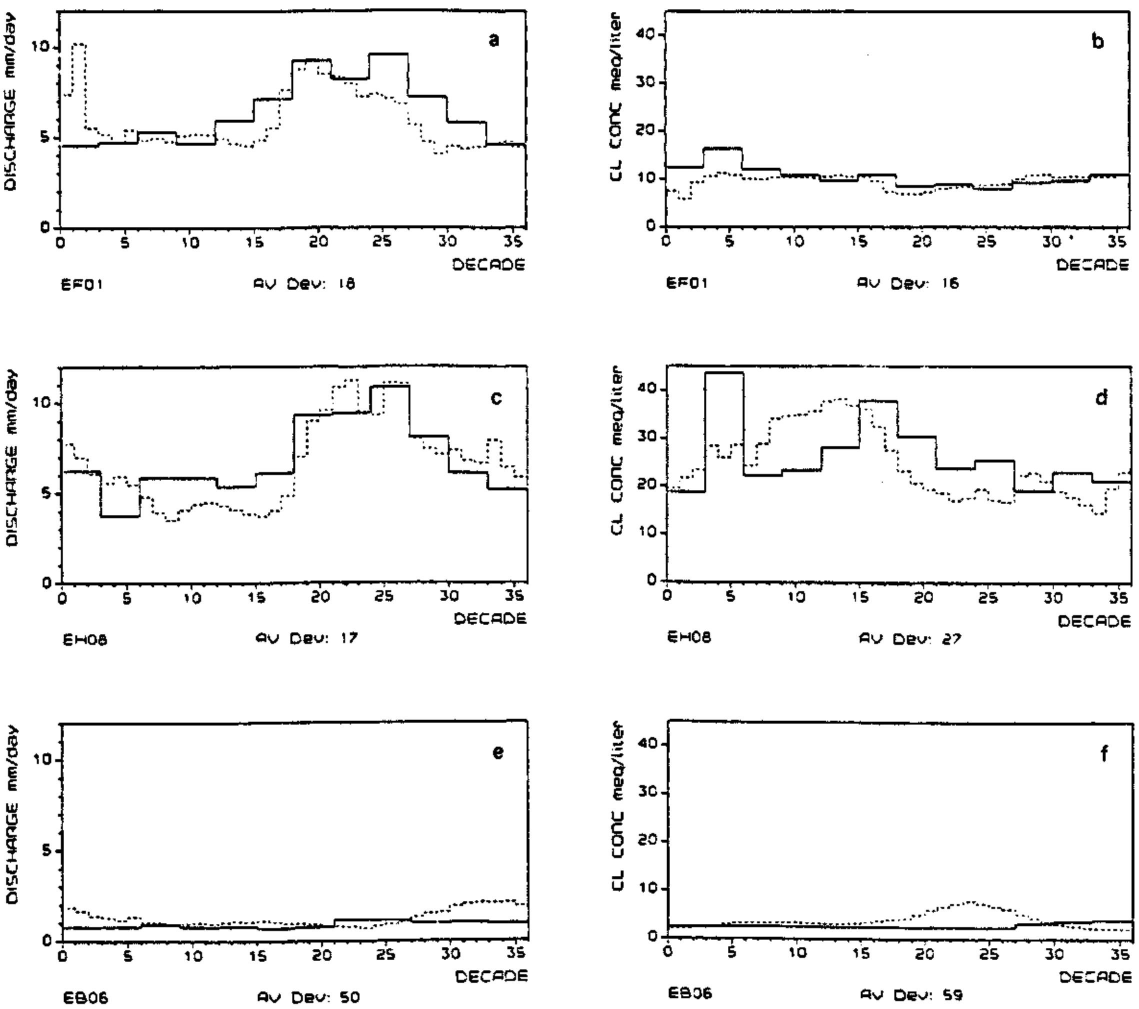

Fig 19. Simulated and observed drainage discharges (mm.day^{-1}) and chloride concentrations (meq.liter^{-1}) for the three smallest single catchments in the study area.

a - discharge Farasqur	(29,000 feddan)	b - concentration
c - discharge Main Qassabi	(26,000 feddan)	d - concentration
e - discharge Saada	(20,000 feddan)	f - concentration
—measurements;		--- simulations

For 99% of the area covered by the drain discharge and water quality monitoring programme carried out by the Drainage Research Institute, the SIWARE model performance for the year 1986 complies to the accuracy requirements preset by the Steering Committee. This good performance has been reached by the calibration of a number of relevant model parameters.

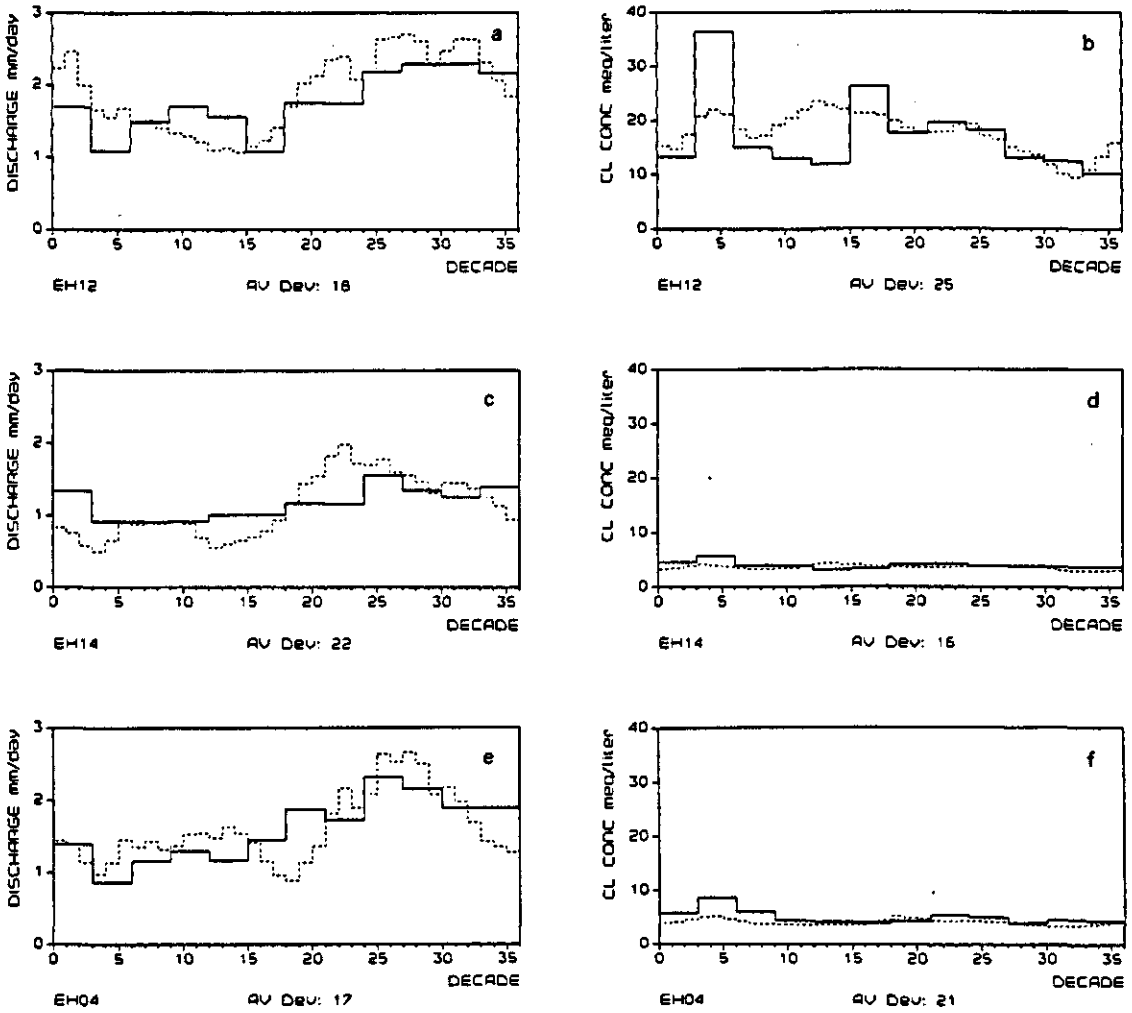

Fig 20. Simulated and observed drainage discharges (mm.day^{-1}) and chloride concentrations (meq.liter^{-1}) for the three largest single catchments in the study area.

a - discharge Saft	(198,000 feddan)	b - concentration
c - discharge Kemeeza	(165,000 feddan)	d - concentration
e - discharge Nizam	(104,000 feddan)	f - concentration
—measurements;		— simulations

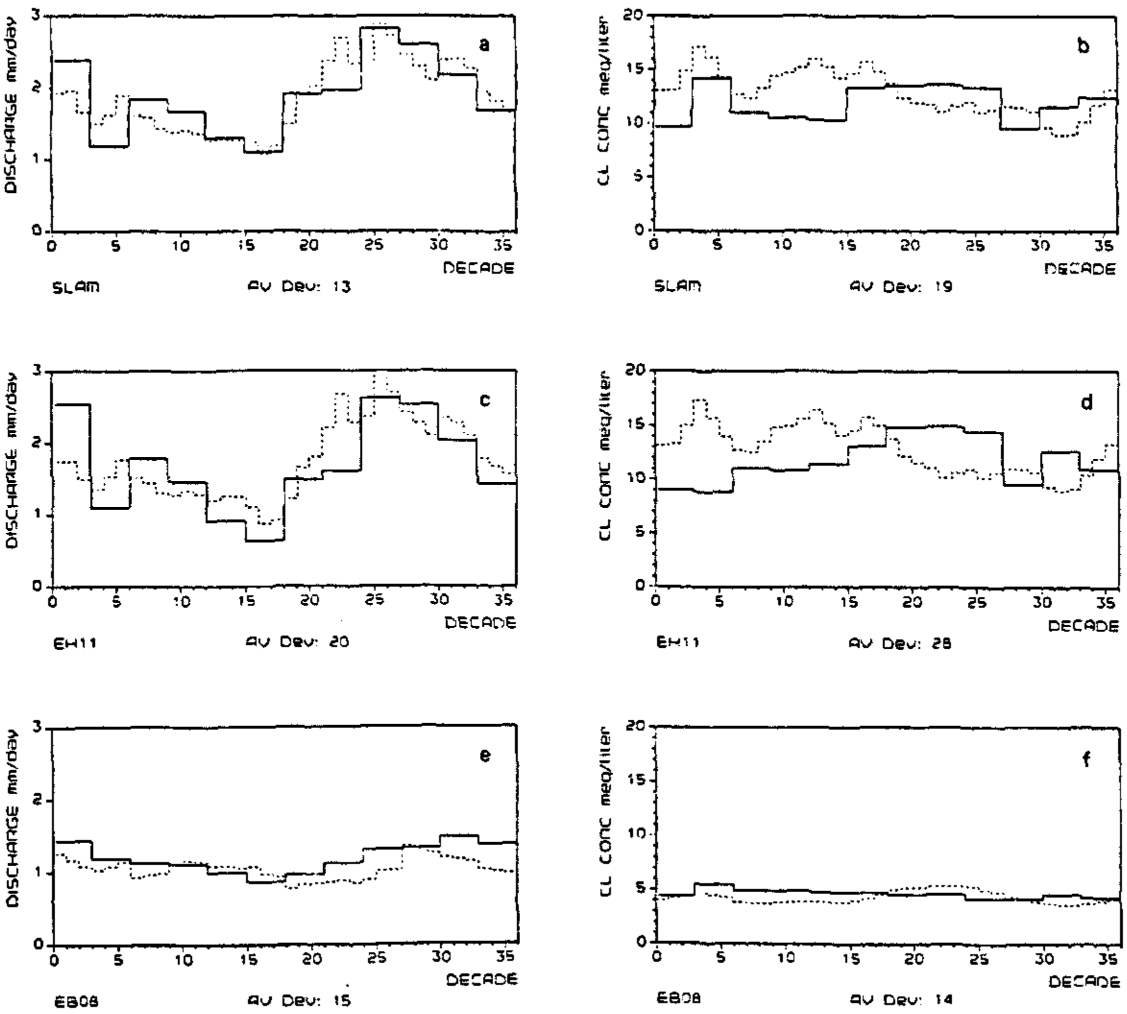

Fig 21. Simulated and observed drainage discharges (mm.day^{-1}) and chloride concentrations (meq.liter^{-1}) for three composite catchments in the study area.

a - discharge Salam	(915,000 feddan)	b - concentration
c - discharge Hadus	(654,000 feddan)	d - concentration
e - discharge Bahr Baqar	(494,000 feddan)	f - concentration
— measurements;		— simulations

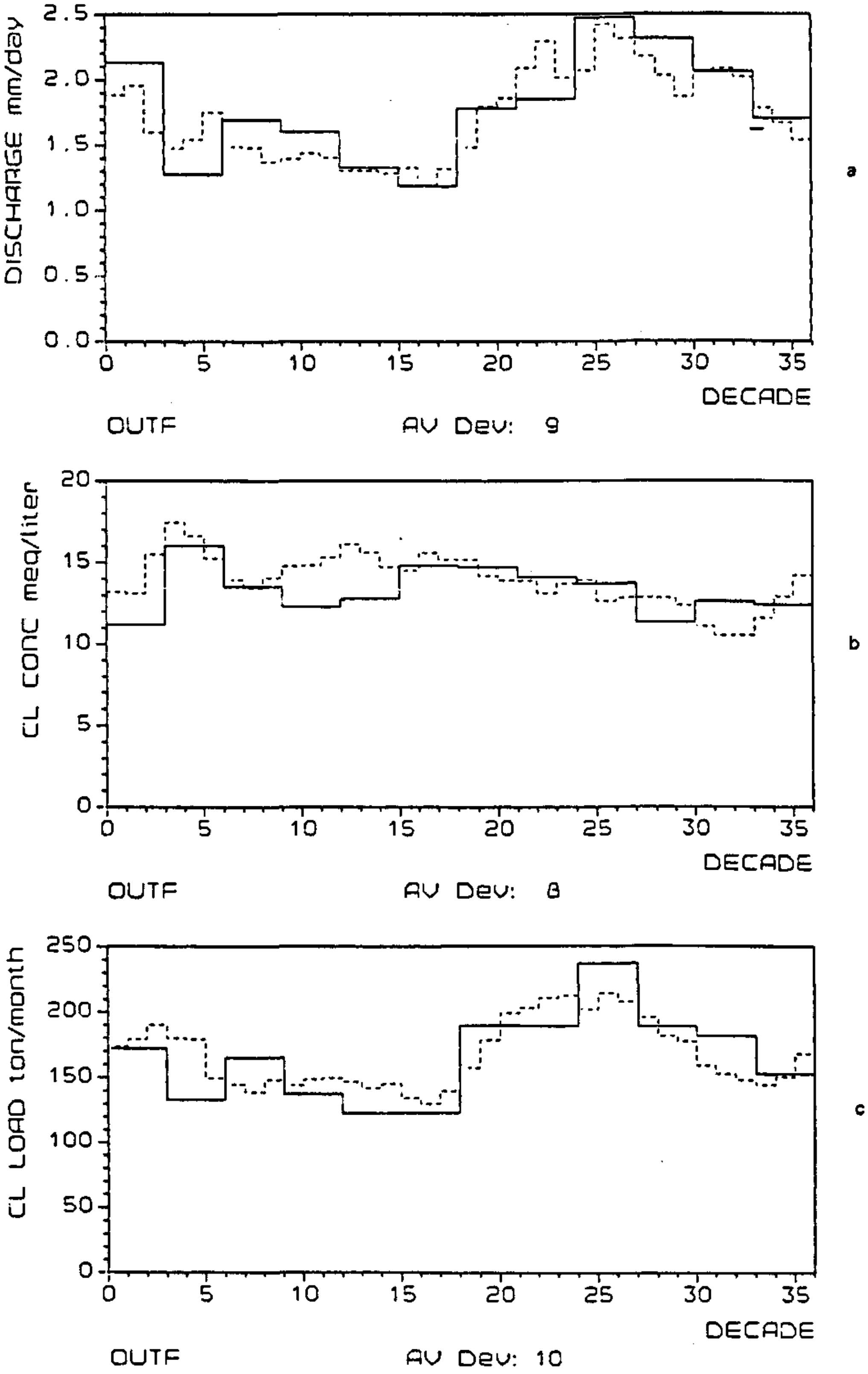

Fig 22. Simulated and opserved drainage discharges (mm.day^{-1}), chloride concentrations (meq.liter^{-1}) and chloride loads (tonne.month^{-1}) for the study area in 1986.

a - discharge b - concentration c - chloride load

— measurements; --- simulations

4.3. Validation period 1984/1988

Accurate simulation results with model parameter values which have been calibrated for the same period does not prove that the simulation model represents reality sufficiently well, nor does it prove that the model parameter values used are representative for the actual values in physical reality. The reliability of calibrated model parameters remains questionable. Since more parameters are calibrated simultaneously, it is very well conceivable that a different combination of parameter values will produce a similar quality of output data.

For judging the model performance for the calibration period attention has been paid to the seasonal distribution of drain discharge and salinity by using the average monthly deviation parameter. Also during the validation period the agreement of seasonal distribution with the measured one is important. The first concern of the modeler, however, is that the trend in the simulated yearly totals for the validation period is in agreement with the observations. Therefore, the main emphasis in this paragraph will be on the comparison of the simulated and observed yearly totals for the validation period.

Determining the predictive value of a simulation model should always be done for different circumstances than those used for model parameter calibration. This procedure, i.e. checking the model performance for different circumstances, is called validation. The observation period from 1984 till 1988 covers a substantial range of variation in water supply to the Eastern Nile Delta (table 9). Calibration of model parameters has been done for the more or less average supply of 1986.

Table 9. Nile water supply to and drain discharge from the Eastern Nile Delta during the validation period 1984 - 1988. Figures in 10^9 $m^3.year^{-1}$.

year	supply Nile water	drain discharge	official reuse	difference with preceding year		
				supply	discharge	reuse
1984	12.243	4.633	0.801	-	-	-
1985	11.969	4.355	0.804	-2.2%	-6.0%	+ 0.4%
1986	11.645	4.281	0.925	-2.7%	-1.7%	+15.0%
1987	11.249	3.948	0.814	-3.4%	-7.8%	-12.0%
1988	10.322	3.652	0.652	-9.2%	-7.5%	-19.9%

Due to the recent prolonged drought period in the catchment of the river Nile the water supply to Lake Nasser, which forms the storage reservoir for Egypt, has been less than the withdrawal of water. As a consequence of the lower storage level, the Ministry of Public Works and Water Resources started to decrease the irrigation water supply to the Egyptian agriculture in 1985. The Nile water supply to the Eastern Nile Delta has been progressively reduced from 2.2% in 1985 to 9.2% in 1988. The reduction in supply of 1985 has not been compensated by additional measures and, as a consequence, the total drainage reduced with as much as 6.0%. In 1986 the reduction in the supply of 2.7% has been compensated by increasing the reuse of drainage water. One new reuse pump station Blad El Ayed came into operation, while Hanut pump station the pumped discharge was been increased. The reductions in water supply during 1987 and 1988 could not be compensated by additional reuse of drainage water. Given the reuse pump station infrastructure the maximum reuse possibilities were used during these years. Consequently, a reduction of 12% in reuse quantity resulted in 1987 and almost 20% in 1988. The large reduction in the water supply in 1988 was complemented by the water management measure to reduce the rice area with about 25% from 472,300 feddans in 1987 to 357,300 feddans in 1988.

4.3.1. Water allocation and distribution

The water allocation and distribution appear to be predicted fairly well by the SIWARE model for the validation period (fig 23). For some of the intakes (e.g. Rayah Tawfiki and Mansureya) the simulations deviate systematically from the observations. The same holds true for the simulation results of the irrigation canal side branches (fig 23b). Since the deviations are systematic, this means that the simulated trends are correct.

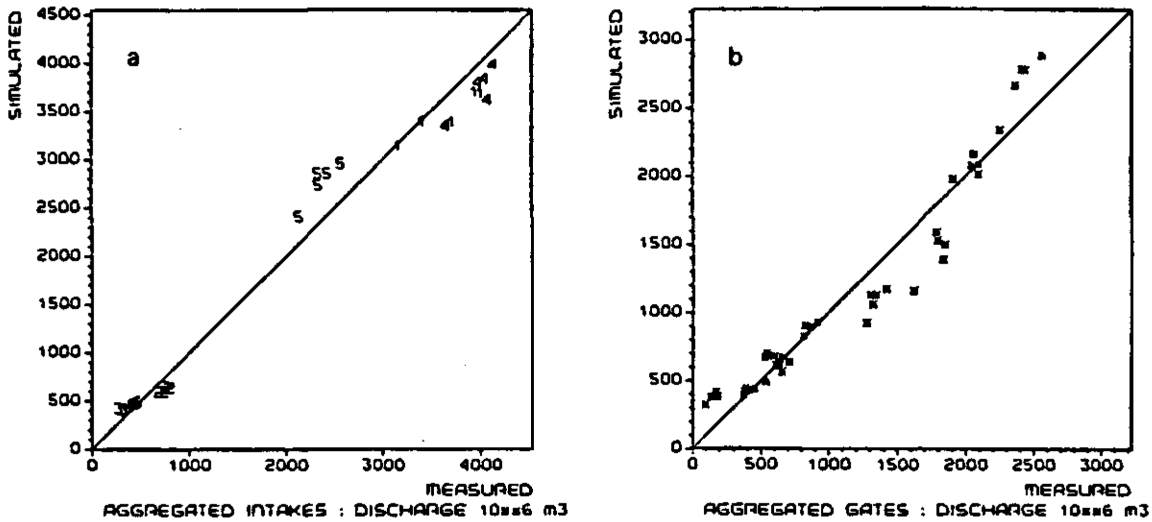

Fig 23. Comparison of simulated year discharges with observations for the validation period 1984 - 1988.

a - intakes: 1 - Ismaileya intake 2 - Sharqaweya intake 3 - Bassoseya intake
4 - Rayah Tawfiki intake 5 - Mansureya intake 6 - Abu Managa intake
b - side branches

That differences in the trends between individual side branches may be considerable is illustrated by comparing the discharges to Bahr Mois and to Bouhia Canal (fig 24), which are both side branches of Rayah Tawfiki main Canal. In Bahr Mois the range of variation in discharge over these years, both measured as well as simulated is about 10% between 2,000 and 2,200 million $m^3.year^{-1}$. In Bouhia Canal on the contrary the range of variation is about 25% between 950 and 700 million $m^3.year^{-1}$. The main reason for this difference in ranges is the change in area cultivated with rice in the area served by Bouhia Canal in 1988. In the area served by Rayah Tawfiki Canal the reduction of rice area in 1988 was much less.

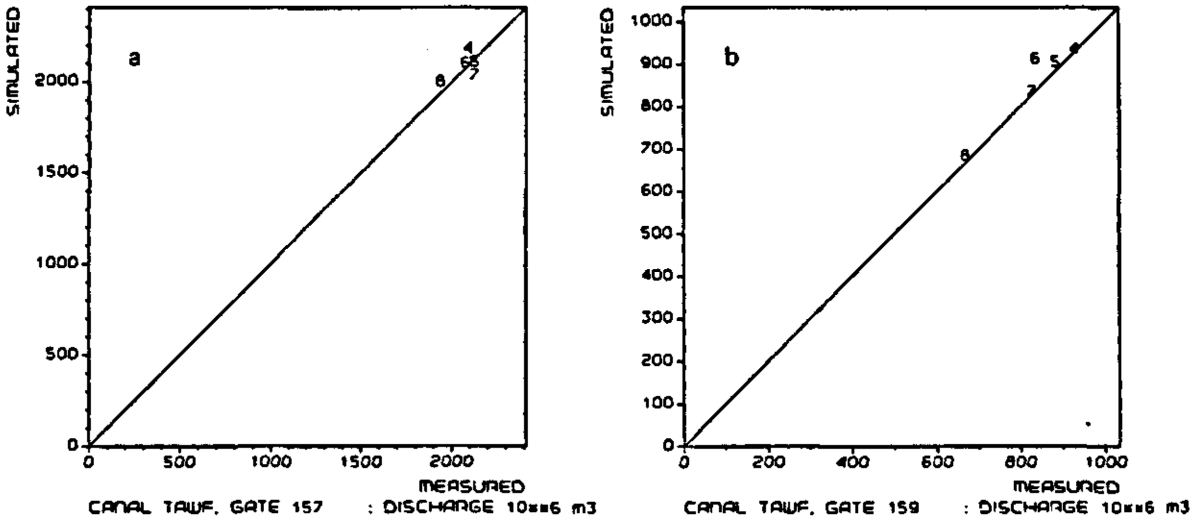

Fig 24. Comparison of simulated year discharge of two side branches of Rayah Tawfiki with observations for the period 1984 - 1988.

a - Bahr Mois b - Bouhia Canal

4 - 1984; 5 - 1985; 6 - 1986; 7 - 1987; 8 - 1988

4.3.2. Drain discharge and salinity

The total simulated drainage, chloride concentration and the chloride load from the study area for the validation period 1984 - 1988, using the calibrated model parameters (calibrated on data of 1986), agrees quite well with the observed values (fig 25). The average deviations in the monthly values increase slightly from 9% for 1986 to 12% for the validation period for the discharge; from 8% to 14% for the chloride concentration; and from 10% to 13% for the chloride load.

The differences between simulations and observations tend to be larger for small catchments than for the larger ones (fig 26). For the chloride concentration the differences between simulations and observations are larger than for the discharge. For the year total discharges for catchments larger than 400,000 feddans, the agreement between both simulations and measurements is excellent (fig 26b).

The purpose of model input parameter validation is to determine the predictive value of the model. Model results should meet two requirements: first, they should be sufficiently accurate (covered by the average monthly deviation during the calibration period), and secondly they should be sufficiently reliable. In this context, reliability of the model simulations means: does the model predict the same trend as the field observations. In order to judge this reliability the predictive value parameter has been defined. The predictive value is calculated as the ratio of the average deviation of the yearly simulated totals from the average trend divided by the range of the observed yearly total values.

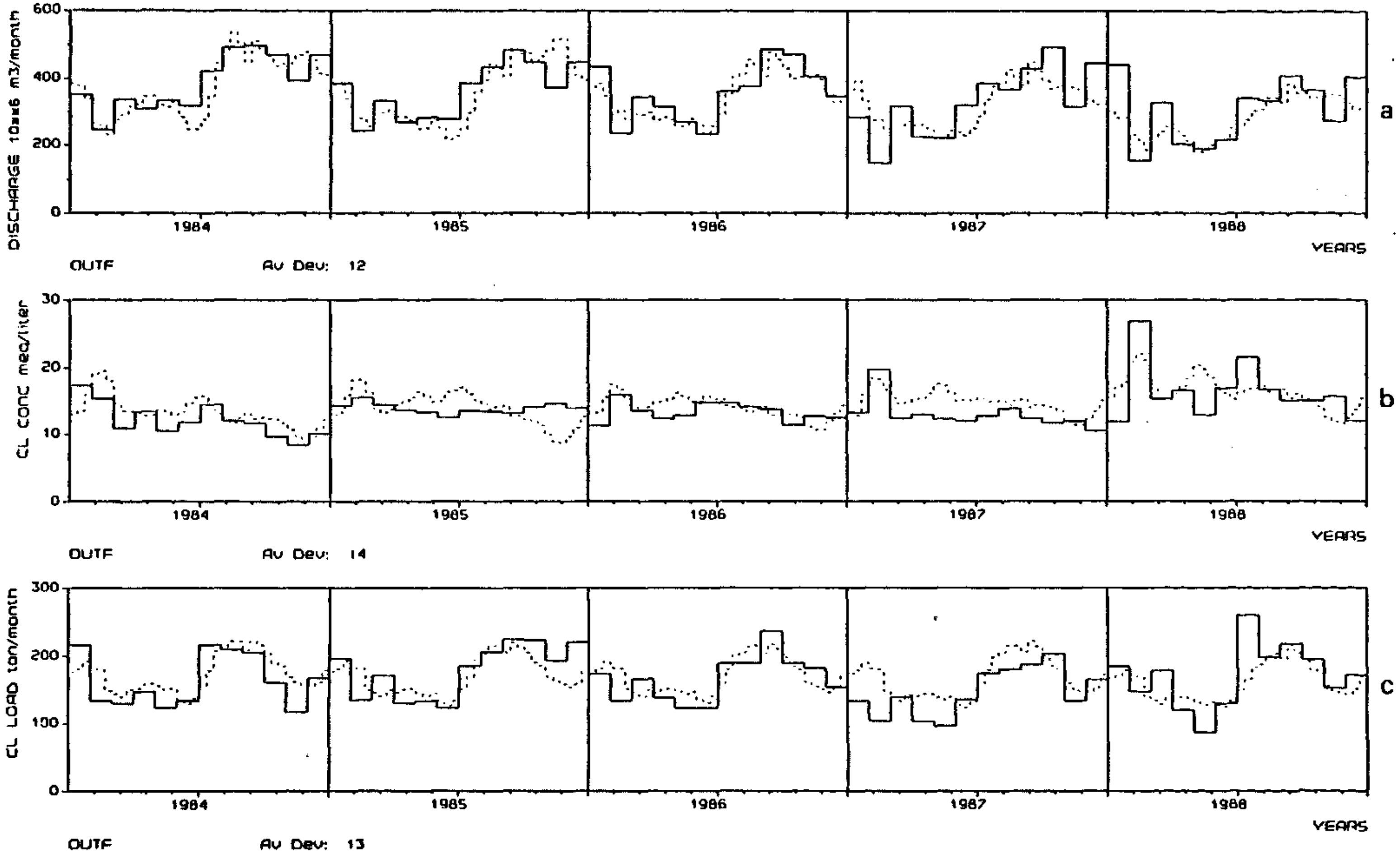

Fig 25. Comparison simulated and observed discharges, salinities, and chloride load from the study area during the validation period 1984 - 1988.

a - discharge; b - chloride concentration; c - chloride load.

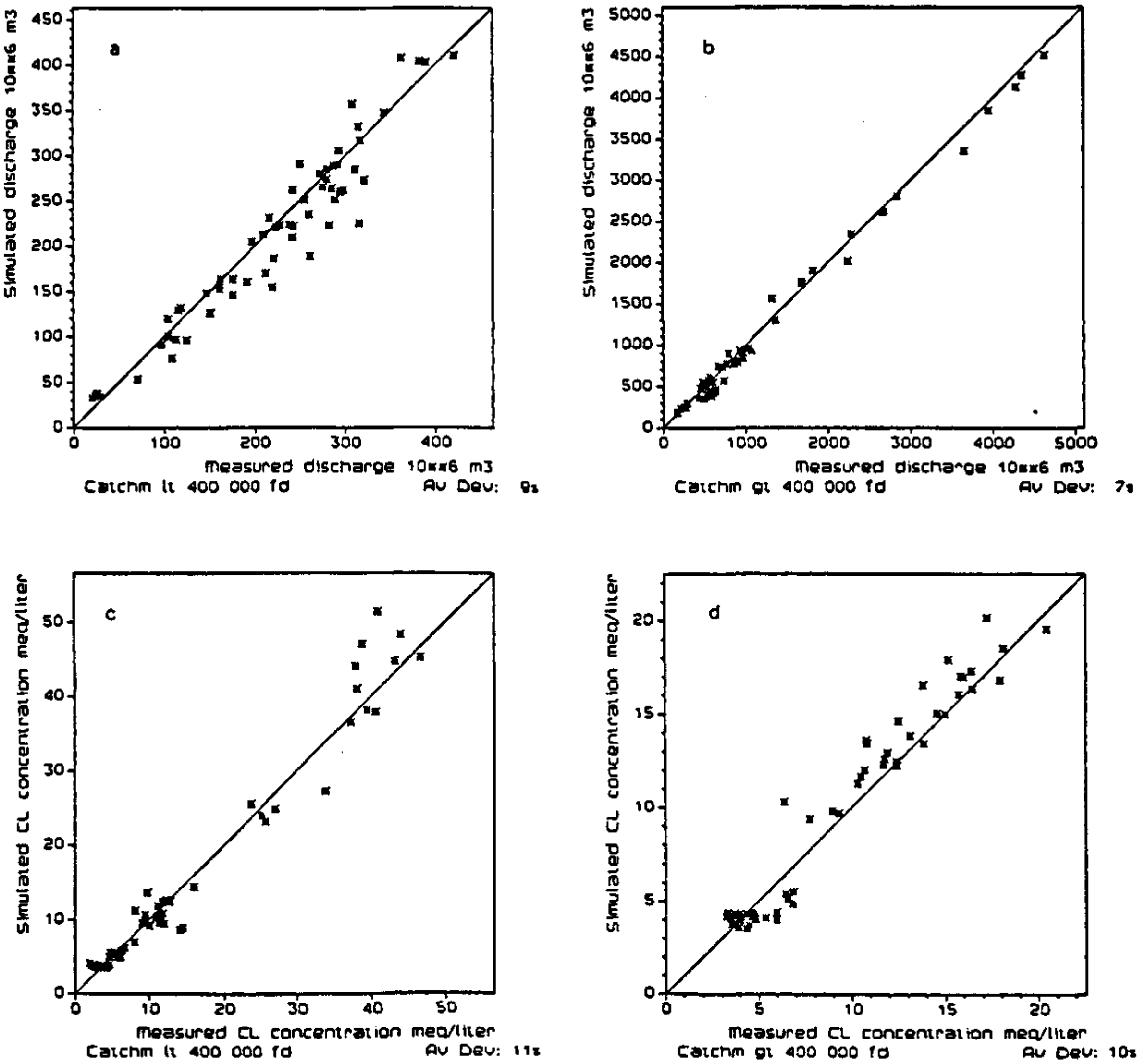

Fig 26. Comparison of simulated and observed year discharges and salinities for all distinguished catchments for the validation period 1984 - 1988.

a - discharge, catchments smaller than 400,000 feddan

b - discharge, catchments larger than 400,000 feddan

c - chloride concentration, catchments smaller than 400,000 feddan

d - chloride concentration, catchment larger than 400,000 feddan

This parameter is illustrated with an example (fig 27). The simulated discharge for Erad pump station is consistently about 25% lower than the observed discharge. The accuracy of the simulated year discharges is not very high. The correlation between simulated and observed discharges is rather good however (fig 27b). This means that the predicted change in discharge, expressed as a percentage, complies with the observed percentage of changes. For Erad pump station this predictive value is 86%, indicating that 86% of the observed change in discharges during the validation period is explained by the model and the remaining 14% represents either measurement inaccuracies or model deviations, or probably both.

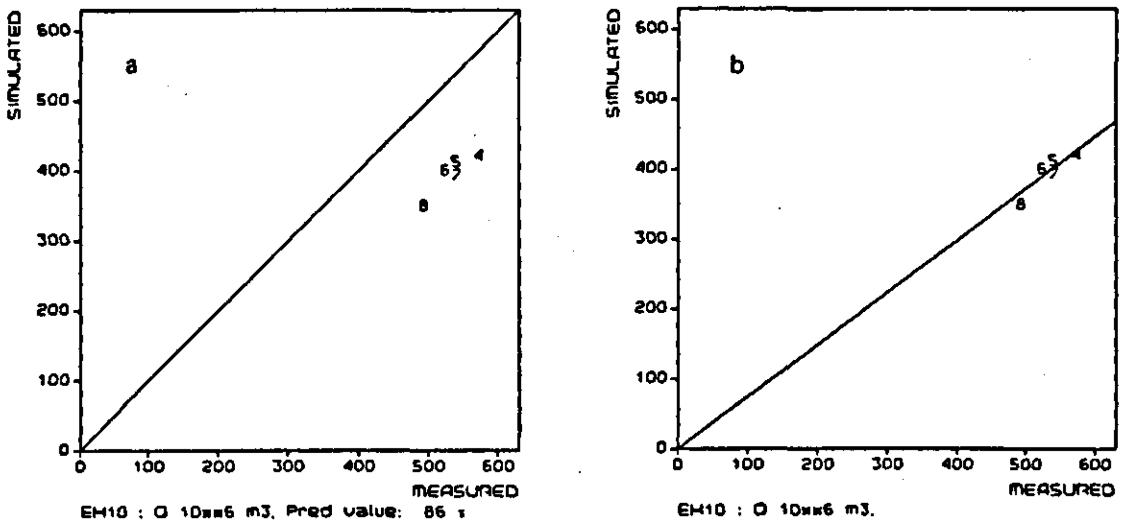

Fig 27. Year discharges Erad pump station validation period 1984 - 1988

a - Comparison of simulations with observations (‾ 45° line)
b - Correlation between simulations and observations (‾ correlation)
4 - 1984; 5 - 1985; 6 - 1986; 7 - 1987; 8 - 1988.

The predictive value of the SIWARE model established in this way should be considered as a conservative estimate of the real predictive value. In some cases both the observed and simulated values show only limited variation. This can be demonstrated by comparing the predictive values of chloride concentration of two catchments, one where leakage conditions prevail, and one where seepage conditions prevail (fig 28). For Saada bridge catchment in the southern part of the Eastern Delta leakage conditions prevail, and the reduction in discharge in 1988 does not result in any increase in salinity, both in the observations and in the simulations. As such, the simulations can be considered reliable. Because the range between maximum and minimum concentration is so small, the predictive value calculated is also very small, i.e. 38% (fig 28a). For Additional Qassabi pump station, which shows a comparable scatter during the period 1984 - 1987, the reduction in supply in 1988, and the removal of rice in this catchment, causes an increase in saline seepage and both simulated and observed chloride concentration show an increase in this year (fig 28b), resulting in a predictive value of 81%. It can thus be concluded that a high predictive value proves the model validity, but also that a low predictive value does not automatically prove that the model is not valid. In order to prove the validity of the model approach a sufficiently large range of discharges and salinities has to be used in order to avoid a too large influence of measurement inaccuracies.

The predictive value parameter can be used to determine whether the model and the model parameters have been validated sufficiently. With a predictive value of more than 50% (at least 50% of the observed variations are proven to be explained by the model) the SIWARE model can be considered as reasonably validated. With a predictive value of more than 75% the model can be considered as sufficiently validated. Applying these criteria, the drain discharge and salinity of the complete study area can be considered as sufficiently validated (fig 29). Only 7% of the observed variation in discharge and 21% of the observed change in salinity are not proven to be explained by the SIWARE model. The fact that for salinity the predictive value is lower may be (partly) explained by the lower measurement accuracy of water quality parameters, compared to discharge (Roest and El Quosy, 1988). A second possible explanation for this difference may be the implicit assumption made for the calibration procedure, i.e. soil salinity equilibrium in the calibration year 1986.

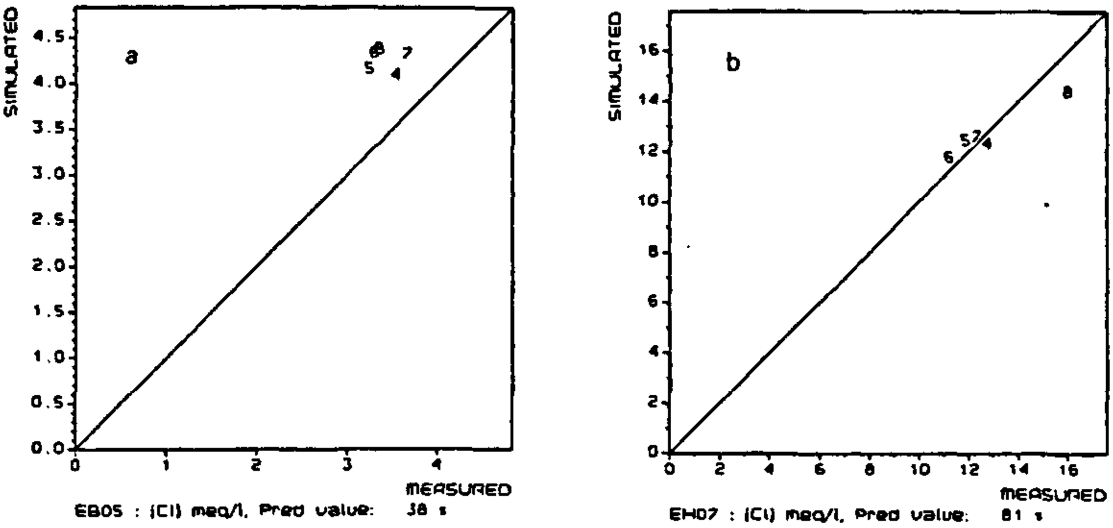

Fig 28. Comparison of simulated and observed average yearly chloride concentration of the drainage water during the validation period 1984 - 1988.

a - Saada bridge catchment b - Additional Qassabi pump station

4 - 1984; 5 - 1985; 6 - 1986; 7 - 1987; 8 - 1988.

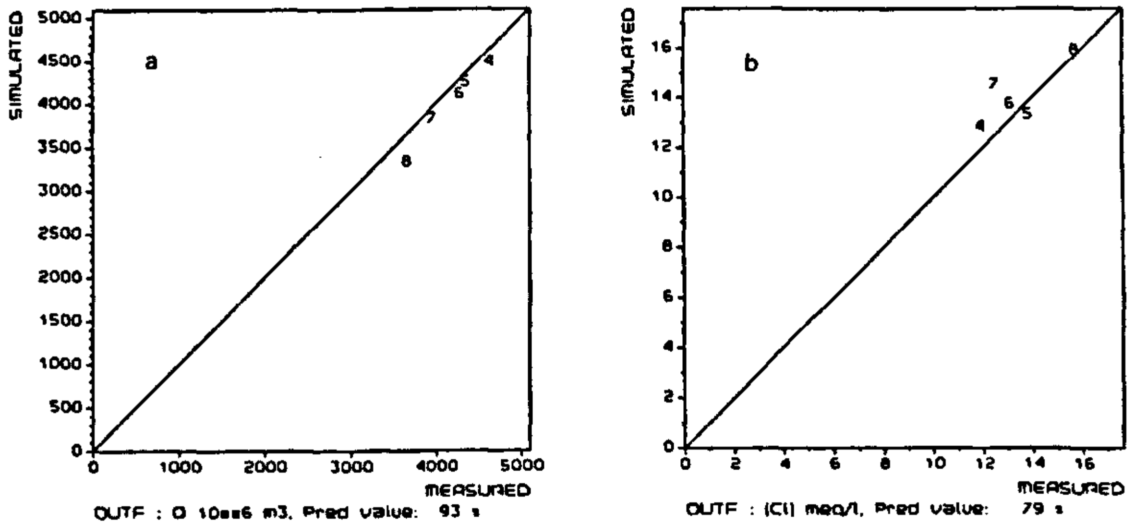

Fig 29. Validation of the SIWARE model on Delta level for year discharge and chloride concentration.

a - discharge b - chloride concentration

4 - 1984; 5 - 1985; 6 - 1986; 7 - 1987; 8 - 1988.

This assumption of soil salinity equilibrium may be valid for the majority of the catchments in the Eastern Delta, but is certainly not true for areas which have recently been taken into cultivation. For these areas desalinization can be expected to continue for a considerable number of years after reclamation.

On catchment level the average predictive value for discharge is about 80% (fig 30), which is much lower than the 93% value for the complete study area. For the average yearly chloride concentration the predictive value is about 65% on catchment level, which is lower than the 79% value for the complete study area, but also lower than the value for discharge (fig 30). This means that the validation of the SIWARE model on catchment level is less good compared to Delta level.

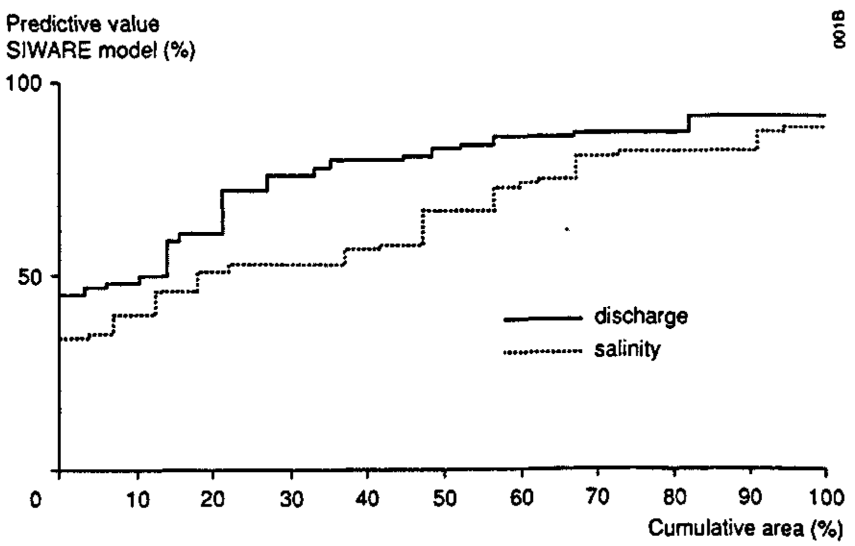

Fig 30. Validation of the SIWARE model on catchment level. Relation between predictive value and the percentage of the area covered by the measurement programme below this predictive value.

For discharge the model is not yet validated for about 10% of the study area on catchment level (predictive value below 50%) and for chloride concentration the SIWARE model is not yet validated for about 20% of the area. In 70% of the area, covered by the measurement programme as well as model simulations, the validation results for discharge are excellent (predictive value more than 75%). For salinity the validation results are excellent in about 40% of the study area (fig 30).

4.4. Analysis water management Eastern Nile Delta in 1986

The average irrigation water supply to the Eastern Nile Delta is around 5 mm.day^{-1}. The drain discharges range from 1 mm.day^{-1} in the southern part to values as high as 8 mm.day^{-1} in the north (fig 19). The explanation for these differences in drain discharges have always been difficult. The SIWARE model simulation results with respect to drain discharges and salinities agree quite well with the observations. Consequently, the simulation results may be used to explain the magnitude of the different water and salt balance components as well as the regional differences which have been observed in the monitoring programme.

4.4.1. Overall water and salt balance

In the overall water balance of the Eastern Nile Delta (fig 31), a number of sub-balances can be distinguished. Some of these sub-balances concern the irrigation canal system, some the areal water balances, and some the drainage canal balances. The following sub-balances are considered:

- the overall areal water balance for the Eastern Nile Delta;
- the water balance of the main irrigation canal system;
- the areal water balance of all Irrigation Districts together (calculation unit level in the model);
- the water balance of the distributary and meskaa canal system;
- the areal water balance of all agricultural fields together (farm level);
- the water balance of the minor drainage canals (within the Irrigation Districts);
- the water balance of the main drainage canal system.

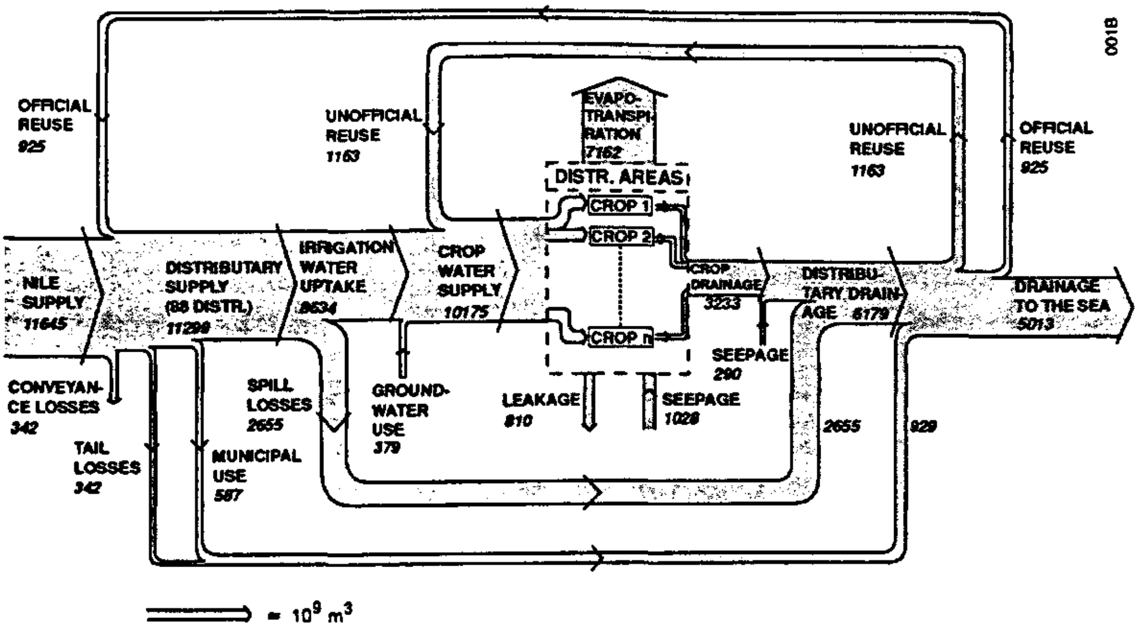

Fig 31. Water balance components Eastern Nile Delta in 1986.

The discussion of the overall water and salt balances given below concerns the complete Eastern Nile delta, including the calculation units outside the study area. Consequently, the total discharge to the sea in terms of water and chloride cannot be compared with the results of the Drainage Research Institute measurement programme which is confined to the major part of the study area only.

Water balances

On Eastern Nile Delta level three main water balance components can be distinguished in the water balance of this area (fig 31): the total Nile water supply to the Eastern Delta of 11,645 million $m^3.year^{-1}$ in 1986; the evapotranspiration of 7,162 million m^3 (62% of the Nile water supply); and drainage to the sea of 5,013 million m^3 (43% of the Nile water supply). These three components are balanced by an amount of 545 million $m^3.year^{1}$ (5% of the Nile water supply) caused by net gains from the aquifer and rainfall in the northern part of the Eastern Nile Delta in the winter period. On Eastern Nile Delta level the water management system can be classified as rather efficient: 62% of the irrigation water (Nile supply) is used for crop evapotranspiration.

The total water supply through the irrigation network (distributary water supply) to the Irrigation Districts is 11,299 million $m^3.year^{-1}$. This quantity is composed of 10,374 million m^3 of Nile water (92%) and 925 million m^3 of officially reused drainage water by pump stations (8%). The conveyance losses from the main irrigation system are approximately 3% (342 million m^3); the tail-end losses 3% (342 million m^3); and the municipal and industrial water consumption 5% (587 million m^3) of the Nile water supply (fig 31). The overall effect of these losses and gains in the main irrigation system causes a high overall efficiency: the Irrigation District water supply is a mere 3% lower than the Nile water supply. This high efficiency is mainly caused by the official reuse of drainage water, because it accounts for almost all losses in the main irrigation canal system.

Also on Irrigation District level three main water balance components can be considered: the irrigation network water supply of 11,299 million $m^3.year^{-1}$ (fig 31); the evapotranspiration of 7,162 million m^3 (63% of distributary supply); and the distributary drainage of 6,179 million m^3 (55% of distributary supply). These three main components are balanced by an amount of 2,042 million m^3, caused by unofficial reuse of drainage water (1,163 million m3); groundwater use (379 million m^3); and seepage gains from the aquifer (508 million m^3). Again, the water management system performance on Irrigation District level in the Eastern Nile Delta can be classified as rather efficient: 63% of the water supply is used for crop evapotranspiration.

The total water supply provided by the farmers to the crops in 1986 was 10,175 million $m^3.year^{-1}$. This quantity is composed of 8,634 million m^3 of distributary water supply (85%); 379 million m^3 of groundwater use (4%); and 1,163 million m^3 of unofficial reuse of drainage water (11%). The spillway losses from the distributary and meskaa canals are considerable: 23% (2,655 million m^3) of the distributary water supply. The overall effect of these losses and gains from the irrigation canal system within the Irrigation Districts make it quite efficient: the irrigation crop water supply is only 10% less than the distributary water supply through the irrigation network (fig 31).

The three main water balance components on crop level (on-farm irrigation level) are the irrigation supply of 10,175 million $m^3.year^{-1}$; the evapotranspiration of 7,162 million m^3 (70%); and crop drainage of 3,233 million m^3 (32%). These main water balance components are balanced by net gains from the aquifer through seepage (1,028 million m^3) minus leakage (810 million m^3) of 2%. The on-farm irrigation management system can be classified as very efficient: 70% of the irrigation water supplied by farmers is actually used for crop evapotranspiration (fig 31).

The total drainage coming from the distributary areas (Irrigation Districts) of 6,179 million $m^3.year^{-1}$ is composed of 3,233 million m^3 of crop drainage (52%); 290 million m^3 of drainage canal seepage (5%); and 2,655 million m^3 of spillway losses from the distributary and meskaa canals (43%). Despite the fact that losses at Irrigation District level are not excessive, these losses apparently constitute a considerable (43%) component of the drainage water produced (fig 31).

The drainage to the sea of 5,013 million $m^3.year^{-1}$ is composed of 6,179 m^3 of distributary drainage (82%), and 929 million m^3 of municipal and industrial drainage and tail-end losses (18%), and is balanced by the official and unofficial reuse of drainage water of respectively 925 million m^3 (15% of the distributary drainage) and 1,163 million m^3 (19% of the distributary drainage).

Salt balances

Each quantity of water transported implies the transport of salts. In the SIWARE simulation model the salt transport is confined to the chloride ion. Based on the simulation results the overall balances of chloride can be drafted (fig 32).

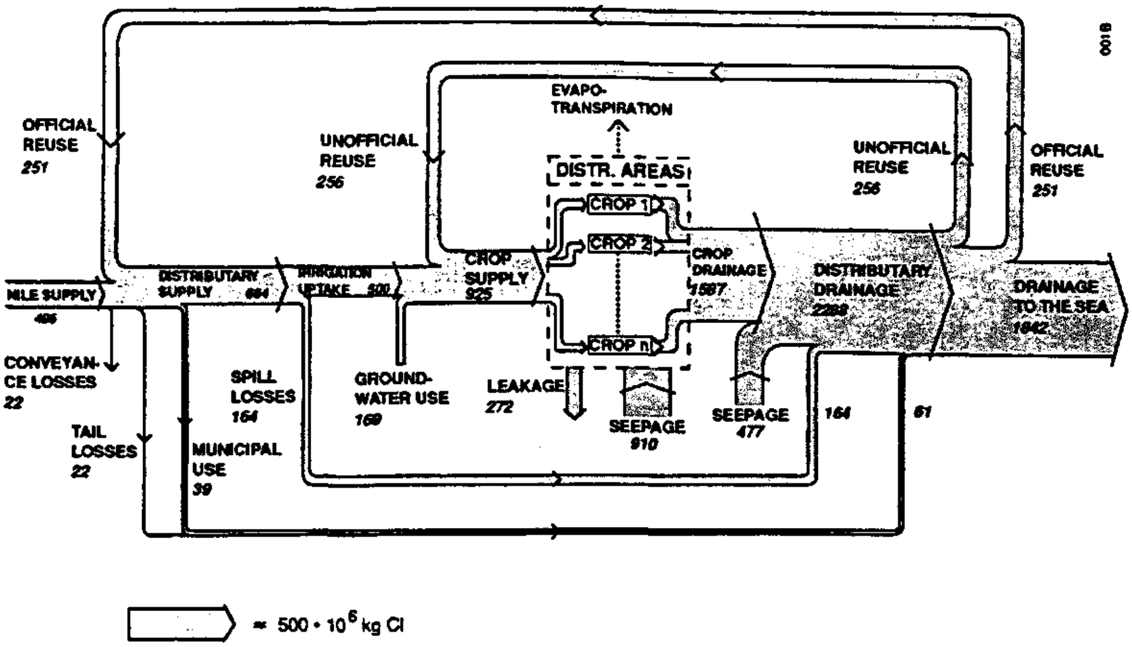

Fig 32. Chloride balance components Eastern Nile Delta in 1986.

Considering the chloride balance on Eastern Nile Delta level, the supply through the Nile is 496 million $kg.year^{-1}$, and the discharge to the sea 1,842 million $kg.year^{-1}$, which is about 3.7 times the Nile supply. Both components are balanced by losses and gains of salt to and from the aquifer (fig 32). Since soil salinity equilibrium has been assumed for the calibration year 1986, it must be concluded that desalinization of the subsoil (deeper than roughly 5 to 10 meter) is taking place.

The distributary chloride supply through the irrigation canal network is 664 million kg (34% more than the Nile supply) and is composed for 66% of Nile supply and for 34% of official reuse of drainage water, and is balanced by the conveyance losses, tail-end losses, and municipal and industrial water use of 11% (fig 32). The official reuse of drainage water is only 8% of the distributary water supply, but constitutes 34% of the distributary chloride supply, which implies that the average salinity of the officially reused water is approximately 4 times that of the Nile water supply.

The total chloride supply to the crops through irrigation amounts to 925 million kg.year^{-1} (39% more than the distributary supply; or 86% more than the Nile supply) and is composed of 54% of distributary chloride supply, 18% is supplied with groundwater use, and 28% with the unofficial reuse of drainage water. Although only 15% of the crop water supply originates from groundwater use and unofficial reuse of drainage water, the chloride contribution of these water balance components is 46% of the total crop chloride supply through irrigation.

The total chloride drainage of crops is 1,587 million kg.year^{-1} (72% more than crop the chloride supply through irrigation; 2.4 times the distributary supply; or 3.2 times the Nile supply). The crop chloride drainage is composed for 58% of the crop chloride supply and 40% is chloride supply from the aquifer (fig 32): 57% is supply through seepage and 17% is losses through leakage. For the water balance, seepage is a relatively unimportant component (10% of the crop water supply). For the chloride balance, however, seepage contributes for 57% to the total crop chloride drainage.

4.4.2. Spatial distribution

In the overall balance the irrigation water uptake by farmers from the distributary and meskaa canals forms the largest single water balance component of 85% of the crop water supply through irrigation (fig 31). In the southern part of the study area, and at the tail-ends of the irrigation system this irrigation water uptake is less than 1,500 mm.year^{-1} (6,300 m^3.feddan^{-1}). In the Irrigation Districts located at the upstream reaches of the main system the uptake is more than 1,500 mm (fig 33a). Unofficial reuse of drainage water is only 11% of the total crop water supply. In certain calculation units in the northern part of the study area, however, where drainage water is easily available because drainage water has been lifted by drainage pump stations, the magnitude of unofficial reuse approaches the irrigation uptake (fig 33b). The same holds true for the seepage flux, which is only 10% in the average water balance, but is in the same order of magnitude as irrigation uptake in the northern part of the study area along the Nile branch, along the Manzalah Lake, and in a few calculation units adjacent to the Ismaileya Canal (fig 33c). Groundwater (only 4% of the average crop water supply) is absent in the northern part of the study area (because the salinity is not acceptable), but may be considerable in the southern part (fig 33d).

In the spatial distribution of the chloride supply through irrigation uptake, the official reuse of drainage water can easily be recognized (fig 34a). The calculation units served with a mixture of both Nile water and drainage water from Wadi and

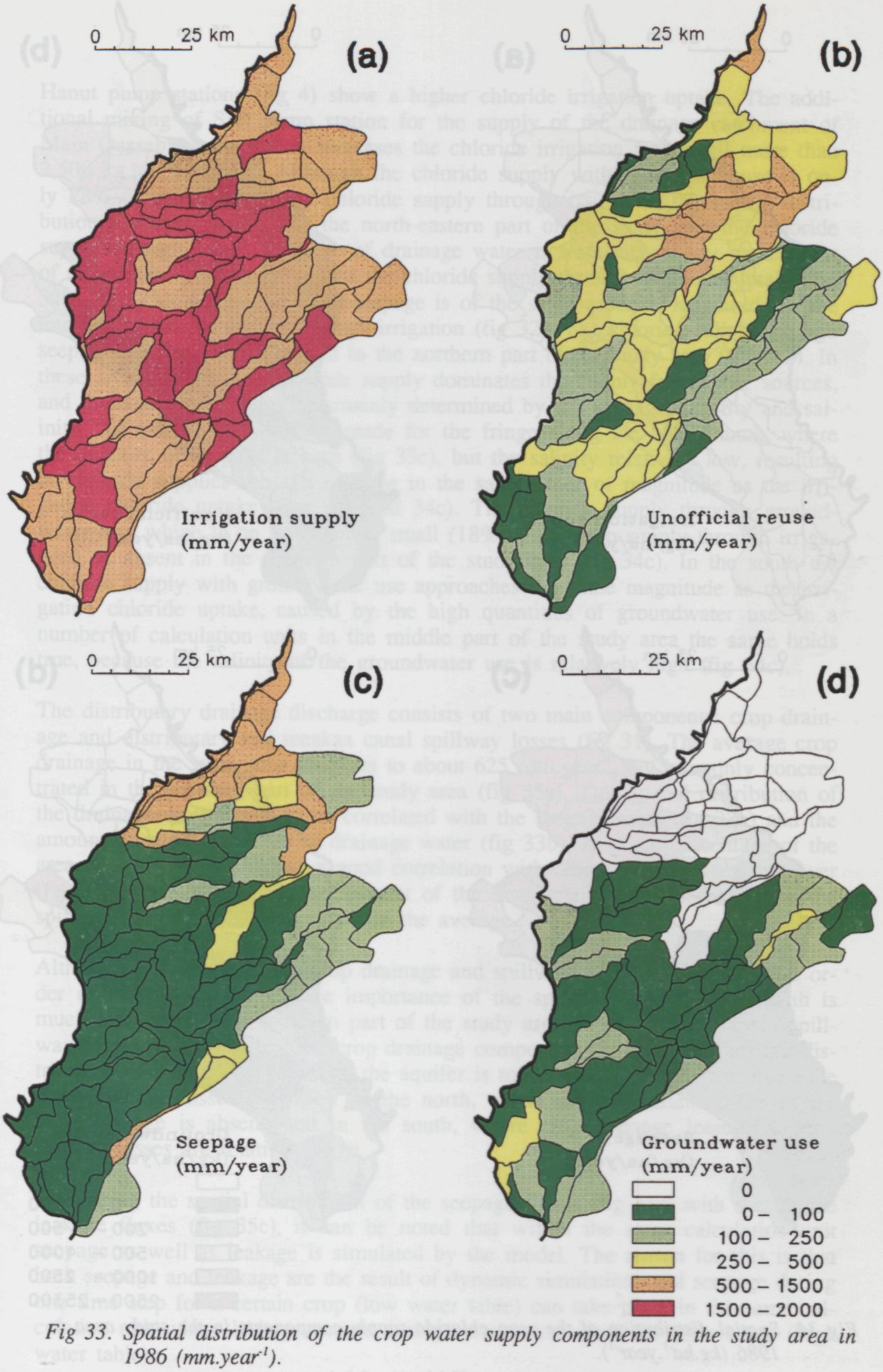

Fig 33. Spatial distribution of the crop water supply components in the study area in 1986 (mm.year^{-1}).

a - irrigation water uptake b - unofficial reuse of drainage water

c - seepage contribution d - groundwater use

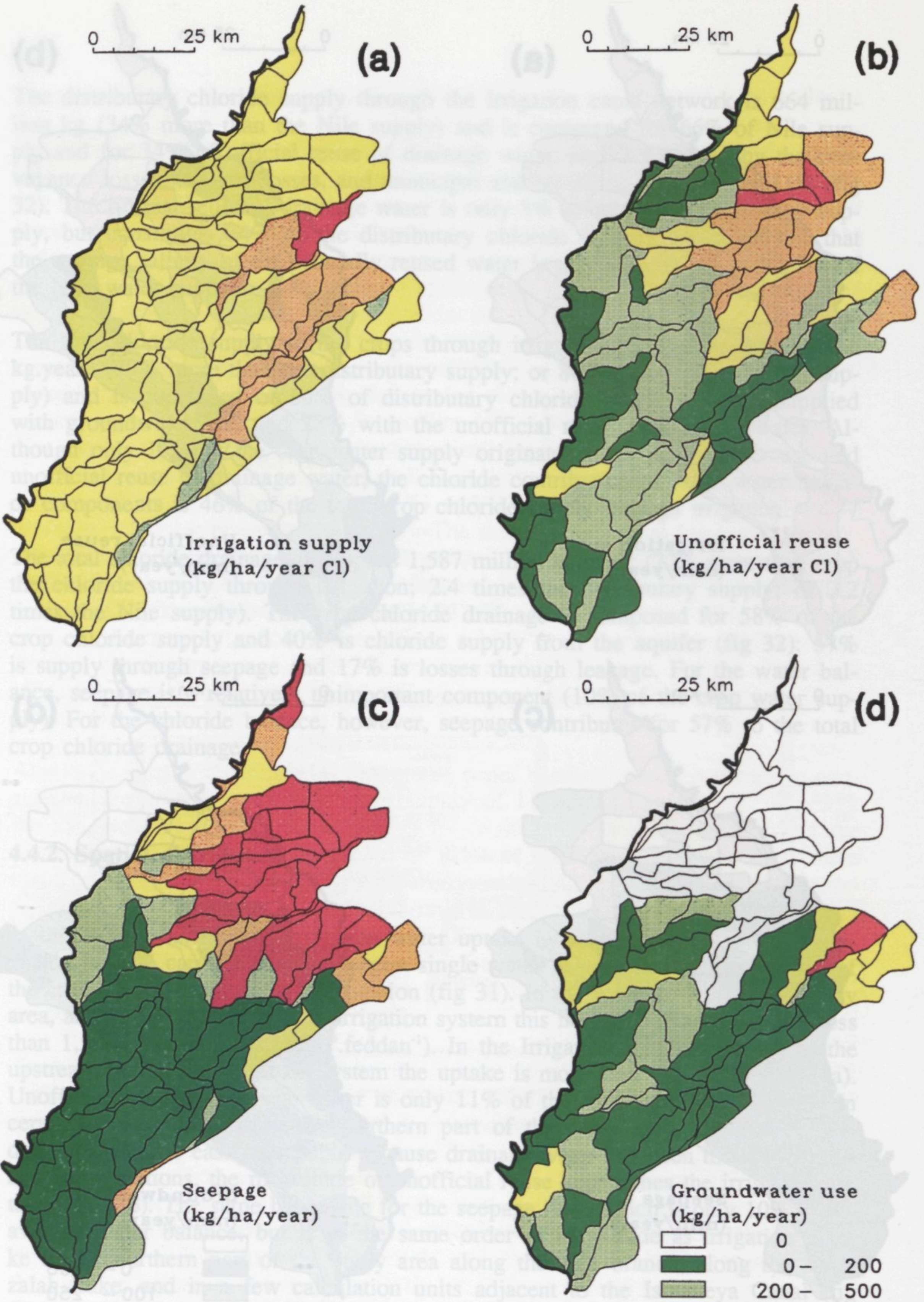

Fig 34. Spatial distribution of the crop chloride supply components in the study area in 1986 (kg.ha^{-1}.year^{-1}).

a - irrigation chloride uptake
b - unofficial reuse of drainage water
c - seepage contribution
d - groundwater use

Hanut pump stations (fig 4) show a higher chloride irrigation uptake. The additional mixing of Saft pump station for the supply of the drainage catchment of Main Qassabi pump station increases the chloride irrigation uptake till more than 2,500 kg.ha^{-1} (fig 34a). Although the chloride supply with unofficial reuse is only 28% of the average crop chloride supply through irrigation, the spatial distribution is rather unequal. In the north-eastern part of the study area the chloride supply through unofficial reuse of drainage water is frequently in the same order of magnitude, (or even more), as the chloride supply through irrigation uptake (fig 34b). The chloride supply with seepage is of the same order of magnitude as the total crop chloride supply through irrigation (fig 32). The chloride supply through seepage is mainly concentrated in the northern part of the study area (fig 34c). In these areas the seepage chloride supply dominates the supply from other sources, and drainage water salinity is mainly determined by the seepage quantity and salinity. An exception should be made for the fringe along the Nile branch, where the quantity of seepage is high (fig 33c), but the salinity relatively low, resulting in chloride supplies through seepage in the same order of magnitude as the irrigation chloride uptake (figs 34a and 34c). The chloride supply through groundwater use, which is on the average small (18% of the crop supply through irrigation), is absent in the northern part of the study area (fig 34c). In the south the chloride supply with groundwater use approaches the same magnitude as the irrigation chloride uptake, caused by the high quantities of groundwater use. In a number of calculation units in the middle part of the study area the same holds true, because the salinity of the groundwater use is relatively high (fig 34c).

The distributary drainage discharge consists of two main components: crop drainage and distributary and meskaa canal spillway losses (fig 31). The average crop drainage in the study area amounts to about 625 mm.year^{-1}, but is mainly concentrated in the northern part of the study area (fig 35a). This spatial distribution of the drainage rates seems to be correlated with the seepage rates (fig 33c) and the amount of unofficial reuse of drainage water (fig 33b). Also the percentage of the area grown with rice shows a good correlation with drainage discharges, however (fig 8b). The second main component of the distributary drain discharge are the spillway losses of 425 mm.year^{-1} on the average.

Although both components, crop drainage and spillway losses, are in the same order of magnitude, the relative importance of the spillway losses in the north is much less than in the southern part of the study area, where frequently the spillway losses are larger than the crop drainage component (fig 35b). The spatial distribution of the leakage losses to the aquifer is more or less complementary to the crop drainage losses (fig 35c). In the north, where the crop drainage losses are high, leakage is absent, and in the south, where crop drainage losses are low, leakage losses are relatively high.

Comparing the spatial distribution of the seepage fluxes (fig 33c) with that of the leakage fluxes (fig 35c), it can be noted that within the same calculation unit seepage as well as leakage is simulated by the model. The reason for this is that both seepage and leakage are the result of dynamic simulations and seepage during one time step for a certain crop (low water table) can take place in the same calculation unit where leakage occurs during certain time steps for other crops (high water table).

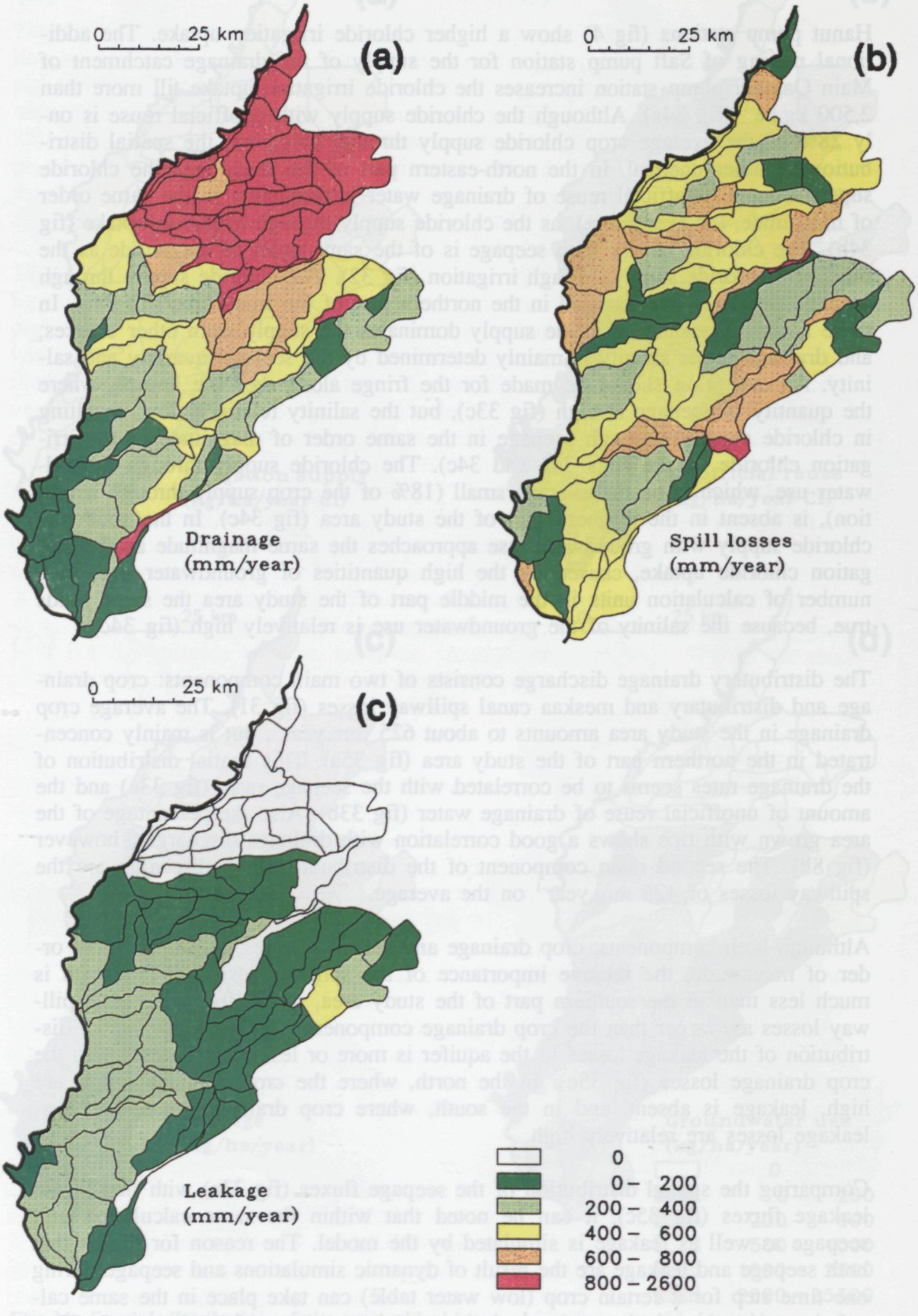

Fig 35. Spatial distribution of the distributary drainage components in the study area in 1986 (mm.year^{-1}).

a - crop drainage
b - distributary and meskaa spill losses
c - leakage to the aquifer

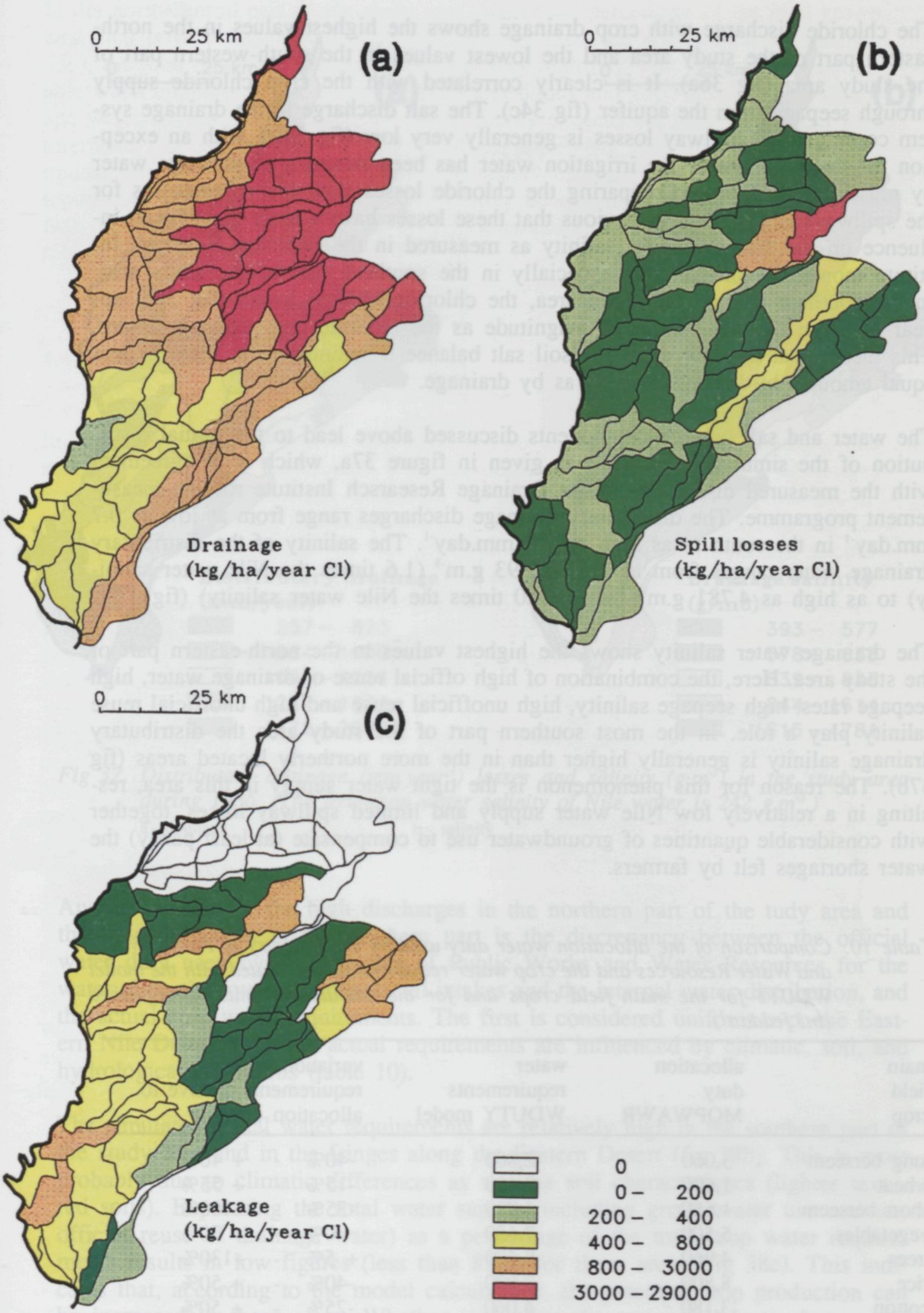

Fig 36. Spatial distribution of the distributary chloride losses components in the study area in 1986 (kg.ha^{-1}.year^{-1}).

a - crop drainage b - distributary and meskaa spill losses

c - leakage to the aquifer

The chloride discharge with crop drainage shows the highest values in the north-eastern part of the study area and the lowest values in the south-western part of the study area (fig 36a). It is clearly correlated with the crop chloride supply through seepage from the aquifer (fig 34c). The salt discharge to the drainage system coming from spillway losses is generally very low (fig 36b), with an exception for the areas where the irrigation water has been mixed with drainage water by reuse pump stations. Comparing the chloride losses with the water losses for the spillways (fig 35b), it is obvious that these losses have a large (beneficial) influence on the drainage water salinity as measured in the Drainage Research Institute monitoring programme, especially in the southern part of the study area. In the southern part of the study area, the chloride leakage losses (fig 36c) appear to be in the same order of magnitude as the chloride crop drainage losses. This means that in these areas the soil salt balance is maintained in more or less equal amounts by leakage as well as by drainage.

The water and salt balance components discussed above lead to the spatial distribution of the simulated discharge as given in figure 37a, which is in agreement with the measured discharges in the Drainage Researsch Institute routine measurement programme. The distributary drainage discharges range from as low as 0.7 mm.day^{-1} in the south to as high as 7.9 mm.day^{-1}. The salinity of the distributary drainage water ranges from as low as 393 g.m^{-3} (1.6 times the Nile water salinity) to as high as 4,781 g.m^{-3} (almost 20 times the Nile water salinity) (fig 37b).

The drainage water salinity shows the highest values in the north-eastern part of the study area. Here, the combination of high official reuse of drainage water, high seepage rates, high seepage salinity, high unofficial reuse and high unofficial reuse salinity play a role. In the most southern part of the study area the distributary drainage salinity is generally higher than in the more northerly located areas (fig 37b). The reason for this phenomenon is the tight water supply in this area, resulting in a relatively low Nile water supply and limited spillway losses, together with considerable quantities of groundwater use to compensate (at least partly) the water shortages felt by farmers.

Table 10. Comparison of the allocation water duty used by the Ministry of Public Works and Water Resources and the crop water requirements calculated with the model WDUTY for the main field crops and for the calculation units distinguished (m3.feddan^{-1}).

main field crop	allocation duty MOPWAWR	water requirements WDUTY model	variation water requirements relative to allocation duty
long berseem	3,060	2,800	-40% - + 40%
wheat	1,600	2,130	-15% - + 55%
short berseem	1,650	1,920	-35% - +100%
vegetables	5,500	7,630	0% - + 70%
trees	4,960	8,500	+ 5% - +130%
rice	8,800	7,920	-40% - + 50%
cotton	3,180	4,060	-25% - + 50%
maize	2,690	3,470	0% - + 50%
calculation units	6,560	7,720	-20% - + 50%

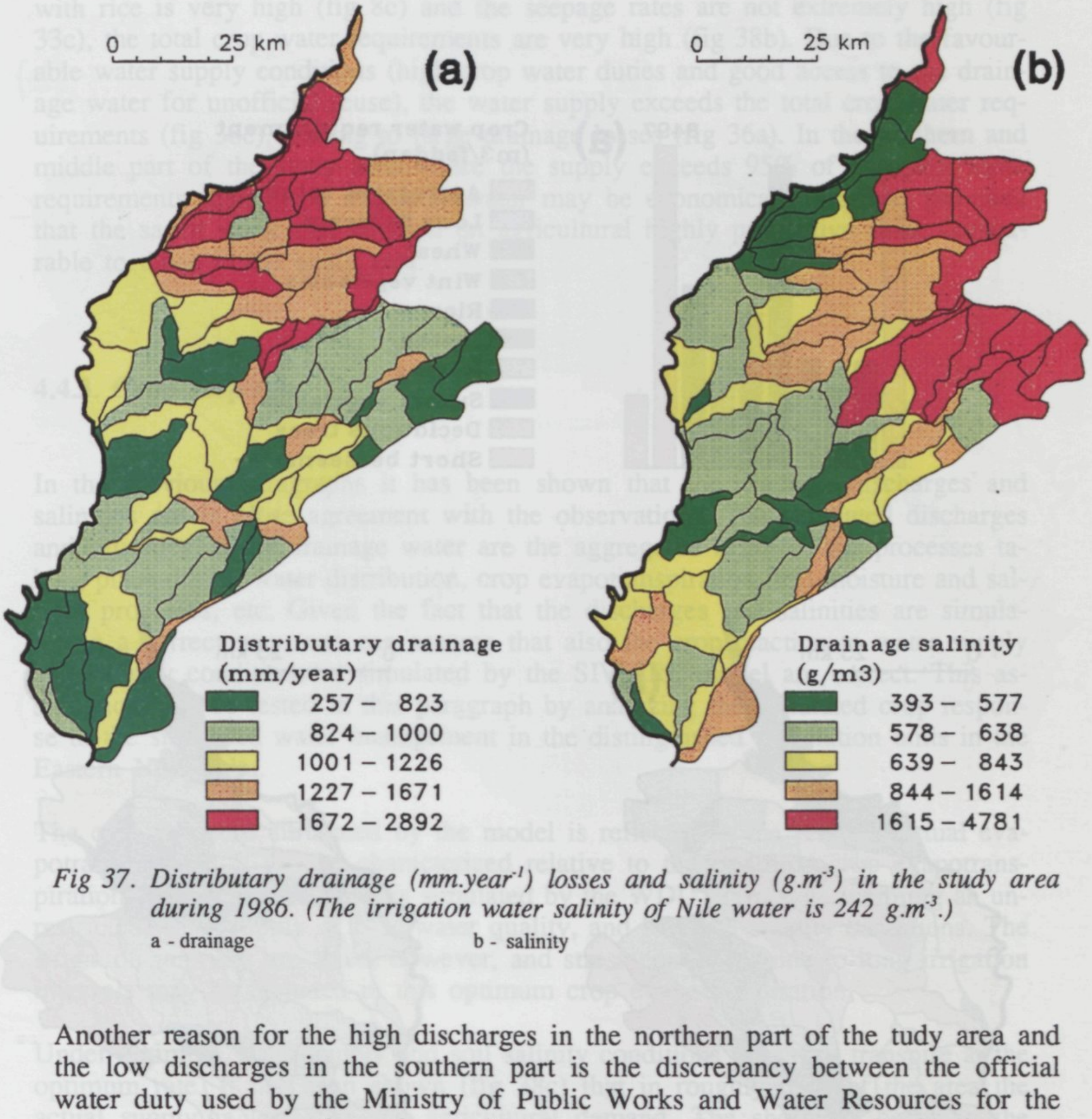

Fig 37. Distributary drainage (mm.year^{-1}) losses and salinity (g.m^{-3}) in the study area during 1986. (The irrigation water salinity of Nile water is 242 g.m^{-3}.)

a - drainage b - salinity

Another reason for the high discharges in the northern part of the tudy area and the low discharges in the southern part is the discrepancy between the official water duty used by the Ministry of Public Works and Water Resources for the water allocation over the main canal intakes and the internal water distribution, and the actual crop water requirements. The first is considered uniform over the Eastern Nile Delta, while the actual requirements are influenced by climatic, soil, and hydrological conditions (table 10).

The simulated actual water requirements are relatively high in the southern part of the study area and in the fringes along the Eastern Desert (fig 38b). This is most probably due to climatic differences as well as soil characteristics (lighter textured soils). Expressing the total water supply (including groundwater use and unofficial reuse of drainage water) as a percentage of the total crop water requirements results in low figures (less than 85%) for these areas (fig 38c). This indicates that, according to the model calculations, the potential crop production can be increased in these areas. Whether increasing the water supply to these areas should be recommended from an economical point of view remains questionable, however. Generally, production functions are curved near the maximum, indicating that increases in production become less as the input (water supply) is increased.

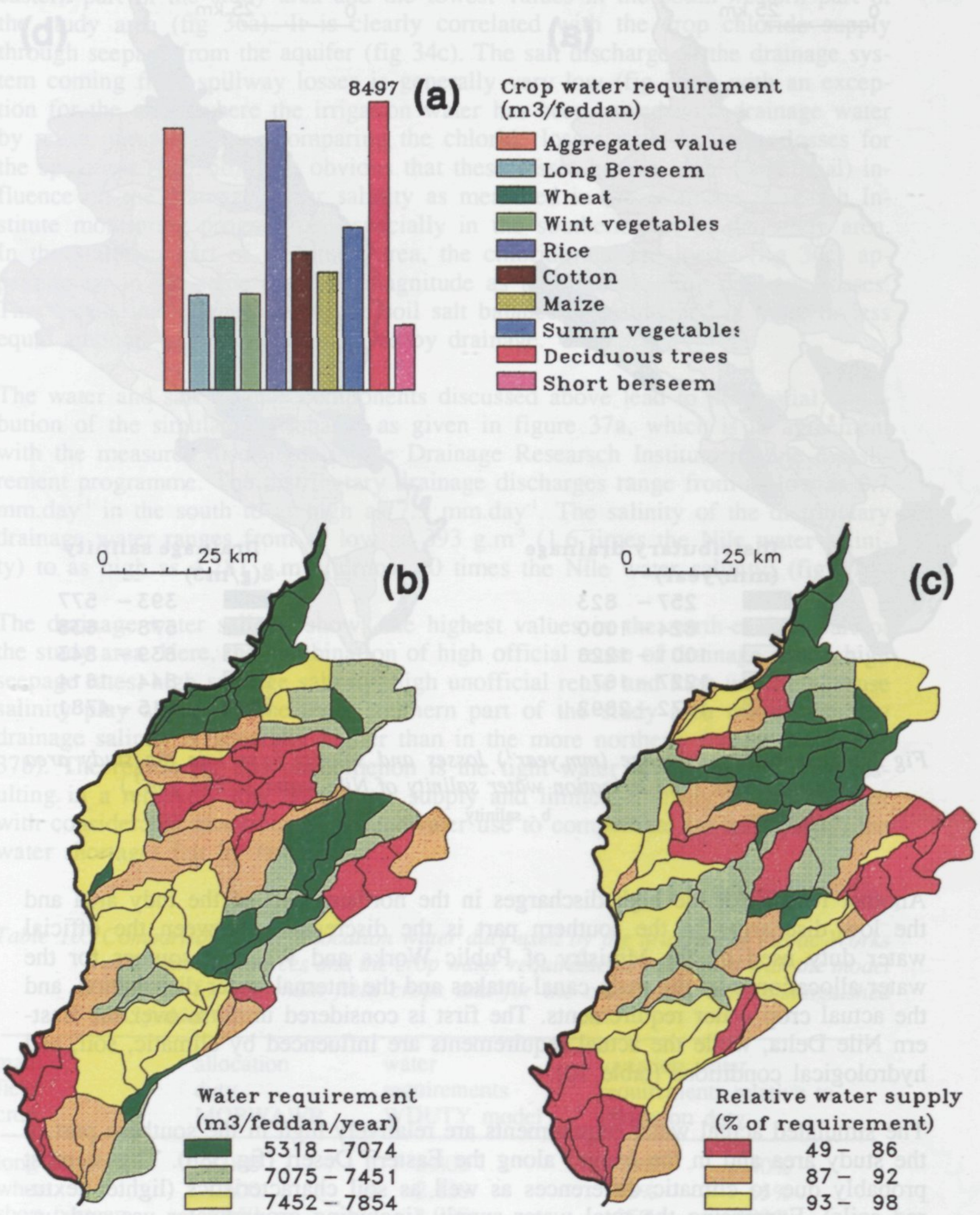

Fig 38. Total crop water supply expressed as a percentage of total crop water requirements (%), and crop water requirements ($m^3.feddan^{-1}$) during 1986.

a - average crop water requirements study area ($m^3.feddan^{-1}$);

b - spatial distribution total crop water requirements ($m^3.feddan^{-1}$)

c - crop water supply as % of crop water requirements

In the north-central part of the study area, where the percentage of the area grown with rice is very high (fig 8c) and the seepage rates are not extremely high (fig 33c), the total crop water requirements are very high (fig 38b). Due to the favourable water supply conditions (high crop water duties and good access to the drainage water for unofficial reuse), the water supply exceeds the total crop water requirements (fig 38c), leading to large drainage losses (fig 36a). In the northern and middle part of the study area where the supply exceeds 95% of the crop water requirements savings on irrigation water may be economically feasible, provided that the saved water can be used on agricultural highly productive soils, comparable to those in the study area.

4.4.3. Crop response

In the previous paragraphs it has been shown that the drainage discharges and salinities are in close agreement with the observations. The simulated discharges and salinities of the drainage water are the aggregated result of the processes taking place during water distribution, crop evapotranspiration, soil moisture and salinity processes, etc. Given the fact that the discharges and salinities are simulated in a correct way, one can assume that also the crop reaction to water supply and salinity conditions as simulated by the SIWARE model are correct. This assumption will be tested in this paragraph by analyzing the simulated crop response to the simulated water management in the distinguished calculation units in the Eastern Nile Delta.

The crop response simulated by the model is reflected in the realized actual evapotranspiration. It can be characterized relative to the optimum crop evapotranspiration. The latter parameter is simulated by the WDUTY model, assuming an unrestricted water supply of Nile water quality, and low soil salinity conditions. The irrigation intervals are fixed, however, and stress conditions due to long irrigation intervals may be included in this optimum crop evapotranspiration.

Under optimum water supply and soil salinity conditions the crops transpire at the optimum rate. It has been shown (fig 38c) that in roughly 65% of the area the actual supply is less than the agricultural demand. The shortages occur in the southern part of the study area, where water control by the Ministry of Public Works and Water Resources is tight (small irrigation command areas), and the evaporative demand is high due to climatic and hydrological conditions. The same holds true for the fringe along the Eastern desert, and for some locations at the tail-ends of the irrigation system (fig 38c). These water supply conditions are reflected in the spatial distribution of the simulated relative crop evapotranspiration (fig 39a). In the north-eastern part of the study area evapotranspiration rates seem to react more heavily to water shortages than in the southern part of the study area. The reason is the higher soil salinity in this part of the study area (fig 39b). Apparently crop evapotranspiration is reduced here due to high soil salinity conditions.

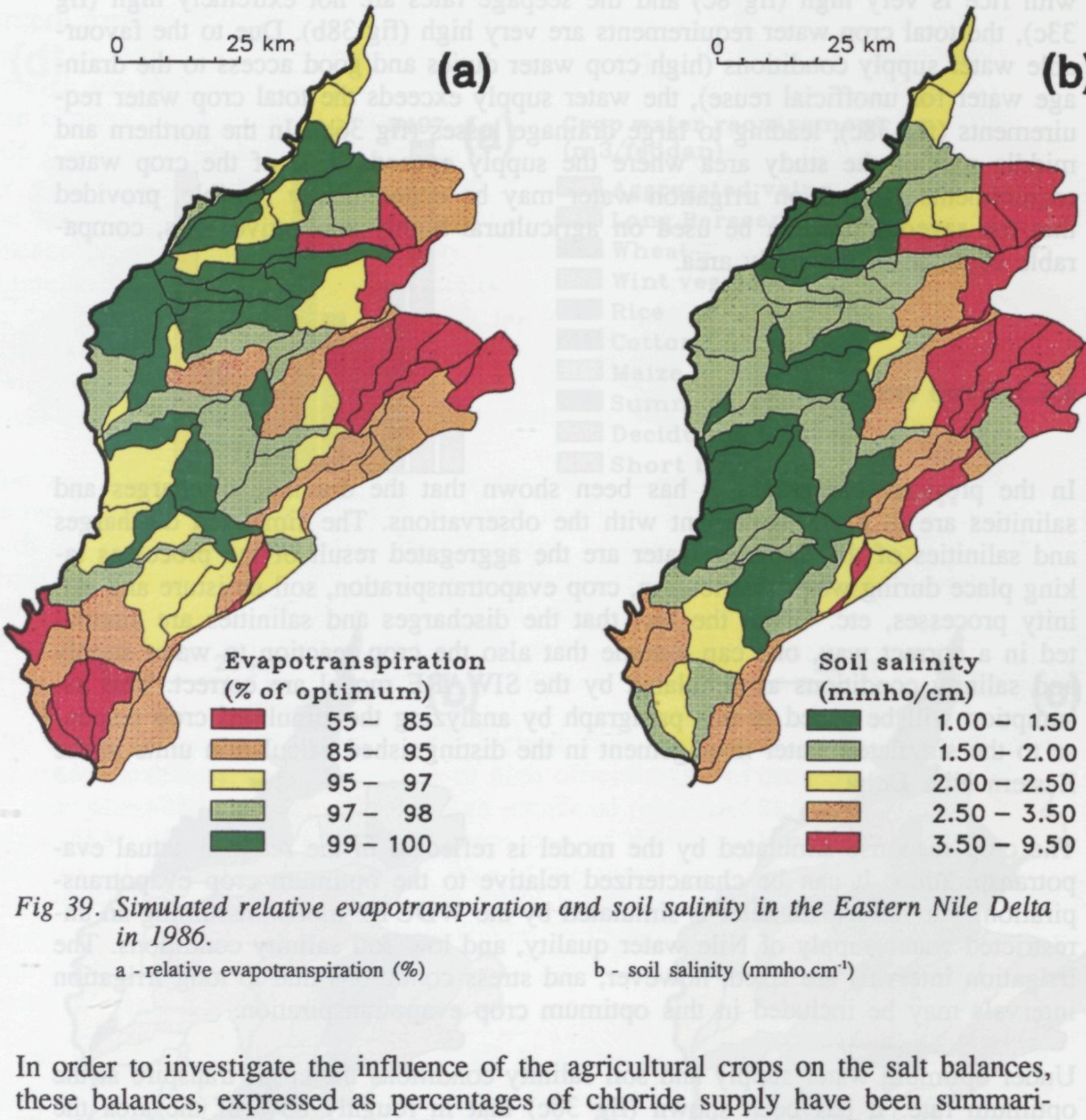

Fig 39. Simulated relative evapotranspiration and soil salinity in the Eastern Nile Delta in 1986.

a - relative evapotranspiration (%) b - soil salinity (mmho.cm^{-1})

In order to investigate the influence of the agricultural crops on the salt balances, these balances, expressed as percentages of chloride supply have been summarized for the main winter crops (fig 40) and main summer crops (fig 41). All supply (irrigation, unofficial reuse, and seepage) and discharge (drainage and leakage) components are given in these figures. For winter crops the highest seepage contribution is noticed for the wheat crop, which is irrigated only lightly, because the crop is known to be sensitive to high groundwater tables. Consequently, the wheat crop has an adverse effect on the soil salinity, because the total discharge of salts is less than the total supply (fig 40). For the other winter crops (vegetables and berseem) the salt balance is favourable and the removal of salts exceeds the supply (fig 40).

During the summer season, two crops have favourable leaching conditions (rice and vegetables), and two crops have a salinization effect (maize and cotton; fig 41). Especially for cotton the salt balance is very unfavorable: the discharge of chloride is less than 50% of the chloride supply to the soil profile. Cotton receives only light irrigations, and the production of cotton bolls is promoted by water stress conditions. The presented salt balances illustrate the function of the rice crop in the Nile Delta of Egypt to maintain a favourable soil salinity status of the soil.

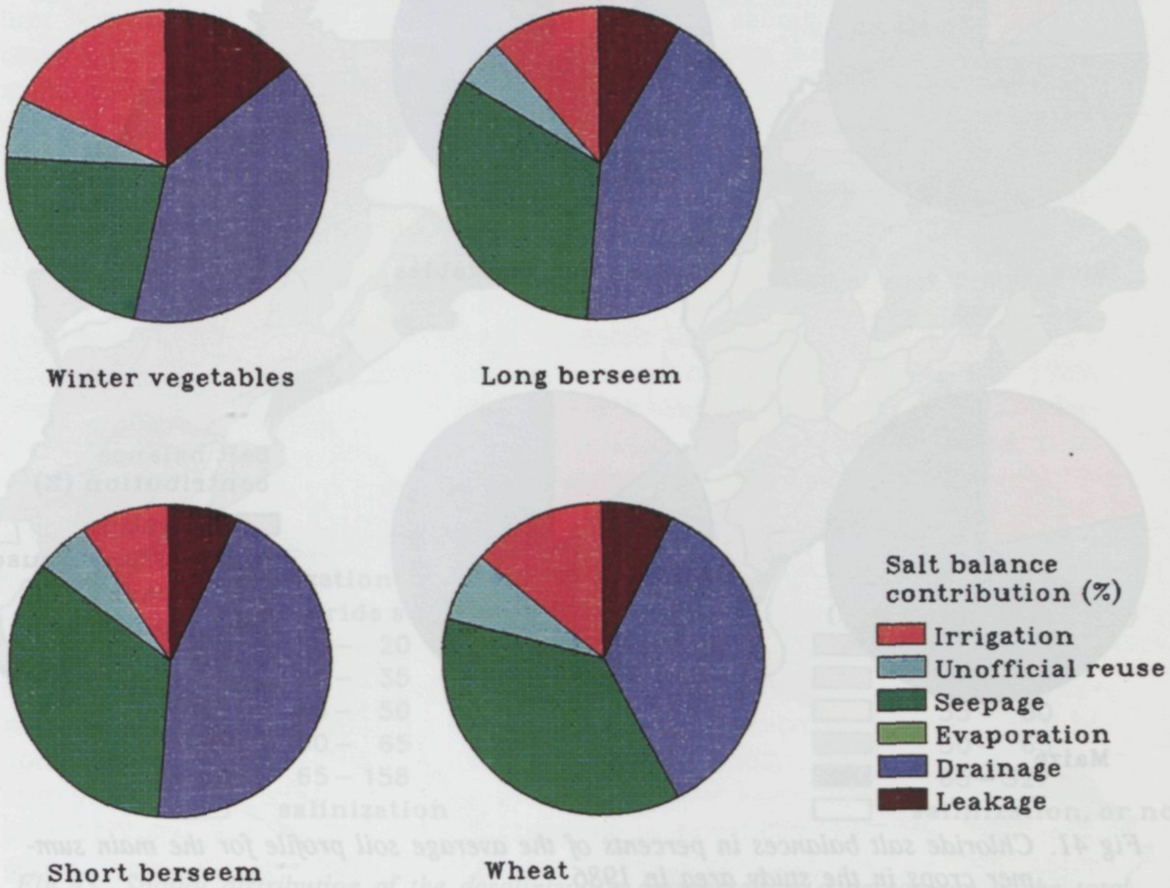

Fig 40. Chloride salt balances in percents of the average soil profile for the main winter crops in the study area in 1986.

For both the summer and the winter crops the soil profile salt balances follow the sequence of the relative irrigation priority (table 6), meaning that the crop with the highest priority has the most favourable salt balance (vegetables in winter and rice in summer period) and the crop with the lowest irrigation priority has the most unfavourable salt balance (wheat in winter and cotton in summer period). The salt balances presented seem logical. In Egypt rice is considered as a reclamation crop for soil desalinization and it is very well known, that wheat and cotton have a salinization effect on the soil. In the Egyptian literature not much well documented field data on crop salt balances are available. Abdalla et al (1990) presented the salt discharges for the main field crops in the Mashtul Pilot Area, covering an observation period of three years. This drainage pilot area is located slightly north of Zagazig in the Eastern Nile Delta (fig 2). The calculation units in the model approach that are situated near this location are units 41, 42 and 50 (fig 3). The correlation between the simulated salt discharges of the main field crops (average of these three calculation units) and those reported (Abdalla et al, 1990) is remarkably good for rice, maize and long berseem (fig 42). For cotton, short berseem and wheat the agreement is less, but the ranges indicated in figure 42 approach the measured values closely.

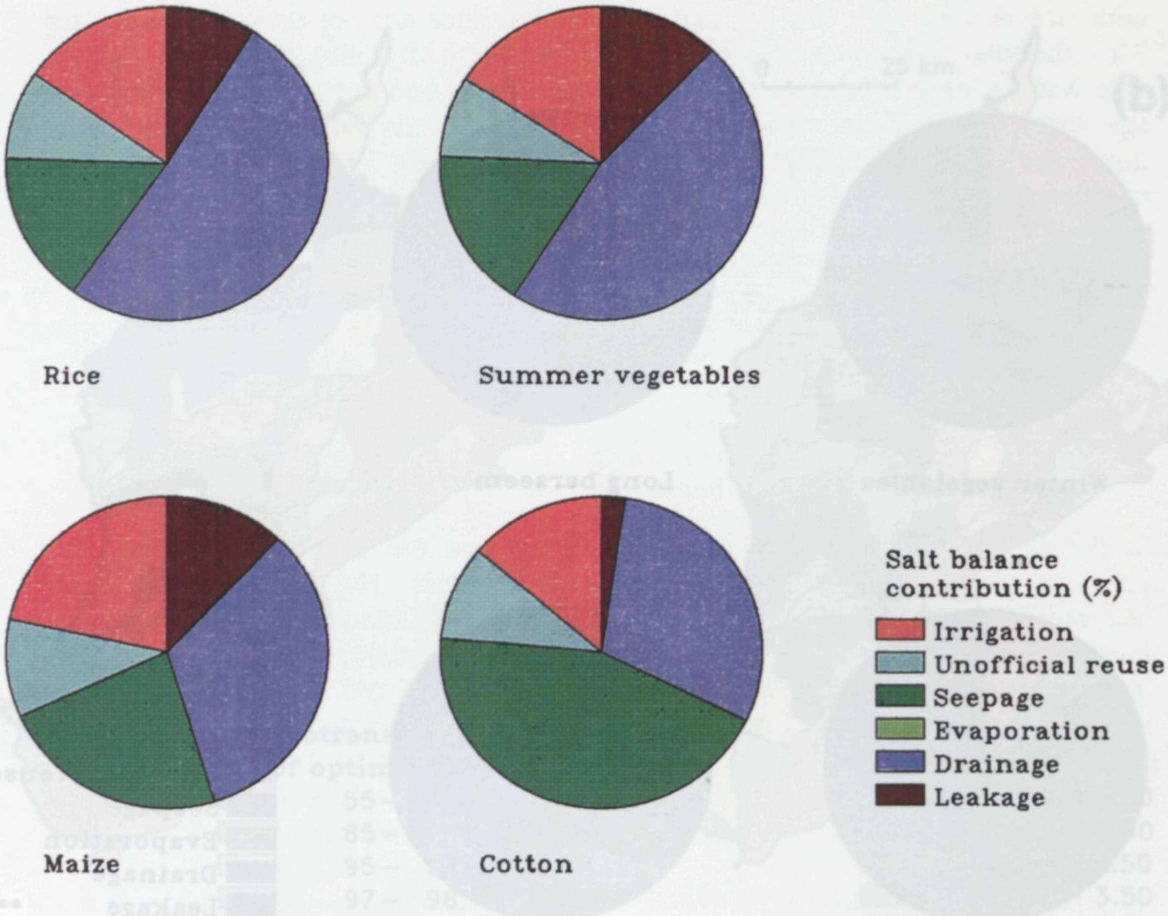

Fig 41. Chloride salt balances in percents of the average soil profile for the main summer crops in the study area in 1986.

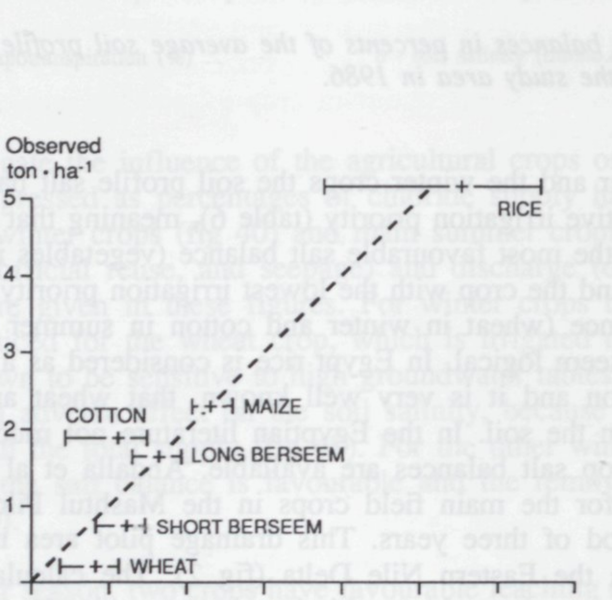

Fig 42. Comparison of the simulated salt discharge (ton.ha^{-1}) of the area north of Zagazig in the Eastern Nile Delta (average of calculation unit 41, 42, and 50) for the six main field crops (simulated by the SIWARE model for 1986) with observed values in the Mashtul Pilot Area during the period 1983 - 1986.

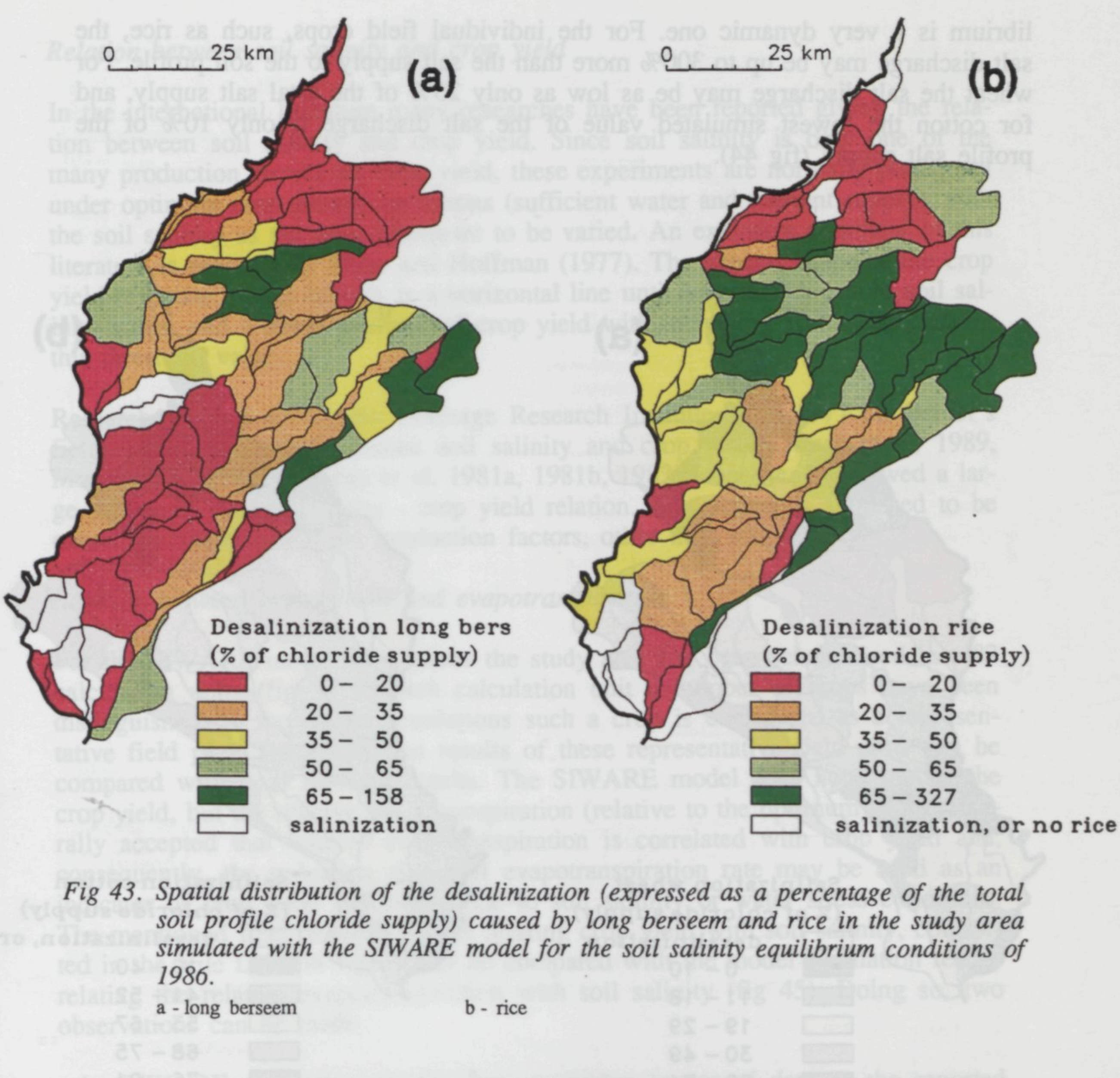

Fig 43. Spatial distribution of the desalinization (expressed as a percentage of the total soil profile chloride supply) caused by long berseem and rice in the study area simulated with the SIWARE model for the soil salinity equilibrium conditions of 1986.

a - long berseem b - rice

The spatial distribution of the desalinization caused by the long berseem crop (fig 43a), expressed as the percentage of the total chloride supply to the soil profile, shows low values (lower than 20%) in the southern and utmost northern part of the Nile Delta. These low values in the north are most probably caused by the high seepage rates (fig 33c).

Higher desalinization occurs during the growing of long berseem in the middle part of the Eastern Nile Delta (fig 43a). The same holds true for the spatial distribution of the desalinization caused by the rice crop (fig 43b).

The spatial distribution of the salinization caused by the wheat crop and the cotton crop (fig 44) show a similar pattern: lower values in the southern part and in the utmost north, and high salinization figures in the middle and eastern part of the Eastern Nile Delta.

Although, in the SIWARE model simulations salt equilibrium has been assumed for the calibration year 1986, these model results suggest that the assumed equilibrium is a very dynamic one. For the individual field crops, such as rice, the salt discharge may be up to 300% more than the salt supply to the soil profile. For wheat the salt discharge may be as low as only 25% of the total salt supply, and for cotton the lowest simulated value of the salt discharge is only 10% of the profile salt supply (fig 44).

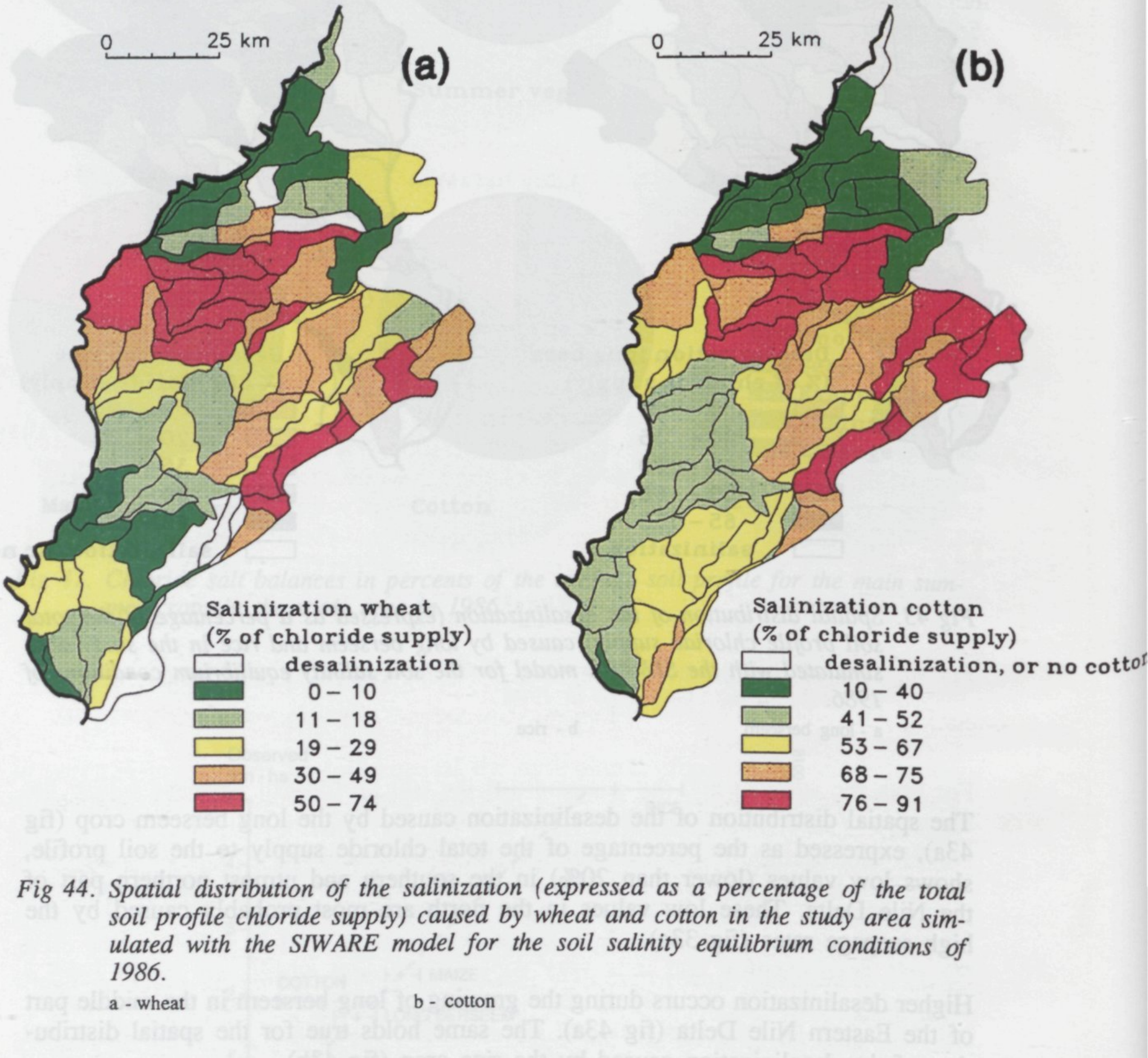

Fig 44. Spatial distribution of the salinization (expressed as a percentage of the total soil profile chloride supply) caused by wheat and cotton in the study area simulated with the SIWARE model for the soil salinity equilibrium conditions of 1986.

a - wheat   b - cotton

A number of common questions in irrigated agriculture which are posed by the Authorities responsible for the water management are the following:

- what are the soil salinities which are acceptable for the crops;
- how much irrigation water is required for agriculture;
- what is the effect of under-irrigation on crop yields;
- what is an acceptable upper limit for the irrigation water salinity.

Relation between soil salinity and crop yield

In the international literature many researches have been reported giving the relation between soil salinity and crop yield. Since soil salinity is only one of the many production factors for crop yield, these experiments are normally performed under optimum crop growth conditions (sufficient water and nutrient supply), with the soil salinity as the only parameter to be varied. An extensive overview of this literature is reported by Maas and Hoffman (1977). The general shape of the crop yield response to soil salinity is a horizontal line until a certain threshold soil salinity value, and a linear decrease of crop yield with increasing soil salinity above this threshold value.

Research, carried out by the Drainage Research Institute since 1977 on farmer's fields into the relation between soil salinity and crop yield (Amer et al, 1989, Morsi et al, 1987, Ramadan et al, 1981a, 1981b, 1983), consistently showed a large scatter in the soil salinity - crop yield relation. This scatter is supposed to be caused by variations in the production factors, other than soil salinity.

Relation between soil salinity and evapotranspiration

For the SIWARE model simulations the study area has been schematized into 82 calculation units (fig 3). In each calculation unit a number of crops have been distinguished. In the model simulations such a crop is considered as a representative field plot. The simulation results of these representative field plots can be compared with field research results. The SIWARE model does not simulate the crop yield, but the relative evapotranspiration (relative to the optimum). It is generally accepted that relative evapotranspiration is correlated with crop yield and, consequently, the reduction of actual evapotranspiration rate may be used as an indicator of crop yield depression due to soil salinity or water stress conditions. The mentioned field research results relating crop yield with soil salinity, conducted in the Nile Delta in Egypt. can be compared with the model simulation results relating the relative evapotranspiration with soil salinity (fig 45). Doing so, two observations can be made:

- the SIWARE simulation results show a similar scatter of data as the reported field researches;
- the crop yield reductions measured in the field research tend to appear at lower soil salinities than the evapotranspiration reduction simulated with the SIWARE model.

For the interpretation of the SIWARE simulation results with respect to crop response there is an advantage over the field researches carried out in the past. In the model simulations the water supply to the crops is also known. By singling out the model results for which the water supply is clearly at or above the optimum, the only production factor left (in the model) is the soil salinity. Taking the results for the crop long berseem as an example, no clear-cut relationship between soil salinity and relative evapotranspiration can be observed taking all simulated values into account (fig 46a). Below the soil salinity value of 2 mmho.cm^{-1} the reduction in evapotranspiration varies from 0% to 32% and in the soil salinity range between 4 and 8 mmho.cm^{-1} this reduction ranges between 12% and 21% (fig 46a). By selecting only the simulated values for which the total seasonal crop water supply is larger than 95% of the agricultural demand (simulated with the model WDUTY),

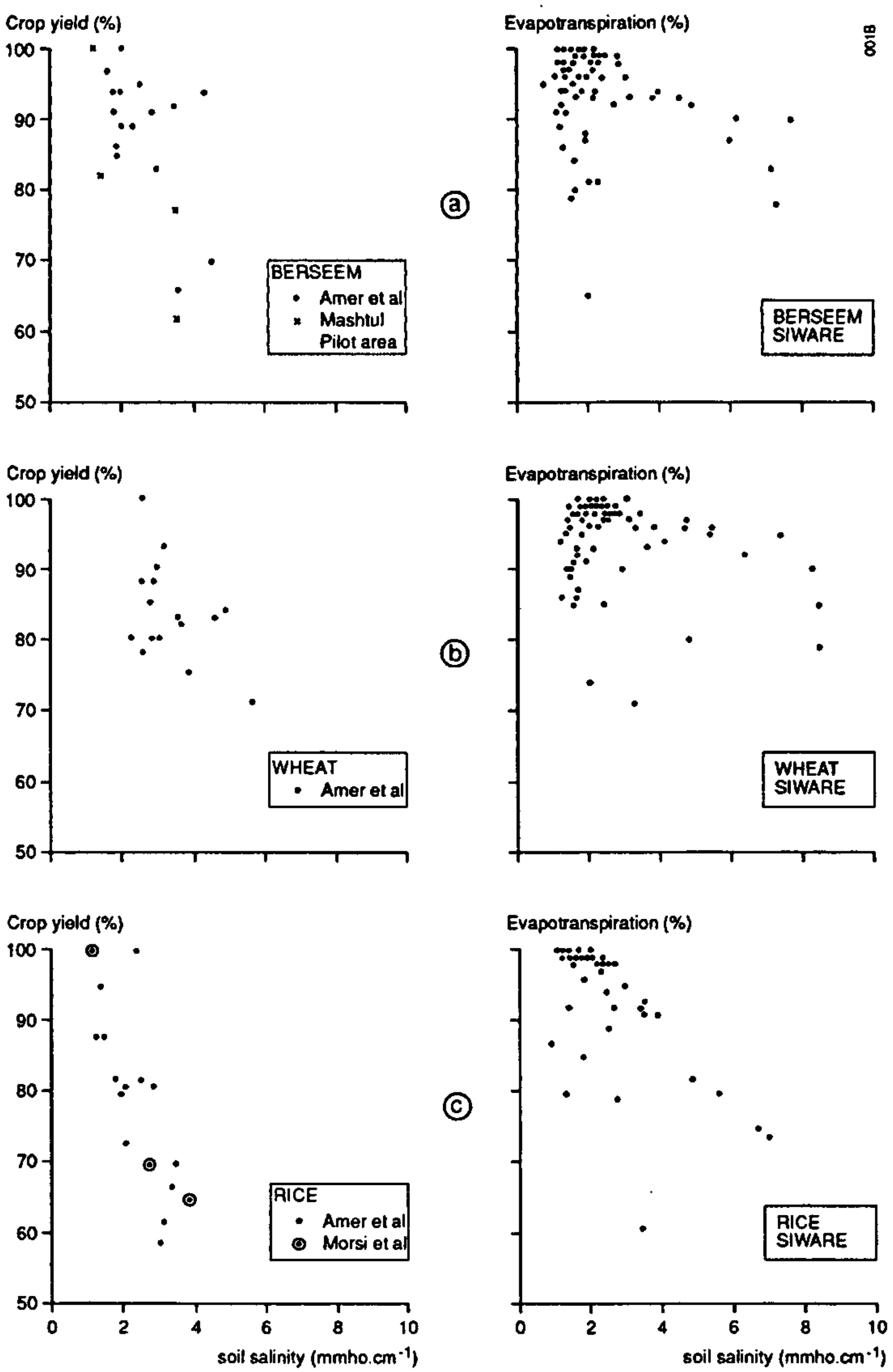

Fig 45. Comparison of observed crop yield response to soil salinity (field research results at farmer's fields) and simulated relative evapotranspiration response (simulated with the SIWARE model for the 82 calculation units in the study area).

a - berseem b - wheat c - rice

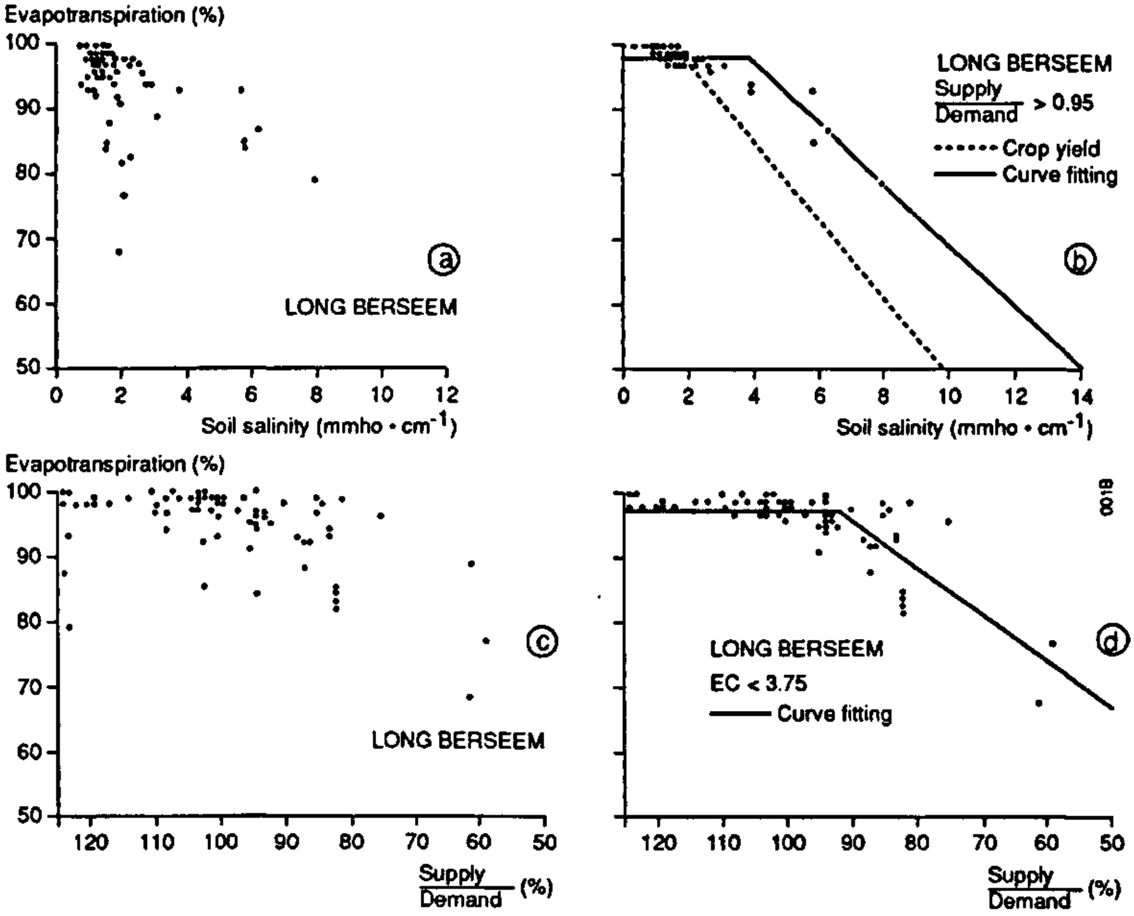

Fig 46. Relationship between the relative crop evapotranspiration of long berseem simulated with the SIWARE model for the 82 calculation units in the study area and the two production factors considered: soil salinity and water supply.

a - relation soil salinity and relative evapotranspiration

b - relation soil salinity and relative evapotranspiration under conditions of sufficient water supply

c - relation water supply and relative evapotranspiration

d - relation water supply and relative evapotranspiration under non-stress soil salinity conditions

a good correlation between soil salinity and relative evapotranspiration can be obtained (fig 46b). The remaining scatter in the data given may be explained by the fact that in figure 46b the average soil salinity till drain depth is given, and in the SIWARE model the evapotranspiration reacts to the soil salinity of the root zone. Also the water supply situation may explain part of the remaining scatter. It is very well conceivable that during certain parts of the growing season shortages of water occurred, and that crop evapotranspiration was reduced due to water shortages, although the seasonal water supply may have been sufficient. The crop yield response reported by Maas and Hoffman (1977) is also included in this figure. For long berseem the crop yield appears to react at lower soil salinities than the simulated crop evapotranspiration response (fig 46b). This seems to confirm the second observation made by comparing the field research results with the SIWARE simulation result (fig 45a).

The analysis for long berseem mentioned before has been repeated for all crops considered in the SIWARE model analysis and for the cropping pattern of 1986. The results are given in table 11 in terms of threshold values and slope of the relative evapotranspiration - soil salinity value above this threshold value. Comparing these simulation results with the reported crop yield response to soil salinity according to Maas and Hoffman (1977) it is noticed that, with an exception for cotton and rice, the crop yield starts to reduce at lower soil salinities than the simulated crop evapotranspiration (table 11). The largest difference is observed for the deciduous tree crops. For this crop the yield starts to decrease already at soil salinity values above 2 mmho.cm^{-1}, while evapotranspiration continues at maximum rates until a soil salinity of more than 3 times this threshold value (i.e. until 7.2 mmho.cm^{-1}. In all cases the reported slope of the crop yield - soil salinity relation is steeper than the slope of the evapotranspiration relation (table 11).

Table 11. Soil salinity threshold values (mmho.cm^{-1}) below which no evapotranspiration is not reduced (SIWARE model simulations) and crop yield is not reduced (Maas and Hoffman, 1977). Reduction in relative evapotranspiration per unit increase of soil salinity (%.mmho^{-1}.cm) above the threshold value (SIWARE model simulations) and reduction in crop yield per unit increase of soil salinity above the threshold value (Maas and Hoffman, 1977). Soil salinity measured in the soil water extract.

	evapotranspiration		crop yield	
crop	threshold	slope	threshold	slope
wheat	5.5	4.5	6.0	7.1
long berseem	3.8	4.7	1.5	5.7
short berseem	4.1	5.0	1.5	5.7
winter vegetables	1.6	9.0	1.5 *	15.0
cotton	7.4	5.0	7.7	5.2
maize	3.9	8.5	1.7	12.0
rice	2.3	11.0	3.0	12.0
summer vegetables	1.4	14.0	1.5 *	15.0
trees	7.2	4.0	2.0 **	14.0
crop pattern 1986	2.8	6.0	-	-

* average values for strawberries, broad beans, beans, cabbage, lettuce, onions, potatoes and tomatoes have been used;

** average values for dates, oranges, grapefruit and grapes have been used.

Relation between water supply and evapotranspiration

Looking at the relation between relative evapotranspiration of the long berseem crop and the water supply (relative to agricultural demand; fig 46c), again no clear-cut correlation between both can be established. When the supply is equal to, or larger than, the agricultural demand, the relative evapotranspiration reduction varies from 0% to 21% and for supply ranges between 75% and 65% of the agricultural demand this reduction varies from 4% to 32% (fig 46c). Singling out the simulation results of the areas having a soil salinity below the threshold value of 3.75 mmho.cm^{-1} for the relative evapotranspiration (fig 46b), a rather good correlation between relative evapotranspiration and relative water supply is found (fig 46d). According to this relation the crop water supply to long berseem can be reduced with 8% below the agricultural demand without reduction in evapotranspiration (threshold value), and each subsequent reduction of water supply with one additional percent will result in an evapotranspiration reduction of 0.7%.

The above mentioned procedure has been repeated for all crops and for the cropping pattern of 1986 (table 12). For summer vegetables and for cotton the agricultural demand (water requirement) calculated with the model WDUTY seems to be the most critical: a reduction of more than 1% for summer vegetables and 3% for cotton already reduces crop evapotranspiration. The agricultural water requirements appear to be least critical for rice and winter vegetables: for rice a water supply of 16% less than the agricultural demand, and for winter vegetables 15% less, still gives the optimum crop evapotranspiration (table 12). Below this threshold water supply level, the most sensitive crops to reductions in the water supply are again the rice and winter vegetable crops, and the least sensitive are wheat and short berseem. For the cropping pattern of 1986 the analysis points out (table 12) that the total crop water supply in the study area may be 8% below the agricultural demand, without affecting the crop evapotranspiration. Each reduction of one % of water supply below this threshold value results in a reduction of evapotranspiration of 0.74%.

The crop response for the cropping pattern of 1986 in the study area, simulated with the SIWARE model, is presented in figure 47.

Table 12. Crop response (relative evapotranspiration) to water supply simulated by SIWARE in 1986.

crop	relative supply threshold value	% evapotranspiration reduction per % reduction water supply
wheat	91	0.48
long berseem	92	0.72
short berseem	96	0.60
winter vegetables	85	0.91
cotton	97	0.76
maize	93	0.84
rice	84	1.48
summer vegetables	99	0.72
trees	96	0.75
cropping pattern 1986	92	0.74

Relation between evapotranspiration and dry matter production

So far the crop reaction according to the SIWARE model simulations have been considered in terms of relative evapotranspiration (relative to the optimum). Generally, evapotranspiration is linearly correlated to the total dry matter production of the agricultural crops. The crop yield, which of course is the main interest to farmers, may react differently to water stress conditions than the total dry matter production. For crops like berseem for instance, soil moisture stress conditions may induce additional root growth at the expense of shoots, resulting in a larger crop yield decrease than the decrease in evapotranspiration. For some grain crops it is known that moisture stress conditions reduces first the straw production and to a lesser extent the grain yield. The crop yield - water supply relations may be rather complicated, because of moisture sensitive growth periods such as the flowering period.

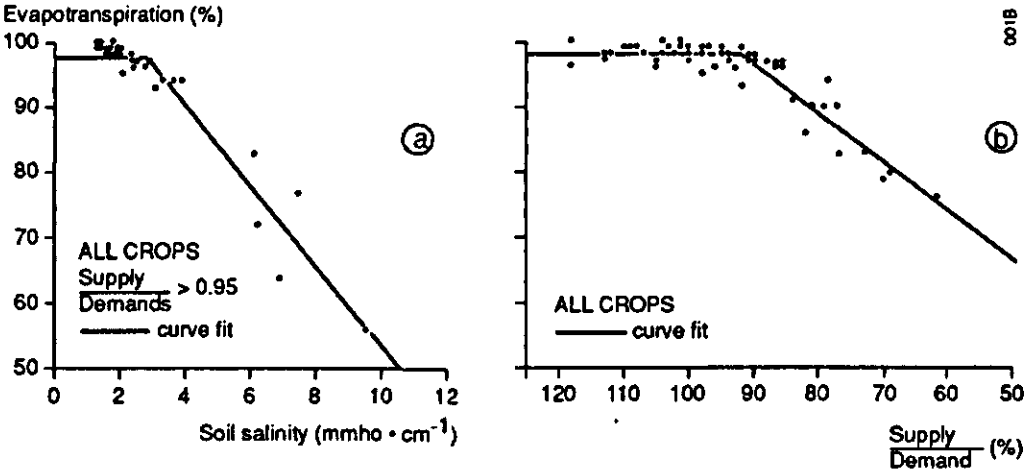

Fig 47. Aggregated crop response to soil salinity and water supply, based on the SIWARE simulation results for 1986.

a - soil salinity response b - water supply response

Relation between evapotranspiration and crop yield

The major effect of soil salinity on crop response is caused by the increase of the soil water potential due to the osmotic pressure. This means that the major mechanism of the effect of soil salinity on evapotranspiration is similar to the effect of a lower moisture content in the crop root zone (physiological drought). Consequently, it can be assumed that the crop yield decrease caused by the soil salinity, and the crop evapotranspiration decreases simulated by the SIWARE model as a result of soil salinity (table 11) are consistent with each other. Similarly, it can be assumed that the evapotranspiration reductions due to water shortages (table 12) cause similar crop yield decreases. Under these conditions both relations can be combined and the relation between relative crop evapotranspiration and crop yield is obtained. The correlation found following this procedure is rather good (fig 48). The crops for which the yields are most sensitive to reductions in evapotranspiration appear to be deciduous trees and maize (table 13). Cotton is by far the least sensitive crop, which complies with the general knowledge that this crop should be grown under stress conditions in order to promote the boll production. Also the grain yield of wheat and rice appear to be quite tolerant to reductions in evapotranspiration (table 13).

Table 13. Ratio of crop yield reduction (%) and evapotranspiration reduction (%) and the threshold value for evapotranspiration reduction (%), above which this ratio is valid for the major field crops and the actual cropping pattern. Relations are based on SIWARE model simulation results for the 82 calculation units in the study area for 1986.

crop	crop yield/ evapotranspiration ratio (-)	evapotranspiration threshold value (%)
wheat	1.11	2.0
long berseem	1.98	1.3
short berseem	1.81	1.5
winter vegetables	1.57	2.9
cotton	0.70	1.8
maize	2.55	-1.5
rice	0.87	0.2
summer vegetables	0.95	2.2
trees	10.55	12.9
cropping pattern 1986	1.42	2.3

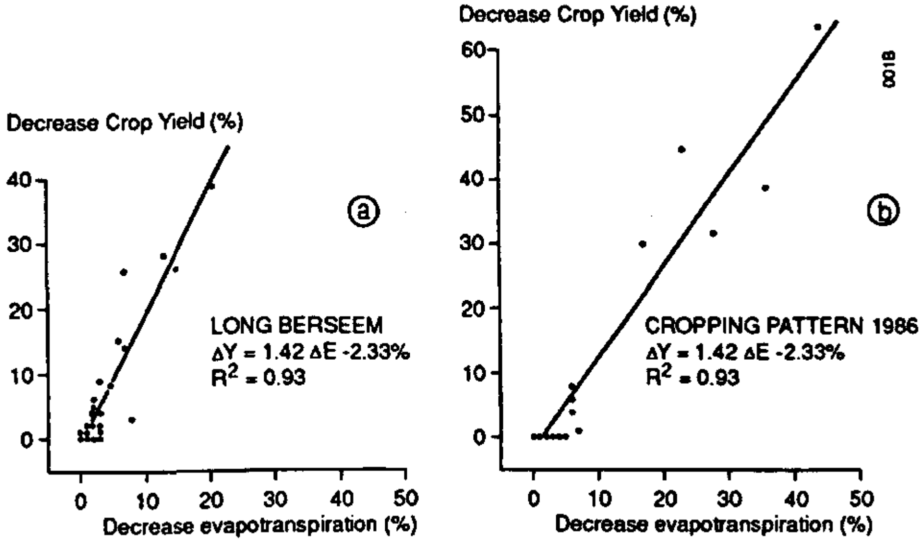

Fig 48. Relation between crop yield decrease and evapotranspiration reduction. The relation found is based on comparison of the SIWARE simulation results for 1986 with the international literature.

a - long berseem b - cropping pattern 1986

For both the cotton and the maize crop the established relationships (table 13) are supported by data reported in the Egyptian literature. Chaudry (1969) investigated the relation between water use, nitrogen fertilization and crop yield of cotton. The water use was varied by changing the irrigation interval from 8 days (minimum) till 29 days (maximum). Omitting the data for the irrigation interval of 8 days, which is unrealistically low for the cotton crop, the following crop yield decreases (in percents) as a result of the decreases (in percents) in actual evapotranspiration can be calculated:

- 1.16% crop yield decrease per % evapotranspiration reduction for 125 kg.ha^{-1} N;
- 0.80% crop yield decrease per % evapotranspiration reduction for 90 kg.ha^{-1} N;
- 0.73% crop yield decrease per % evapotranspiration reduction for 50 kg.ha^{-1} N;
- 0.59% crop yield decrease per % evapotranspiration reduction when no N fertilization was applied;

This observed range of coefficients complies very well with the value of 0.70 extracted from the model simulations for cotton (table 13). For the maize crop a coefficient of 2.5 can be calculated from the data reported by Talha (1966) and a coefficient of 3.5 based on the data reported by Awadalla (1970). The last author found that at lower production levels (crop yield lower than 20% of the optimum) the crop yield reaction to reduction in evapotranspiration becomes less sensitive with a coefficient of roughly 0.40, resulting in a weighted average value of 2.9. Both reported researches comply very well with the value of 2.55 obtained from the SIWARE model simulations in the Eastern Nile Delta for 1986.

Relation between water supply and crop yield

By combining the crop yield - evapotranspiration relations (table 13) with the water supply - evapotranspiration relationships (table 12), the dependence of the crop yield on the actual water supply situation as simulated by the model can be established for each defined crop. The crop yield reactions established in this way (fig 49) reflect the hydrological and climatological conditions as well as the irrigation regime which has been fixed (in terms of irrigation intervals; table 3). The sensitivity for water shortages with respect to agricultural water requirements appears to be different for different crop production levels (fig 49). At 100% crop yield vegetables are the most sensitive summer crop and berseem the most sensitive winter crop. At this level rice is the least sensitive summer crop and vegetables the least sensitive winter crop. At 75% crop production level, however, maize and berseem are the most sensitive and cotton and wheat the least sensitive crops. Based on the cropping pattern of 1986 and the individual crop yield reactions (figs 49a and 49b), the aggregated crop yield reduction as a consequence of water supply reductions can be calculated, assuming that the crop water supply for each crop will be reduced proportionally. The resulting relationship (fig 49c) indicates that for water supply reductions up to 15% the crop yield reduction is less than proportional. Reductions in the water supply larger than 15% will give a more or less linear reduction in crop yield of 1.2% per percent water supply reduction. Consequently, the optimum water supply most probably will be in between the agricultural demand and 0.85 of this quantity. During 1986 the total crop water supply to the study area (including unofficial reuse of drainage water by farmers) was 1,750 mm.year^{-1} and the agricultural demand 1,840 mm.year^{-1}. This means a supply of roughly 5% lower than the agricultural demand. Based on these figures the conclusion can be drawn that on the average and on on-farm water management level the system has been operated very close to the optimum during 1986.

The relative sensitivity of the crop yield of the major field crops to soil salinity appears to be less complicated than the sensitivity to water supply (fig 50). For the summer crops vegetables appears to be the most sensitive, closely followed by maize. Rice is intermediate, and cotton is by far the least sensitive crop to soil salinity (fig 50a). For the winter crops vegetables is again the most sensitive. Berseem starts reducing at the same threshold value, but has the lowest decline in

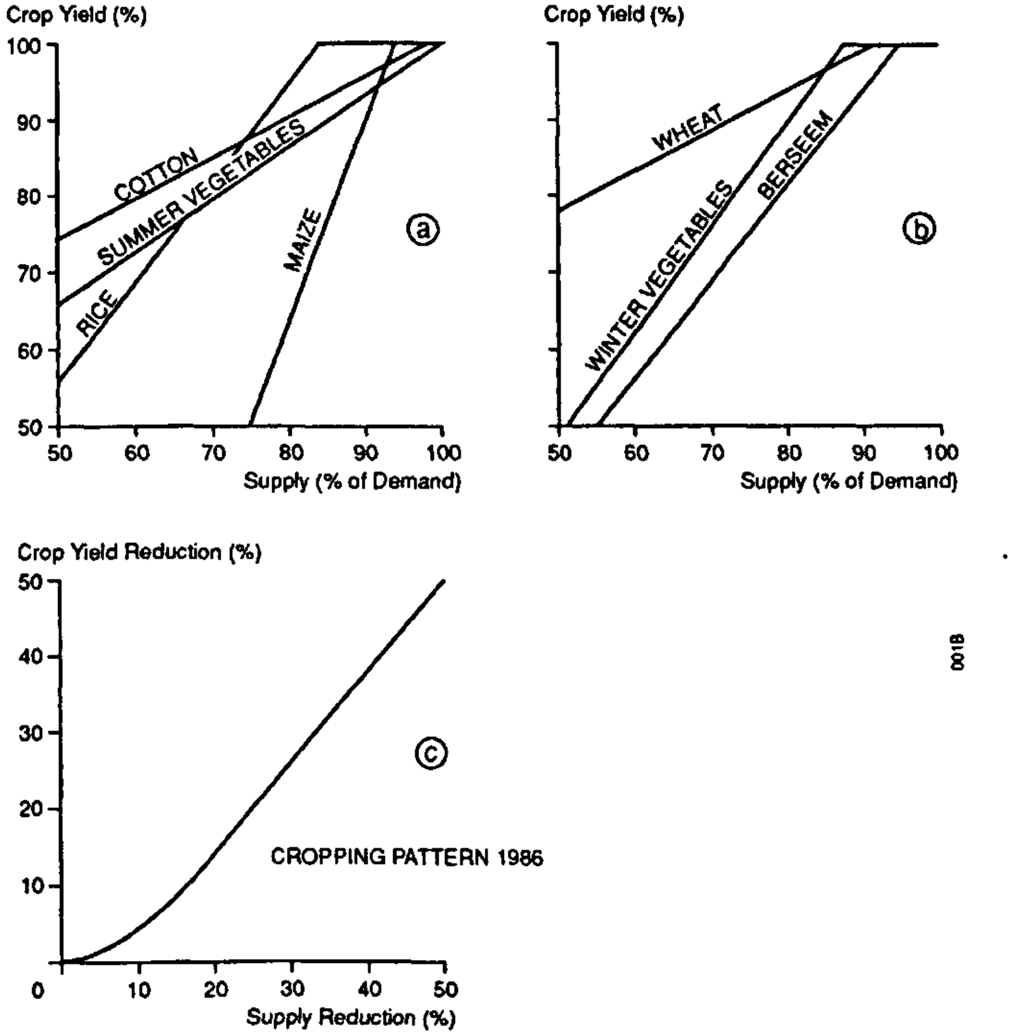

Fig 49. Relation between water supply (% of agricultural requirement) and crop yield (%) based on the SIWARE model simulations for the study area in 1986.

a - summer crops b - winter crops c - cropping pattern 1986

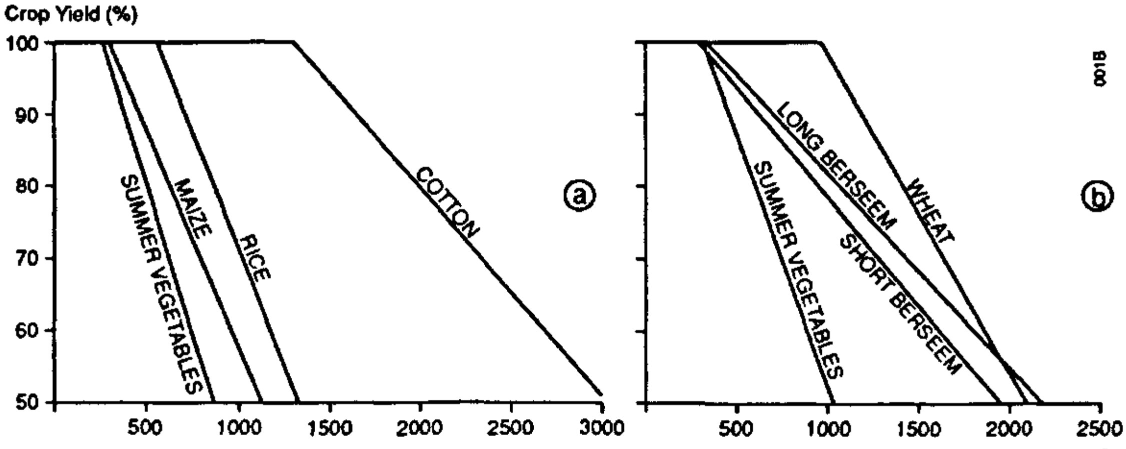

Fig 50. Relationship between soil salinity and crop yield (after Maas and Hoffman, 1977).

a - summer crops b - winter crops

crop yield per unit increase in soil salinity and wheat is the least sensitive winter crop (fig 50b).

The crop response to soil salinity and water supply simulated by the SIWARE model as discussed so far seems to be realistic and complies with the research results performed on major field crops under Egyptian conditions. For the water manager the crop yield versus water supply relationships (fig 49) are very useful, because they may support decisions related to an optimization of the water supply. The crop yield versus soil salinity relationships on the other hand, are not very easy to interpret for the water manager. Soil salinity is the long term result of on-farm water management. Consequently, soil salinity cannot easily be manipulated by the water manager. Soil salinity depends on the amount of water supply and the salinity of the irrigation water, but also on the local hydrological conditions such as soil permeability, drainage conditions, aquifer pressure and salinity of the aquifer. Last but not least, the irrigation regime as applied by farmers for the different field crops may have a considerable influence on the soil salinity. The parameter which is under largely control of the water manager (besides the amount of water supply) influencing the soil salinity is the irrigation water salinity. The operational question in this respect is: which salinity of the mixture of irrigation water and reused drainage water is still acceptable for normal irrigation practice. El Guindi and Amer (1979) give a summary of the irrigation water quality criteria based on the international literature available. The problem with applying such criteria to other conditions than those for which they have been developed is that they depend on the local climatological and hydrological conditions. The SIWARE model simulations for the 82 calculation units in the study area offer the opportunity to test these salinity criteria to the local Egyptian conditions. The fact that the model simulations are proven to be correct (within certain limits) supports this suggestion.

Relation between irrigation water salinity and soil salinity

It seems logical to assume a certain relation between irrigation water salinity and the resulting soil salinity. Examining this relationship for the crop long berseem (fig 51a), it appears that such a relation may be present, but that the scatter of the data is considerable. The scatter most probably can be attributed to differences in hydrological conditions, but also to differences in the relative amount of water supply. In an attempt to explain (at least part of) the scatter, the seasonal leaching fraction has been calculated for each of the calculation units distinguished in the model analysis. This leaching fraction is defined as the amount of irrigation applied (including unofficial reuse of drainage water) diminished with the seasonal amount of evapotranspiration. In the analysis this seasonal leaching has been calculated as the difference between the sum of drainage and leakage diminished with the quantity of upward seepage. The model simulation results for long berseem for the 82 calculation units can be classified according to this seasonal leaching percentage into three categories: the category with the lowest leaching percentages; one with the medium leaching percentages; and one with the highest leaching percentages. For each category the relationship between irrigation salinity and soil salinity has been established (fig 51a, 51b, and 51c). For both the low and the medium leaching fractions the scatter in the data points has been reduced considerably by this procedure. For the highest leaching fraction this was much less the case (fig 51d). The average relationship for the three categories separately show clear differences. On the average the soil salinity resulting from irrigation with a certain salinity is much higher under low leaching conditions than that under higher leakage conditions (figs 51b and 51d).

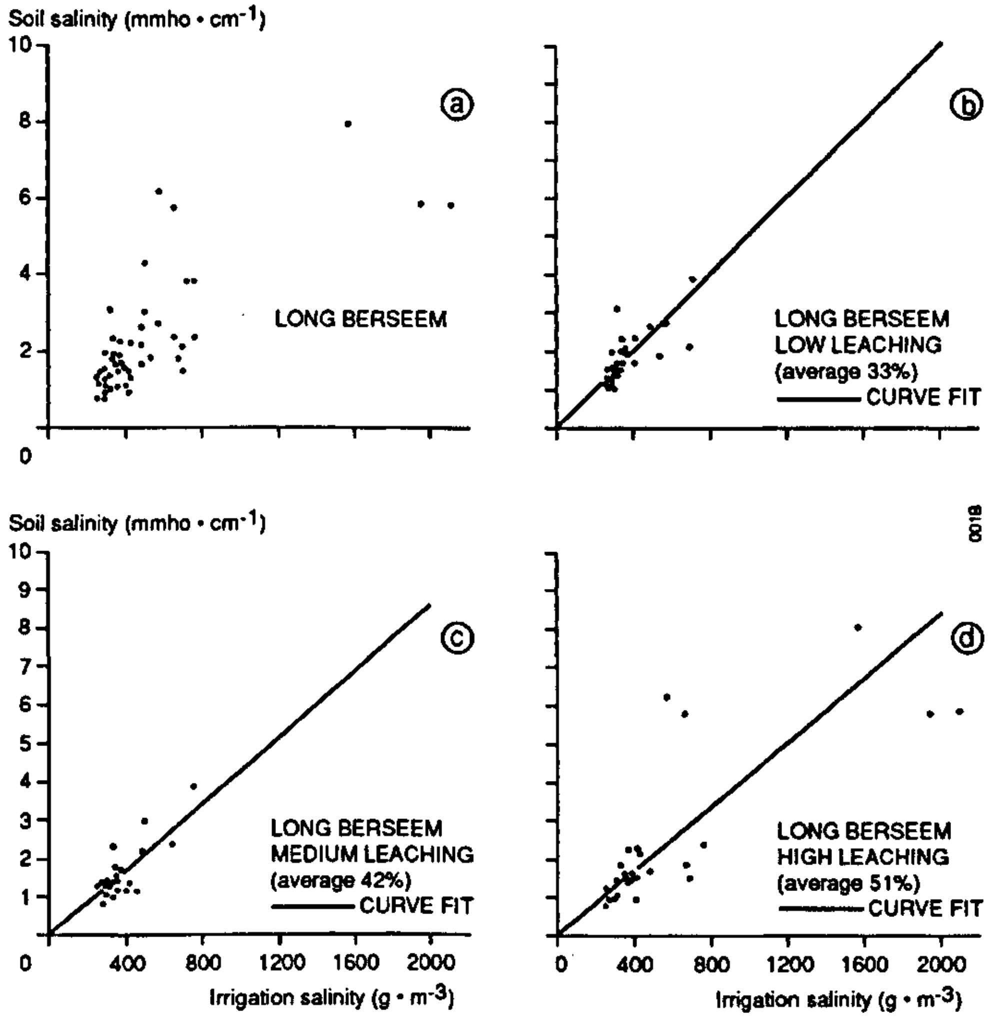

Fig 51. Relationship between the irrigation water salinity (g.m^{-3}) and soil salinity (mmho.cm^{-1}) for the long berseem crop for the calculation units in the study area simulated with the SIWARE model for the year 1986.

a - all data | b - low leaching percentage
c - medium leaching percentage | d - high leaching percentage

Because of the importance of the leaching percentage on the ratio between soil salinity and irrigation water salinity, it has been decided to investigate this matter into more detail. For this purpose the leaching percentages and associated soil salinity and irrigation salinity values for all crops in the study area have been tabulated according to increasing leaching percentage. Next, the data have been classified into groups with a difference of 5% leaching between two successive groups. Per group the average ratio between soil salinity and irrigation water salinity has been determined. The minimum leaching percentage considered was 0% (fig 52a) and the maximum was 65% (fig 52b). This means that values below -3% and above 67% have not been considered in this analysis. The difference between the two ratios obtained is considerable: the same irrigation salinity produces a 60%

higher soil salinity when zero leaching is applied compared to 65% leaching (fig 52). The terminology 'zero leaching' seems contradictory. If no leaching takes place, the soil salinity continues to increase until crop production is no longer possible. In the present analysis leaching has been defined on the basis of the complete soil profile, however, and zero leaching does not mean that the crop root zone is not leached during the growing season. Moreover, the definition of the seasonal leaching percentage, as used in this analysis, does not consider depletion or supplementation of the soil moisture storage reservoir during the growing season. Crops like cotton and wheat for instance, are kept extremely dry at the end of the growing season and consequently the leaching percentages calculated give an underestimation of the real leaching conditions. For crops like rice and vegetables the reverse holds true and the seasonal leaching percentages give an overestimation of the real leaching conditions.

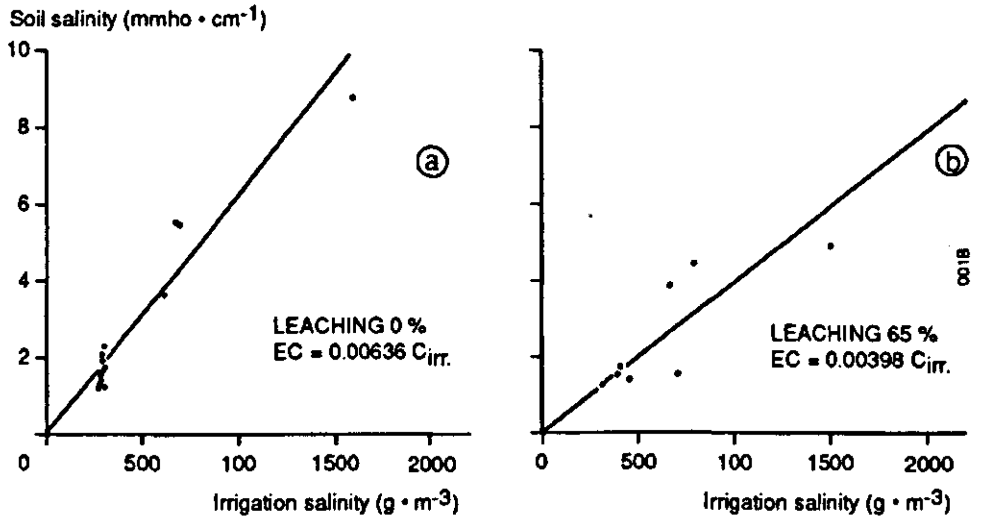

Fig 52. Relation between soil salinity and irrigation water salinity.
a - low leaching (0%) b - high leaching (65%)

In order to check mutual dependencies in the relation between the ratio of soil salinity and irrigation water salinity and the leaching percentage, also the irrigation salinity and the soil salinity have been plotted against the leaching percentages for each class (fig 54). Up to leaching fractions of 50% the irrigation salinity (including unofficial reuse of drainage water) varies around an average value of 400 g.m^{-3}. Above this leaching percentage the irrigation salinity appears to be higher (fig 54a). In other words, the leaching percentage in the study area normally varies between 0 and 50%. For irrigation water salinities above 400 g.m^{-3} farmers tend to apply more leaching than 50%, most probably to counteract the salinization effect of these high irrigation water salinities. This observation is confirmed by examining the relation between soil salinity and leaching percentage (fig 54b). Higher leaching appears to have a favourable influence on the average soil salinity, until the leaching percentage reaches a value of about 50%. Above this leaching percentage the soil salinity increases with increasing leaching. Of course this increased salinity is not caused by the increased leaching, but by the higher irrigation water salinity (fig 54a).

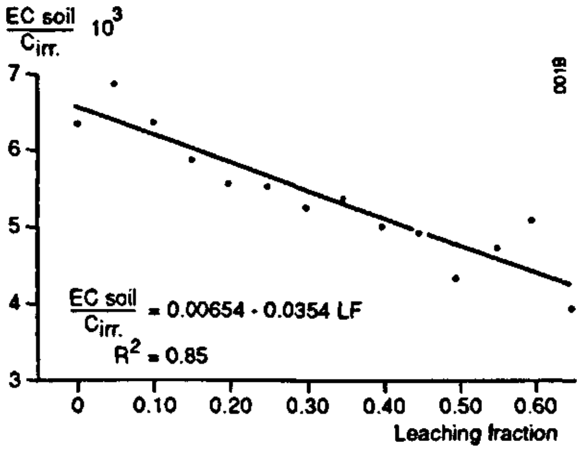

Fig 53. Relation between the ratio of soil salinity (mmho.cm^{-1}) and irrigation water salinity (g.m^{-3}) and seasonal leaching fraction derived from the SIWARE model simulations in the study area for 1986.

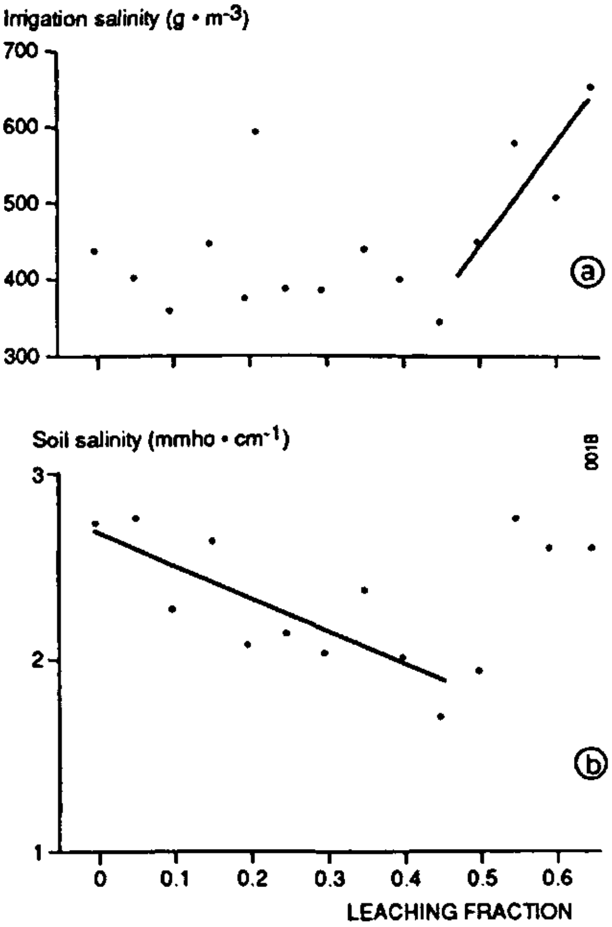

Fig 54. Relation between leaching fraction, irrigation water salinity and soil salinity for the study area during 1986.

a - irrigation salinity b - soil salinity

The ratio between soil salinity and irrigation water salinity obtained for the respective leaching percentage classes appears to show a very good correlation with the leaching fraction of each class separately (fig 53). This relation can be used by water managers to translate the irrigation water salinity to soil salinity, provided that the leaching percentage is known. Unfortunately, this is generally not the case, however.

The relationships between irrigation salinity and soil salinity discussed before are quite interesting, because they prove that the model simulations produce logical results, which in itself can be considered as a model validation. The practical usefulness of the relations given in figures 53 and 54 is limited because the parameter to be known for using the relationships is the seasonal leaching percentage for the crop considered. Moreover, specific soil and crop characteristics which are important, such as crack formation, rooting depth soil moisture depletion, etc. are neglected in this analysis.

For practical purposes it is more useful to divide per crop the simulation results in three more or less equal classes of leaching fraction and determine the ratio between soil salinity and irrigation salinity per class. This analysis, which has been done for long berseem (fig 51), has been performed for all crops and also for the aggregated cropping pattern of 1986 (table 14). In this table the average leaching percentage of each category has been included. The crops wheat, cotton, maize, and deciduous trees appear to have lower leaching percentages than the average. The crops berseem (both long and short), vegetables (both winter and summer) and rice show above average leaching percentages (table 14). The average leaching percentage of the cotton crop for low leaching conditions of -19% indicates a groundwater contribution to the evapotranspiration of this crop under these circumstances.

Table 14. Leaching percentages and ratio of soil salinity over irrigation water salinity (10^3.mmho.cm^{-1}/g.m^3) for the main field crops in the study area during 1986, simulated with the SIWARE model for high, medium and low leaching conditions.

	leaching conditions					
	favourable		medium		unfavourable	
crop	% leaching	EC/c_{irr}	% leaching	EC/c_{irr}	% leaching	EC/c_{irr}
wheat	33	6.02	22	5.60	3	7.61
long berseem	51	4.17	42	4.31	33	5.03
short berseem	53	3.99	42	4.92	34	5.70
winter vegetables	55	4.17	46	4.56	25	5.99
cotton	20	5.46	13	5.81	-19	6.86
maize	35	4.89	28	4.87	13	5.60
rice	62	4.86	52	5.41	43	5.82
summer vegetables	57	5.04	44	4.75	29	7.04
trees	30	11.03	20	11.73	0	19.88

The ratio of soil salinity and irrigation water salinity and the average leaching fraction appears to show a good correlation with each other (fig 55). For the summer crops the relations for rice and summer vegetables are significantly different from those for cotton and maize. The reason for this difference must be sought in the rooting depths of these crops (table 5). A larger rooting depth means extraction of soil moisture to a larger depth in the soil profile, and consequently leads to a higher leaching efficiency (fig 55a). For the winter crops the differences in rooting depth are less pronounced and the resulting relationships are closer together (fig 55b).

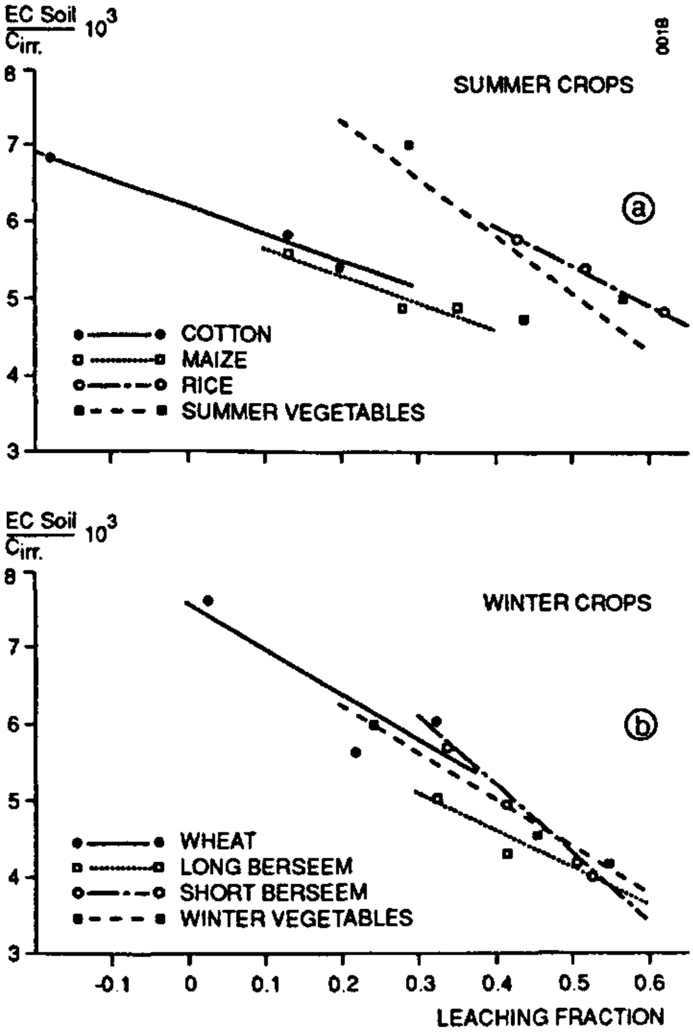

Fig 55. Relation between the ratio of soil salinity and irrigation water salinity for the main field crops in the study area for low, medium, and high leaching conditions. Results based on the model simulations with the SIWARE model for 1986.

a - summer crops b - winter crops

Relation between irrigation water salinity and crop yield

The ratio between soil salinity and irrigation water salinity can be used to convert the relationships between crop yield and soil salinity (fig 50) to relationships between crop yield and irrigation water salinity (fig 56). For average leaching conditions the cotton crop appears to be the least sensitive summer crop and vegetables the most sensitive for irrigation water salinity (fig 56a). Up to crop yield decreases of about 50% wheat is the least sensitive winter crop, but below 50% crop yield decrease berseem is the least sensitive (fig 56b). Vegetables appear to be the most sensitive winter crop. In table 15 the threshold value's and the decline in crop yield per unit (g.m^{-3}) increase in irrigation water salinity for high, medium and low leaching conditions are given for the major field crops.

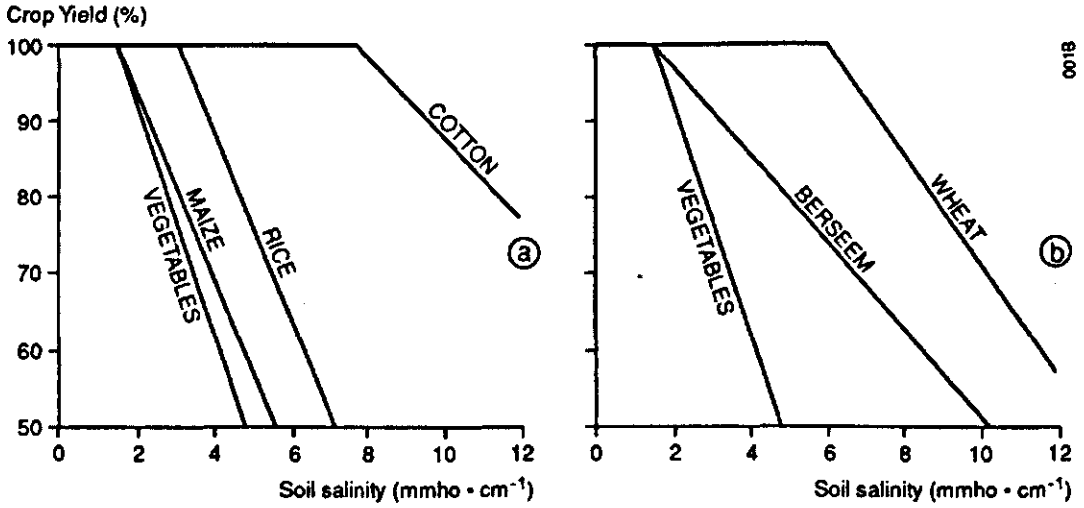

Fig 56. Relationship between crop yield and irrigation water salinity for average leaching conditions during 1986 in the study area based on SIWARE model simulations.
a - summer crops b - winter crops

For irrigation water salinities below 400 g.m^{-3} no major crop yield problems are expected under average leaching conditions. For an irrigation water salinity of 800 g.m^{-3}, during summer time, the vegetable crop is seriously affected (crop yield reduction of almost 50%). During the winter period the vegetable crop yield is reduced with about 35% for such an irrigation water salinity and also the maize crop suffers a crop yield decrease of about 30%. Consequently, under average leaching conditions, vegetables and maize should be excluded from the cropping pattern at irrigation water salinities above 800 g.m^{-3}. With an irrigation water salinity of 1,200 g.m^{-3} also the rice crop suffers a serious crop yield depression of about 40% under average leaching conditions (fig 56). The berseem crop yield is affected with about 15% at this irrigation water salinity level. Irrigation water salinities above 1,200 g.m^{-3} consequently prohibit, besides the vegetable crop, also the successful cultivation of rice. For the summer period cotton is the only alternative left for irrigation water salinities above 1,200 g.m^{-3} under average leaching conditions. With an irrigation water salinity of about 1,600 g.m^{-3} the cotton crop is not yet seriously affected under average leaching conditions, but all winter crops will suffer yield decreases. Wheat will produce about 30% less, while berseem shows a yield reduction of more than 35% (fig 56).

Summarizing, the following irrigation water salinity classification can be made for average leaching conditions:

- salinity below 400 $g.m^{-3}$:	no problems;
- salinity from 400 - 800 $g.m^{-3}$:	increasing problems with vegetables and maize;
- salinity from 800 - 1,200 $g.m^{-3}$:	increasing problems with rice; serious problems with vegetables and maize;
- salinity above 1,200 $g.m^{-3}$:	increasing problems with berseem and wheat; serious problems with rice; cultivation of vegetables and maize impossible.

Relation between irrigation water salinity and crop production

Combining the crop yield - irrigation water salinity relations (table 15) with the cropping pattern for the Eastern Nile Delta for 1986, the relation between the total crop production and the irrigation water salinity for the complete Eastern Nile Delta can be drafted (fig 57). Large differences can be noticed for the different leaching conditions which have been defined before. In this context high leaching conditions imply a sufficient water supply and good internal (soil profile) drainage conditions. Low leaching conditions are caused either by an insufficient water supply or bad internal drainage conditions (for instance due to low soil permeability or seepage conditions), or by a combination of both. The relationships derived (fig 57) indicate that higher irrigation water salinities are permissible, provided that the irrigation water supply is adequate and drainage conditions are good, for instance by installing a subsurface drainage system. In the range of crop production levels up to 75%, the irrigation water salinity apparently may be increased by roughly 50% on the condition that the drainage conditions are improved and the water supply is adequate. At 90% crop yield level the salinity of the irrigation water may increase from 500 $g.m^{-3}$ to 750 $g.m^{-3}$ by changing low leaching conditions to high leaching conditions (fig 57). At 75% crop yield level the salinity may rise from 800 $g.m^{-3}$ to 1,200 $g.m^{-3}$.

Table 15. Crop response to irrigation water salinity for high, medium, and low leaching conditions. Threshold value ($g.m^{-3}$) and yield decline (%) per unit increase of irrigation salinity ($g.m^{-3}$).

	leaching conditions					
	favourable		medium		unfavourable	
crop	threshold	decline	threshold	decline	threshold	decline
wheat	1,070	0.039	960	0.044	810	0.052
long berseem	370	0.024	330	0.027	300	0.030
short berseem	370	0.024	300	0.030	260	0.034
winter vegetables	370	0.061	320	0.070	250	0.089
cotton	1,360	0.028	1,300	0.029	1,090	0.034
maize	310	0.057	300	0.060	270	0.067
rice	620	0.058	560	0.065	520	0.070
summer vegetables	330	0.069	270	0.083	220	0.100
trees	200	0.149	150	0.185	100	0.270

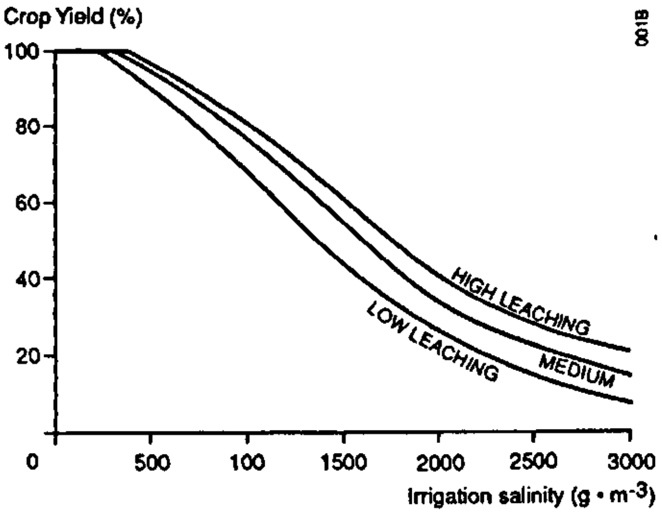

Fig 57. Relation between relative crop yield and irrigation water salinity for the average cropping pattern in the Eastern Nile Delta for low (22%), medium (35%), and high (47%) leaching conditions.

The relation between crop yield and irrigation water salinity (fig 57) can also give an indication of the crop yield increase due to improvement of drainage conditions. For an irrigation water salinity of 400 g.m^{-3} the increase is roughly 6% and for a salinity of 1200 g.m^{-3} the increase is about 26%. It should be kept in mind, however, that the crop yield increase by improving drainage conditions derived from figure 57 does not give the total potential crop yield increase that results from improving drainage conditions. The installation of a subsurface drainage also implies in general the lowering of the groundwater table, whereby crop root growth which may have been impeded by high groundwater tables, is no longer limited. Under these conditions the agricultural water requirement itself will change (increase) due to higher optimum evapotranspiration rates. In other words the potential crop yield of subsurface drained fields will be higher. This effect should be superimposed on the crop yield increases which can be derived from the relationship given in figure 57.

5. WATER MANAGEMENT STRATEGIES

5.1. Introduction

Before any simulation model can be used for predictions it should be sufficiently calibrated and validated. This has been shown in the previous chapter. Consequently, application of the SIWARE model to the Eastern Nile Delta for the evaluation of alternative water management strategies is warranted. Although the SIWARE model has been sufficiently calibrated and validated, the simulation results should still be interpreted with caution. Application of the model to ranges and conditions not covered during the validation, may cause deviations in the absolute values of the simulations when compared to reality. Interpretation of model simulation results should therefore be confined to the mutual comparison of alternative water management strategies and not too much value should be attached to the absolute simulation results.

It has been mentioned before that the water management system in the Eastern Nile Delta can be classified as rather efficient. Consequently, the margins for changes in the present water management system are not very large. This means also that changes in the model results, such as for instance total drainage discharge, soil salinity, crop transpiration, etc, will not be very large. When changing the water management in an area such as the Eastern Nile Delta, generally two effects are superimposed: a short term effect as a result of the changes in the water supply, its distribution, and its salinity; and a long term effect as a result of changes in the salinity of the distinguished water balance components. This long term effect is sometimes also referred to as the 'memory' of the system. In order to avoid disturbances of long term effects on the comparison between alternative water management strategies, equilibrium soil salinity conditions should be obtained for each cluster of strategies. This 'clearing of the system's memory' is accomplished by running the SIWARE model for a period of at least 50 years for a strictly defined reference situation. For all alternative strategies belonging to such a cluster the same initial conditions for soil moisture and salinity obtained with this long term reference simulation will be used.

One of the main objectives for the analysis of different water management strategies is to determine the availability of reusable drainage water for irrigation. The amount of reused drainage water is part of the water management strategy (fig 1), because it reduces the amount of Nile water needed. On the other hand, the actual amount of drainage water available for reuse is the outcome of a certain water management strategy. If both quantities (the assumed quantity when allocating the Nile water, and the actual available quantity) differ, the water allocation was not optimal. If the drainage water actually available is more than assumed by the water manager, less Nile water could have been used. If the actual available drainage water was less than assumed by the water manager, more Nile water should have been used. With the SIWARE model this allocation of water, differentiated for the distinguished irrigation command canals, can be simulated beforehand. During runtime a message file is created by the model in which differences between assumed and realized quantities of drainage water for reuse are reported. By updating the reuse quantities for the water allocation and running the model again, a consistent water management strategy can be obtained.

In practice not all simulated amounts of drainage water available for reuse is actually reused. Generally reuse pump stations are constructed in a small branch of the main drain from where they withdraw the drainage water. In this way the main drain itself functions as a by-pass for emergency cases, and excess water which is not reused will continue in the main drain. During 1986 the reuse of drainage water has been maximized, and still about 30% of the simulated available drainage water for reuse was not utilized for this purpose. The reasons for this phenomenon may be a low demand for water in the winter period; mismatches between the pump unit capacities and the available amount of drainage water; or calamities, such as electricity cuts. The percentage of unused available drainage water varies from 90% during the winter months with low demand and low drainage flows, till 20% during the summer months with high demand and high drainage flows. Based on the simulation results for 1986 and the actual reused quantities the fractions of simulated drainage water which are actually reused have been established (table 16). In the message file created by the SIWARE model the simulated available quantities of reuse are multiplied with these fractions.

Table 16. Fraction of the available drainage water which is actually reused for irrigation. Results based on the simulations and observations of 1986.

	fraction		
pump station	winter	spring/autumn	summer
Wadi	0.37	0.71	0.86
Blad El Ayed	0.56	0.87	1.00
Hanut	0.62	0.75	0.75
Saft	0.22	0.32	0.26

winter = january - february
spring/autumn = march - may and october - december
summer = june - september

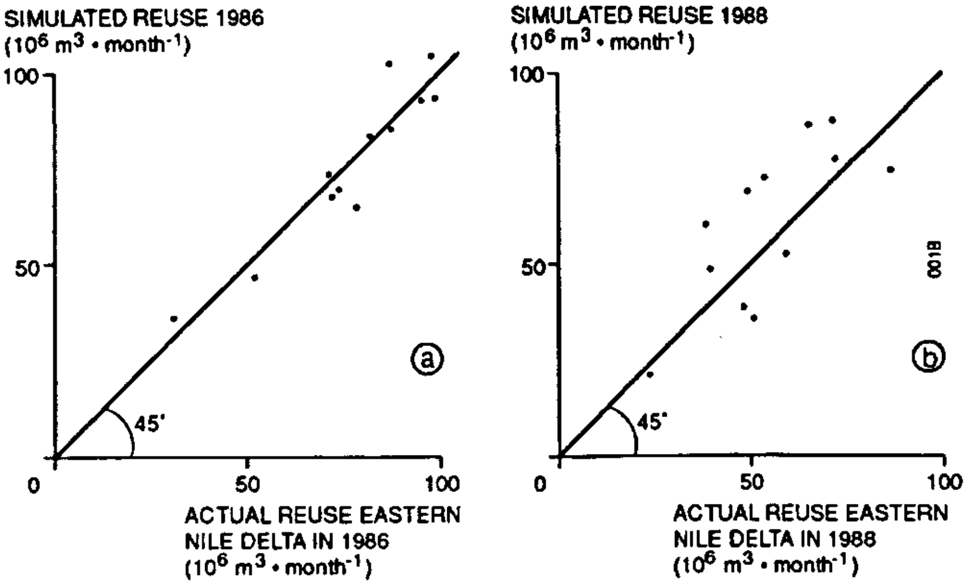

Fig 58. Comparison of actual reuse of drainage water in the Eastern Nile Delta with the simulated reuse of drainage water (after multiplication with the factors given in table 16).

Using these correction factors for the simulated available reuse, an average deviation in the monthly reuse quantities of 7% is obtained for the simulation (calibration) year 1986 (fig 58a). For the simulation (validation) year 1988 the average monthly deviation is larger, about 25% (fig 58b).

In consultation with the Steering Committee three groups of water management scenarios have been selected for analysis with the SIWARE model. They are the following:

- rice area and allocation duty strategies;
- extension of agricultural area strategies;
- local water management improvement strategies.

The rice crop is known to have large water requirements of about 2 to 3 times those of the other summer crops. Savings of irrigation water can thus be realized by exchanging the rice in the crop rotation by other summer crops. During 1988 this was the case, when the Ministry of Public Works and Water Resources was faced with a serious water shortage. The decision was made then, to forbid the growing of rice in the southern part of the Eastern Nile Delta and to replace this crop in these areas by maize. During the implementation of this water management strategy a problem was encountered. The reuse of drainage water appeared to be much less than anticipated beforehand. As a consequence, the water allocation had to be adjusted during the implementation of this strategy. The practical question of the Ministry of Public Works and Water Resources regarding the rice strategies is the following: which quantities of drainage water are available when the rice areas are reduced step by step in the Eastern Nile Delta. Another method of saving on Nile water supply to the Eastern Nile Delta is to reduce the allocation water requirement of the rice crop. The philosophy behind reducing the allocation water requirement for rice is that farmers may be forced to use the available water more efficiently, thereby reducing the losses of irrigation water. The results of the rice strategies are treated in chapter 5.2.

Horizontal expansion of the agricultural area in the Eastern Desert is foreseen in the planning of the Ministry of Public Works and Water Resources in the near future. The extension anticipated is about 350,000 feddans, at a pace of 44,000 feddans per year. This would increase the present gross agricultural area in the Eastern Nile Delta of about 1.8 million feddans with almost 20%. The practical question of the Ministry of Public Works and Water Resources in this respect is the following: which allocation of irrigation water has to be applied if, starting from the cropping pattern and water supply of 1988, the irrigation water for an additional area in the Eastern Delta of 44,000 feddans.year^{-1} has to be made available, taking into account the reductions in the amounts of drainage water available for reuse. The results of the extension strategies are treated in chapter 5.3.

As has been mentioned before in chapter 4.4.2., there is a considerable discrepancy between the water duties used by the Ministry of Public Works and Water Resources for the water allocation, target level control and gate opening procedures, and the agricultural, spatially variable water requirements as experienced by the farmers. In the traditional irrigation water management in the Nile Delta, the water management control was very tight. Farmers were obliged to use sakkias for irrigating their fields. The supply pipes to the sumps from where sakkias take their water had a limited size and were under control of the Ministry of Public Works and Water Resources. Consequently, farmers were forced to irrigate during night hours as well. The introduction of small capacity, movable diesel pumps has created an overcapacity in the available irrigation tools, and farmers (located near the intake gates of the irrigation system) are no longer compelled to irrigate during the night. As a result farmers at the downstream end of meskaas sometimes have to use drainage water, because farmers upstream take more than their equal share. The Ministry of Public Works and Water Resources is well aware of this problem. The Steering Committee requested to evaluate with the SIWARE model the consequences of improving the local water management conditions by the elimination of these diesel pumps. The results of these strategies are treated in chapter 5.4.

For each of the three clusters of water management strategies defined above, a reference situation has been defined. The initial conditions with respect to soil moisture and soil salinity conditions have been obtained by running the SIWARE model for a period of 50 years. For each cluster of strategies this reference situation is different. Consequently, the results of a certain strategy from one cluster cannot be compared to the results from a strategy from another cluster. Identical initial conditions are a prerequisite for the mutual comparison of water management strategies.

5.2. Rice area and allocation duty strategies

5.2.1. Introduction

The rice crop is a very profitable crop for farmers and rice has become the main staple food in Egypt. The rice crop, however, requires large amounts of irrigation water, because it is grown under ponding conditions, thereby causing substantial water losses. The function of rice in the cropping pattern is that it leaches salt, accumulated in the root zone during the growing season of other crops (fig 41). This leaching is more important in the northern part of the Eastern Nile Delta. In the south, the soils are lighter textured (better internal drainage conditions), leakage conditions prevail, and the soil salinity is less.

Because of the high rice water requirements of almost 2 to 3 times those of other summer crops, the Egyptian farmer is not allowed to grow any quantity of rice he wants. The Ministry of Public Works and Water Resources has divided the Eastern Nile Delta in so-called rice zones (fig 59a). In the southern part of the Eastern Nile Delta (rice zone 5) the growing of rice is forbidden, because leaching of salts is not necessary here. In the most northern part (rice zone 1) it is allowed to plant 50% of the area with rice, because leaching of accumulated salts is a prerequisite in an area dominated by saline seepage from the aquifer (fig 59a).

For the rice strategies this practical subdivision of the Eastern Nile Delta in rice zones has been followed in the model simulations. Five rice area reduction strategies can thus be recognized by taking the rice out of cultivation in zone 5 first; in zone 4 next; and so on. The alternative crop replacing the rice which is taken out of cultivation is maize. The savings on water are considerable: the Ministry of Public Works and Water Resources uses an allocation duty of 8,800 $m^3.feddan^{-1}$ for rice and 2,700 m^3.feddan^{-1} for maize, resulting in a water saving of 6,100 m^3 for each feddan of rice taken out of cultivation.

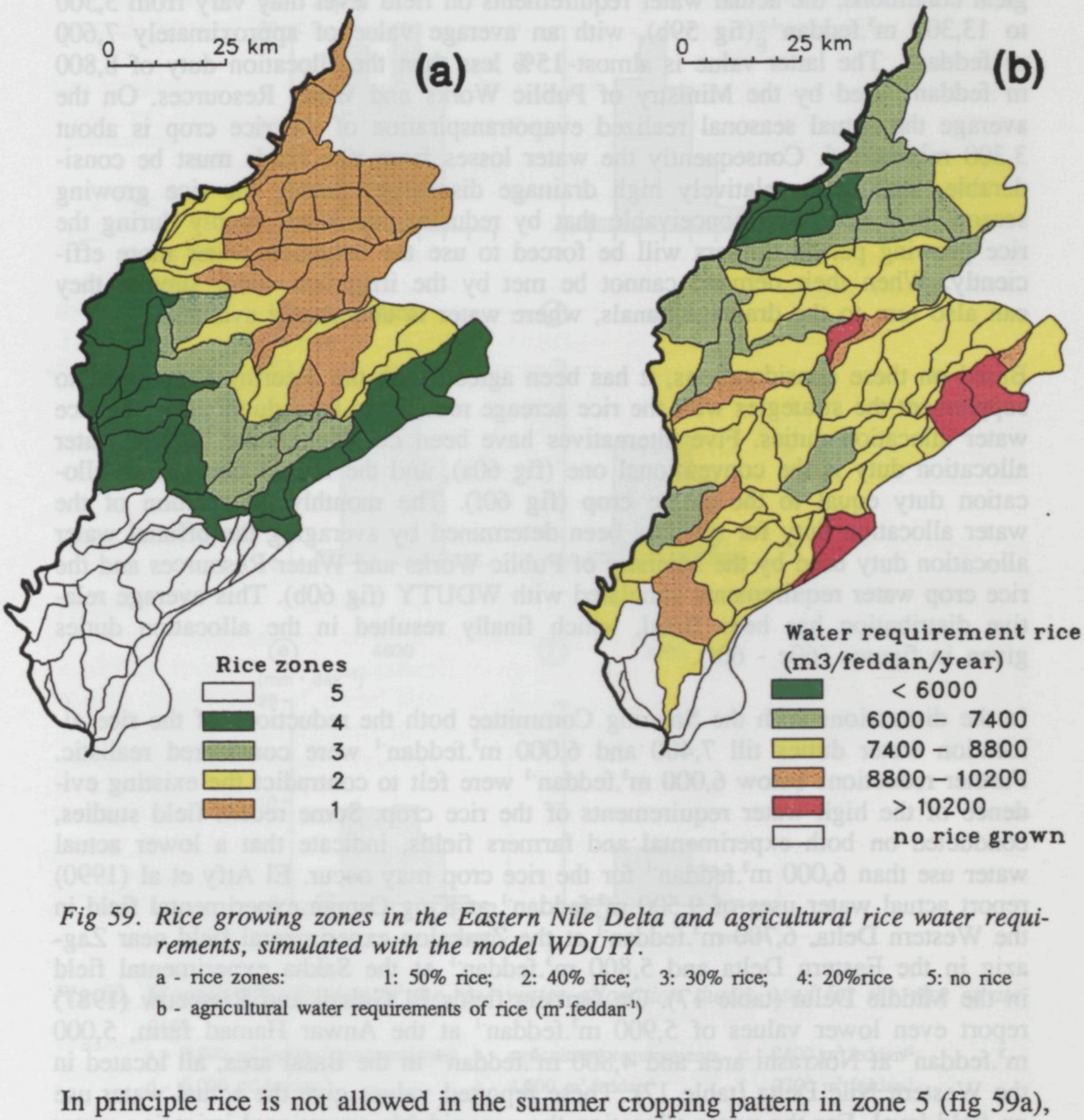

Fig 59. Rice growing zones in the Eastern Nile Delta and agricultural rice water requirements, simulated with the model WDUTY.

a - rice zones: 1: 50% rice; 2: 40% rice; 3: 30% rice; 4: 20%rice 5: no rice

b - agricultural water requirements of rice (m^3.feddan^{-1})

In principle rice is not allowed in the summer cropping pattern in zone 5 (fig 59a), although in reality some rice is grown here. For the definition of the rice area reductions strategies the reference cropping pattern has to be defined. For this purpose both the cropping patterns of 1984 and 1988 have been compared and the maximum percentage of rice occurring in each calculation unit has been selected as the reference. The water supply to the Eastern Nile Delta for this reference strategy has been taken equal to the allocation requirements for this specific cropping pattern. Due to the interference of the official reuse of drainage water, which can be deducted from the gross allocation requirements, a few iterations had to be made. A 50 year run has been carried out to obtain equilibrium conditions for soil salinity. These soil moisture and salinity conditions have been used for all rice strategies as initial conditions. This facilitates the interpretation when comparing the different rice strategies mutually.

The allocation water duty used by the Ministry of Public Works and Water Resources is considered uniform within the Eastern Nile Delta. Calculations with the WDUTY sub-model showed that due to differences in climatic, soil and hydrological conditions, the actual water requirements on field level may vary from 5,500 to 13,300 m^3.feddan^{-1} (fig 59b), with an average value of approximately 7,600 m^3.feddan^{-1}. The latter value is almost 15% less than the allocation duty of 8,800 m^3.feddan^{-1} used by the Ministry of Public Works and Water Resources. On the average the actual seasonal realized evapotranspiration of the rice crop is about 3,300 m^3.feddan^{-1}. Consequently the water losses from rice fields must be considerable, leading to relatively high drainage discharges during the rice growing season. It is very well conceivable that by reducing the water supply during the rice growing period farmers will be forced to use the irrigation water more efficiently. When their demand cannot be met by the irrigation water supply, they can also turn to the drainage canals, where water is abundantly available.

Based on these considerations, it has been agreed with the Steering Committee to supplement the strategies with the rice acreage reductions by reductions in the rice water allocation duties. Five alternatives have been considered: the highest water allocation duty is the conventional one (fig 60a), and the lowest one has an allocation duty equal to the maize crop (fig 60f). The monthly distribution of the water allocation duty for rice has been determined by averaging the official water allocation duty used by the Ministry of Public Works and Water Resources and the rice crop water requirements simulated with WDUTY (fig 60b). This average relative distribution has been fixed, which finally resulted in the allocation duties given in figures (60c - 60f).

In the discussions with the Steering Committee both the reductions of the rice allocation water duties till 7,400 and 6,000 m^3.feddan^{-1} were considered realistic. Further reductions below 6,000 m^3.feddan^{-1} were felt to contradict the existing evidence of the high water requirements of the rice crop. Some recent field studies, conducted on both experimental and farmers fields, indicate that a lower actual water use than 6,000 m^3.feddan^{-1} for the rice crop may occur. El Atfy et al (1990) report actual water uses of 9,500 m^3.feddan^{-1} at King Osman experimental field in the Western Delta, 6,700 m^3.feddan^{-1} at the Zankalon experimental field near Zagazig in the Eastern Delta and 5,800 m^3.feddan^{-1} at the Sakha experimental field in the Middle Delta (table 17). On farmers fields El Guindi and Risseeuw (1987) report even lower values of 5,900 m^3.feddan^{-1} at the Anwar Hamad farm, 5,000 m^3.feddan^{-1} at Nokrashi area and 4,800 m^3.feddan^{-1} in the Basal area, all located in the Western Nile Delta (table 17). These reported values give the actual water use on field level. For the water allocation the unavoidable operational irrigation water losses have to be added, in order to assure a good water distribution among farmers fields.

Based on these field researches, the allocation water duty of 4,600 m^3.feddan^{-1} has been included in the rice strategies as the lower limit of a practical reduction in the rice water allocation duty. As an absolute extreme water saving strategy, an allocation duty of 2700 m^3.feddan^{-1} for rice has been added. For this extreme, the gross water savings are equal to the gross water savings obtained by removing all rice from the cropping pattern in the complete Eastern Nile Delta. Both options (removal of all rice and allocation duty for rice equal to that of maize, 2,700 m^3.feddan^{-1}) are considered unrealistic from a practical point of view.

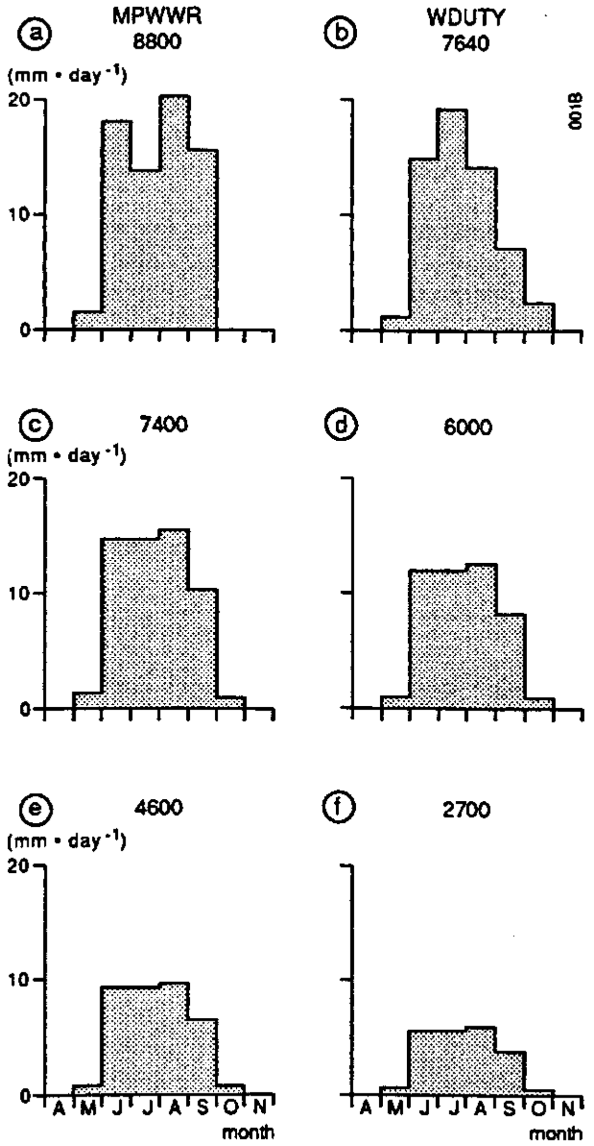

Fig 60. Monthly distribution of the rice water allocation duties used for the rice strategies.

a - 8,800 m³.feddan⁻¹ (conventional) b - agricultural requirements c - 7400 m³.feddan⁻¹
d - 6,000 m³.feddan⁻¹ e - 4,600 m³.feddan⁻¹ f - 2700 m³.feddan⁻¹

Considering the monthly distribution of the water allocation duties for the reduction strategies (figs 60c - 60f) with those of the field researches (fig 61), it can be noticed that they resemble the monthly distribution of the field researches more than that of the official allocation duty (fig 60a). In the Anwar Hammad farm, a shortage of water at the start of the rice growing period is impeding the agricultural practices. As a result, the farmer has delayed the transplanting of rice, shifting the peak water use to August (fig 61a). The farmer also used drainage water with a relatively high salinity to compensate for the shortage in irrigation water. In the Nokrashi area the peak water use occurs in July. The water shortage in the beginning of the rice growing season is less serious here. In the Basal area no water shortage occurred and the water quality was good. The peak water use in this area is in the month June, during the rice transplanting period. In none of the field observations the peak water demand of August as occurring in the official Ministry of Public Works and Water Resources (fig 60a) rice water allocation duty can be observed.

Table 17 Total irrigation water gifts ($m^3.season^{-1}$) to the rice crop in experimental and farmers fields.

area	seasonal reported water gift (m^3)		
King Osman (Western Delta)	9,525		
Zankalon (Eastern Delta)	6,709		
Sakha (Middle Delta)	5,783		
	1977	1978	1979
Anwar Hamad (Western Delta)	5,670	6,300	5,628
Nokrashi (Western Delta)	5,292	5,334	4,956
Basal (Western Delta)	-	-	4,893

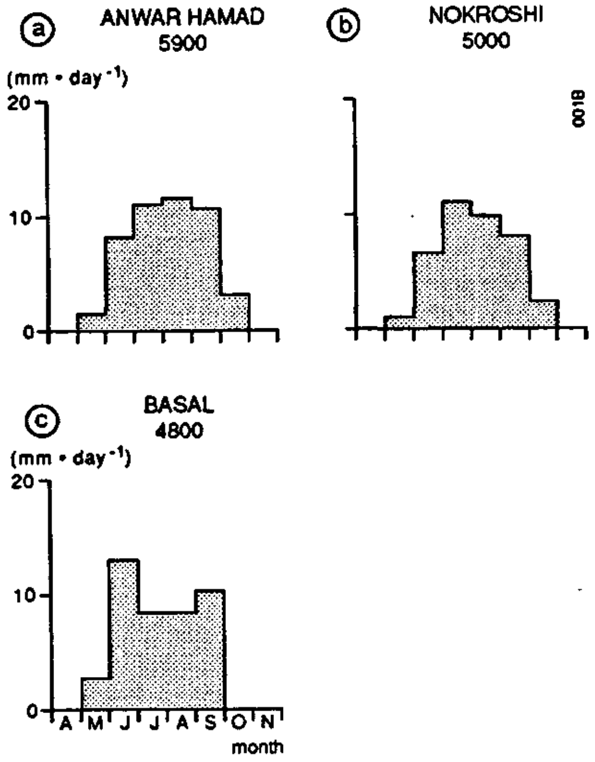

Fig 61. Actual monthly rice water use distribution observed of farmers fields in the Western Nile Delta during the period 1977 - 1979 reported by El Guindy and Risseeuw (1987).

a - Anwar Hamad farm b - Nokrashi area c - Basal area

Based on the before mentioned reductions in rice area and allocation water duties, the alternative rice strategies given in table 18 have been defined. In the ensuing text in this chapter these strategies will be referred to by the two parameters given in table (18). The first parameter gives the rice area in thousands of feddans, the second parameter gives the rice allocation duty in hundreds of m^3 per feddan.

Table 18. Definition of rice area and water duty strategies.

Rice area (feddans)	rice allocation duty (m^3.feddan^{-1})				
	8,800	7,400	6,000	4,600	2,700
510,385	(510,88)	(510,74)	(510,60)	(510,46)	(510,27)
468,356	(468,88)	(468,74)	(468,60)	(468,46)	-
375,264	(375,88)	(375,74)	(375,60)	(375,46)	-
308,872	(309,88)	(309,74)	(309,60)	(309,46)	-
209,635	(210,88)	(210,74)	(210,60)	(210,46)	-
-	(0,88)	-	-	-	-

In addition to these 22 rice area and water duty scenarios one more scenario has been formulated. For this strategy the water allocation duty has been considered spatially variable: 8,800 m^3.feddan^{-1} in the southern part of the study area (rice zone 5); 7,750 in rice zone 4; 6,700 in rice zone 3; 5,650 in rice zone 2; and 4,600 m^3.feddan^{-1} in the most northern part of the study area (rice zone 1). The spatial distribution of these water allocation duties follows more or less the agricultural water requirements of the rice crop (fig 59b). This scenario with variable allocation duty is coded (510,VA).

5.2.2. Water savings

Reuse of drainage water through official reuse pump stations results in savings on irrigation water. The area supplied with a mixture of fresh Nile water and reused drainage water needs less water from the Nile supply. When water management measures are introduced with the objective to save on irrigation water, possible reductions in the amount of drainage water available for reuse have to be taken into account. Replacing one feddan of rice by one feddan of maize reduces the gross allocation requirement with the difference in allocation duties of both crops, i.e. 8,800 - 2,700 = 6,100 m^3 of irrigation water. If this feddan of rice to be replaced by maize is located inside the catchment of a reuse pump station, however, the drainage water available for reuse reduces also. This reduction is the difference between the drainage of one feddan of rice and one feddan of maize. Consequently, the water supply to the irrigation canal in which this drainage water is to be reused, has to be corrected for this difference. The net Nile water savings of water management measures, such as replacing rice by maize and decreasing the allocation duty of the rice crop, are therefore always less than the reductions in the total gross allocation requirements, which includes the official reuse of drainage water.

Examining the results of the 23 rice area and allocation duty reduction strategies (table 19) confirms this. In all strategies defined, where either the rice area or the rice water duty has been reduced, the official reuse of drainage water falls short of the amount calculated for the reference strategy (510,88). The maximum reduction in the gross water requirements (including the official reuse of drainage water) considered is 3,195 million m^3.year^{-1}. Generally, there are two ways to achieve this water allocation reduction: either by reducing the rice area, or by reducing the rice water allocation duty. The practical question now is which method of saving water is the best with the minimum of negative effects.

Table 19. Eastern Nile Delta water balance for the 23 defined rice area and water duty strategies. All figures in million m^3.year^{-1}

The first number in the strategy identification refers to the rice area in thousands of feddans; the second number refers to the allocation duty in hundreds of m^3.feddan^{-1}.

strategy number	gross water requirement	official reuse	Nile water supply	irrigation losses	drainage to sea	system efficiency
(510,88)	12,760	851	11,909	3,444	5,199	56
(468,88)	12,491	787	11,704	3,369	5,104	56
(375,88)	11,903	704	11,199	3,137	4,774	57
(309,88)	11,488	641	10,848	2,973	4,548	58
(210,88)	10,868	565	10,302	2,736	4,222	59
(0,88)	9,581	528	9,053	2,156	3,276	64
(510,74)	11,968	771	11,197	2,828	4,551	59
(468,74)	11,768	727	11,042	2,798	4,498	59
(375,74)	11,328	664	10,664	2,629	4,284	60
(309,74)	11,016	610	10,405	2,614	4,151	60
(210,74)	10,550	578	9,992	2,482	3,926	61
(510,60)	11,234	693	10,540	2,479	4,022	62
(468,60)	11,094	662	10,433	2,473	3,998	62
(375,60)	10,787	613	10,174	2,431	3,878	62
(309,60)	10,570	584	9,986	2,394	3,798	62
(210,60)	10,247	546	9,701	2,332	3,675	62
(510,46)	10,572	625	9,902	2,251	3,572	64
(468,46)	10,447	607	9,840	2,265	3,569	64
(375,46)	10,269	578	9,692	2,265	3,527	64
(309,46)	10,145	560	9,585	2,254	3,493	64
(210,46)	9,958	537	9,422	2,234	3,453	63
(510,27)	9,565	549	9,016	2,043	3,138	65
(510,VA)	11,364	740	10,624	2,569	4,031	62

Effect on official reuse of drainage water

By the reduction of the rice area, replacing the rice by maize in the southern part of the Eastern Nile Delta first, the reuse of drainage water is affected (fig 62a). If the allocation duty for rice is maintained at the present figure of 8,800 m^3.feddan^{-1}, the official reuse of drainage water reduces with about 150 million m^3 for each 1,000 million m^3 of reduction in total gross allocation requirements (fig 62a). This means that 15% of the water savings envisaged by reducing the rice area are not realized due to the reduction in the reuse of drainage water. If the rice area is reduced below 210,000 feddans, the official reuse reduces much less with

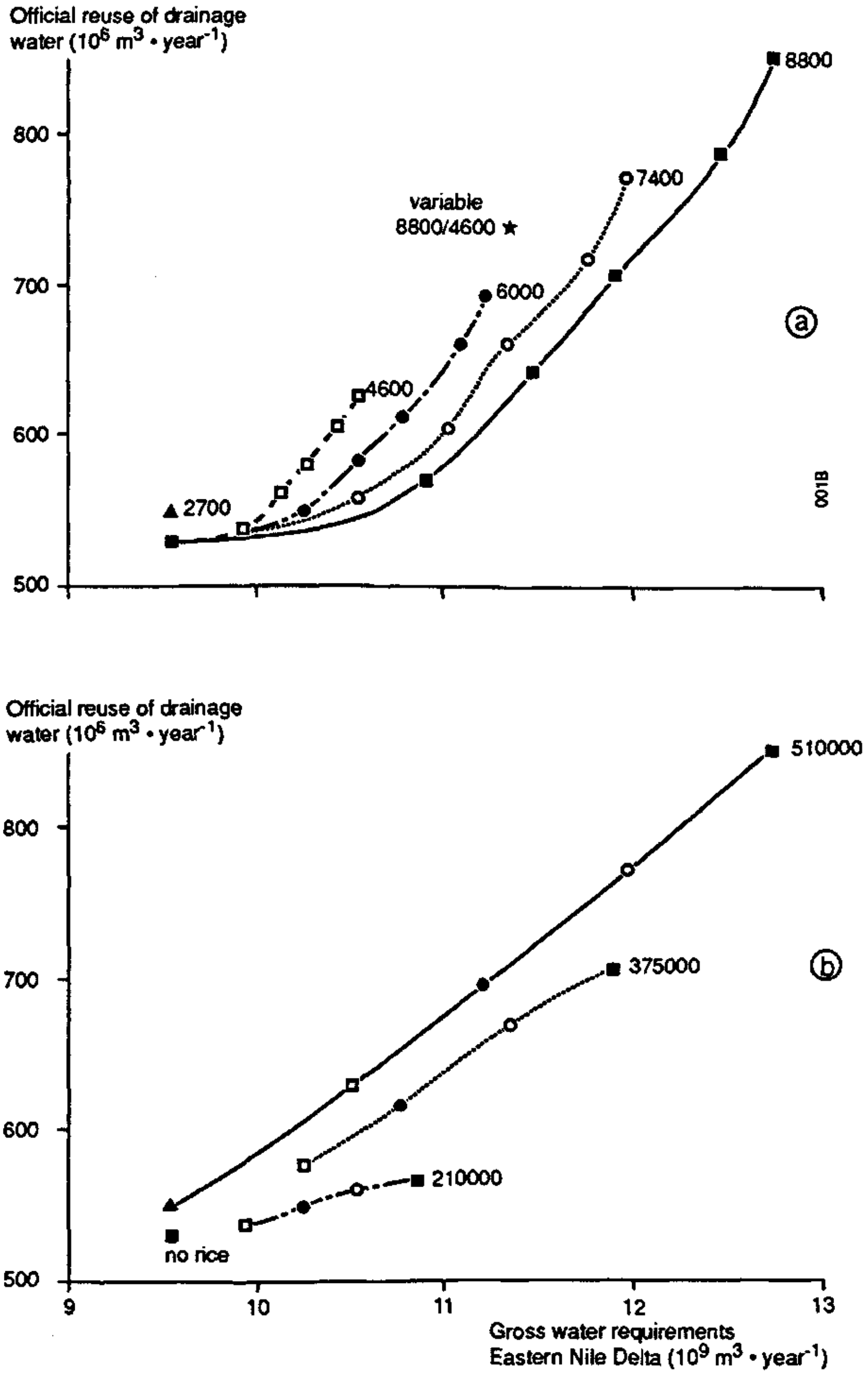

Fig 62. Relation between gross water requirements Eastern Nile Delta and the official reuse of drainage water for the 23 distinguished rice area and allocation water duty strategies.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

only 15 million m^3 per 1,000 million m^3 reduction in gross water requirements (fig 62a). The reason for this is that the reuse pump stations are mainly located in the central and southern part of the Nile Delta. Taking rice out of cultivation in areas outside the catchments of the reuse pump stations does not influence their discharge.

With the reduction of the allocation water duty of rice, the reduction in the official reuse is much less. If the rice area is maintained at the present figure of 510,000 feddan, the official reuse of drainage water reduces with about 100 million m^3 for each 1,000 million m^3 of reduction in the gross allocation requirements (fig 62b). This means that in this case about 10% of the water savings envisaged are not realized. This percentage is more or less constant over the complete range of allocation duties investigated. For the maximum reduction till 2,700 $m^3.feddan^{-1}$, this results in an official reuse of drainage water of 20 million m^3 more than for the complete removal of rice from the cropping pattern. Both strategies have the same gross allocation requirement.

The strategy with the variable allocation duty (510,VA) has a higher official reuse of drainage water for the same gross water requirement than any other strategy with a comparable gross water requirement (fig 62a). The highest allocation duty is used in the southern part of the Eastern Nile Delta were the majority of the drainage water is reused, and the lowest duty in the northern part were almost no drainage water is reused.

By the reduction of the gross water allocation to the Eastern Nile Delta also the reuse of drainage water reduces. The net water savings are therefore less than the reduction in the total water allocation. Water savings by reducing the allocation duty of rice is more efficient than through the reduction of the rice area. When reducing the allocation duty, the reduction is effective for about 90% due to the associated reduction in reuse of drainage water. When reducing the rice area, the reduction is effective for 85% only, for the same reason.

Effect on irrigation water losses

The rice crop requires large amounts of irrigation water because it is grown under ponding conditions. During the rice growing period the irrigation canals are operated at their maximum capacity (peak demand). Consequently the irrigation water losses are also at their maximum during this period. When substituting the rice crop by maize, or by decreasing the allocation duty for rice, the total irrigation losses (the sum of conveyance, tail-end, and spillway losses) decrease (table 19).

Maintaining the allocation duty at the conventional 8,800 $m^3.feddan^{-1}$, the reduction in the gross water requirements of 1,000 million m^3 of water by reducing the rice area results in a reduction of the irrigation losses of 400 million m^3 (fig 63a). This means that growing of the rice crop results in 40% more irrigation water losses than growing the maize crop. In other words: by the elimination of rice from the summer cropping pattern the operation of the irrigation system becomes more efficient. This reduction in irrigation water losses is fairly constant over the complete range of rice area reductions (from 510,000 feddan till zero).

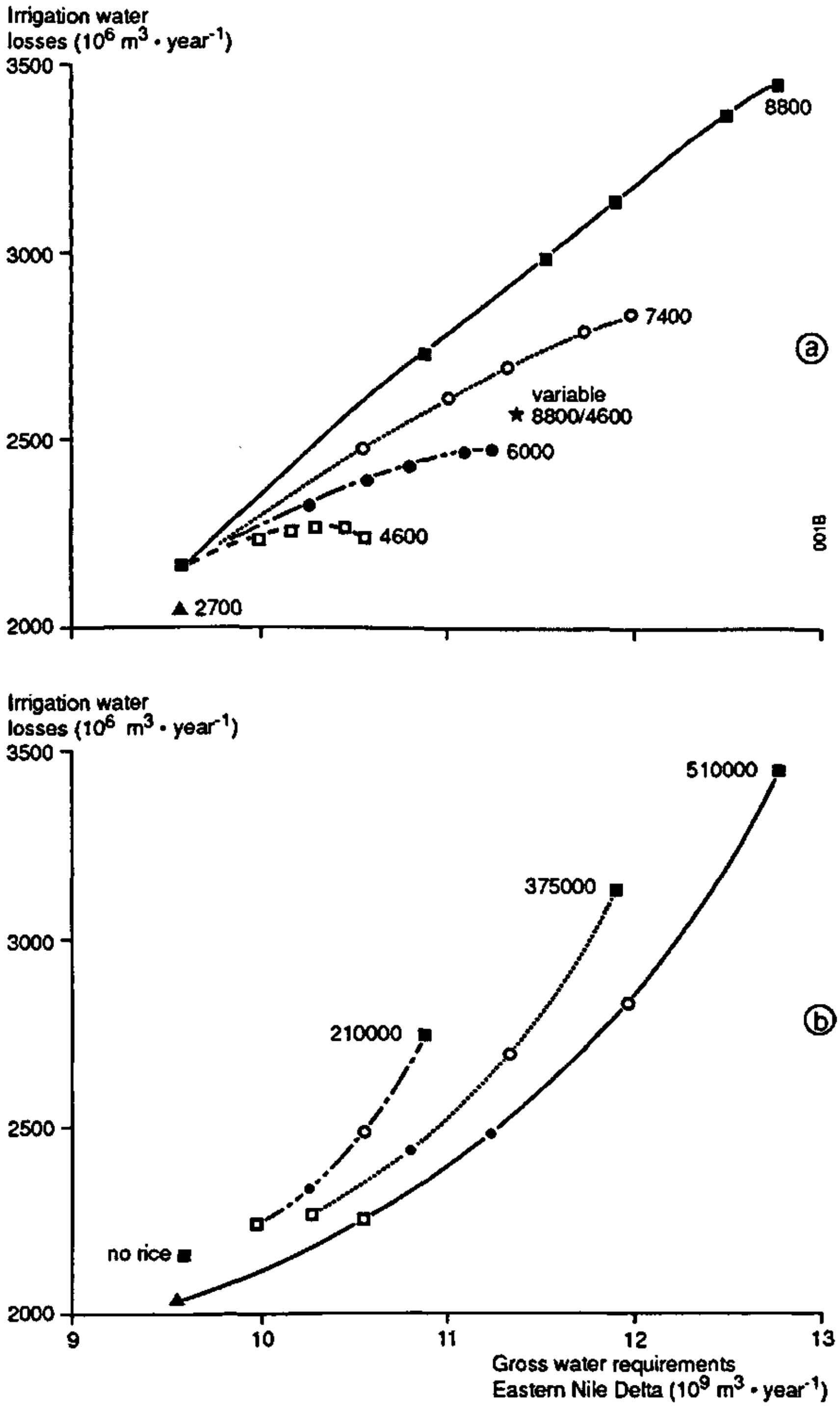

Fig 63. Relation between gross water requirements Eastern Nile Delta and the total irrigation water losses (conveyance losses, tail-end losses, and spillway losses) for the 23 distinguished rice area and allocation water duty strategies.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

Also by reduction of the allocation duty the losses of irrigation water are reduced (fig 63b). In this case the reduction of the losses is the largest by reducing the allocation from 8,800 till 7,400 m^3.feddan^{-1}, 775 million m^3 per reduction of the gross water requirements of 1,000 million m^3. Further reductions of the allocation duty for rice with 1,400 m^3.feddan results in a reduction of the losses with 475 million m^3 and 350 million m^3 per reduction of the gross water requirement with 1,000 million m^3 (fig 63b). The last reduction considered until an allocation duty of 2,700 m^3.feddan^{-1} gives a reduction of the irrigation losses of 20% of the reduction in gross water requirements only.

This last strategy (510,27) with a rice allocation duty equal to that of maize results in 110 million m^3 less irrigation water losses than the strategy without rice (0,88) which has an equal gross water requirement (fig 63b). This difference is caused by the greater agricultural water requirements of strategy (510,27).

The savings of irrigation water by reducing the rice area are compensated with about 40% by reduction in irrigation water losses. The savings of irrigation water by the reduction of the allocation duty of rice are compensated by reductions in the irrigation water losses to an even larger extent: 75% and 45% for the first two reductions considered. For the next two subsequent reductions the compensations are 35% and 20% respectively. Saving of irrigation water by reducing the rice allocation duty until 6,000 m^3.feddan^{-1} is therefore superior to the reduction of the rice area to reach comparable savings. This superiority is caused by the larger reduction in irrigation water losses, resulting in a much smaller reduction in irrigation water uptake by farmers.

Effect on unofficial reuse

Two possible effects of the rice area and allocation duty strategies on the unofficial reuse of drainage water may be expected. Due to the reduction in the irrigation water losses and drainage quantities a reduction in unofficial reuse as a result of a lower availability of drainage water may occur. Due to the lower supply of irrigation water to the agricultural areas, farmers will be compelled to use more drainage water unofficially, in order to supply sufficient water to their crops.

By reducing the rice area, starting in the southern part of the Eastern Nile Delta, the first effect appears to be dominant (fig 64a). For each 1,000 million m^3 of reduction in the gross water requirements, the unofficial reuse of drainage water reduces with about 60 million m^3, or 6% (fig 64a). Due to this reduction in official reuse the total crop water supply reduces more than the irrigation water uptake by farmers.

Maintaining the rice in the cropping pattern, but reducing the water supply by the reduction in the rice allocation duty, results in an increase in unofficial reuse of drainage water (fig 64b) for the first two reductions considered. The increase is about 5% of the reduction in gross water requirements. This means that for each 1,000 million m^3 of reduction in gross water requirements farmers are able to compensate about 50 million m^3 of this reduction by increasing the unofficial reuse. By reducing the allocation duty for rice below 6,000 m^3.feddan^{-1}, however, the unofficial reuse drops sharply with 4% and 23% respectively. Apparently these reductions in the water supply have increased the irrigation efficiency to such an extent, that the availability of drainage water for unofficial reuse becomes a limitation.

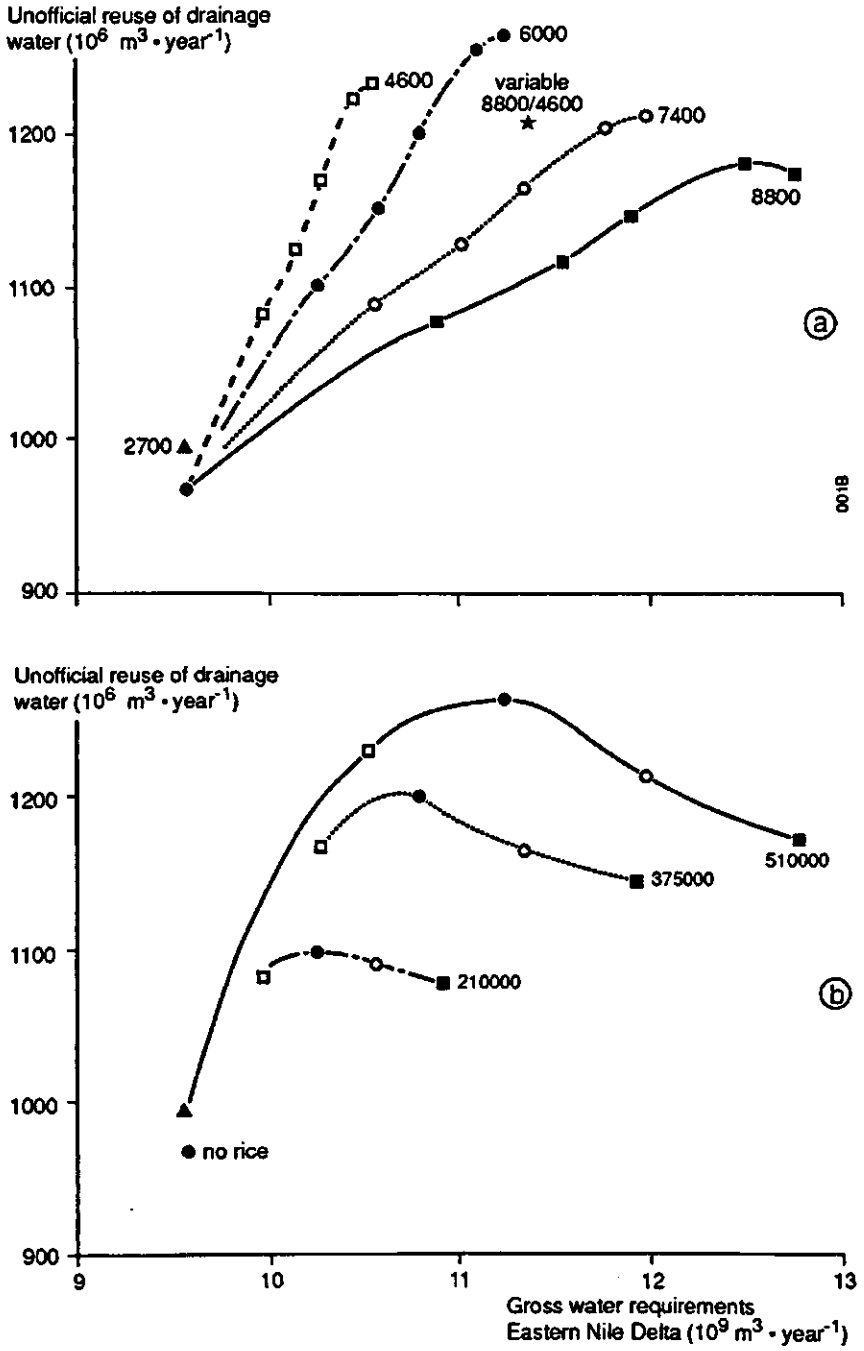

Fig 64. Relation between gross water requirements Eastern Nile Delta and the unofficial reuse of drainage water for the 23 distinguished rice area and allocation water duty strategies.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

Effect on crop water supply

All these changes in official and unofficial reuse of drainage water and changes in irrigation water losses have effects on the net crop water supply. In order to evaluate the different strategies these effects have to be combined. In the following discussion three levels of reduction in the gross water requirements will be treated: a reduction of 1,000 million; 2,000 million; and a reduction of 3,000 million m^3.

Reducing the rice area to achieve a 1,000 million m^3 reduction in water requirements results in a reduction of the official reuse of 170 m^3 (fig 62a). The resulting net water savings are then 830 million m^3. The irrigation water losses are reduced with 370 million m^3 in this case (fig 63a). Consequently the irrigation water uptake by farmers reduces with 460 million m^3 only. The reduction in unofficial reuse is 40 million m^3 (fig 64a) and the total crop water irrigation reduces with 500 million m^3 only. This reduction in crop water supply is a mere 60% of the net savings on Nile water supply to the Eastern Nile Delta.

If the allocation duty for rice is reduced to achieve a 1,000 million m^3 reduction in water requirements, a reduction of the official reuse of 100 million m^3 is realized (fig 62b). In this case the net water savings are 900 million m3 . Since the irrigation water losses are reduced with 750 million m^3 for this alternative (fig 63b), the irrigation water uptake by farmers reduces with 150 million m^3 only. The unofficial reuse increases with about 55 million m^3 (fig 64b), so the crop water supply reduces with 95 million m^3 only. This reduction in crop water supply is 11% of the net water savings only.

These remarkable results can be ascribed to the flexibility in the water management system in the Eastern Nile Delta. Apparently, saving of irrigation water by reducing the allocation duty of rice makes a better use of this flexibility than the alternative method of replacing rice by maize.

In a similar manner the reduction in crop water supply for a reduction of 2,000 million m^3 in the gross water requirements can be calculated. In this case it turns out that by reducing the rice area the crop water supply reduces with 62% of the net Nile water savings, and by reducing the allocation duty of rice the crop water supply reduces with 33% of the net savings.

If the gross water requirements are reduced with 3,000 million m^3, the difference between both approaches is much less. Reduction of the rice area results in a reduction in crop water supply of 62% and reducing the allocation duty leads to a reduction of 53% in the crop water supply. This means that the flexibility of the water management system is exploited profitably by reducing the allocation duty of rice till the value of 6,000 $m^3.feddan^{-1}$ is reached, but below this value not much additional benefits are obtained in improving the efficiency, compared to reductions in the rice area.

Effect on drainage to the sea

Due to the savings on irrigation water the flow of drainage water to the sea can be expected to reduce accordingly. Reducing the rice area to achieve a reduction in gross water requirements of 1,000 million m^3, results in a reduction of the total discharge from the Eastern Nile Delta to the sea with about 550 million m³ (fig 65a). This means that the total drainage reduces more than proportional to the reduction in net irrigation water supply to the Eastern Nile Delta. Each percent reduction in Nile water supply reduces the drainage with 1.4%.

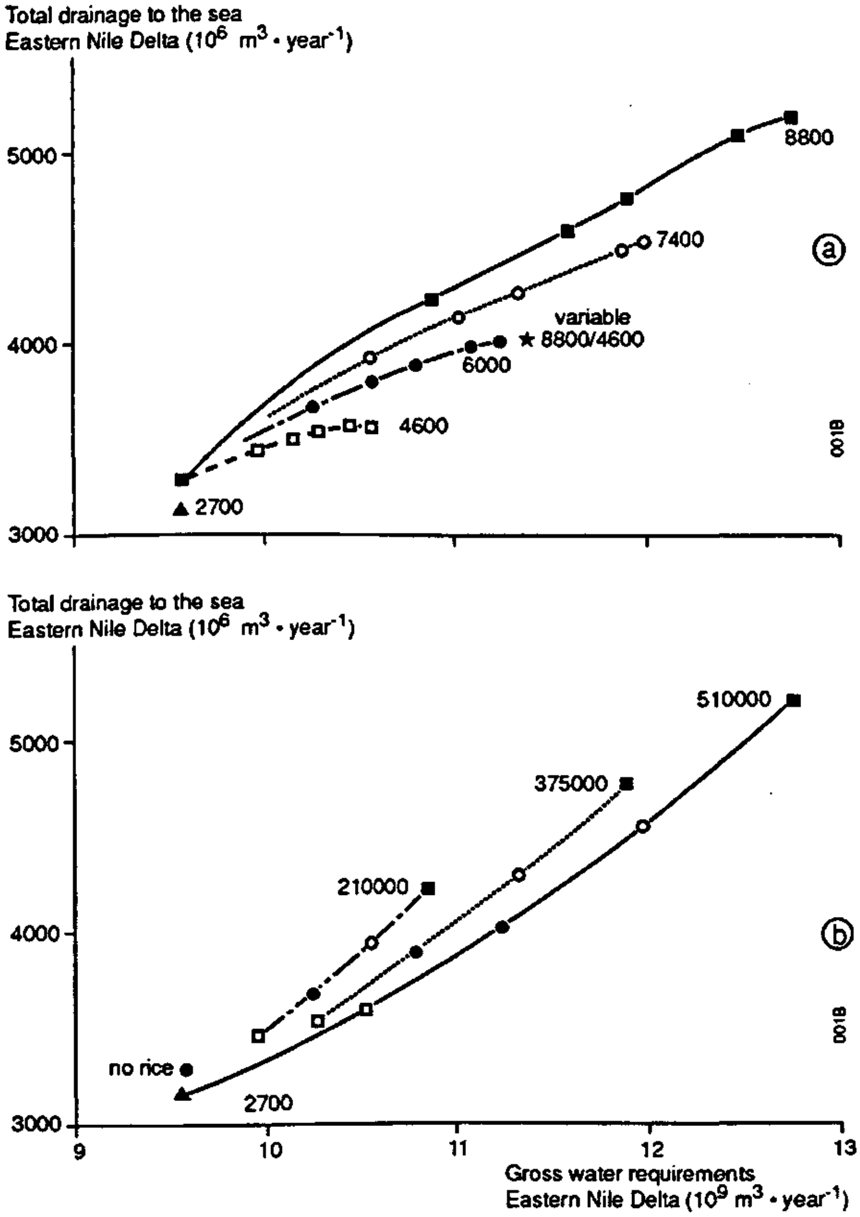

Fig 65. Relation between gross water requirements Eastern Nile Delta and the total drainage to the sea for the 23 distinguished rice area and allocation water duty strategies.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

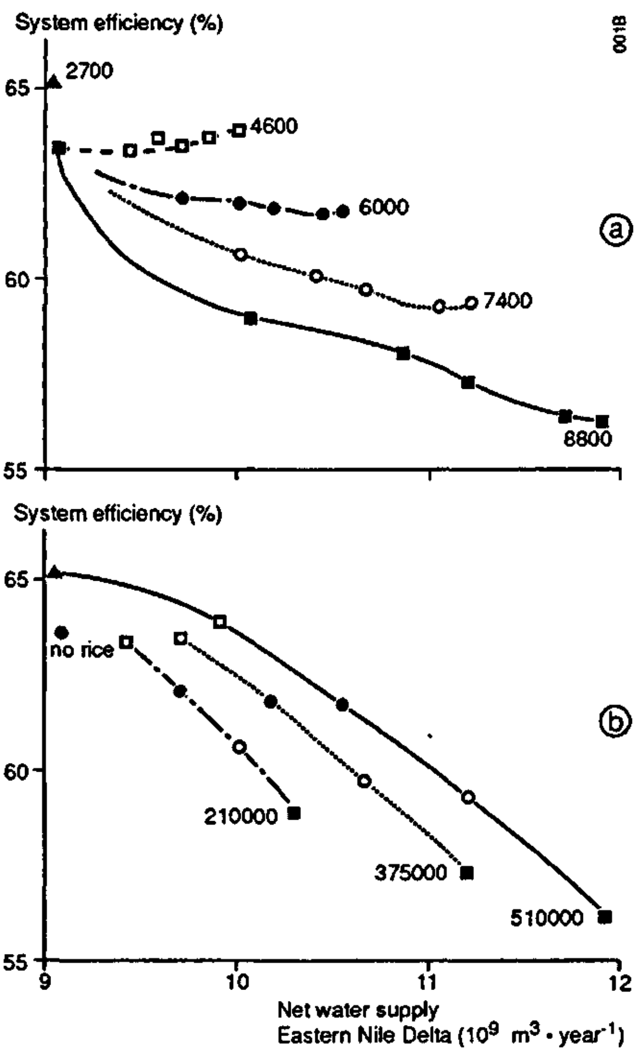

Fig 66. Relation between the net water requirements Eastern Nile Delta and the system efficiency for the 23 distinguished rice area and allocation water duty strategies.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

If the rice area is maintained and the gross water requirements are reduced by reducing the allocation duty of rice, the drainage water discharge reduces more. In this case a reduction in gross water requirements of 1,000 million m^3 results in a reduction of total drainage of about 800 million m^3 (fig 65b). This means that in this case a reduction in the net Nile water supply gives a 2.1% reduction in drainage water discharge.

Effect on system efficiency

A practical definition of the water management system efficiency is the percentage of the Nile water supply which is not discharged through the main drainage system to the sea. Both water management measures investigated have a positive effect on the system efficiency. Maintaining the conventional allocation duty for rice at the present value of 8,800 m^3.feddan^{-1} and reducing the rice area increases the efficiency with about 2% for each 1,000 million m^3 of Nile water saved (fig 66a). For the lower allocation duties the increase in efficiency becomes less. At the allocation duty of 4,600 $m^3.feddan^{-1}$ the efficiency even decreases upon a decreasing rice area (fig 66a). The maximum efficiency which can be reached by reducing the rice area is 64% (table 19; fig 66a).

Maintaining the rice and reducing the allocation duty of rice has a much larger effect on the system efficiency (fig 66b). In this case the efficiency increases with about 4% for each 1,000 million m^3 of Nile water saved, which is almost double the effect of reducing the rice area. The maximum efficiency which can be reached by this water management measure (65%) is slightly higher than the maximum which can be reached by reducing the rice area.

Conclusions

The total reduction in the net irrigation water supply considered with the studied alternative strategies covers a range until 2,900 million $m^3.year^{-1}$. For reductions of the water supply till 50% of this maximum (till roughly 1,500 million m^3), the analysis of the water balance components points in the direction that it is better to save on irrigation water by reducing the allocation duty of the rice crop instead of reducing the area grown with rice. For reductions of net Nile water supply larger than 1,500 million m^3 the model analysis still indicates an advantage of reducing the allocation duty, but the difference with reducing the rice area is not large.

5.2.3. Crop reaction

In the rice area and water allocation duty strategies discussed in this chapter, the water supply to the Eastern Nile Delta during the summer period (rice growing season) is reduced. In the previous paragraph it has been discussed that farmers compensate the diminished water supply by using the available water more efficiently, and by increasing the unofficial reuse of drainage water.

The distribution of the amount of water available at farm level among the different crops, which are simultaneously in the field, is the responsibility of the farmer. He will give the crop which he considers the most important the largest share of the (limited) available water. This means that a lower allocation duty for the rice crop not only affects the rice production, but also that of the other summer crops in the field. During the summer period rice is considered as the highest priority crop, followed by vegetables and maize (table 6). Cotton is considered the lowest priority crop, because it withstands stress conditions easily. Consequently, it can be expected that the reduction of the water supply during summer has the least influence on the rice crop, and the highest on cotton.

Since crop production is related to the realized evapotranspiration, the crop reaction will be considered here as the relative evapotranspiration (table 20) with respect to the reference simulation run, strategy (510,88).

Table 20. Water savings and relative evapotranspiration of the main summer crops for the 23 rice area and allocation duty strategies.

strategy	water savings (%)	relative evapotranspiration (%)			
		rice	maize	cotton	cropping pattern
(510,88)	-	100.0	100.0	100.0	100.0
(468,88)	1.7	99.2	99.5	99.7	99.4
(375,88)	5.9	97.2	98.6	99.6	98.7
(309,88)	8.9	96.1	97.0	98.8	97.9
(210,88)	13.4	94.5	93.4	97.6	96.4
(0,88)	23.9	-	89.2	96.1	94.0
(510,74)	5.9	99.9	99.2	99.5	99.7
(468,74)	7.2	99.0	99.0	99.2	99.2
(375,74)	10.4	97.1	98.1	99.0	98.4
(309,74)	12.6	95.9	96.4	98.4	97.7
(210,74)	16.0	94.4	93.3	97.6	96.3
(510,60)	11.4	98.8	97.5	97.6	98.7
(468,60)	12.4	97.9	97.7	97.5	98.4
(375,60)	14.5	96.0	97.2	97.5	97.8
(309,60)	16.1	95.1	95.7	97.4	97.2
(210,60)	18.5	94.0	93.0	96.9	96.0
(510,46)	16.8	95.7	95.5	94.8	97.0
(468,46)	17.3	94.9	96.2	94.9	96.9
(375,46)	18.6	92.8	96.2	95.3	96.6
(309,46)	19.5	92.7	94.9	95.6	96.3
(210,46)	20.8	92.0	92.6	95.8	95.5
(510,27)	24.2	82.7	91.6	88.4	92.3
(510,VA)	10.8	98.8	98.9	98.4	99.2

Rice crop

In the northern part of the Eastern Nile Delta the evaporative demand is slightly lower than in the southern part and in the desert fringes. Due to the reduction of the rice area in the southern part of the Eastern Nile Delta, the irrigation water in the north shows an increase (higher salinity of the reused drainage water). By these two factors the rice crop evapotranspiration is reduced gradually by the reduction in the rice grown area while maintaining the official allocation duty at 8,800 m^3.feddan^{-1} (fig 67a). This reduction cannot be explained by the reduction in the water supply, which is reduced only for the areas where the rice crop has been exchanged for maize. The reason for this reduction must therefore be sought in the higher irrigation water and soil salinities in the northern part of the Eastern Nile Delta.

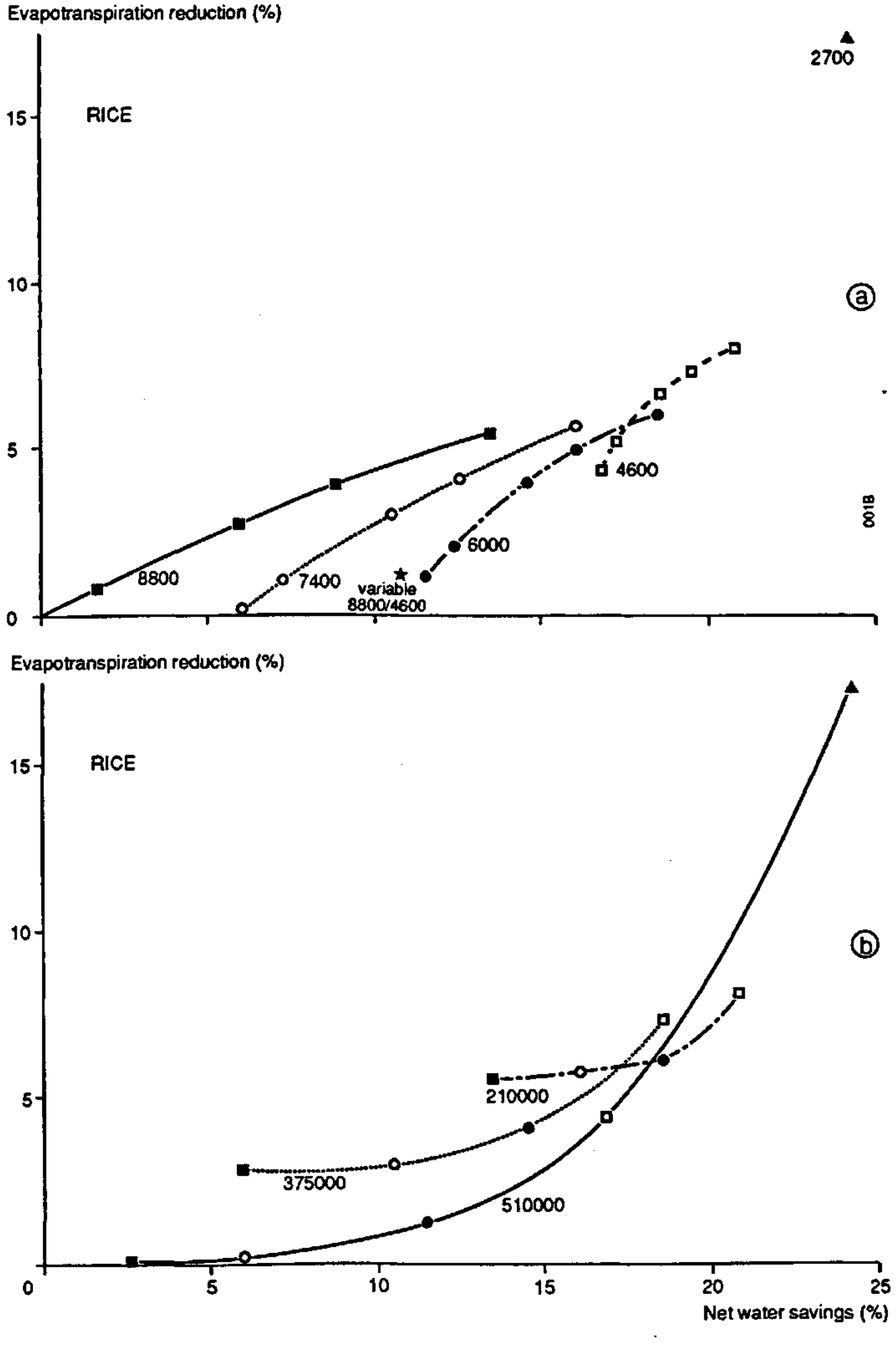

Fig 67. Relative evapotranspiration of the rice crop for the 23 distinguished rice area and allocation duty strategies in relation to the net water savings.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

The crop reaction of rice to reducing the area grown with rice for the allocation duties of 7,400 and 6,000 m^3.feddan^{-1} follows more or less the same pattern (fig 67a). For the allocation duty of 4,600 m^3.feddan^{-1}, however, the relative evapotranspiration of rice reduces more drastically with almost 8%. Under these water supply conditions the rice crop apparently starts to suffer from water shortages and the crop yields are reduced. For the allocation duty of 2,700 m^3.feddan^{-1} this phenomenon is even more clear (fig 67a) and the evapotranspiration of the rice crop is reduced with 17% (table 20).

Maintaining the rice area intact, but saving water by reducing the allocation duty of rice results in much smaller reductions in relative rice evapotranspiration rates compared to reducing the rice area (fig 67b). For the rice area of 510,000 feddan, reducing the allocation duty from 8,800 m^3.feddan^{-1} to 7,400 m^3.feddan^{-1} results in a water saving of about 6% without noticeable reduction of evapotranspiration. The relation between net water savings and evapotranspiration reduction for the rice area of 510,000 feddan and that of 210,000 feddan intersect at strategy (210,60) (fig 67b). The water savings at this intersection point are about 18.5%. The allocation duty for the rice area of 510,000 feddans for this intersection point is about 4,400 m^3.feddan^{-1}. For water savings larger than this 18.5% the rice crop evapotranspiration rate is maintained at a higher level by reducing the rice area till 210,000 feddan with allocation duties above this 4,400 m^3.feddan^{-1} (fig 67b).

Savings on the use of fresh irrigation water, and maintaining the productivity of the rice crop at a highest possible level, is achieved by reducing the water allocation duty of rice from 8800 m^3.feddan^{-1} to 4,600 m^3.feddan^{-1}, rather than by reducing the rice area. By this procedure savings on irrigation water up to 18.5% can be obtained at the expense of 7% evapotranspiration losses. If larger water savings than 18.5% are required the growing of rice should be confined to the northern rice zone only (zone 1).

Maize crop

The effect of reducing the rice area, while maintaining the allocation duty of rice at 8,800 m^3.feddan^{-1}, on the relative evapotranspiration of maize is small for the first two reductions until 375,000 feddan (fig 68a). Further reduction of the rice area by replacing rice by maize results in a sharper decrease in the average productivity of the maize crop. Maize is quite sensitive to high soil salinity and produces less good in the northern part of the Eastern Nile Delta. For the lower rice allocation duties of 6,000 and 4,600 m^3.feddan^{-1}, prohibition of rice cultivation in the southern part of the Eastern Nile Delta appears to have a positive effect on the relative evapotranspiration of maize (fig 68a). Apparently, the agricultural water requirements in the southern part of the delta are such, that for allocation duties lower than 7400 m^3.feddan^{-1}, the maize crop is suffering at the expense of water given to the rice crop. This means, on the other hand, that for allocation duties above 6,000 m^3.feddan^{-1}, the maize crop in the south is benefitting from the water allocated for the rice crop, but given to the maize crop by the farmer.

Reduction of the allocation duty of rice has a much smaller negative effect on the productivity of the maize crop compared to reducing the rice area (fig 68b). For water savings up to about 10% the minimum adverse effect is obtained by reducing the allocation duty of rice until 6,000 m^3.feddan^{-1}. Larger water savings, maintaining the productivity of the maize crop at its maximum attainable level is obtained by prohibiting the growing of rice in the first two rice zones (4 and 5). Reduction of the rice area below this 375,000 feddan is not recommended from the viewpoint of maintaining the maize productivity. The growing of rice in the most northern belt only (rice area 1) is in all cases unfavourable for the average maize crop yield (fig 68b).

The strategy with the variable water duty (510,VA) turns out to be quite effective with respect to the relative evapotranspiration of the maize crop (table 20).

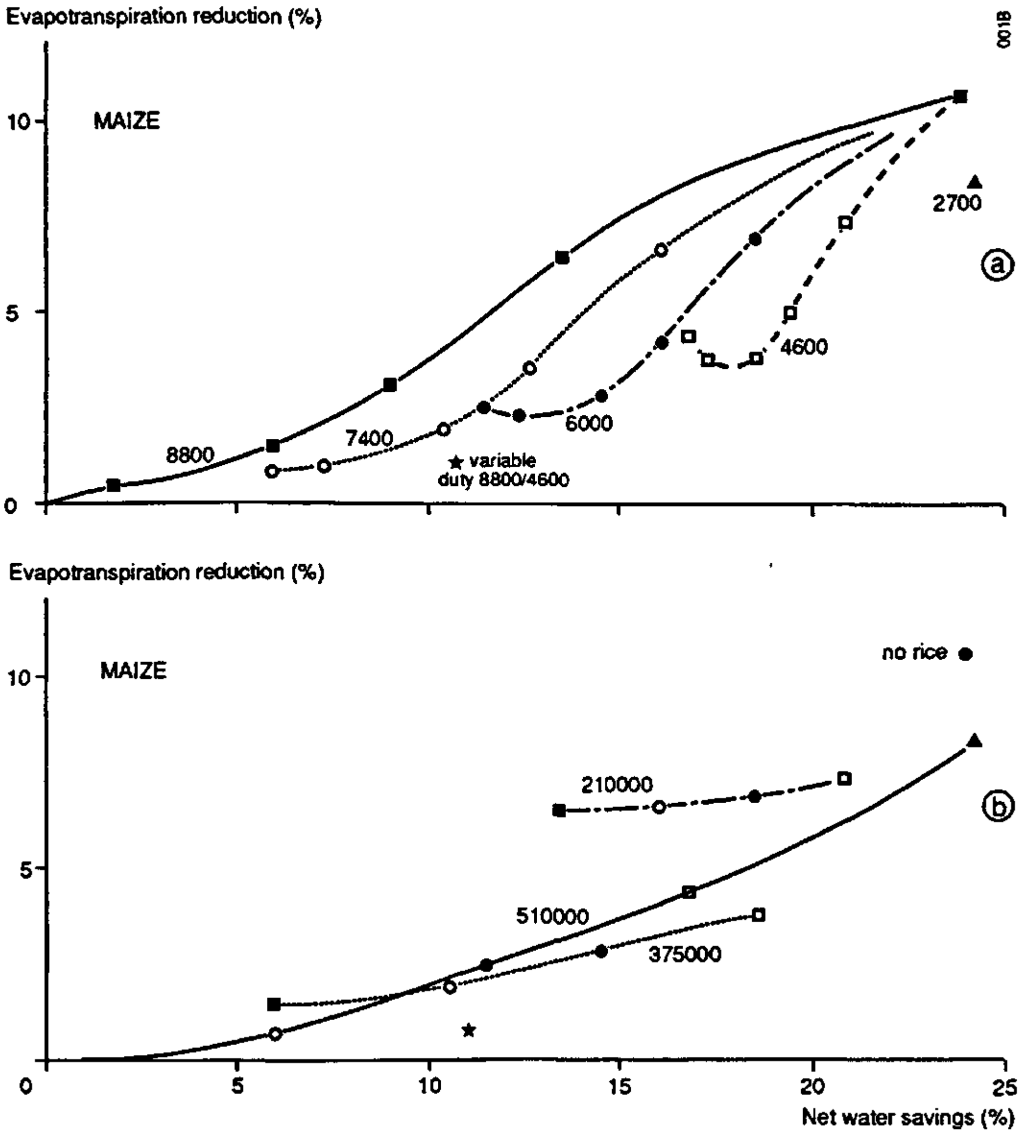

Fig 68. Relative evapotranspiration of the maize crop for the 23 distinguished rice area and allocation duty strategies in relation to the net water savings.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

Cotton crop

The reaction of the cotton crop to reductions in the rice areas and rice allocation duties is quite different from that of rice and maize (fig 69). Maintaining the allocation duty of rice at 8,800 $m^3.feddan^{-1}$, reductions in the rice area result in only minimal reductions in the relative evapotranspiration of the cotton crop (fig 69a). At 24% water savings the relative evapotranspiration goes down with only 4%. Maintaining the rice area and reducing the allocation duty however results in large losses in relative evapotranspiration (fig 69b).

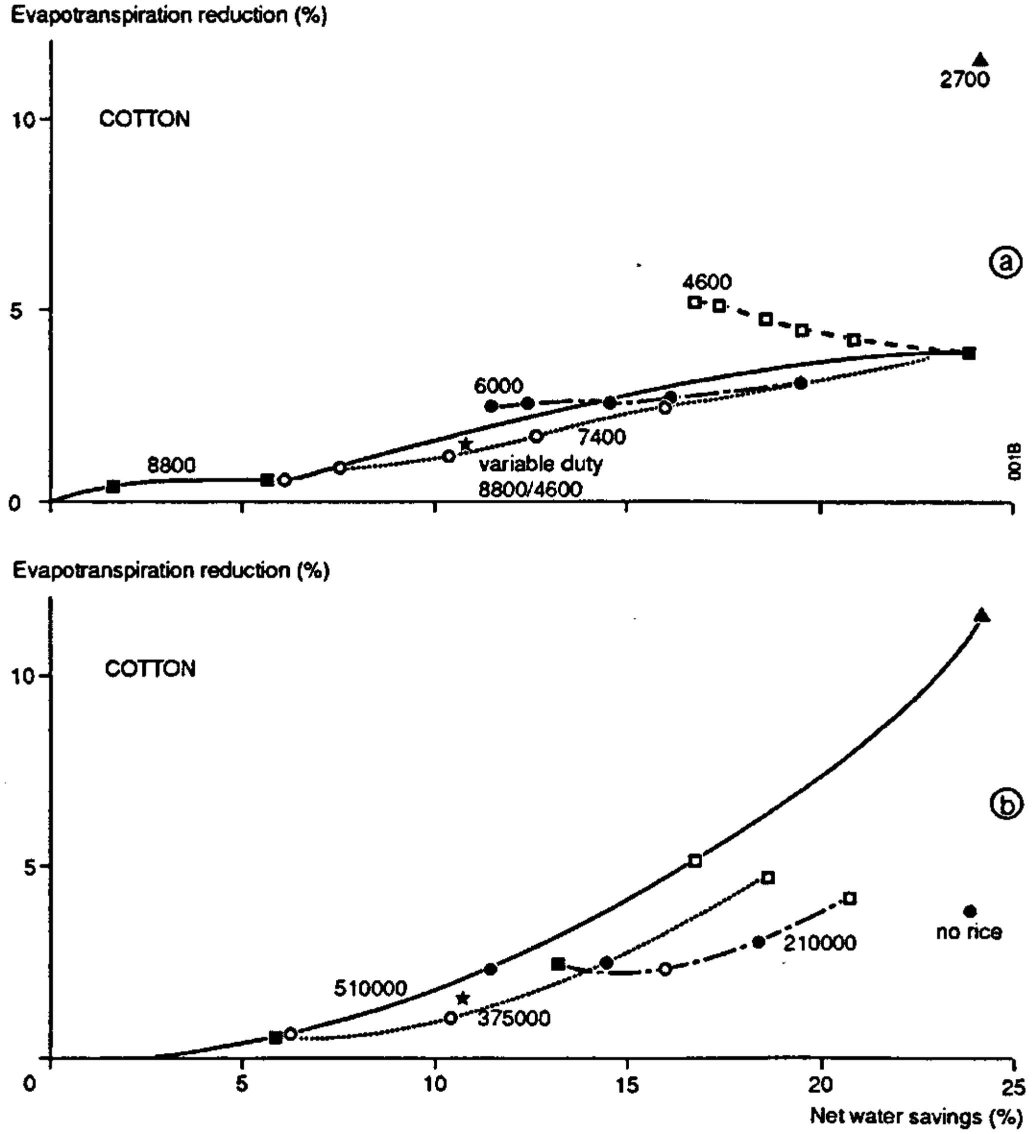

Fig 69. Relative evapotranspiration of the cotton crop for the 23 distinguished rice area and allocation duty strategies in relation to the net water savings.

a - the lines connect strategies with equal allocation duty and different rice areas

b - the lines connect strategies with equal rice area and different allocation duties

The reason for this difference in reaction of the cotton crop compared to the rice and maize crop is the irrigation priority ranking of the cotton crop, which is the lowest. As a consequence any shortage of irrigation water is felt first by the cotton crop, contrary to rice and maize. When the water allocation duty of rice is reduced until 4,600 m^3.feddan^{-1}, the cotton crop is even benefitting from reductions in the area grown with rice (fig 69a). For savings on irrigation water of about 24%, the crop damage of cotton is even 3 times as large when rice is grown (12% evapotranspiration reduction), compared to the alternative without rice (4% evapotranspiration reduction).

Cropping pattern

The overall effect of the 23 rice area and allocation duty strategies can be considered in terms of the composite effect on the evapotranspiration. For the strategies with a different rice area the differences in potential evapotranspiration have to be taken into account, however. For the reference strategy (510,88), the average evapotranspiration of the rice crop was 748 mm.year^{-1}. For maize this average value is 705 mm.year^{-1}. Since in the different strategies the rice area and the maize area are different, the total evapotranspiration, simulated by the SIWARE model for the cropping pattern, has been corrected for this difference in evapotranspiration of 43 mm.year^{-1}. This correction has to be weighted with the change in the fraction of the Eastern Nile Delta which is grown with rice. Since the percentage of rice for the reference strategy is 27.45%, the maximum correction (increase) in the simulated evapotranspiration of the cropping pattern for strategy (0,88) was 12 mm. This is about 1% of the reference strategy evapotranspiration.

The implication of comparing the evapotranspiration of the complete cropping pattern with that of the reference strategy is that each reduction in evapotranspiration is valued equally. In other words, the reduction in evapotranspiration of for instance the rice crop with one mm is considered equal to one mm reduction in each one of the other crops.

According to the composite reaction of the cropping pattern (table 20) water savings up to 11.5% of the Nile water supply for the reference strategy are obtained with minimal crop damage by reducing the water allocation duty of rice from 8,800 m^3.feddan^{-1} till 6000 m^3.feddan^{-1} (fig 70). Water savings from 11.5 till 14.5% should be realized by the subsequent reduction of the rice area from 510,000 till 375,000 feddan. Water savings from 14.5 till 18.5% are best obtained by reducing the rice allocation duty from 6,000 m^3.feddan^{-1} till 4,600 m^3.feddan^{-1}. Water savings larger than 18.5% should not be obtained by reducing the allocation duty below 4,600 m^3.feddan^{-1}, but by further reduction of the rice cultivation (table 21).

All these conclusions are based on the implicit assumption that the economic value of each crop is proportional to its actual evapotranspiration, because each mm reduction in evapotranspiration is valued equally.

Table 21. Combination of the water management measures reducing rice area and reducing rice allocation duty which give the minimal cropping pattern evapotranspiration depression.

water savings range (%)	water management measures		evapotranspiration reduction range (%)
	rice duty range (m^3.feddan^{-1})	rice area range (1,000 feddan)	
0 -> 11.5	8,800 -> 6,000	510	0 -> 1.3
11.5 -> 14.5	6,000	510 -> 375	1.3 -> 2.2
14.5 -> 18.5	6,000 -> 4,600	375	2.2 -> 3.4
18.5 -> 24	4,600	375 -> 0	2.4 -> 4.5

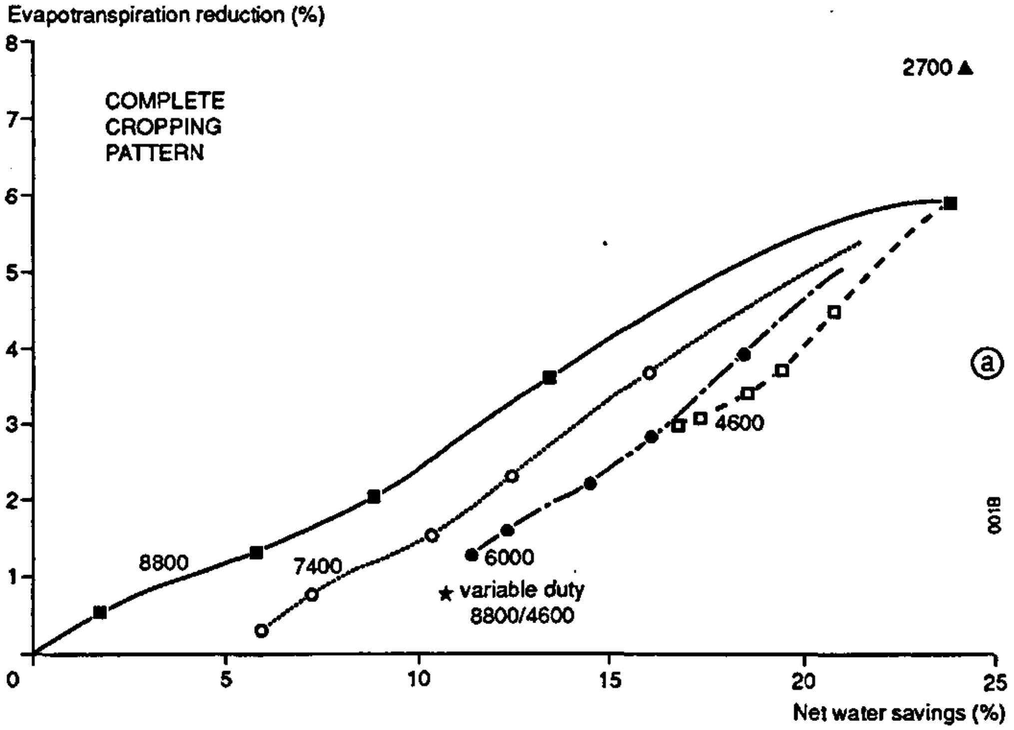

Fig 70. Evapotranspiration reduction of the cropping pattern (corrected for the differences in rice and maize areas) in relation to the net water savings for the 23 distinguished rice area and allocation duty strategies.

Lines connect strategies with equal allocation duty and different rice areas

Crop production

In chapter 4 a relation has been established between the relative evapotranspiration and the relative crop yield (table 13). In principle for all crops considered in this analysis these relationships can be used to convert the relative evapotranspiration values to relative crop yields. The results of such an analysis should be considered as a rough indication of the real crop yields only, because the relationships used (table 13) are empirical and have been derived for the cropping pattern of 1986, for the average leaching conditions in the Eastern Nile Delta during this year. Due to the changes in the cropped areas of rice and maize in the distinguished strategies, the largest changes in total crop production take place for these crops. Therefore the analysis of crop production for the 23 strategies is restricted here to the production of maize and rice (table 22).

The maximum rice area considered is about 510,000 feddans and the corresponding minimum maize area roughly 500,000 feddans. A decrease of the rice area with 100% therefore corresponds with an increase in the maize area of about 102%.

The relative total crop production of rice is obtained as follows: the relative evapotranspiration values for rice (table 20) are first corrected for the crop yield reduction (1% reduction in evapotranspiration corresponds to 0.87% reduction in grain yield). Next, the relative crop yield is multiplied with the relative rice area (table 22). The resulting relation between the net water savings and the relative total rice production is given in figure 71a.

Table 22. Water savings, relative rice and maize yield, and relative total production of rice and maize for the 23 rice area and water allocation duty strategies. All figures are relative to the reference strategy (510,88).

strategy	water savings (%)	crop yields (%)		crop production (%)		
		rice	maize	rice	maize	total
(510,88)	-	100.0	100.0	100.0	100.0	100.0
(468,88)	1.7	99.3	98.8	92.1	106.8	95.5
(375,88)	5.9	97.6	96.3	72.4	121.7	97.1
(309,88)	8.9	96.6	92.4	58.7	129.4	94.1
(210,88)	13.4	95.3	83.2	38.9	133.6	86.2
(0,88)	23.9	-	72.6	-	147.0	73.5
(510,74)	5.9	99.9	98.1	99.9	98.1	99.0
(468,74)	7.2	99.1	97.4	91.3	105.3	98.3
(375,74)	10.4	97.4	95.2	72.3	120.3	96.3
(309,74)	12.6	96.5	90.9	58.6	127.4	93.0
(210,74)	16.0	95.1	83.0	38.8	133.2	86.0
(510,60)	11.4	99.0	93.6	99.0	93.6	96.3
(468,60)	12.4	98.2	94.1	90.5	101.7	96.1
(375,60)	14.5	96.6	92.7	71.6	117.2	94.4
(309,60)	16.1	95.8	89.0	58.2	124.7	91.4
(210,60)	18.5	94.8	82.1	38.7	131.8	85.2
(510,46)	16.8	96.3	88.6	96.3	88.6	92.4
(468,46)	17.3	95.5	90.3	88.0	97.6	92.8
(375,46)	18.6	94.7	90.2	69.5	114.0	91.8
(309,46)	19.5	93.6	87.1	56.9	122.0	89.4
(210,46)	20.8	93.0	81.0	38.0	130.1	84.0
(510,27)	24.2	85.0	78.5	85.0	78.5	81.7
(510,VA)	10.8	98.9	97.2	98.9	97.2	98.1

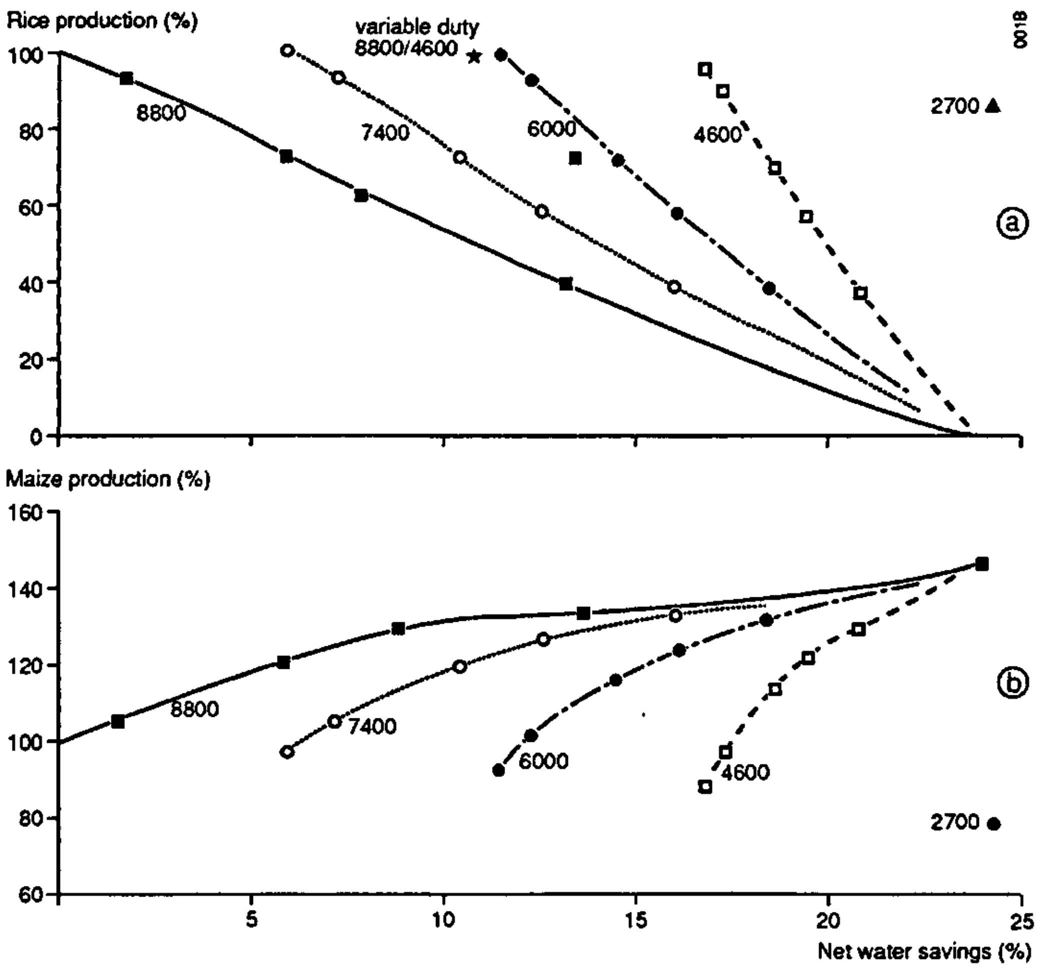

Fig 71. Crop production of the 23 rice area and allocation duty strategies relative to the reference strategy (510,88) in %.

Lines connect the strategies with the same allocation duties

a - rice b - maize

About 10% of the net water savings may be obtained with about 55% of the original rice production by reducing the rice area with about 45% till about 290,000 feddan, maintaining the allocation duty at 8,800 m^3.feddan^{-1}. The same water savings can also be obtained with 75% of the original rice production by reducing the rice area with about 25% till about 390,000 feddan, reducing the allocation duty till 7,400 m^3.feddan^{-1}. Water savings of 10% can also be obtained with 99% of the original rice production, by maintaining the original rice area at 510,000 feddan, but reducing the allocation duty till about 6,400 m^3.feddan^{-1} (fig 71a).

Also for water savings of more than 10%, similar choices between alternatives can be made resulting in different rice production levels for the same water savings. For the maximum water savings considered (24%), a rice production of 0% results from not cultivating rice, strategy (0,88). The maximum rice production that can be obtained, saving 24% of water, is 85% of the original rice production. This is realized by reducing the water allocation till 2,700 m^3.feddan^{-1} (fig 71a). The results of such a strategy (510,27) should be interpreted carefully, however, because the reduction in allocation duty for rice is enormously lower than the 8,800 m^3.feddan^{-1} used in the reference strategy.

For the maize crop the same procedure has been followed to convert the relative evapotranspiration into crop production (table 22). For maize 1% evapotranspiration reduction corresponds to 2.55% grain yield reduction. Comparing the results for maize (fig 71b) with those for rice, it is noticed that the reaction of the maize production is opposite to that of rice. This is logic, because a reduction in the rice area automatically increases the maize area. Since in the reference strategy the area of maize and rice are almost equal, the percentage increase of the maize area almost equals the percentage decrease of the rice area.

Due to the sensitivity of the maize crop to the top soil salinity, the crop yield in the northern part of the Eastern Nile Delta is much lower than in the southern part, resulting in a less than proportional increase in maize production (fig 71b).

The 10% water savings discussed above could be obtained with 55% of the original rice production by reducing the rice area. The corresponding maize production is about 130% (fig 71b). For the same water savings the rice production could also be maintained at 75% by reducing the allocation duty until 7,400 m^3.feddan^{-1}. The corresponding maize production is 118%. If 10% of water is saved with a rice production level of 99% by reducing the allocation duty until roughly 6,500 m^3.feddan^{-1} and maintaining the rice in the cropping pattern, the corresponding maize production level is 95% (fig 71b).

Strategy appraisal

Nile water is a limited available commodity in Egypt and should therefore be treasured. Since good productive soil is much less a limitation for agricultural production compared to water, the available water should be used in the best possible way to achieve the maximum economic return.

Savings on the use of Nile water in the long term are therefore necessary to reclaim additional agricultural land. The practical question regarding the economical use of irrigation water is then: to what extent and in which way can water be saved in the existing agricultural area in order to gain in total crop production by reclaiming new lands.

For the selection of the best strategy, the total crop production of such a strategy has to be compared with the water savings. These water savings can be used to reclaim new agricultural land, but in cases of foreseen water shortages the saved water can also be stored for the next year to ascertain a sufficient water supply. In the strategies studied, the largest changes in crop production occur for the maize and the rice crops. By adding both productions together, taking the reference strategy (510,88) as 100%, the relation between water savings and total production can be established (table 22).

Generally, a water saving strategy can be classified as attractive when it contributes to the national economy. Considering water as the only production factor, this is the case when water savings are larger than the income losses due to crop production decreases. This is only true, of course, if the saved water can be used in other areas (land reclamation) or during other periods (storing for later use) successfully. In other words, the (future) benefits should be larger than the costs (production decrease). Examining the strategies with the reductions in the rice area and maintaining the rice allocation duty at 8,800 m^3.feddan^{-1} (fig 72), it can be seen that it seems attractive to decrease the rice area until the break even point of 210,000 feddan. Further reduction of the rice area below 210,000 feddan leads to larger production losses than the water savings, meaning that using the saved water elsewhere no longer compensates for the production losses. The removal of rice from the southern part of the Eastern Nile Delta causes relatively small production losses, or even increases the total production in case of a rice allocation duty of 4,600 m^3.feddan^{-1} (fig 72). This supports the official rule of the Ministry of Public Works and Water Resources that in this area (rice zone 5) the cultivation of rice is not allowed (fig 59a).

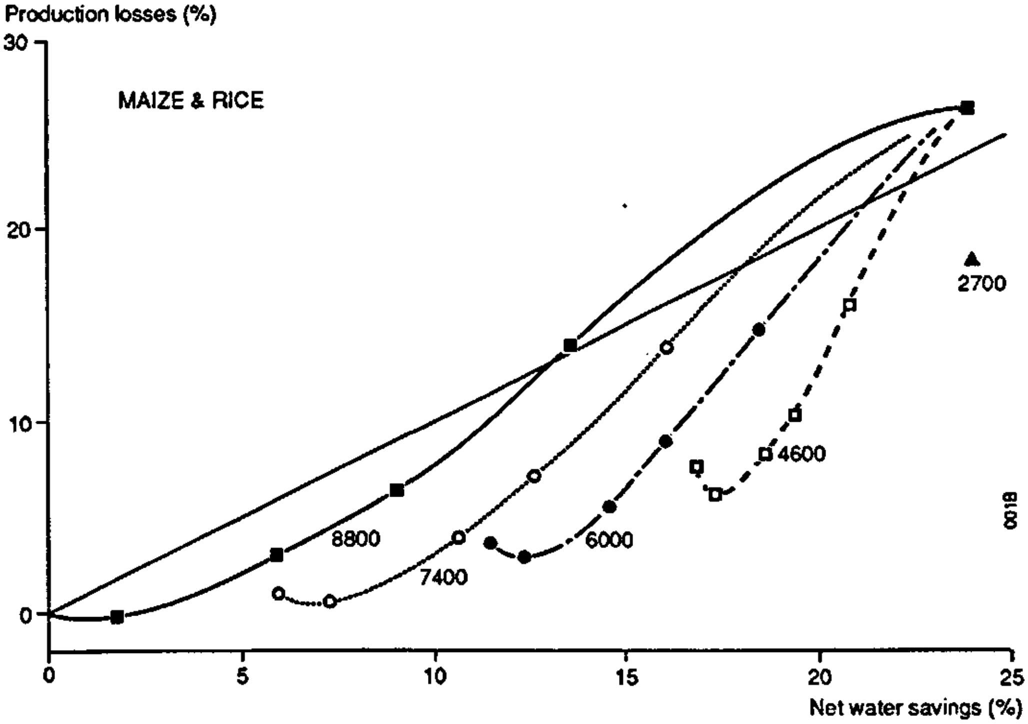

Fig 72. Relation between the production losses of maize and rice (in percentage of the reference strategy (510,88)) and net Nile water savings for the 23 rice area and allocation duty strategies. The production of one feddan of maize and one feddan of rice have been assumed equal in the reference strategy.

Lines connect strategies with the same allocation duties

— break even line (water saving equal production losses)

Two of the 23 strategies studied appear to be unattractive and should never be implemented. These are the strategies (210,88) and (0,88), which are both dealing with large reductions in the rice area (table 22). The most attractive strategy has the largest difference between water savings and production losses. This is strategy (375,46) with no rice in zone 4 and 5 and a water allocation duty of 4,600 m^3.feddan^{-1} (fig 72). The production losses are 8.2% and the water savings 18.6%.

The net gains of this strategy is then the difference of 10.4% of saved water which can be used elsewhere, or during other periods, to produce additional rice and maize.

Financial and economic analysis

For a proper comparison of water management strategies the crop yields of the different crops have to be totalized. For this purpose the net income generated by each crop has to be known. Such an analysis should be based on net income because a certain crop yield reduction of, say 5%, does not necessarily mean that also the production costs such as fertilizers, pesticides, and manual labour inputs are decreased. Therefore the net changes in income are generally larger than the reductions in crop production.

Furthermore, the restriction to the two major crops rice and maize as used above, gives a too optimistic view of the real effects, which include other crops as well. For the estimation of the financial returns of agriculture, use has been made of results of farmers' interviews in a number of villages in the Nile Delta published by El Guindi et al (1982a, 1982b, 1982c, and 1982d). The financial and economic prices of inputs and outputs have been taken from Beun (1981). These data per crop are summarized in table 23. These crop yield and price data are based on the period around 1980. They have been used due to lack of more recent data, but the analysis would better be based on more recent data of, say 1990.

Table 23. Average crop yield (El Guindi et al, 1981a, 1981b, 1981c, 1982d), financial cost and production value (El Guindi et al, 1981a, 1981b, 1981c, 1982d) and economic cost and production value (Beun, 1981) for the six major field crops in the Nile Delta in Egypt. Prices and production levels of 1979/1980.

crop	crop yield (kg.feddan^{-1})	financial analysis cost (LE.feddan^{-1})	financial analysis gross income (LE.feddan^{-1})	economic analysis cost (LE.feddan^{-1})	economic analysis gross income (*) (LE.feddan^{-1})
long berseem	5,565	28	223	47	223 (**)
short berseem	1,595	20	64	30	64
wheat	1,719	53	170	96	292 (***)
rice	2,621	50	179	97	430
maize	1,702	67	154	116	181
cotton	1,371	70	411	180	1,027

* - excluding labour costs
** - economic prices assumed equal to financial prices
*** - including the production value of straw

Assuming that the cost of production remains constant when the water supply is reduced, the financial consequences (for the farmer) as well as the economic consequences (for the country) can be estimated. In this analysis it has been assumed that the water which is saved by the distinguished strategies can be used in the next year for crop production. This means that the economic (or financial) return of the saved irrigation water is the same as the average benefits during the year considered. In other words: the saved water increases the total area irrigated, not during the year considered, however, but during the next year. Savings of 10% of Nile water, result than in securing the irrigation water for an additional 10/0.90 = 11.1% of the area for the next year. The total benefits of such a strategy savings of 10% is than the extra income of this 11.1% additional area, reduced with the income losses of the present 100% area (losses due to water savings), diminished by the cost of production of the 111.1% of the area cultivated.

The results of this analysis indicates that the farmers' income is in all cases positively influenced by the water saving strategies studied (table 24). It should be kept in mind, however, that the results given are valid only for situations with a serious water shortage, i.e. that without the water savings the water supply for the next calendar year will be insufficient. In case of an abundant availability of Nile water, the alternative value of the saved water is nil, and water savings are consequently of no value.

Table 24. Water savings, increase in area cultivated, and changes in the farmers and national income for the 23 rice area and water allocation duty strategies. All figures are relative to those of the reference strategy (510,88).

strategy	water savings (%)	increase agricultural area (%)	changes farmers' income			changes national income		
			year 1 (%)	year 2 (%)	total (%)	year 1 (%)	year 2 (%)	total (%)
(510,88)	-	-	-	-	-	-	-	-
(468,88)	1.7	1.7	-1.2	+1.7	+0.5	-2.4	+1.7	-0.7
(375,88)	5.9	6.3	-3.7	+6.0	+2.3	-7.3	+5.8	-1.5
(309,88)	8.9	9.7	-6.3	+9.1	+2.8	-11.5	+8.6	-2.9
(210,88)	13.4	15.5	-11.5	+13.8	+2.3	-18.5	+12.7	-5.8
(0,88)	23.9	31.5	-20.4	+25.1	+4.7	-31.2	+21.7	-9.5
(510,74)	5.9	6.3	-0.5	+6.3	+5.8	-0.5	+6.3	+5.8
(468,74)	7.2	7.8	-1.7	+7.7	+6.0	-2.7	+7.6	+4.9
(375,74)	10.4	11.6	-4.2	+11.1	+6.9	-7.7	+10.7	+3.0
(309,74)	12.6	14.4	-6.8	+13.4	+6.6	-12.0	+12.7	+0.7
(210,74)	16.0	19.1	-11.5	+16.9	+5.4	-18.6	+15.6	-3.0
(510,60)	11.4	12.9	-2.1	+12.7	+10.6	-2.0	+12.7	+10.7
(468,60)	12.4	14.1	-3.0	+13.7	+10.7	-4.5	+13.5	+9.0
(375,60)	14.5	17.0	-5.3	+16.1	+10.8	-8.9	+15.5	+6.6
(309,60)	16.1	19.2	-7.6	+17.8	+10.2	-12.6	+16.7	+4.2
(210,60)	18.5	22.7	-12.0	+20.0	+8.0	-19.0	+18.4	-0.6
(510,46)	16.8	20.2	-4.3	+19.3	+15.0	-4.5	+19.3	+14.8
(468,46)	17.3	20.9	-5.0	+19.9	+14.9	-6.3	+19.6	+13.3
(375,46)	18.6	22.8	-7.0	+21.2	+14.2	-10.8	+20.4	+9.6
(309,46)	19.5	24.2	-8.8	+22.1	+13.3	-14.2	+20.8	+6.6
(210,46)	20.8	26.3	-12.8	+23.0	+10.2	-19.8	+21.1	+1.3
(510,27)	24.2	32.0	-10.5	+28.6	+18.1	-11.7	+28.3	+16.6
(510,VA)	10.8	12.0	-1.2	+11.9	+10.7	-1.3	+11.9	+10.6

Reducing the rice area and maintaining the allocation duty of rice at 8,800 m^3.feddan^{-1} in cases of serious water shortages appears to have only small effects on the farmers' income (fig 73a). A reduction of the rice area below 309,000 feddan, however, results in a smaller benefit than the reduction until this value. For the lower allocation duties the effect on the farmers income is always larger (fig 73a). At allocation duties of 7,400 and 6,000 m^3.feddan^{-1}, however, reducing the rice area below 375,000 feddan already gives a lower increase of farmers income. For the allocation duty of 4,600 m^3.feddan the highest increase in farmers' income is obtained with the complete rice area of 510,000 feddan (fig 73a).

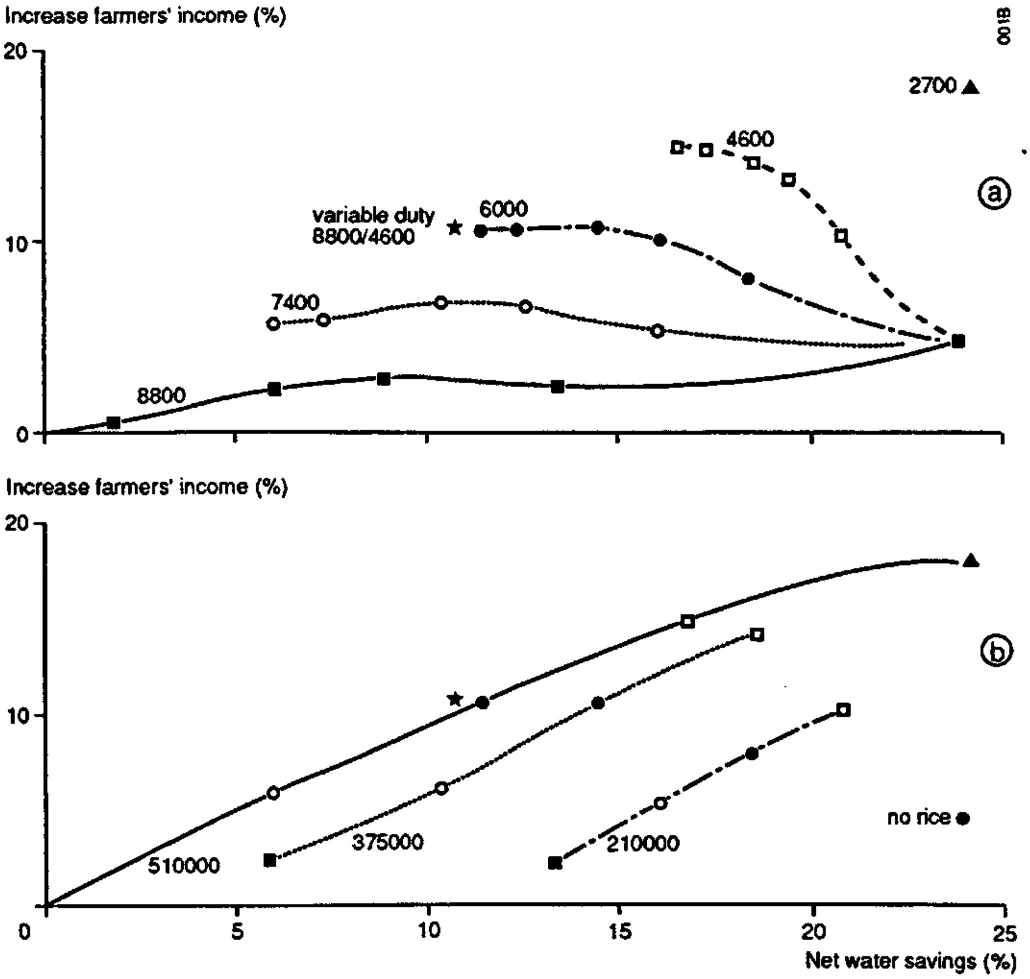

Fig 73. Effect of the 23 alternative water saving rice area and allocation duty strategies on the farmers' income in case of serious water shortage.

a - lines connect points with equal allocation duty

b - lines connect points with equal rice area

Apparently, maintaining the rice area at 510,000 feddan, and reducing the allocation duty of rice, is the best method to save water in case of a serious water shortage, when the objective is to secure the farmers' income (fig 73b). The strategy with the variable duty (510,VA) is not significantly different from the other scenarios with the rice area maintained at 510,000 feddan. For the larger water savings the differences in the financial analysis based on model simulations are largest. For water savings around 24% for instance the simulated increase in farmers income may be around 18% with strategy (520,27), or about 4.5% with strategy (0,88) (fig 73). It should be kept in mind however that the model results at such low water duties are less reliable, and that the spatial distribution of the agricultural production may be unacceptably affected by these water supply reductions.

The effect of water saving strategies on the farmers' income is only one of the aspects to be taken into account. Due to all kinds of subsidies and price distortions, implemented by the government to influence agricultural production, the national income may be differently affected by these measures. Taking the economic prices of 1979/1980 (table 23), it turns out that reducing the rice area has an unfavourable effect on the national income (fig 74). In total 7 out of the 23 strategies studied are economically unattractive. Reducing the allocation duty of rice, on the other hand, appears to be the better method to save on Nile water in case of a water shortage for safeguarding the national income.

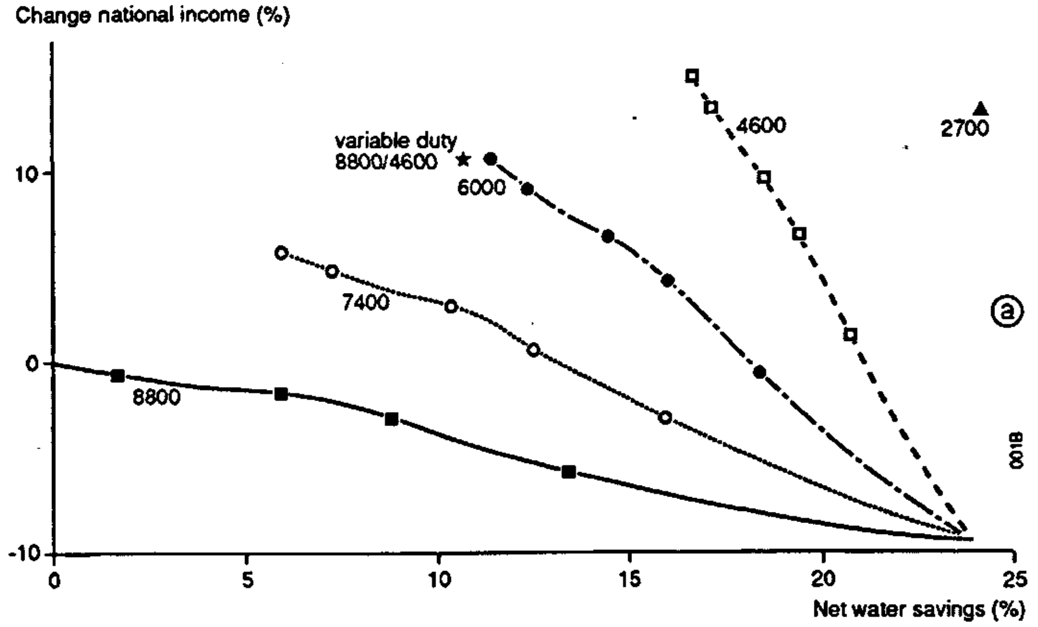

Fig 74. Effect of the 23 alternative water saving rice area and allocation duty strategies on the national income in case of serious water shortage.
lines connect points with equal allocation duty

The financial and economic analyses presented here point out that water savings by reducing the rice allocation duty is better for both the farmers' income and the national income, taking the prices of 1979/1980. The difference between both approaches indicates the sensitivity of the outcome for the prices and price ratios used. It is therefore recommended that the analysis is repeated with more up-to-date figures of say 1989/1990. The results presented are valid only for the condition that saving of water is absolutely necessary in order to guarantee agricultural activities for the next years on a more or less similar level. If the water availability is sufficient, saving of water serves no purpose.

Spatial distribution

So far the crop reaction has been considered as the average value for the complete study area. It is conceivable that a certain strategy scores good in terms of average crop yield for the study area, but that the negative effects (crop yield depression) are not evenly distributed over the Eastern Nile Delta. If so, such a strategy could be rejected, because this it may be socially unacceptable that a restricted group of farmers suffers from crop yield reductions, while the production and income of other farmers are not, or only slightly, affected.

For the reference strategy (510,88) about 12% of the study area has a crop yield of less than 75% (table 25). Only about 2% out of this 12% has a crop yield of less than 50%. For water savings in the order of magnitude of 6% two options are available: reducing the rice area till 375,000 feddan or reducing the rice allocation duty till 7,400 m^3.feddan^{-1}. Reducing the allocation duty is less unfavourable for the yearly average farmers' income (99% of the reference strategy) compared to reducing the rice area (yearly average farmers' income of 96%). The percentage of the study area with a crop yield of less than 75% appears to be equal for both strategies (table 25). In case of reducing the rice area the percentage of the study area with crop yields less than 50% is 3%; reduction of the allocation duty results in only 2% of the area with crop yields less than 50%.

Table 25. Water savings, average yearly farmers' income, and percentages of the study area with crop yield reductions for a number of rice area and water allocation duty strategies. The water savings and farmers' income are relative to the reference strategy (510,88).

strategy	water savings (%)	farmers' income (%)	% of study area with relative crop yield		
			> 75%	50-75%	< 50%
(510,88)	-	100.0	88	10	2
(375,88)	5.9	96.2	88	9	3
(510,74)	5.9	99.5	88	10	2
(309,88)	8.9	93.7	88	9	3
(375,74)	10.4	95.8	88	9	3
(510,60)	11.4	98.0	88	9	3
(510,VA)	10.8	98.8	88	10	2
(210,74)	16.0	88.5	82	15	3
(309,60)	16.1	92.4	88	9	3
(510,46)	16.8	95.7	79	17	4
(0,88)	23.9	79.6	79	16	5
(510,27)	24.2	89.5	66	28	6

Water savings in the order of magnitude of about 10% can be achieved by four alternative strategies (table 25). The strategy with variable rice allocation duties (510,VA) obviously scores the best with respect to farmers' income (99%), closely followed by the strategy with the reduced allocation duty (510,60) (98%). The spatial distribution for the variable duty strategy is slightly better than that of the reduced allocation duty strategy (table 25). Both strategies with the reduced rice areas (309,88) and (375,74) score lower for the average farm income and have a comparable frequency distribution of crop yield reductions with the other two scenarios.

For water savings of about 16% three scenarios can be considered (table 25). Reducing the allocation duty of rice till 4,600 m^3.feddan^{-1} results in an average decline in farmers' income of 4% only, but in crop yield depressions of more than 25% in about 21% of the study area. The alternatives, with smaller reductions in the allocation duty, reveal larger decreases in the farmers' income, and slightly lower percentages (18% and 12%) of the study area with crop yield reductions of more than 25% (table 25).

So far the differences in the crop yield distribution for strategies with similar water savings did not differ much. For water savings in the order of magnitude of 24% a large difference can be noticed (table 25). Reducing the allocation duty of rice to a value as low as 2,700 m^3.feddan^{-1} for strategy (510,27) results in an average decline of farmers income of 10% only, but in a crop yield reduction of more than 25% in 34% of the study area. In about 6% of the study area the crop yield decline is even more than 50%. Taking the rice completely out of cultivation for strategy (0,88) results in a double decrease of the average farmers' income of about 20%, but the crop yield reductions are more evenly distributed. For this strategy only 21% of the study area suffers from crop yield decreases of more than 25%.

Areas suffering large crop yield reductions are mainly located at the tail-ends of the irrigation canal system for the strategy with the lowest rice allocation duty, saving some 24% of Nile water (fig 75b). The same phenomenon can be observed for the alternative (where rice is taken out of cultivation), but to a lesser extent (fig 75c).

Based on the above considerations regarding the spatial crop yield reduction distribution, it can be concluded that reduction of the allocation duty appears to be the superior method to save on Nile water, compared to reducing the rice area. Below allocation duties of 4,600 m^3.feddan^{-1}, however, the water shortages caused by these reductions in the water supply while maintaining the agricultural water requirements by maintaining the rice in the cropping pattern, cause an unequal water distribution. As a consequence farmers at the tail-ends of the irrigation system receive less than their equal share of the irrigation water, and are suffering more than proportionally with respect to crop production and thus in income. This may be socially unacceptable.

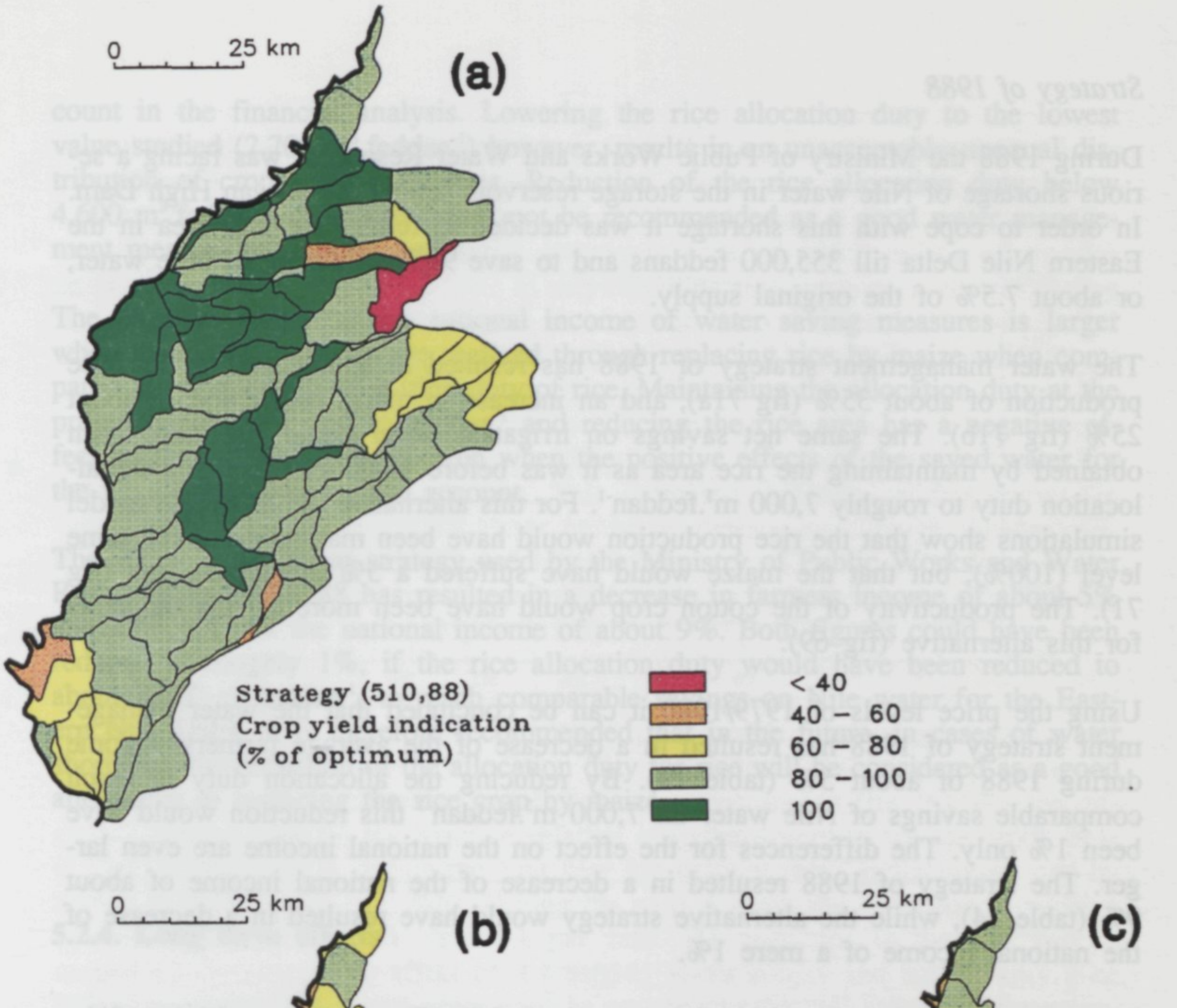

Fig 75. Spatial distribution of relative crop yields (relative to the optimum) in the study area for three rice area and allocation duty strategies.

a - reference strategy (**510,88**), no water savings

b - strategy (**510,27**), saving 24% Nile water by reducing the allocation duty till 2,700 $m^3.feddan^{-1}$

c - strategy (**0,88**), saving 24% of Nile water by taking the rice out of cultivation

Strategy of 1988

During 1988 the Ministry of Public Works and Water Resources was facing a serious shortage of Nile water in the storage reservoir behind the Aswan High Dam. In order to cope with this shortage it was decided to reduce the rice area in the Eastern Nile Delta till 355,000 feddans and to save 925 million m^3 of Nile water, or about 7.5% of the original supply.

The water management strategy of 1988 has resulted in a reduction of the rice production of about 35% (fig 71a), and an increase in maize production of about 25% (fig 71b). The same net savings on irrigation water could also have been obtained by maintaining the rice area as it was before 1988, and reducing the allocation duty to roughly 7,000 $m^3.feddan^{-1}$. For this alternative the SIWARE model simulations show that the rice production would have been maintained at the same level (100%), but that the maize would have suffered a 5% production loss (fig 71). The productivity of the cotton crop would have been more or less the same for this alternative (fig 69).

Using the price levels of 1979/1980 it can be concluded that the water management strategy of 1988 has resulted in a decrease of the average farmers' income during 1988 of about 5% (table 24). By reducing the allocation duty to reach comparable savings of Nile water till 7,000 $m^3.feddan^{-1}$ this reduction would have been 1% only. The differences for the effect on the national income are even larger. The strategy of 1988 resulted in a decrease of the national income of about 9% (table 24), while the alternative strategy would have resulted in a decrease of the national income of a mere 1%.

The above comparison should be interpreted carefully. Due to the sensitivity of the economic and financial results to the price levels used, the absolute levels of income reductions may differ considerably. The relative advantage of the strategy with a reduced rice allocation duty over the strategy of 1988 is expected to be the same for the price levels of 1989/1990, however.

Conclusions

Due to the reduction in the rice area as well as to the reduction in the rice allocation duty the actual evapotranspiration of the summer crops are affected. The effect of reducing the rice area on the actual evapotranspiration rates of the summer crops, except for cotton, are larger compared to reducing the rice allocation duties to reach comparable savings.

Going from the south to the north, the exchange of rice by maize results in increasing production losses of rice. These losses are not completely compensated by the increase in the total maize production, due to the higher soil and irrigation water salinities in the northern part of the study area. In rice zones 1 and 2 the exchange of rice by maize is therefore not recommended.

The negative effect on the average farmers' income of water saving measures is less if water savings are realized by reducing the rice allocation duty compared to replacing rice by maize. In case of serious water shortages, endangering the crop production of the coming period, however, none of the strategies studied has a negative effect on the farmers' income, if these future effects are taken into account in the financial analysis. Lowering the rice allocation duty to the lowest value studied (2,700 m^3.feddan^{-1}) however, results in an unacceptably unequal distribution of crop yield reductions. Reduction of the rice allocation duty below 4,600 m^3.feddan^{-1} should therefore not be recommended as a good water management measure to save on water.

The negative effect on the national income of water saving measures is larger when these water savings are realized through replacing rice by maize when compared to reducing the allocation duty of rice. Maintaining the allocation duty at the present figure of 8,800 m^3.feddan^{-1} and reducing the rice area has a negative effect on the national income, even when the positive effects of the saved water for the next years is taken into account.

The water management strategy used by the Ministry of Public Works and Water Resources during 1988 has resulted in a decrease in farmers income of about 5% and a decrease of the national income of about 9%. Both figures could have been reduced to roughly 1%, if the rice allocation duty would have been reduced to about 7,000 m^3.feddan^{-1}, to reach comparable savings on Nile water for the Eastern Nile Delta. It is therefore recommended that in the future, in cases of water shortages, the reduction of the allocation duty for rice will be considered as a good alternative to replacing the rice crop by maize.

5.2.4. Long term effects

When changing the water management in a region such as the Eastern Nile Delta, two effects can be expected. The first effect is immediate as a result of the changes in volumes of both irrigation and drainage water. Crop evapotranspiration is affected in the same year in which such measures are implemented. On the longer term (a few years), secondary effects on crop evapotranspiration can be expected as a result of changing soil salinities. This, on its turn, will change the drainage salinity of such a field with increasing soil salinity. The use of this drainage water further downstream can then further decrease evapotranspiration rates in the receiving areas where this drainage water is being reused.

In order to investigate these long term effects the 23 distinguished rice area and allocation duty strategies have been simulated with the SIWARE model for a period of 50 years. This period was considered long enough to obtain more or less equilibrium conditions as far as salinity is concerned.

Changes with time

Reducing the rice area appears to increase the average soil salinity in the study area fast during the first years, and slower during the subsequent period (fig 76a). The average soil salinity of the reference strategy (510,88), which has been taken as the starting point, is about 2.9 mmho.cm^{-1}. For strategy (0,88), i.e. replacing all rice by maize, this soil salinity increases during the first 5 years of implementing this strategy with 0.8 mmho.cm^{-1}, or about 6% per year. During the next period of 5 years, the average soil salinity build-up slows down to about 1.2% per year until it reaches the value of 3.9 mmho.cm^{-1} after 10 years (fig 76a). The next increase

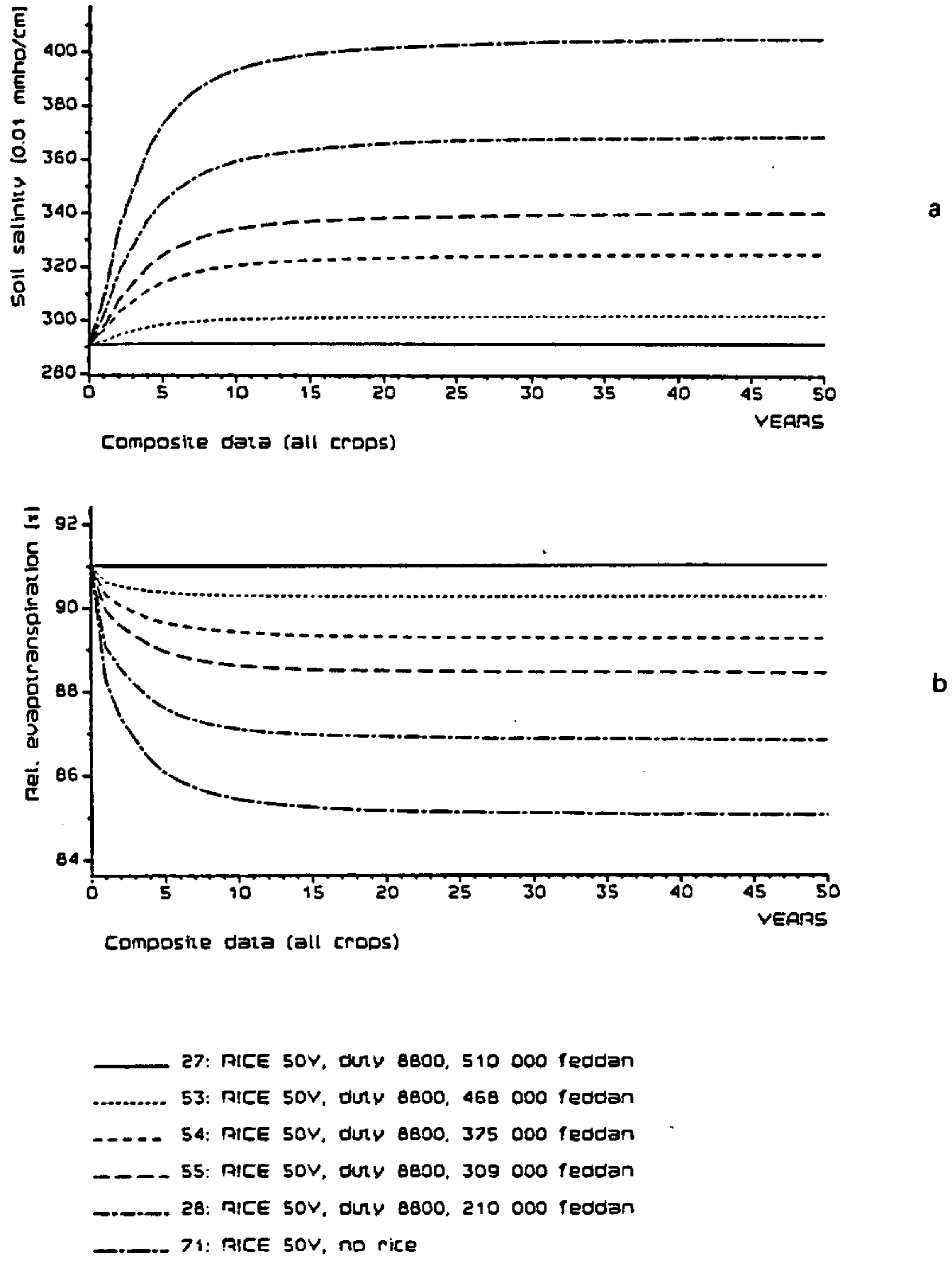

Fig 76. Long term (50 years) effect of reducing the rice area on the average soil salinity in the study area and on the relative evapotranspiration rate (relative to the optimum) of the cropping pattern.

a - soil salinity (mmho.cm^{-1}) b - relative evapotranspiration (%)

of soil salinity with 0.1 mmho.cm^{-1} takes about 5 years, which is another 0.4% per year. Finally, it takes the last 35 years of the simulation, to increase the average soil salinity in the study area with another 0.1 mmho.cm^{-1} (0.01% per year). The total increase of soil salinity of this strategy is 41%, of which only a 6% increase is realized during the first year of implementing this strategy, and 35% during the ensuing period. Moreover, it can be observed from the simulated average soil salinity time-series (fig 76a), that the soil salinity build-up is not yet completed after a simulation period of 50 years, but continues at a fairly constant rate beyond this period. Most probably this is the result of the cascade effect through which soil salinity increases in the southern part of the study area are causing increases in drainage water salinities. This increased drainage salinity causes, in turn, additional soil salinity increases in the northern parts through the (un)official reuse of drainage water. Therefore, soil salinity equilibrium conditions will be reached depending on the number of serial cascades (calculation units) which are using drainage water from the previous ones.

Complementary to the increase in soil salinity, the relative evapotranspiration of the cropping pattern (relative to the optimum, i.e. ample water supply and no soil salinity problems) decreases (fig 76b). The soil salinity build-up appears to be more gradual than the decrease in relative evapotranspiration (fig 76). For the reference strategy (**510,88**) the average relative evapotranspiration for the study area is 91%. The reduction during the first year for strategy (**0,88**), replacing all rice by maize, is about 2.5% (fig 76b). During the next 4 years the reduction in relative evapotranspiration is 2.5%, or 0.6% per year. The reduction in the first year is caused by the composite effect of a changing water supply and soil salinity. The reduction in the subsequent years may be ascribed to the soil salinity increase only. Extrapolating the soil salinity effect on relative evapotranspiration to the first simulation year, it can be concluded that due to the changed water supply the relative crop evapotranspiration rate reduces with about 2% for this strategy, and that during the first 5 years an additional 3% evapotranspiration reduction is caused by the increasing soil salinity. Similar to the increase of soil salinity, the decrease in relative evapotranspiration slows down in time: 0.6% per year during the first 5 years; 0.1% per year for the second 5 years; 0.06% per year for the third period of 5 years; and 0.005% per year for the last 35 years simulated. The total decrease of relative evapotranspiration due to replacing all rice by maize is 6% after 50 years (fig 76b), of which a reduction of 2.5% is realized during the first year and 3.5% during the ensuing 49 years. The decrease of relative evapotranspiration will continue beyond the period of 50 years studied, be it, at a very slow pace. This means that the ultimate effect of these strategies is not yet realized after 50 years.

The salinity of the crop drainage (excluding the spillway losses) reveals even larger changes during the first year (fig 77), compared to the relative evapotranspiration. The average crop drainage salinity of the reference strategy (**510,88**), which has been used as a starting point for the reduced rice area strategies, is about 1,430 g.m^{-3}. In the first simulation year of strategy (**0,88**), where all rice is replaced by maize, this salinity increases to 1,790 g.m^{-3}, or about 25%. During the next 4 years the drainage salinity increases with 5.5% only (1.4% per year). The fast reaction of the crop drainage salinity during the first year must be explained by the phenomenon of the fast drainage through cracks in the clayey soils in the Eastern Nile Delta. Due to this fast drainage effect of the reduced water supply (reduced irrigation water losses), the drainage water salinity reacts faster than the soil salinity. During the subsequent years the increase in crop drainage salinity is caused by the gradual salinization of the soil at greater depth: 0.7% per year during the second 5 year period; 0.55% per year during the third period of 5 years; and 0.08% per year during the last 35 years of model simulations. The total increase of the crop drainage salinity during the 50 year period studied is equal to the increase in soil salinity, 41% (fig 77). The increase of the crop drainage salinity in the first year is 25% (for soil salinity 6%), and during the ensuing period 16% (for soil salinity 35%).

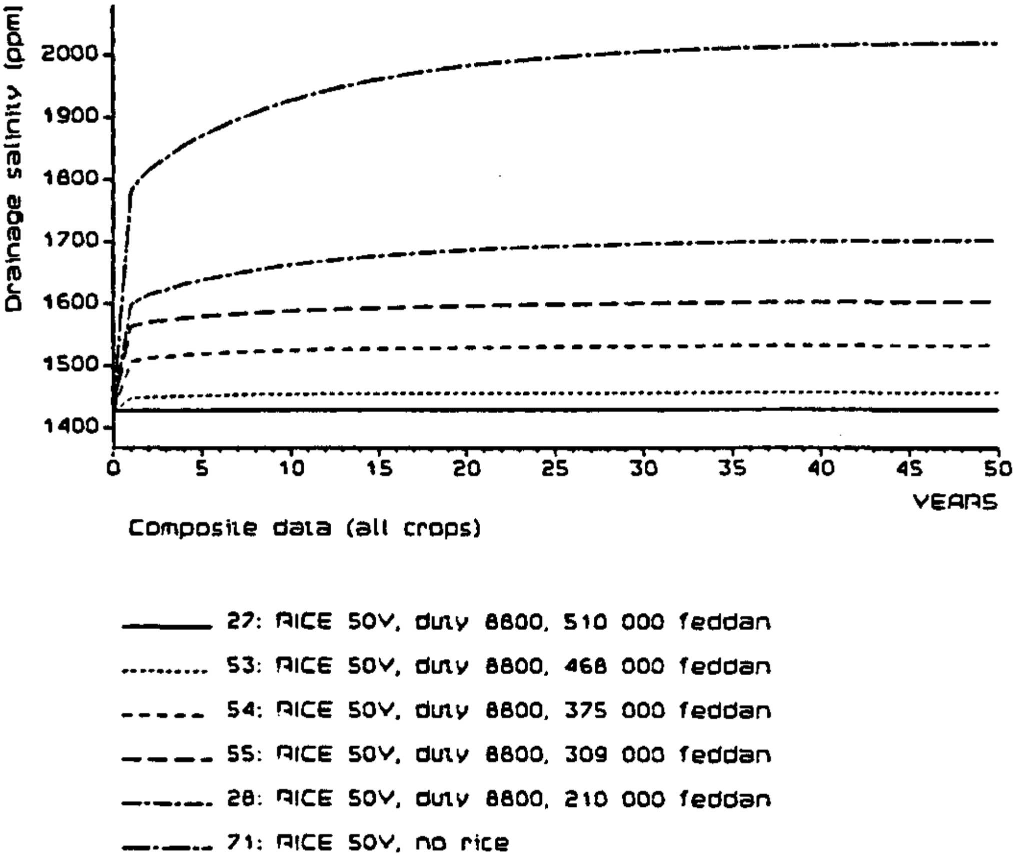

Fig 77. Long term (50 years) effect of reducing the rice area on the average crop drainage salinity (g.m^{-3}) for the cropping pattern in the study area. (Crop drainage excludes the spillway losses at the tail-ends of the distributary and meskaa canals.)

Summer and winter crops can be expected to react differently to the water savings realized by reducing the rice area and/or reducing the rice allocation duty. The water savings will occur in the summer period during the rice growing period. In winter time the water supply remains the same. Consequently, for the winter crops the only effect of the water savings expected will be through the increased soil salinity and, possibly, the irrigation water salinity. For the berseem crop the average soil salinity for the study area increases from 2.2 mmho.cm^{-1} for the reference strategy (510,88) till 3.3 mmho.cm^{-1} after 5 years for strategy (0,88), replacing all rice by maize (fig 78a). This is about 10% per year. After 5 years the soil salinity build-up slows down to 1.8% per year during the second 5 year period; 0.6% per year during the third 5 year period; and 0.015% per year during the last 35 years

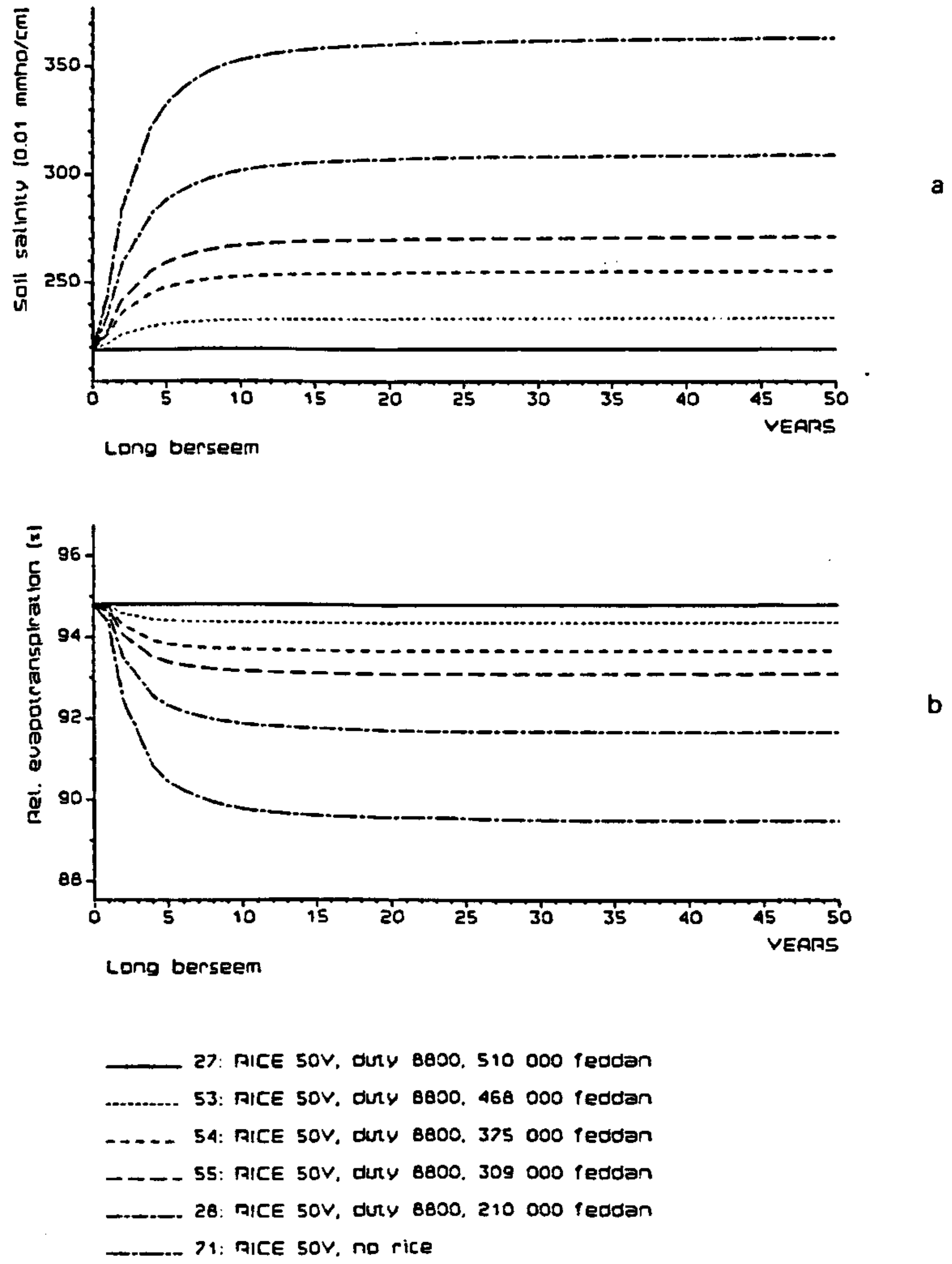

Fig 78. Long term (50 years) effect of reducing the rice area on the average soil salinity area and the relative evapotranspiration rate (relative to the optimum) in the study area for the long berseem crop.

a - soil salinity (mmho.cm^{-1}) b - relative evapotranspiration (%)

of the simulation period. The total soil salinity increases during this 50 years amounts to about 65% (41% for the cropping pattern), of which 10% is realized during the first year (6% for the complete cropping pattern). The changes in soil salinity of the winter crop berseem appears not to differ much from the average development of soil salinity for the complete cropping pattern (fig 78a). The relative increase is more (65% for berseem; 41% for the cropping pattern), but the initial soil salinity level of both is also different (from 2.2 till 3.6 mmho.cm^{-1} for berseem and from 2.9 till 4.0 mmho.cm^{-1} for the cropping pattern).

For the relative evapotranspiration (relative to the optimum) of the cropping pattern it has been discussed before that two effects are superimposed. The first (immediate) effect is the reduction of evapotranspiration rates due to the changes in water supply. The second effect is a reduction due to increases in soil salinity. For the winter crop long berseem the first effect should be absent, because the water supply conditions during the winter period are not affected by reducing the rice area or the rice allocation duty (fig 78b). During the first year of simulation the relative evapotranspiration changes with 0.5% from 95 to 94.5% by replacing all rice by maize in strategy (0,88) (fig 78b). During the subsequent 4 years of simulation the relative evapotranspiration changes with approximately 1% per year. The explanation for the phenomenon that during the first year of simulation this decrease is only half the decrease afterwards may be the fact that berseem is grown from October till May, whereas the water saving measures start in June. The simulations for berseem for the first year start in January, taking the unchanged soil salinity of the reference strategy (510,88). Until the month May the simulations for strategy (0,88) for the berseem crop are identical to those obtained for the reference strategy. When in October the berseem crop is sown, i.e. after the summer crops have been in the field, the simulations for berseem continue with the increased soil salinity. During the first year of simulations berseem has a low soil (normal) salinity during the first half the growing period, and during the next half of the growing period an increased soil salinity. The average increase during the first year is therefore 50% only. After the first 5 years of simulation the decrease in relative evapotranspiration slows down to 0.1% per year during the second 5 year period; 0.02% for the third 5 year period; and 0.001% per year for the last 35 years of simulation (fig 78b). The total decrease of relative evapotranspiration of the berseem crop due to replacing all rice by maize is about 5.5% (6% for the average cropping pattern), of which 0.5% decrease is realized during the first year of implementing such a strategy (2.5% for the average cropping pattern) and 5% during the ensuing 49 year period (3.5% for the cropping pattern). These results show that changing the water management during the summer period may have a negligible effect on the winter crops on short notice (during the first year of implementing such changes), but that on the long term the changed soil salinity conditions cause a similar crop reaction as for the summer crops.

Also the development of the crop drainage salinity of the berseem crop with time (fig 79) differs considerably from that of the average cropping pattern. The crop drainage salinity of the reference strategy of 1,800 g.m^{-3} for berseem increases during the first year of simulation with about 1% only till 1,820 g.m^{-3} by replacing all rice by maize (fig 79). During the next 4 years it increases with about 1.5% per year. After the first 5 years of simulation the increase in crop drainage salinity slows down to 0.65% per year during the second 5 year period; 0.45% per year during the third 5 year period; and 0.1% per year during the last 35 years of model simulations (fig 79). The total increase of the berseem crop drainage salinity is 17% (41% for the cropping pattern), of which 1% is realized during the first year (25% for the cropping pattern) and 16% during the ensuing period of 49 years (16% for the complete cropping pattern). The large increase during the first year for the cropping pattern has been ascribed to the lower irrigation water supply to the crops due to the changed water management. The limited increase of crop drainage salinity for the winter crop berseem supports this explanation: for this crop the water supply has not changed and consequently this sudden change in salinity is absent.

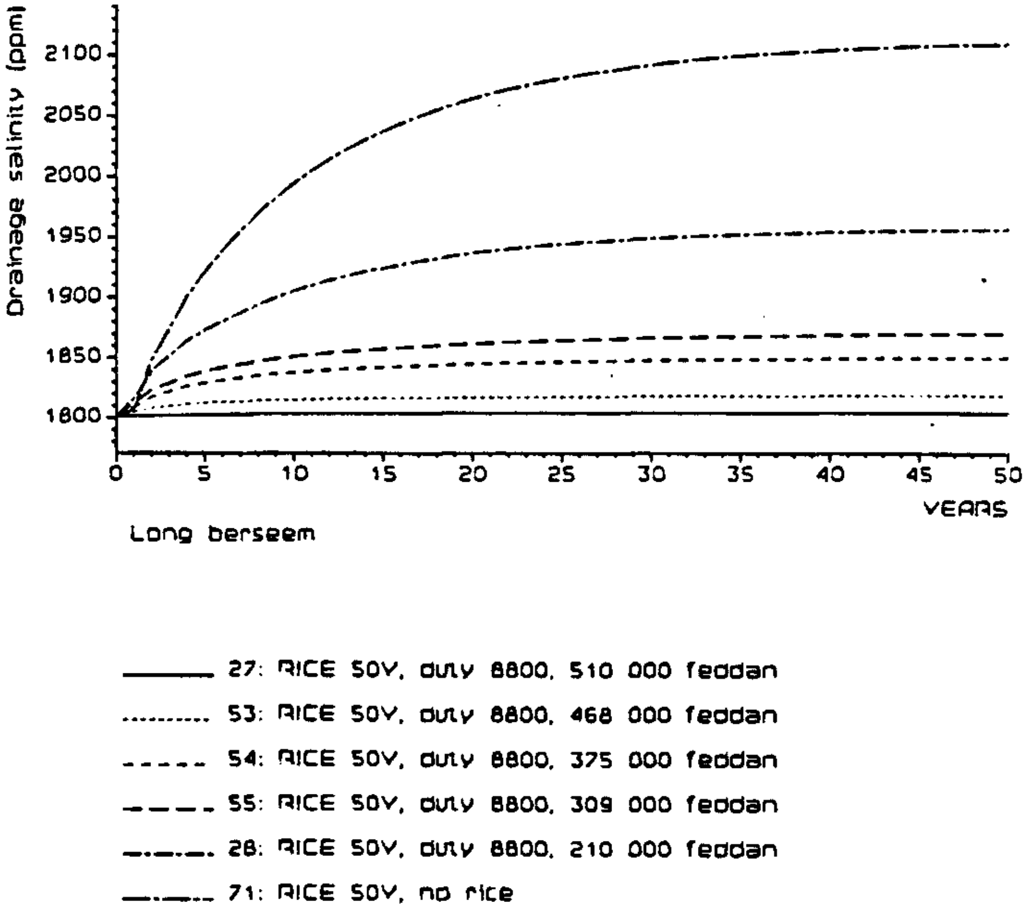

Fig 79. Long term (50 years) effect of reducing the rice area on the average berseem crop drainage salinity (g.m^{-3}) in the study area. (Crop drainage excludes the spillway losses at the tail-ends of the distributary and meskaa canals.)

Long term spatial distribution

The increase in soil salinity due to replacing rice by maize, strategy (0,88), are expected to be concentrated mainly in the areas where the largest percentages of rice were located in the reference strategy (510,88). Comparing the short term effect on the soil salinity of replacing rice by maize (fig 80b) with the soil salinity in the reference strategy (fig 80a), only small differences can be observed. The spatial distribution of the soil salinity appears to be affected only minimal by this change in cropping pattern. On the long term, however, the changes are much larger (fig 80c). The percentage of the study area with a soil salinity above 4 mmho.cm^{-1}, which is about 12% for both the reference strategy and the short term

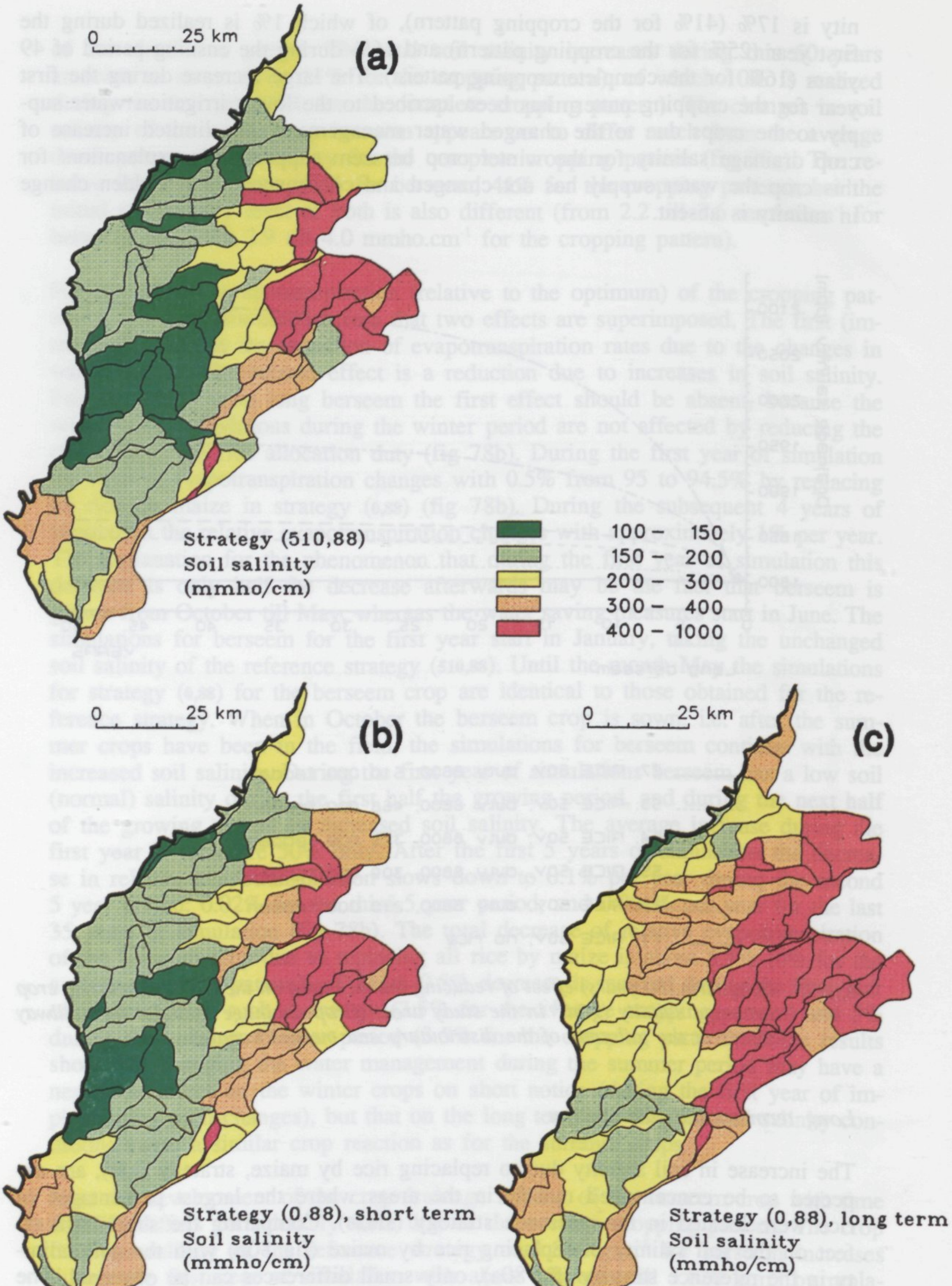

Fig 80. Spatial distribution of the average soil salinity ($mmho.cm^{-1}$*) for the cropping pattern.*

a - reference strategy (510,88) b - short term strategy (0,88) c - long term strategy (0,88)

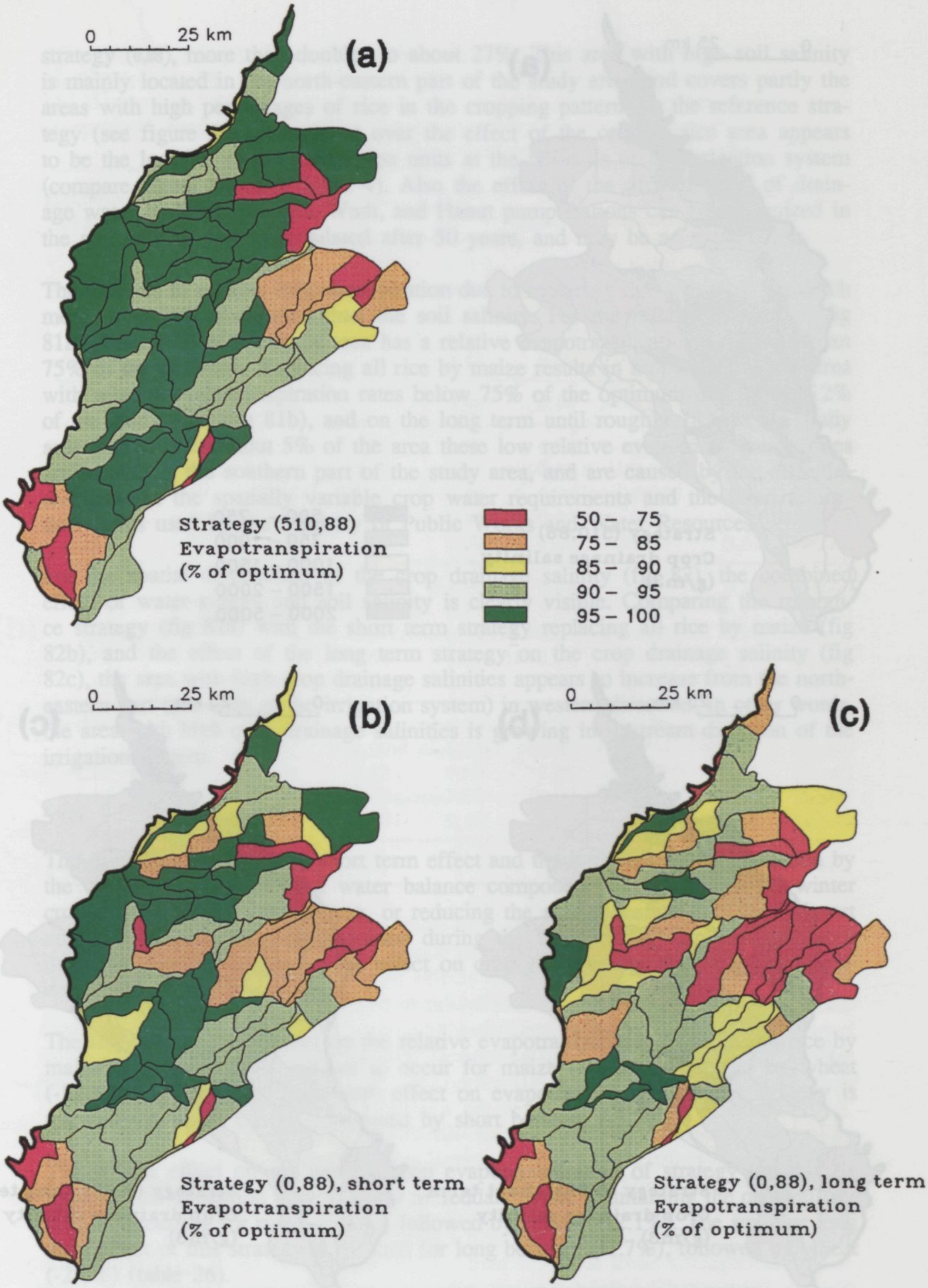

Fig 81. Spatial distribution of the relative evapotranspiration rates (relative to the optimum) in % for the cropping pattern.

a - reference strategy (510,88) b - short term strategy (0,88) c - long term strategy (0,88)

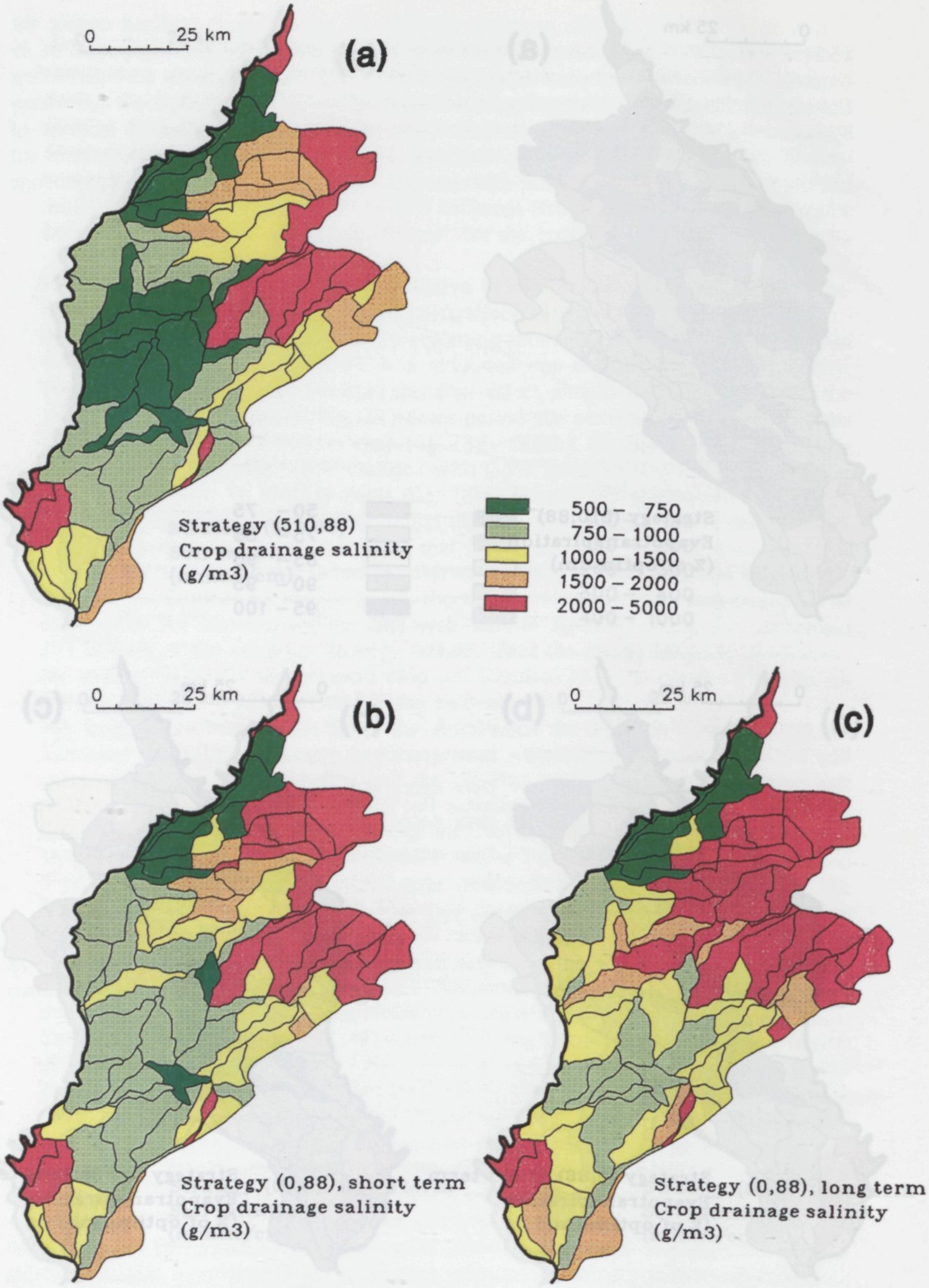

Fig 82. Spatial distribution of the crop drainage salinity (excluding the spillway losses of distributary canals and meskaas in g.m^{-3} for the cropping pattern.
a - reference strategy (**510,88**) b - short term strategy (**0,88**) c - long term strategy (**0,88**)

strategy (**0,88**), more than doubles to about 27%. This area with high soil salinity is mainly located in the north-eastern part of the study area, and covers partly the areas with high percentages of rice in the cropping pattern for the reference strategy (see figure 59a). Dominant over the effect of the original rice area appears to be the location of the calculation units at the tail-ends of the irrigation system (compare figure 80c and figure 4). Also the effect of the official reuse of drainage water by Blad El Ayed, Wadi, and Hanut pump stations can be recognized in the soil salinity pattern simulated after 50 years, and may be an explanation.

The changes in relative evapotranspiration due to replacing rice by maize are much more irregularly distributed than the soil salinity. For the reference strategy (fig 81a) about 10% of the study area has a relative evapotranspiration rate lower than 75% of the optimum. Replacing all rice by maize results in an increase of the area with relative evapotranspiration rates below 75% of the optimum until about 12% of the study area (fig 81b), and on the long term until roughly 18% of the study area (fig 81c). In about 5% of the area these low relative evapotranspiration rates are located in the southern part of the study area, and are caused by the differences between the spatially variable crop water requirements and the fixed allocation duties used by the Ministry of Public Works and Water Resources.

For the spatial distribution of the crop drainage salinity (fig 82), the combined effect of water supply and soil salinity is clearly visible. Comparing the reference strategy (fig 82a) with the short term strategy replacing all rice by maize (fig 82b), and the effect of the long term strategy on the crop drainage salinity (fig 82c), the area with high crop drainage salinities appears to increase from the north-eastern part (tail-ends of the irrigation system) in western direction. In other words, the area with high crop drainage salinities is growing in upstream direction of the irrigation system.

Long term crop reaction

The difference between the short term effect and the long term effect is caused by the changes in the soil and water balance components' salinity. For the winter crops reductions in the rice area, or reducing the rice allocation duty, had almost no effect on crop evapotranspiration during the first year of implementing such measures. On the long term the effect on crop evapotranspiration may be considerable, however (table 26).

The largest long term effect on the relative evapotranspiration of replacing rice by maize in strategy (**0,88**) appears to occur for maize (-15.2%), followed by wheat (-12.1%). The smallest long term effect on evapotranspiration of this strategy is realized for cotton (-5.0%), followed by short berseem (-5.7%).

The largest effect on the relative crop evapotranspiration of strategy (**510,27**), i.e. reducing the allocation duty to 2,700 m^3.feddan^{-1} while maintaining the original rice area, is occurring for rice (-20.1%), followed by cotton (-12.1%). The smallest long term effect of this strategy is realized for long berseem (-1.7%), followed by wheat (-2.1%) (table 26).

Table 26. Long term (after 50 years) relative crop evapotranspiration rates relative to the reference strategy (510,88) for the 23 rice area and water allocation duty strategies.

strategy	water savings (%)	relative evapotranspiration (%) per crop						
		long berseem	short berseem	wheat	rice	maize	cotton	cropping pattern
(510,88)	-	100.0	100.0	100.0	100.0	100.0	100.0	100.0
(468,88)	1.7	99.6	99.8	98.6	99.1	98.7	99.6	99.0
(375,88)	5.9	98.8	99.2	95.9	96.7	96.6	99.1	97.5
(309,88)	8.9	98.1	98.2	94.3	95.1	94.4	98.1	96.3
(210,88)	13.4	96.4	96.9	91.8	92.9	90.0	96.7	93.9
(0,88)	23.9	93.6	94.3	87.9	-	84.8	95.0	90.6
(510,74)	5.9	99.8	99.9	99.8	99.4	99.1	99.5	99.4
(468,74)	7.2	99.4	99.7	98.5	98.4	98.1	99.1	98.6
(375,74)	10.4	98.7	99.2	95.7	96.1	96.0	98.5	98.1
(309,74)	12.6	98.0	98.0	94.0	94.4	93.8	97.6	96.9
(210,74)	16.0	96.3	96.7	91.7	92.1	89.9	96.7	94.8
(510,60)	11.4	99.5	99.6	99.4	97.5	97.2	97.5	98.1
(468,60)	12.4	99.1	99.5	98.0	96.5	96.6	97.2	97.4
(375,60)	14.5	98.4	98.9	95.3	94.3	95.0	96.9	96.2
(309,60)	16.1	97.7	97.8	93.8	92.5	93.0	96.6	95.1
(210,60)	18.5	96.1	96.7	91.5	90.3	89.4	96.0	93.3
(510,46)	16.8	99.1	98.6	98.9	93.4	95.1	94.5	96.0
(468,46)	17.3	98.8	98.5	97.6	92.3	95.0	94.6	95.5
(375,46)	18.6	98.1	98.1	94.9	89.8	93.9	94.7	94.5
(309,46)	19.5	97.4	97.1	93.4	89.1	92.1	94.8	94.0
(210,46)	20.8	95.9	96.1	91.2	87.0	89.0	95.0	92.6
(510,27)	24.2	98.3	96.5	97.9	79.9	90.8	87.9	90.6
(510,VA)	10.8	99.7	99.5	99.6	97.8	98.8	98.2	98.8

The intensity of the crop reaction of wheat to replacing all rice by maize for strategy (0,88) seems to contradict the fact that wheat is relatively tolerant for high soil salinities. The average soil salinity of the wheat crop for strategy (510,27) increases with about 27% from 3.0 mmho.cm^{-1} for the reference strategy till about 3.8 mmho.cm^{-1} after 50 years. For the alternative strategy (0,88) the average soil salinity of wheat increases with about 40% until 4.2 mmho.cm^{-1}. Given the wheat crop reaction of about 2% evapotranspiration reduction for reducing the allocation duty of rice from 8,800 m^3.feddan^{-1} to 2,700 m^3.feddan^{-1}, the maximum reduction expected for replacing rice by maize would be double this effect (about 4%), and not the 12% predicted by the model for strategy (0,88) (fig 83).

Due to the removal of rice in the cropping pattern the growing period of the wheat crop is restricted. The first priority succeeding crop of wheat is rice (table 4). The second priority succeeding crop is maize. The weighted average planting date of rice (table 3) is the 10th of June (from May 15 till July 1) and for maize the 10th of May (from May 1 till May 20). The removal of rice from the cropping pattem consequently causes in the model simulations a 13% shorter growing period of wheat from 180 days in the situation with rice included (510,000 feddans) to 157 days when no rice is cultivated. For all other crops the length of the growing period remains more or less the same.

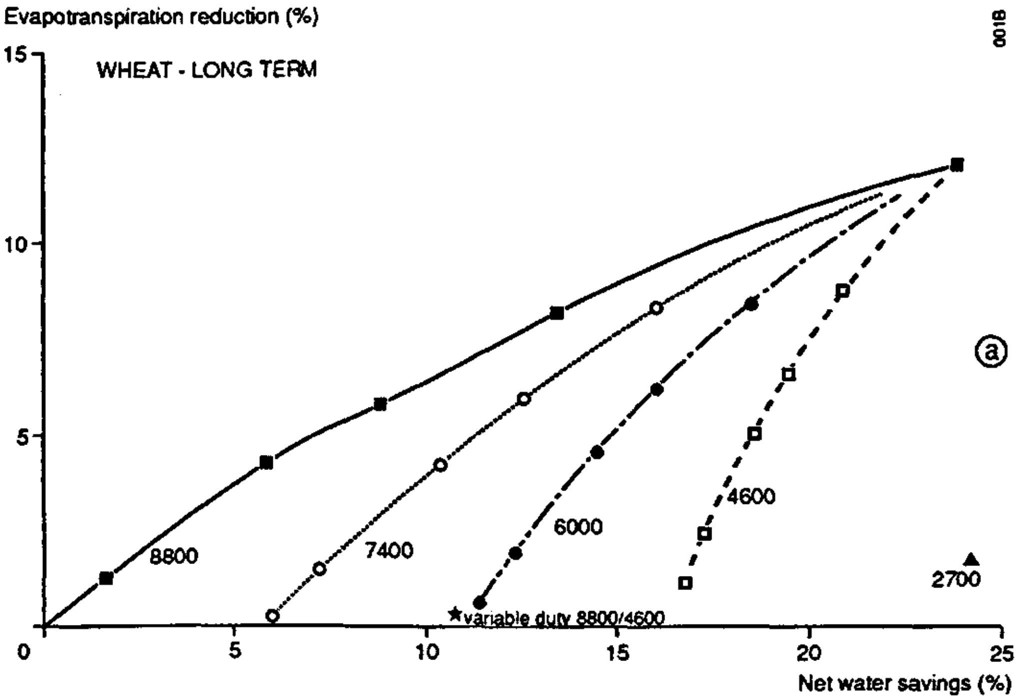

Fig 83. Long term (50 years) relative evapotranspiration rates of the wheat crop for the 23 distinguished rice area and allocation duty strategies in relation to the net water savings.

Lines connect strategies with equal allocation duty and different rice areas

Financial and economic analysis

Along the same lines, and with similar assumptions as used for the short term model simulations, the simulated evapotranspiration results can be converted into changes in farmers' income and the effects on the national income can be quantified (table 27). Comparing these results for the long term with those for the short term (table 27), it is noticed that the differences (decreases in financial and economic returns) are larger for the strategies reducing the rice area than for those reducing the rice allocation duty.

The differences between the short and the long term results on the farmers' income are caused by soil salinity increases. Apparently these increases are more dominant for the strategies with reduced rice areas (fig 84). For the short term evaluation all strategies considered had a positive overall effect on the farmers' income (fig 73), under the condition, of course, that a serious water shortage threatens the security of the water supply in the near future. If these strategies are maintained for a period of 50 years, however, six out of the 23 strategies studied should be rejected, because the overall effect is negative. These are all the strategies with a reduced rice area and a rice allocation duty of 8,800 m^3.$feddan^{-1}$, and strategy (210,74) (fig 84).

Table 27. Water savings, increase in area cultivated, and short term (first year) and long term (50 years) changes in the farmers' and national income for the 23 rice area and water allocation duty strategies. All figures are relative to those of the reference strategy (510,88).

strategy	water savings (%)	increase agricultural area (%)	changes in income			
			farmers' income		national income	
			short term (%)	long term (%)	short term (%)	long term (%)
(510,88)	-	-	-	-	-	-
(468,88)	1.7	1.7	+0.5	-0.3	-0.7	-1.2
(375,88)	5.9	6.3	+2.3	-0.1	-1.5	-3.2
(309,88)	8.9	9.7	+2.8	-0.9	-2.9	-5.6
(210,88)	13.4	15.5	+2.3	-3.9	-5.8	-10.2
(0,88)	23.9	31.5	+4.7	-6.4	-9.5	-17.1
(510,74)	5.9	6.3	+5.8	+5.4	+5.8	+5.5
(468,74)	7.2	7.8	+6.0	+4.9	+4.8	+4.0
(375,74)	10.4	11.6	+6.9	+4.7	+3.0	+0.9
(309,74)	12.6	14.4	+6.6	+2.4	+0.7	-2.4
(210,74)	16.0	19.1	+5.4	-1.2	-3.0	-7.7
(510,60)	11.4	12.9	+10.6	+9.6	+10.7	+9.7
(468,60)	12.4	14.1	+10.7	+8.9	+9.0	+7.9
(375,60)	14.5	17.0	+10.8	+7.3	+6.6	+3.9
(309,60)	16.1	19.2	+10.2	+5.4	+4.2	+0.6
(210,60)	18.5	22.7	+8.0	+0.8	-0.6	-5.9
(510,46)	16.8	20.2	+15.0	+13.1	+14.8	+13.0
(468,46)	17.3	20.9	+14.9	+11.8	+13.3	+10.4
(375,46)	18.6	22.8	+14.2	+9.9	+9.6	+6.2
(309,46)	19.5	24.2	+13.3	+7.4	+6.6	+2.3
(210,46)	20.8	26.3	+10.2	+2.4	+1.3	-4.5
(510,27)	24.2	32.0	+18.1	+14.6	+16.6	+13.6
(510,VA)	10.8	12.0	+10.7	+10.0	+10.6	+10.0

The difference between the short term and the long term effect of the 23 water saving strategies on the national income shows the same trend as the effects on the farmers' income (fig 85). Compared to the short term calculations, the national income of the strategies with the reduced rice areas decreases more than the strategies with the reduced rice allocation duties. On the short term (fig 74) 7 out of the 23 strategies studied were economically unattractive. On the long term 9 strategies are unattractive: all strategies with a reduced rice area and a rice allocation duty of 8,800 m^3.feddan^{-1}; all strategies with the rice confined to rice zone 1, (210,000 feddans rice area); and strategy (309,74) (table 27 and fig 85).

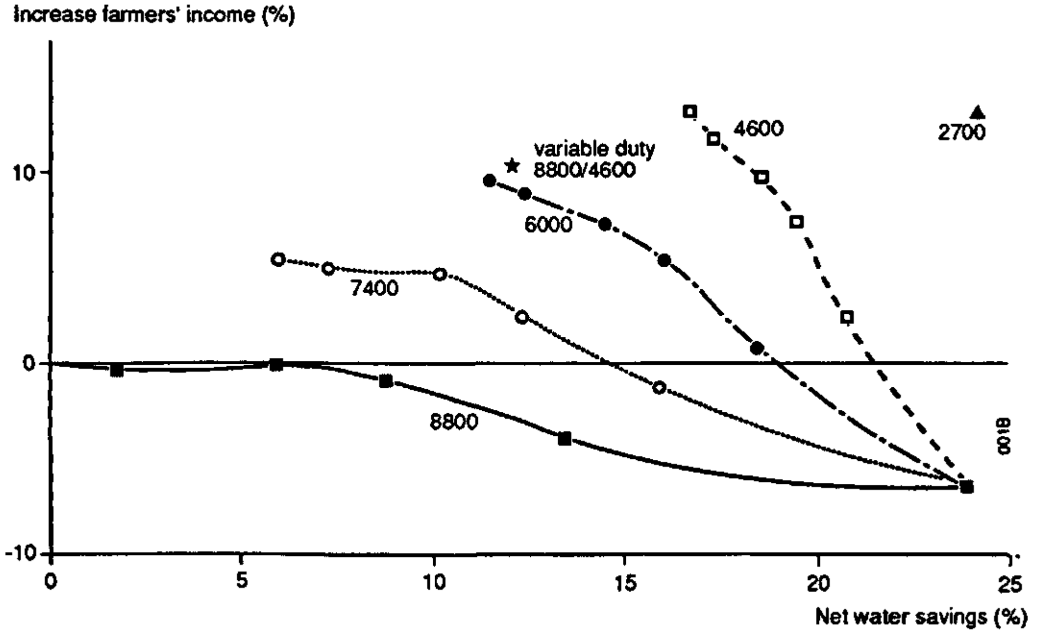

Fig 84. Long term (50 years) effect of the 23 alternative water saving rice area and allocation duty strategies on the farmers' income in case of serious water shortage.

Lines connect points with equal allocation duty

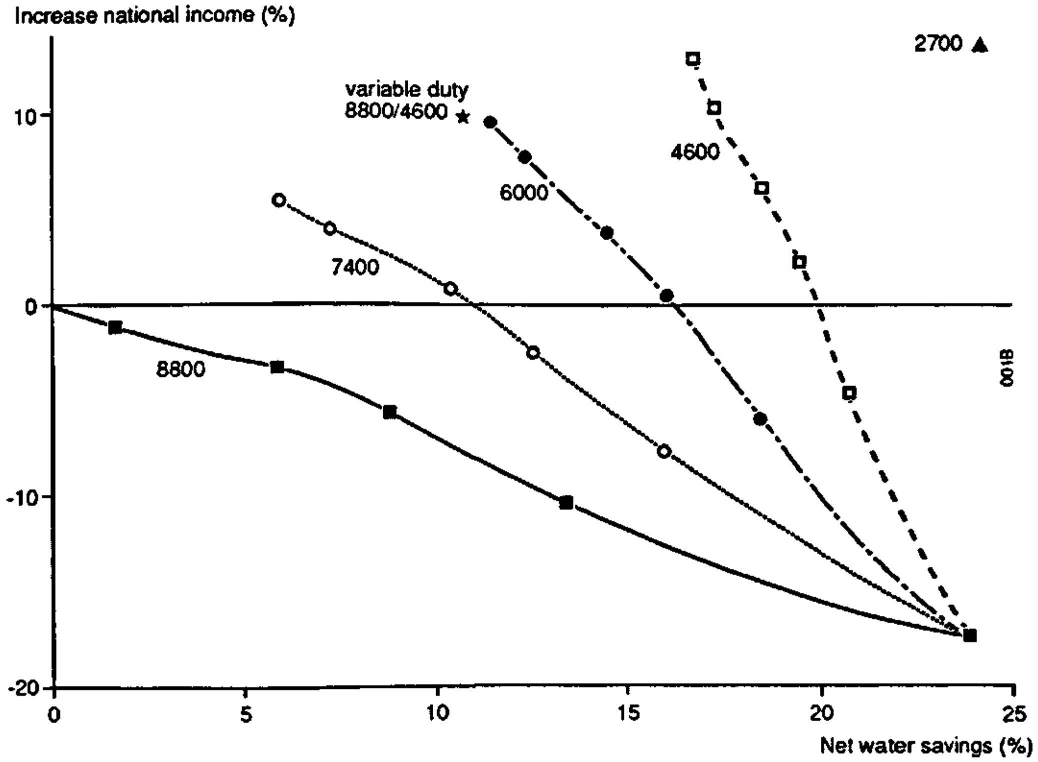

Fig 85. Long term (50 years) effect of the 23 alternative water saving rice area and allocation duty strategies on the national income in case of serious water shortage.

Lines connect points with equal allocation duty

The difference between the short and the long term effects on the farmers' and national income is mainly based on the differences in soil salinity between the short term and the long term model simulations. The sensitivity of the outcome for the soil salinity can be visualized by plotting the long term effect on the farmers' income against the short term effect (fig 86). The larger the reduction in the rice area, the larger the difference between the short term and the long term change in farmers' income appears to be (fig 86). In the previous paragraph it has been concluded that reducing the allocation duty of rice is a superior method of water saving compared to reducing the rice area with respect to the effect on the farmers' income. The results of the simulation period of 50 years for the distinguished strategies confirm this conclusion. On the long term the superior method (reducing the allocation duty) gives only slightly lower changes in farmers' income, and the inferior method (reducing the rice area) results in significant decreases in farmers' income, compared to the short term simulations (fig 86).

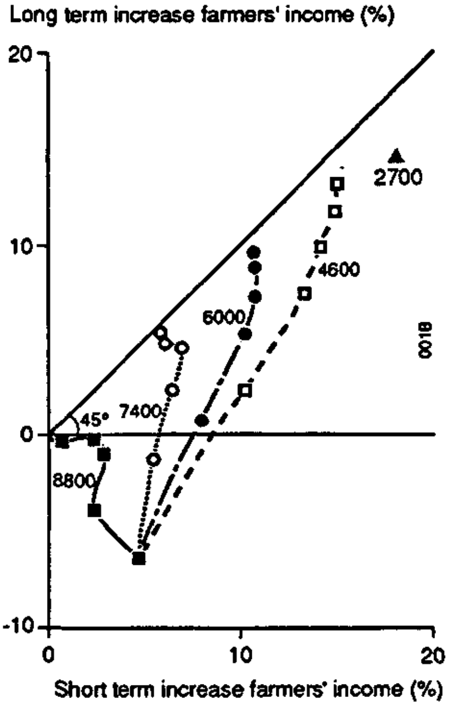

Fig 86. Relation between the overall long term effect (50 years) and short term effect on the farmers' income for 22 of the 23 distinguished rice area and allocation duty strategies.

Lines connect the strategies with equal allocation duties and different rice areas

The same procedure has been followed for the differences between the changes in the national income on the short and long term (fig 87). The main conclusion of this comparison is the same as for the effects on the farmers' income. On the long term the superior water saving method (reducing the allocation duty) gives only slightly lower increases in national income, and the inferior water saving method (reducing the rice area) results in significant decreases in national income, compared to the short term simulations (fig 87).

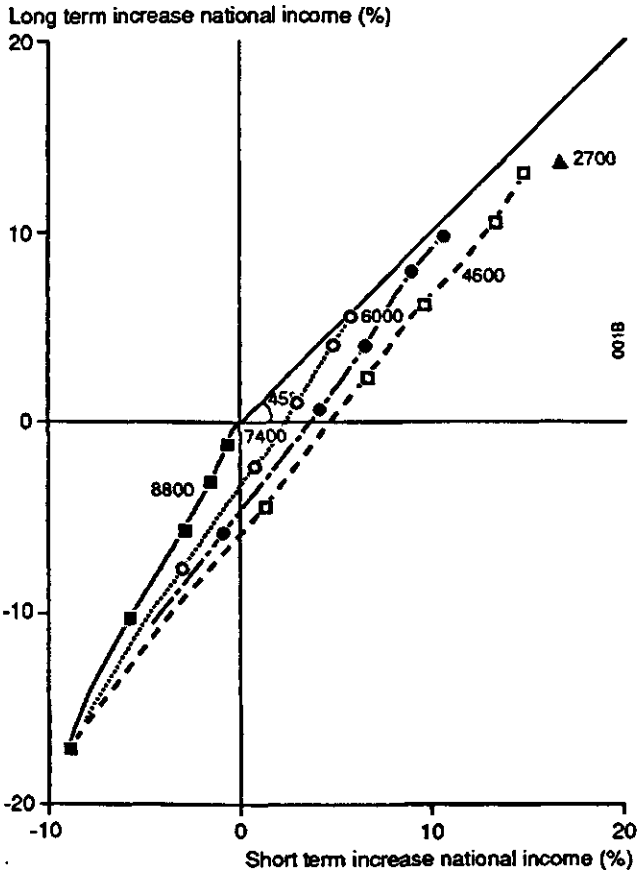

Fig 87. Relation between the overall long term effect (50 years) and short term effect on the national income for 22 of the 23 distinguished rice area and allocation duty strategies.

Lines connect the strategies with equal allocation duties and different rice areas

Comparing the long term effects on farmers' income and on the national income of the various water saving strategies, it can be concluded that the farmers' income is more sensitive to increased soil salinities than the national income. The reason for this different sensitivity is mainly caused by the large difference in the financial return of the cotton crop and the economic return of this crop (340 LE.feddan^{-1} versus 847 LE.feddan^{-1}, table 22). Due to the tolerance of cotton to high soil salinities its crop yield is only slightly affected, and consequently dominates the results of the economic analysis more than the financial analysis due to the more than double returns.

Spatial crop yield distribution

In addition to the effects on the average farmers' income, the spatial distribution of the crop yields (local farmers' income) is a second important consideration for the selection of water saving strategies. For the short term model simulation results it has been concluded before (previous paragraph) that reducing the allocation duty of rice results in a similar spatial crop yield distribution compared to reducing the rice area for water savings till about 16%. In order to reach such water savings the rice area has to be reduced to 210,000 feddans, or the allocation duty for rice till 4,600 m^3.feddan^{-1} (table 25). Although for the long term outcome of the spatial crop yield distribution the results are less good compared to the short term, the same conclusion can be drafted (table 28). Obviously, when the spatial distribution is more or less equal, the strategy with the least effect on farmers' income should be selected as the best alternative approach. These are the strategies with reduced rice allocation duties (table 28).

Table 28. Water savings, long term (after 50 years) average yearly farmers' income, and percentages of the study area with crop yield reductions for a number of rice area and water allocation duty strategies. The water savings and long term farmers' income are relative to the reference strategy (510,88).

strategy	water savings (%)	farmers' income (%)	% of study area with relative crop yield		
			> 75%	50-75%	< 50%
(510,88)	-	100.0	88	10	2
(375,88)	5.9	94.0	85	11	4
(510,74)	5.9	99.2	88	10	2
(309,88)	8.9	90.3	85	11	4
(375,74)	10.4	93.8	85	11	4
(510,60)	11.4	97.0	86	10	4
(510,VA)	10.8	98.2	86	10	4
(210,74)	16.0	82.9	78	17	5
(309,60)	16.1	88.4	81	13	6
(510,46)	16.8	94.1	76	18	6
(0,88)	23.9	71.2	73	20	7
(510,27)	24.2	86.8	63	26	11

For water savings in the order of magnitude of 24% the difference in the spatial crop yield distribution between both approaches (reducing the allocation duty of rice and replacing all rice by maize) is significant (table 28). Reducing the allocation duty of rice to a value as low as 2,700 m^3.feddan^{-1} for strategy (510,27) results on the long term in an average decline of farmers' income of 13% (10% on the short term), but in a crop yield reduction of more than 25% in 37% of the study area (34% on the short term). In about 11% of the study area (6% on the short term) the crop yield decline is even more than 50%. Taking the rice completely out of cultivation for strategy (0,88) results on the long term in a more than double decrease of the average farmers' income of about 28% (20% on the short term), but the crop yield reductions are more evenly distributed. For this strategy only 27% of the study area (21% on the short term) suffers from crop yield decreases of more than 25% on the long term.

Conclusions

During the first year of introducing water saving measures by reducing the rice allocation duty or replacing rice by maize, the winter crops are only slightly affected. If such water saving measures are maintained for a longer period of time, the winter crops are affected by the soil salinity build-up taking place during the summer period.

The change in evapotranspiration rates of summer crops after introducing the above mentioned water saving measures can be characterized by a sudden reduction in the first year (year of introducing such measures), followed by a slow deterioration of the evapotranspiration rates as a result of soil salinity build-up. For winter crops this jump is absent, and the crop reaction is limited to a gradual change.

According to the model simulations, these slow changes in crop reaction due to soil salinization are not yet completed after 50 years, but continue beyond this period. This means that the time required to reach soil salinity equilibrium conditions after changing the water management in the Eastern Nile Delta is more than 50 years.

The financial and economic analysis of the long term SIWARE model simulations results for the 23 distinguished rice area and allocation duty strategies reveals that the superiority of reducing the allocation duty of rice over reducing the rice area is more pronounced after 50 years, compared to the year of introduction of such measures.

Reducing the allocation duty of rice below 4,600 $m^3.feddan^{-1}$ should not be recommended on the long term, however, because farmers located at the tail-ends of the irrigation system suffer more than proportional from crop yield decreases.

5.3 Extension of the agricultural lands

5.3.1 Introduction

The currently prevailing high imports of foodstuffs in Egypt are likely to grow when the population expands further and the cultivated area recedes accordingly. Reclamation of desert and deltaic areas seems the only way to control an undesirable steep increase of the imports.

During the recent decades several studies have been carried out by various Egyptian Authorities, marking areas suitable for reclamation. In a study conducted by the Land Master Plan Project (Assen, 1986), a total area of 2.6 million feddan was identified as reclaimable. The major part of this area comprised desert soils. Based on economic criteria, about 1.0 million feddan was marked as priority area, of which roughly 80% was situated in Lower Egypt, adjacent to the Nile Delta and along the shore of the Mediterranean Sea. In 1987 more than 300,000 feddan were brought under cultivation. For 1992 the target has been set at an additional 600,000 feddan, while by the year 2000 the remaining area should be reclaimed.

Only 7 to 8% of the total reclaimable area will be supplied with groundwater, whereas the remaining lands will be fed with Nile water. Since the total yearly amount of Nile water available for irrigation is not likely to be raised before the

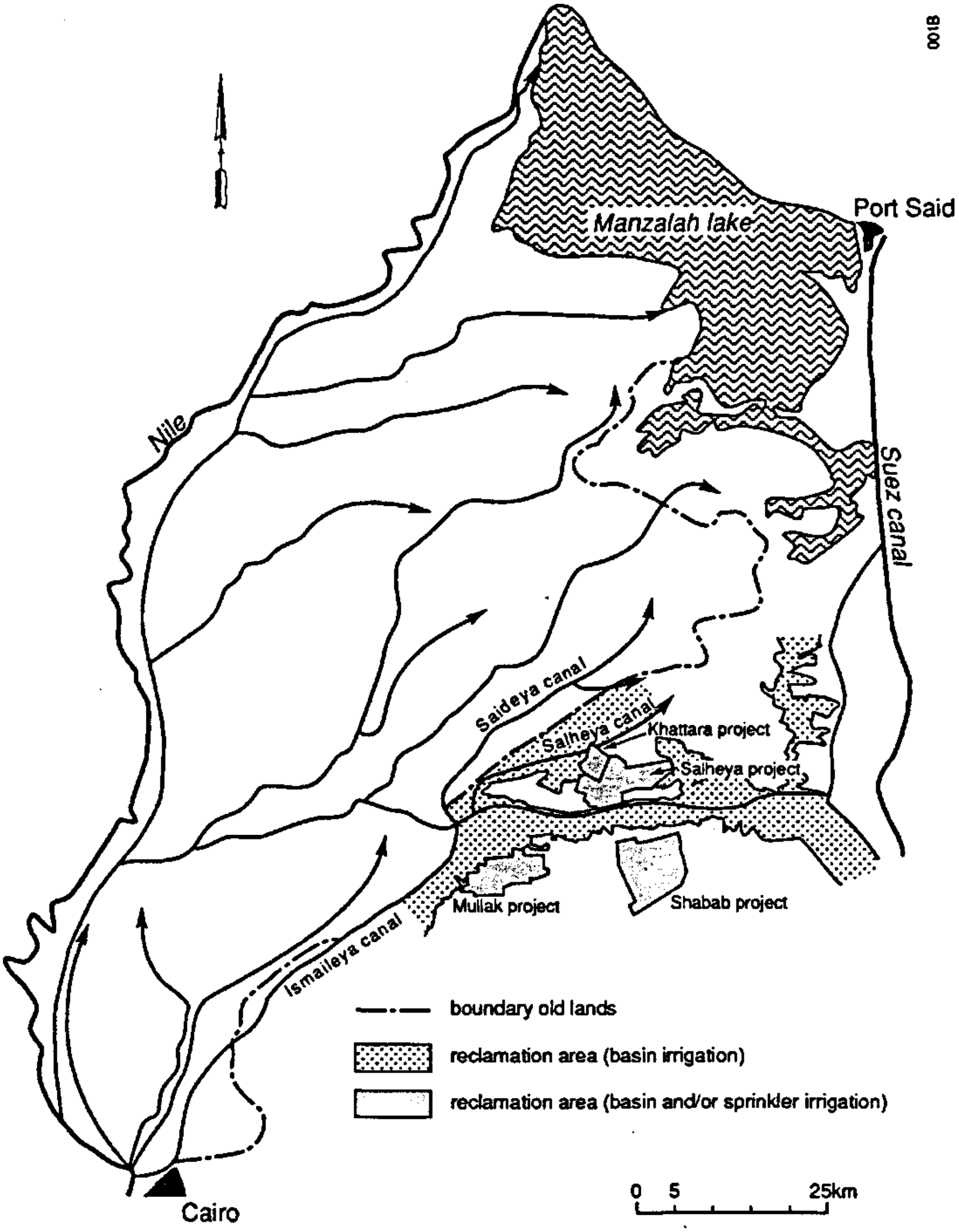

Fig 88. Eastern Nile Delta including already reclaimed areas.

year 2000, the supply to the reclaimed areas will largely go on the account of the supply to the old lands in the Nile Delta and Valley. Reuse of drainage water, withdrawal of groundwater, storage reservoirs, an improved water distribution, and other irrigation methods are expected to offset water shortages.

The reclamation of desert areas requires high investments in infrastructure. It has been envisaged that, depending on the permeability of the generally light textured soils, canals should be lined or even closed conduits should be applied. In the study carried out under the Land Master Plan it appeared that the elevation of the land relative to the waterlevel in the Nile had a considerable impact on the costs of development. The topography, i.e. from a flat to an undulating landscape, may limit the choice of the irrigation method. On flat clay soils the standard basin irrigation can be applied, but undulating sandy soils require the more advanced, and more expensive, sprinkler and/or drip irrigation. Gated pipe irrigation can be used for flat to undulating sandy soils with an intermediate permeability. Extra costs made for the irrigation system can be offset by postponing or even leaving out the installation of a drainage system.

The climatic conditions in the desert areas are generally such that the evaporative demand of the crops will be higher. Also the hydrological conditions will have a large influence on the crop water requirements, although this factor can partly be compensated by more efficient irrigation methods. For the priority areas in the desert, the annual water requirements are estimated by the Ministry of Public Works and Water Resources at a 4,000 $m^3 \cdot feddan^{-1}$ for an adapted cropping pattern. The remaining areas are estimated at a 5,500 $m^3 \cdot feddan^{-1}$ annually. The cropping pattern itself follows climate, soil texture and salinity, and irrigation water availability along with its salinity. Apart from the reclaimed clay soils, which constitute a very small segment of the total reclaimed areas, no rice is grown. Cotton occupies its usual share on the clay soils, but only a relative small area on the sandy loam and silty clay soils is assigned to this crop. Corn, fruit, and vegetables are the predominant crops on the latter and the sandy soils.

So far model simulations have only been performed for the Eastern Nile Delta with an estimated gross agricultural area of 1.83 million feddan, which already includes several reclaimed areas (fig 88). In these simulations the existing situation of 1988 has been taken as a reference. From this starting point onwards, 8 strategies with an extension of 44,000 feddans gross agricultural area each have been simulated. It has been assumed that the extensions follow a yearly sequence, i.e. only one extension will be cultivated per year, succeeded by a new area in the next year. In this way the maximum expansion amounts to 350,000 feddan gross area (+19%), or, starting from 1.43 million feddan net area, 245,000 feddan (+17%). The calculations were concluded by a long term run (50 years) for the maximum extension with 350,000 feddan.

Two specific assumptions underlie the model simulations. These assumptions are directly related to strategies dealing with the reclamation of desert areas. Although the difference in soil moisture retention between desert soils and deltaic soils did not encounter difficulties in the model input data, the productivity of the former soils is generally lower. Actual use of fertilizers in the less fertile reclaimed areas is not known, and therefore the fertility in the reclaimed areas has been assumed at an equal level as for the old lands. Depending on the soil type and the topography, several irrigation methods are applied in the reclaimed areas. In the model simulations no such distinction can be made and, consequently, basin irrigation has been used throughout the whole modelled area. In order to approach the efficiency of the other methods as close as possible, relative small plot sizes have been chosen for the reclaimed desert areas.

Apart from limitations in modelling, a major restriction was given by the fact that no extra water could be made available for agriculture in the reclaimed desert areas. Thus requirements here would have to go on the account of the old lands in the Eastern Nile Delta. Such a policy dictates a optimum use of the available irrigation water. This has been procured by an allocation of the total amount of water over the 6 main intakes, serving the Eastern Nile Delta and the desert areas, proportional to the allocation water duties of the Ministry of Public Works and Water Resources. Furthermore the possibilities for both official and unofficial reuse of drainage water have been fully utilized.

Considering the model input data, the actual cropping pattern in the reclaimed areas has been obtained by extrapolating figures available for existing reclaimed desert areas (Ismaileya District). It has also been assumed that each extension will follow a similar pattern. In the reference simulation part of the desert area is already cultivated. For the extensions these areas are filled with crops first, completely fallow desert areas are followed later.

The initial conditions for model simulations have been acquired from a 50 year run for the 1988 situation with a total connected desert area of 350,000 feddan without crops. The initial soil salinity in these extensions is therefore governed by seepage and bare soil evaporation, which generally leads to high values. This procedure provides a more realistic estimation for initial soil salinity and moisture content. Moreover, assumed equilibrium after 50 years results in horizontal lines for the all the model output reference variables related to salinity, facilitating the interpretation of the results obtained with the various extension strategies. Each simulated strategy has been labelled with an unique number as follows:

short term (1 year)

- 0 , reference run for 1988
- 1 , extension of the area with 44,000 feddan gross agricultural area
- 2 , „ „ „ „ „ 88,000 „ „ „ „
- 3 , „ „ „ „ „ 132,000 „ „ „ „
- 4 , extension of the area with 176,000 feddan gross agricultural area
- 5 , „ „ „ „ „ 220,000 „ „ „ „
- 6 , extension of the area with 264,000 feddan gross agricultural area
- 7 , „ „ „ „ „ 308,000 „ „ „ „
- 8 , „ „ „ „ „ 350,000 „ „ „ „

long term (50 years)

- 10 , extension of the area with 350,000 feddan

5.3.2 Changes in the supply and discharge system

5.3.2.1. The irrigation system

Starting from the main intakes of the irrigation canal system, the following major components are affected by a step-wise increment of the agricultural area:

- allocation of irrigation water to the 6 main intakes;
- drainage water pumped back into the irrigation canal system (official reuse);
- irrigation water uptake by the farmers;
- irrigation system losses over spillways and to the deep groundwater.

The first two components mainly determine the amount of water available for the farmers. The actual uptake by the farmers depends on both the total supply and their water requirements. The difference between supply and uptake, and what cannot be stored temporarily in the irrigation canal, should be released over the spillways to the drainage canal system.

Allocation

The allocation of the irrigation water to the intakes and the distribution of this water over the major irrigation canals fall under the prime responsibility of the Ministry of Public Works and Water Resources. The Nile water supply to the Eastern Nile Delta has been secured by 6 canal intakes, starting just north of Cairo with the Ismaileya canal, Abu Managga pumps and Sharkawiah canal. Finally Basousiah canal, Tawfiki canal and Mansouriah canal receive their water from the Damietta Nile branch (fig 4). Of these 6 canals, only Ismaileya canal serves the reclaimed desert areas, i.e. both the desert areas included in the 1988 modelled area and the extension areas. Taking into account that the total available quantity of irrigation water is fixed, the allocation to Ismaileya canal will show an increase for each extension with 44,000 feddan gross area (table 29). On the other hand, the cumulated supply to the other canals will go down with a similar amount.

In figures 90a and 90b the contents of table 29 are plotted for Ismaileya canal and the other canals combined together. Until strategy 40, i.e. an extension of the initial area with 132,000 feddan (gross), the relation between area and allocation is more or less linear. Bringing new areas under cultivation in the succeeding years results in a flattening of both curves. This effect is caused by the allocation procedure. Although the available water is distributed proportionally to the water allocation duties of the Ministry of Public Works and Water Resources in the area served by a canal intake, the procedure also includes corrections for the amount of official reuse in this area. As already established in chapter 4, reductions in the supply to the old lands (where the official reuse pump stations are located) are followed by a much higher relative reduction in the total annual reuse of drainage water (fig 90d).

In fact, changes in the official reuse cause a re-distribution of the available water over the main canal intakes. A drop in the allocation to the old lands is followed by a drop in the reuse, which on its turn requires a higher share of the Nile water diverted to the old lands (fig 90b). The effects in terms of a deviation from the

Table 29. Annual allocation of irrigation water to the 6 main intakes of the Eastern Nile Delta for the reference run and the 8 extension strategies.

#0 = reference run for 1988
#1 = extension with 44,000 f
#2 = „ „ 88,000 f
#3 = „ „ 132,000 f
#4 = extension with176,000 f

#5 = extension with 220,000 f
#6 = „ „ 264,000 f
#7 = „ „ 308,000 f
#8 = extension with 350,000 f
(extensions in feddan gross area)

	irrigation water allocation (10^6 m^3)					
strat.	Ismaileya canal	Abu Managga canal	Sharkawia canal	Basousiah canal	Tawfiki canal	Mansouriah canal
#0	2,926	336	475	297	3,342	2,810
#1	3,068	329	466	291	3,280	2,751
#2	3,209	322	456	285	3,219	2,693
#3	3,343	316	447	280	3,164	2,635
#4	3,471	309	438	274	3,110	2,580
#5	3,596	304	430	269	3,058	2,528
#6	3,719	298	422	264	3,005	2,477
#7	3,833	292	414	259	2,955	2,429
#8	3,944	287	406	254	2,908	2,383

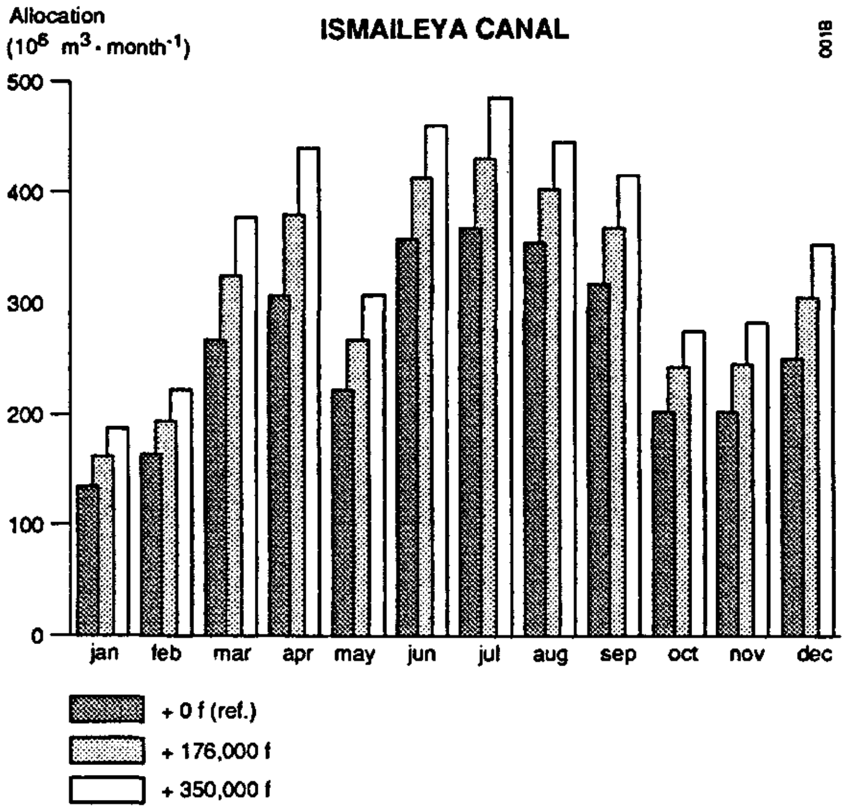

Fig 89. Monthly distribution of the irrigation water allocation to Ismaileya canal for an extension of the Eastern Nile Delta with 176,000 feddan and 350,000 feddan.

linear allocation are quite small, however, since the official reuse amounts to less than 10% of the total Nile water supply, and the changes are limited to only 30% of the total reuse quantity (figs 90a and 90b). The accumulated allocation to the other 5 canals, not including Ismaileya canal, follows the curve for the official reuse, be it in a less pronounced way because Ismaileya canal also serves a substantial part of the old lands (fig 90b).

The interest of the Ministry of Public Works and Water Resources is aimed at the time distribution of the allocation to the different intakes. In figure 89 a monthly distribution is given for Ismaileya canal showing results of the reference run, an extension with 176,000 feddan, and the maximum extension of 350,000 feddan. The bar chart reveals that changes in the official reuse affect the monthly allocation (non-linearity!) to a minor extent as indicated before.

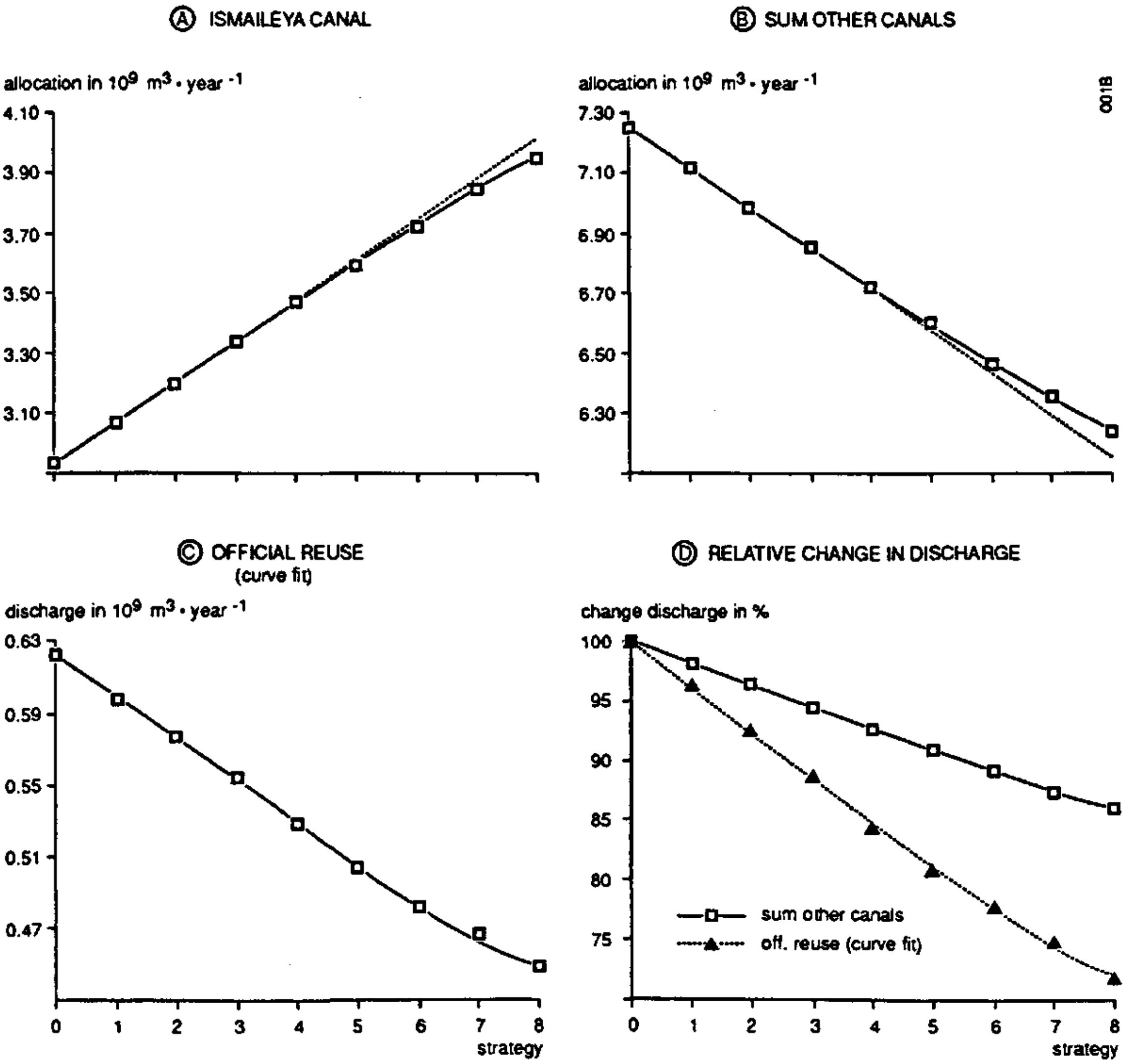

Fig 90. Annual irrigation water allocation to Ismaileya canal (a), cumulated allocation to the 5 other canals (b), official reuse discharges (c), and the relative changes in the discharges (d) for the 8 extension strategies.

Official reuse

Figure 90c presents the total amount of drainage water which can be reused officially for the 8 extension strategies. Although the fall from 622 million m³ (reference) to 448 million m³ (maximum extension) will be hardly noticeable on the total Nile water supply of 10,310 million m³, it still represents 28% of the total official reuse (figs 90c and 90d). Unfortunately, reductions in the allocation to the old lands are followed by approximately two times higher drops in the official reuse, when expressed in percentages (fig 90d). Constructing new pump stations at locations where sufficient drainage water with a reasonable quality is still available could offer some compensation.

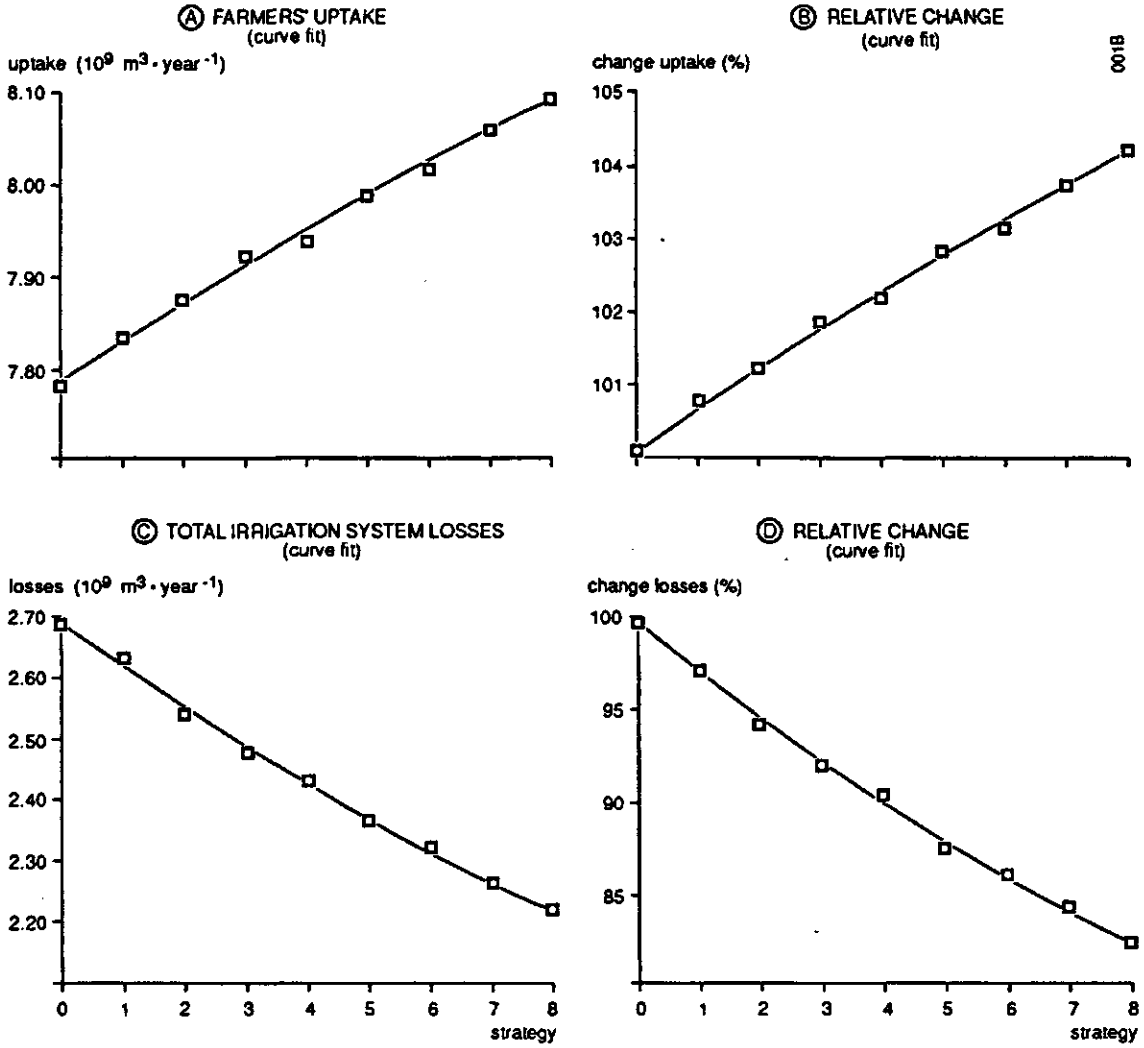

Fig 91. Annual farmers' irrigation water uptake (a), total irrigation system losses (c), and the relative changes of both (b and d) for the 8 extension strategies.

Farmers' uptake

The distribution of an equal amount of irrigation water over a larger area will undoubtedly result in a lower supply to the distributary canals serving the agricultural calculation units located in the old lands. Farmers lifting their irrigation water from these canals will feel the effects. The uptake as an aggregated total, however, increases for the whole modelled area with each increment (fig 91a). Since the total amount of irrigation water remains the same, and the water balance must fit, the increase in uptake should equal the reduction in total irrigation system losses minus the reduction in official reuse. Consequently, the irrigation system efficiency improves, resulting in a 4% higher withdrawal from the canals for the maximum extension with 350,000 feddan (fig 91b). The individual farmers, however, do not profit since the net cropped area has been increased with more than 17%, leaving them with less water than before.

Irrigation system losses

Surplus water, i.e. beyond the farmers' water requirements or uptake capacity, should be released from the irrigation system to prevent local inundation. Part of the water, however, may be stored temporarily in the canals. When waterlevels rise excessively, spillways will start functioning.

The total system losses are made up by the spillway losses in the calculation units internally, the spillway losses at the tail-ends of the irrigation canals, and the conveyance losses to the deep groundwater. Since a larger area has to be irrigated with the same amount of Nile water, losses should decrease. Generally, tightly operated systems tend to be more efficient. Figures 91c and 91d show that the accumulated losses fall considerably with 481 million m^3 or 18% for the maximum extension.

5.3.2.2. The drainage system

On the supply side of the drainage canal system the losses originating from the spillways of the irrigation canals reveal a substantial decrease (fig 91c). Figures 92a and 92b show that also the crop drainage goes down as a result of the higher on-farm efficiency obtained with a lower crop water supply per unit area. Both, the official and the unofficial reuse will depend on the available quantities in the drainage canals.

Figures 92c and 92d make clear that the fall in total reuse is not as dramatic as for the official reuse only. Where the official reuse went down with 174 million m^3, the unofficial reuse decreases with not more than 30 million m^3, and thus the total reuse drops from 1,755 to 1,551 million m^3 (-11.6%) for the maximum extension with 350,000 feddan. Clearly, the diffuse distribution of the unofficial reuse uptake from the drainage canals is affected to a lesser extent by the lower discharges in these canals.

As a result of the much lower discharges to the drainage canal system, and the moderate decline in total reuse, the discharges simulated at the outfalls of the

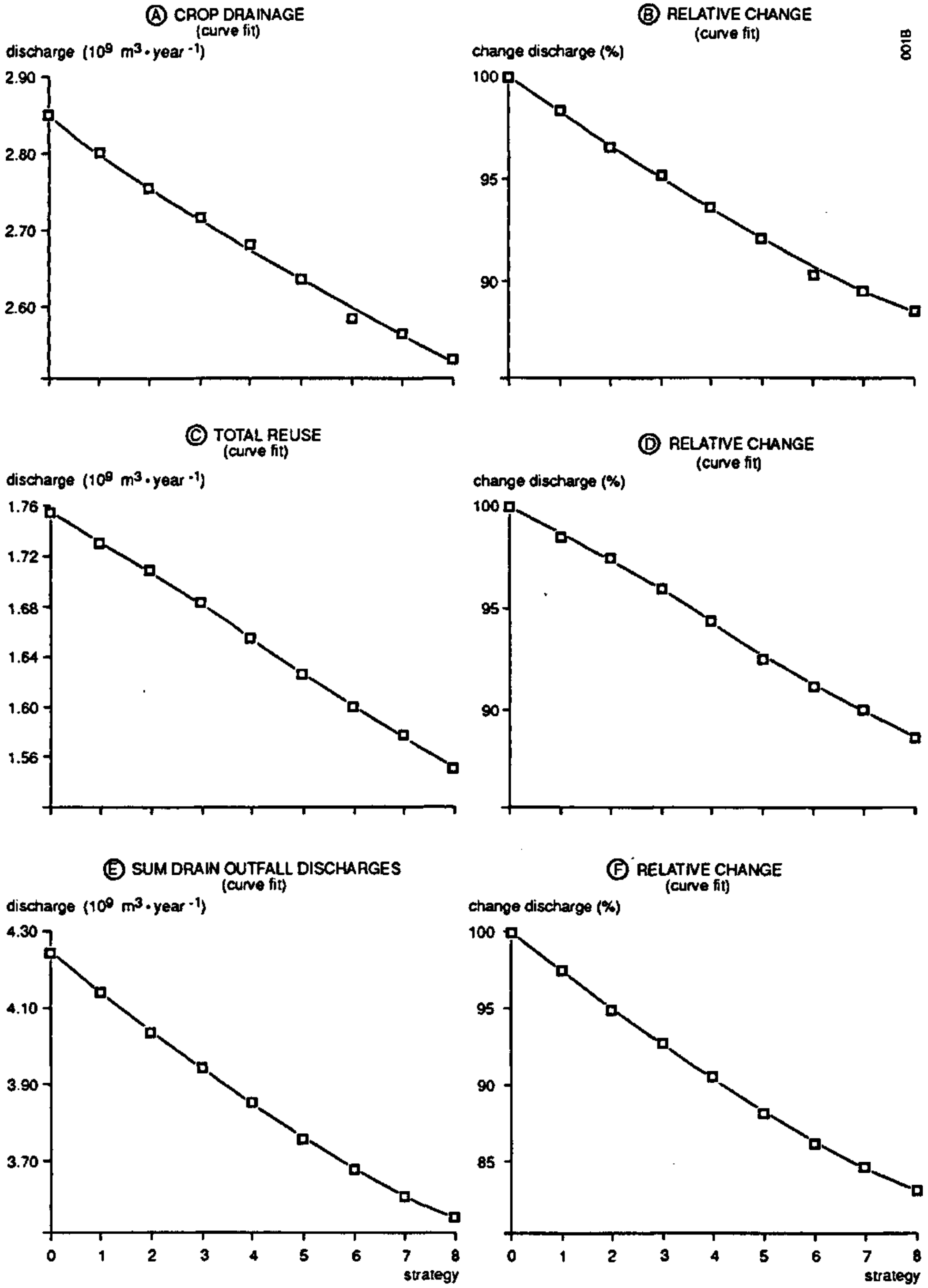

Fig 92. Annual crop drainage (a), total reuse (c), and cumulated discharges at the drain outfalls (e), together with their relative changes (b, d, and f) for the 8 extension strategies.

drainage canals near Lake Manzala show a distinct fall from 4,265 to 3,537 million m^3 (-12%) for the maximum extension (figs 92e and 92f).

5.3.3 Crop reaction

5.3.3.1 Introduction

From the model output, the calculated evapotranspiration can be used as a standard of comparison for the crop reaction of the different strategies. The crop production is, within certain limits, linearly correlated to the evapotranspiration as has been explained in chapter 4. Therefore differences in evapotranspiration can give an impression in what way a crop will respond in terms of actual yield when compared to the reference simulation. Also comparisons between the different strategies mutually can be carried out, provided that these strategies are based on the same conceptual approach.

The evapotranspiration depends on quite a number of variables. Since crop type, cropped areas, climatic zone, etc., come along with the model input data, and input parameters as sowing and harvesting date, irrigation priority and frequency, crop height, rooting depth, soil cover, and maximum ponding period are calibrated, only the actual crop water supply and the (top) soil salinity can be considered as process variables for the evapotranspiration in the model. The crop water supply is composed of the following 3 components:

- uptake from the irrigation canals;
- unofficial reuse;
- groundwater abstraction.

The salinity of the top soil strongly depends on the amount of water applied to the crop, along with its salinity, in relation to the actual evapotranspiration (leaching efficiency). For the short term analysis (1 year) both the crop water supply and the top soil salinity may affect the transpiration rate. In the long term analysis (50 years), however, the salinization or desalinization of the top soil will govern the transpiration rate to a large extent.

5.3.3.2 Short term effects

An extension of the total cropped area will reduce the local irrigation water uptake by farmers when supplied with an amount of Nile water which does not follow the expansion. Moreover, quantities of official and unofficial reuse will decrease as shown before. As a consequence, the local crop water supply will be lower, although its salinity may improve slightly due to a lower contribution of the more saline reuse. When considering the evapotranspiration, it seems unrealistic to assume that a reduced salt content of the crop water supply can offset shortages resulting from expanding the cultivated area.

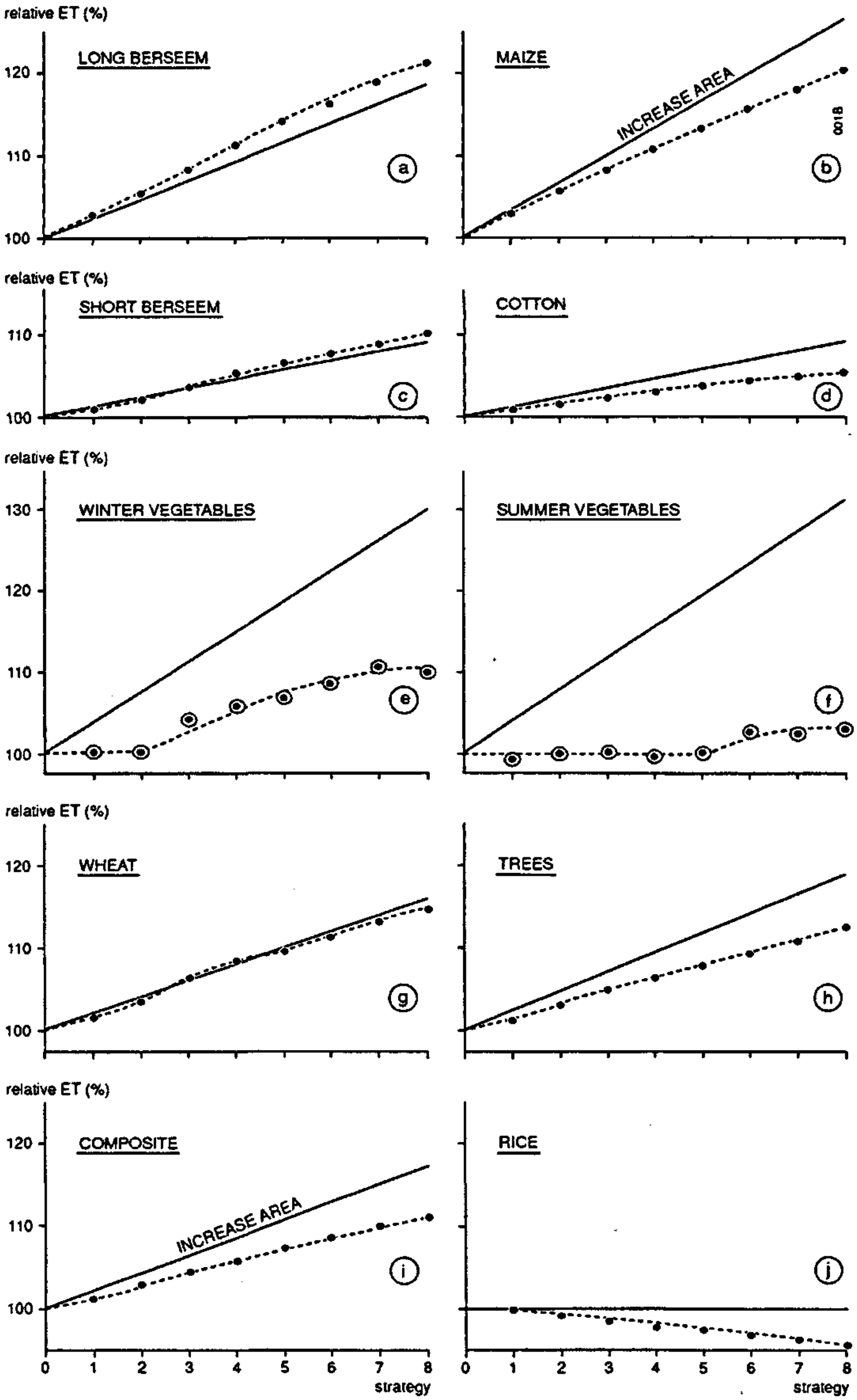

Fig 93. Relative evapotranspiration of the various crops in the total area for the 8 extension strategies (reference = 100).

Agricultural production in the old lands will show a decline. In the reclaimed areas, production should more than compensate for these losses in order to remain economically attractive. In table 30 the percentages occupied by each crop per unit reclaimed area are given. They have been derived from the tables of the Ministry of Public Works for the Ismaileya Irrigation District, which partly comprises already reclaimed desert areas. Furthermore it has been assumed that all the extensions will follow the same crop distribution.

Table 31 presents the simulated crop evapotranspiration in the total area. The figures are corrected for each increment in area of the distinguished crop, and the reference evapotranspiration (run #0) has been set at 100. All the extension runs show an increase in evapotranspiration, with the exception of rice which is not grown in the reclaimed areas. This means that, despite a reduction in evapotranspiration per unit area in the old lands, the evapotranspiration in the reclaimed areas overcompensates the losses there. This also indicates that, under the given assumptions and for the limited amount of Nile water, an expansion of the arable land may indeed raise the country's crop production.

The contents of table 31 are graphically presented in figure 93, together with the relative increase in cultivated area for each crop. The evapotranspiration of winter crops like long and short berseem and wheat follows the area extension rather closely (figs 93a, 93c, and 93g), implying an adequate crop water supply during their growing season. Figure 93a shows that values for long berseem even surpass the relative areal expansion, probably due to climatical reasons (higher potential evapotranspiration). The response of the summer crops is less pronounced, although all crops except rice score better than the reference (figs 93b, 93d, 93f, and 93h). The already tight Nile water supply in summer seems to be unable to provide the total extended area adequately. Among these crops, maize shows the best performance with a 21% higher total evapotranspiration placed against a 26% higher cropped area for an extension with 350,000 feddan (fig 93b).

None of the curves drawn in figure 93 appears to be very smooth. This is demonstrated most prominently by the crops which do not perform very well, namely winter and summer vegetables (figs 93e and 93f). Both crops are known to be sensitive for salt. Salinity effects are exposed in the step-wise ascent of the evapotranspiration for both crops (figs 93e and 93f, encircled points). The initial salinity of the top soil in the envisaged reclaimable areas will be high, due to seepage and bare soil evaporation. Only excessive leaching and the occurrence of other 'leaching crops' in the rotation can incite the vegetable plants to pickup growth. Each time when a new extension is put into use, the aggregated evapotranspiration for the vegetables will be the superimposed result of an increasing production in previously attached areas due to leaching, and a stagnating production in the new area, depending on the initial soil salinities. The same phenomenon holds for the other crops, be it in a less pronounced way. The old lands in the Eastern Nile Delta, also referred to as the study area, should not display these effects. In fact, figure 94 shows declining and generally smooth curves for all crops in the study area. Reductions in evapotranspiration are moderate considering the huge cut in the water supply, and do not exceed the 10% for the maximum extension of 350,000 feddan (table 32, run #8). In the simulations the evapotranspiration

Table 30. Relative areas occupied by the different crops in the extension areas.

crop	relative area (%)
winter crops	
- long berseem	29
- wheat	30
- winter vegetables	16
- short berseem	10
summer crops	
- rice	-
- cotton	10
- maize	53
- summer vegetables	22
deciduous trees	15

Table 31. Evapotranspiration of the summer crops, winter crops, perennial trees, and the aggregated value for all crops in the total area (Eastern Nile Delta including the relevant reclaimed areas), corrected for the actual cropped area and with the reference values set at 100.

#0 = reference run for 1988
#1 = extension with 44,000 f
#2 = „ „ 88,000 f
#3 = „ „ 132,000 f
#4 = extension with 176,000 f

#5 = extension with 220,000 f
#6 = „ „ 264,000 f
#7 = „ „ 308,000 f
#8 = extension with 350,000 f
(extensions in feddan gross area)

crop	evapotranspiration (%)								
	#0	#1	#2	#3	#4	#5	#6	#7	#8
winter crops									
- long berseem	100	103	106	109	111	114	116	119	121
- wheat	100	102	104	106	108	110	112	113	115
- winter vegetables	100	100	100	104	106	106	109	111	111
- short berseem	100	101	102	104	105	107	107	109	110
summer crops									
- rice	100	100	100	99	98	97	97	96	95
- cotton	100	101	102	102	103	104	104	105	105
- maize	100	103	106	109	111	114	116	119	121
- summer vegetables	100	99	100	100	99	100	103	102	103
deciduous trees	100	102	104	105	107	108	109	111	113
aggregated value	100	101	103	105	106	107	109	110	111

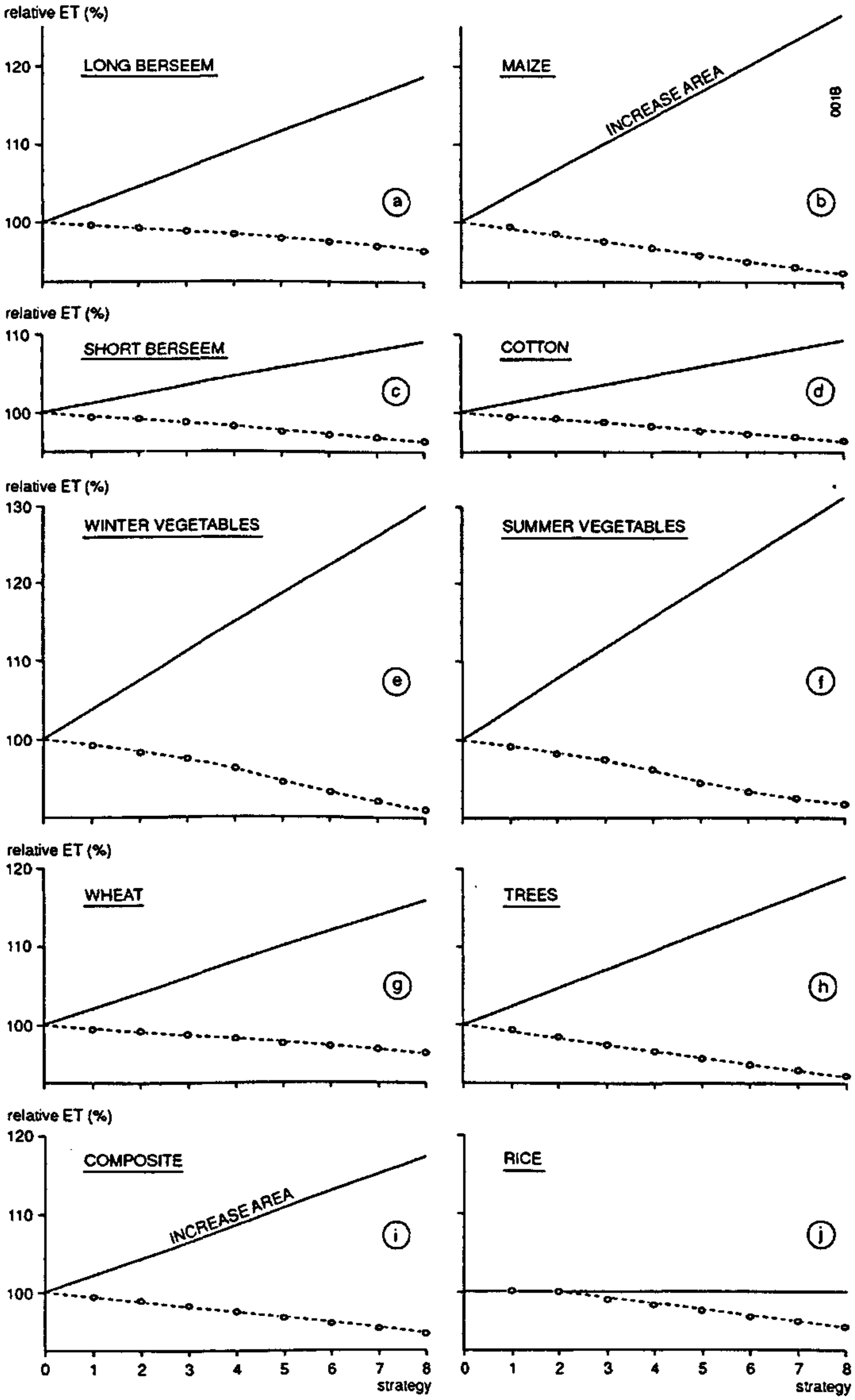

Fig 94. Relative evapotranspiration of the various crops in the study area for the 8 extension strategies (reference = 100).

Table 32. Evapotranspiration of the summer crops, winter crops, perennial trees, and the aggregated value for all crops in the study area (old lands in the Eastern Nile Delta), corrected for the actual cropped area and with the reference values set at 100.

#0 = reference run for 1988
#1 = extension with 44,000 f
#2 = „ „ 88,000 f
#3 = „ „ 132,000 f
#4 = extension with 176,000 f

#5 = extension with 220,000 f
#6 = „ „ 264,000 f
#7 = „ „ 308,000 f
#8 = extension with 350,000 f
(extensions in feddan gross area)

crop	evapotranspiration (%)								
	#0	#1	#2	#3	#4	#5	#6	#7	#8
winter crops									
- long berseem	100	100	99	99	98	98	97	97	96
- wheat	100	100	99	99	98	97	97	96	96
- winter vegetables	100	99	98	97	96	94	94	92	91
- short berseem	100	100	99	99	98	98	97	97	96
summer crops									
- rice	100	100	100	99	98	98	97	96	96
- cotton	100	100	99	99	98	97	97	96	96
- maize	100	99	98	98	97	96	95	94	94
- summer vegetables	100	99	98	97	96	95	93	93	92
deciduous trees	100	99	99	98	97	96	95	94	94
aggregated value	100	99	99	98	97	97	96	95	95

is controlled by 2 process variables as indicated before. By comparing the output values for the crop water supply and the soil salinity with tables 11 and 12 of chapter 4, an impression can be obtained which variable impaired the evapotranspiration of a specific crop in the old lands.

Table 33 gives the average values for the ratio of crop water supply over agricultural demand, the crop water salinity, and the soil salinity for the reference and the maximum extension simulations. From the comparison with tables 11 and 12, it appears that winter and summer vegetables are affected by stress conditions for crop water supply and especially soil salinity, whereas other crops mainly suffer from water shortages. A high threshold value for the supply (winter vegetables) and very low threshold values for the salinity (both winter and summer vegetables), together with the rather steep slopes for the reduction in evapotranspiration (tables 11 and 12) can be hold accountable. This fully confirms the low, calculated evapotranspiration given in table 32 (run #8) for the winter and summer vegetables.

Table 33. Ratio of average crop water supply over agricultural demand, average crop water salinity, and average soil salinity for the summer crops, winter crops, and the perennial trees in the study area (old lands).

#0 = reference run for 1988 #8 = extension with 350,000 f

(supply over demand expressed as a percentage, soil salinity in mmho·cm^{-1} and irrigation water salinity in g·m^{3})

crop	#0			#8		
	supp /dem	soil sal.	irr. sal.	supp /dem	soil sal.	irr. sal.
winter crops						
- long berseem	92	2.51	489	85	2.82	536
- wheat	86	3.25	511	78	3.60	567
- winter vegetables	87	2.54	501	80	2.81	546
- short berseem	85	2.64	550	78	2.99	607
summer crops						
- rice	97	3.00	441	88	3.35	488
- cotton	95	3.08	452	88	3.45	503
- maize	96	2.68	421	89	3.00	469
- summer vegetables	95	2.65	439	88	2.94	490
deciduous trees	96	6.42	451	88	6.94	493

5.3.3.3 Long term effects

Long term effects are related to a salinization or desalinization of the top soil. It has been assumed in the simulations that the crop water supply remains unchanged during the considered period. The crop water salinity might be slightly influenced through the official and unofficial reuse, which are on their turn affected by the salinity of the crop drainage.

A salt accumulation in the top soil is likely to occur in the old lands. A lower crop water supply, caused by a lower share of the available Nile water, will almost certainly reduce the quantities applied for leaching. Also the salinity of the crop water supply is negatively affected by the areal expansion as shown in table 33. The lower salt contribution to the crop water supply by lower reuse quantities is overtaken by the latter's much higher salinity. As a consequence, a salinization of the soil profile becomes unavoidable, which is illustrated for the old lands (study area) in figure 95. The initial average soil salinity equals 3.11 mmho·cm^{-1}, but after extending the cultivated area for 8 years with 44,000 feddan yearly, the average soil salinity climbs till 3.46 mmho·cm^{-1}. Finally, the average soil salinity in the old lands reaches its equilibrium value at 3.57 mmho·cm^{-1} after approximately 20 years with a total extension of 350,000 feddan gross area.

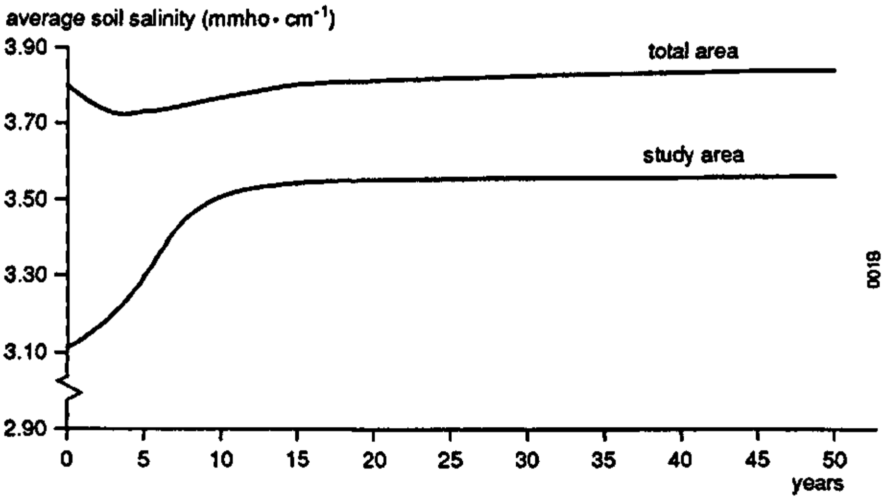

Fig 95. Development of the average soil salinity in the total area and the study area for the 8 extension strategies with time.

In the reclaimed areas, however, another process is set in motion. Bare soils generally have a high salinity, requiring leaching and salt tolerant crops with a leaching potential to remove salts until an acceptable level for the more salt sensitive crops has been reached. This process can be illustrated by figure 96. The curves of the average salinity over the soil profile for the calculation units 89 through 91 show a steep decline from around 5.8 mmho·cm^{-1} to more acceptable levels around 3.1 mmho·cm^{-1} (table 11, chapter 4). The soil salinity for the last 2 units drawn in figures 96d and 96e develops less well. Both units suffer from water shortages inherent to their location at the tail-end of the irrigation canal system. Unit 92 still seems to be able to offer some agricultural production with an aggregated relative evapotranspiration of 74% (average value for the complete cropping pattern and relative to the optimum evapotranspiration), and an average soil salinity of 4.29 mmho·cm^{-1} four years after reclamation started (run #8). However, a rise of the soil salinity till 4.49 mmho·cm^{-1} at the 50 year encircled point will cause further reductions of the evapotranspiration (fig 96d). Unit 93 on the other hand shows an aggregated relative evapotranspiration of only 52%, and an average soil salinity of 5.35 mmho·cm^{-1} one year after reclamation (run #8). Due to severe water shortages hardly any leaching will occur, and subsequently soil salinity rises till 6.19 mmho·cm^{-1} at the 50 year encircled point (fig 96e). The transpiration of all crops, except cotton, trees, and to a lesser extent wheat, will be seriously affected (table 11). Figure 95 shows the effects of a desalinization in the reclaimed areas on the total area. After the 4th extension (run #4, 4th year), the average soil salinity in the total area increases again due to the salinization in the old lands.

Table 34 presents the long term values for the evapotranspiration, adjusted for the increments in area and with the long term reference evapotranspiration set at 100. The absolute values of the long term reference evapotranspiration do not differ from those acquired with the short term reference run, enabling a direct comparison

Table 34. Long term (50 years) evapotranspiration of the summer crops, winter crops, perennial trees, and the aggregated value for all crops in the total area (Eastern Nile Delta including the relevant reclaimed areas), corrected for the actual cropped area and with the reference values set at 100.

#0 = reference run for 1988 #10 = extension with 350,000 f (50 y.)

crop	evapotranspiration total area (%)		evapotranspiration study area (%)	
	#0	#10	#0	#10
winter crops				
- long berseem	100	122	100	96
- wheat	100	115	100	95
- winter vegetables	100	113	100	90
- short berseem	100	111	100	96
summer crops				
- rice	100	95	100	95
- cotton	100	105	100	96
- maize	100	121	100	93
- summer vegetables	100	106	100	91
deciduous trees	100	111	100	93
aggregated value	100	111	100	94

between long (table 34, run #10) and short term values (tables 31 and 32, run #8).

In the old lands a further salinization of the soil in the long run causes additional reductions in evapotranspiration. All crops, except long and short berseem and cotton, are affected when comparing the right-most columns of tables 32 and 34 (extension with 350,000 feddan).

For the total area the desalinization effects of the reclaimed desert areas offsets the salinization of the soil in the old lands. Especially the winter crops are able to increase their evapotranspiration (table 31 right-most column versus table 34 second column). Apart from the summer vegetables, the summer crops maintain their short term evapotranspiration values. Notably, both summer and winter vegetables show the largest increase in evapotranspiration after 50 years. The leaching of the reclaimed desert areas also provides productive conditions for these crops, although it will take a considerable longer period than for other crops. This indicates that for growing vegetables in such areas more sophisticated irrigation methods should be employed. Sprinkler, and especially drip irrigation, can offer a higher leaching efficiency, and are actually used on a large scale already.

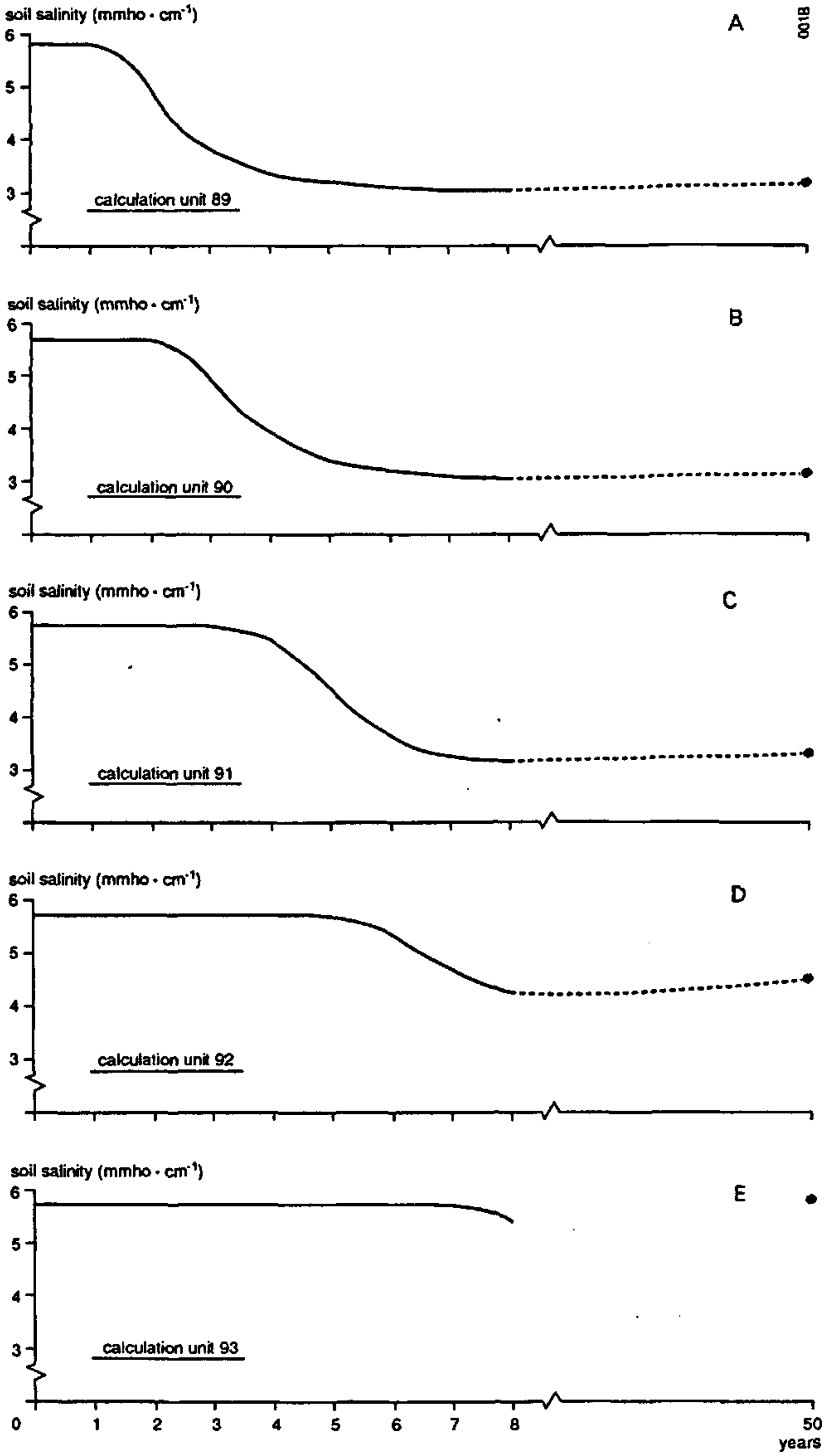

Fig 96. Average soil salinity in 5 'reclaimed' calculation units for the 8 extension strategies, including the long term (50 years) average soil salinity.

Remarkably is also that the perennial trees are finally affected by the increasing soil salinity. Long term simulations show that the average soil salinity under the trees climbs till 7.36 mmho·cm^{-1} compared to 6.94 mmho·cm^{-1} for strategy #8, i.e. one year after the maximum area of 350,000 feddan has been taken into production (table 33). Table 11 shows that 7.36 mmho·cm^{-1} lies above the empirically obtained threshold value of 7.2 mmho·cm^{-1} for trees, thus indicating salinity stress.

An interesting phenomenon is that, despite an increasing average soil salinity in the total area between the 8th and the 50th year (fig 95), the total crop production can be maintained or even slightly elevated. The spatial distribution of the soil salinity, with an intensive desalinization in the reclaimed areas and a relative small increase of the soil salinity in the old lands, offers the only explanation. It also turns out that the winter crops profit to a higher extent, probably due to their better crop water supply which can keep the soil salinity at lower values on both the short and the long term.

5.4 Conclusions

Eight consecutive extension strategies have been simulated with the SIWARE model package. Each extension comprised a gross area of 44,000 feddan located in the desert eastwards of the Eastern Nile Delta. The maximum reclaimed area therefore amounted to 350,000 feddan, which is about 19% of the existing cultivated area of roughly 1.8 million feddan used in the model simulations for 1988.

A reference run has been performed with the SIWARE package for the comparison and justification of the acquired simulation results. Also the long term effects of the maximum extension have been analyzed.

The Ministry of Public Works and Water Resources made clear that no extra irrigation water could be diverted to the reclaimed areas. Consequently, the water requirements in these areas had to be satisfied on the account of the allocation to the old lands in the Eastern Nile Delta.

In order to ensure an optimum allocation of the available Nile water to the various canals, the Ministry of Public Works and Water Resources allocation water duty has been used as a distribution parameter in the model simulations. In addition, the available quantities in the drainage canals at the pump station sites, multiplied with their calibrated percentage, have been fully utilized for official reuse.

A number of assumptions related to the reclamation of desert areas have been followed in the model simulations:

- The cropping pattern in the desert areas has been extrapolated from data provided by the Ministry of Public Works and Water Resources for the Ismaileya Irrigation District, an existing reclaimed desert area;
- In Egypt, part of the desert areas is irrigated by sprinkler and/or drip irrigation. In order to approach the irrigation efficiency of these irrigation methods as close as possible, relative small plot sizes have been chosen in the reclaimed areas;

- The productivity of desert soils in Egypt is generally lower than for deltaic clay soils. This is caused by two main soil characteristics, namely the soil moisture retention and the soil fertility level. In the model simulations differences in the soil fertility have not been accounted for, and consequently a similar fertility level has been assumed for the desert soils.

The conclusions will comprise the following simulation results:

- major water balance components in the irrigation and drainage system;
- crop reaction in terms of evapotranspiration.

Irrigation and drainage system

The Nile water allocation to the old deltaic area between the Damietta Nile branch and the Suez canal (fig 3) decreases as a result of cultivating new areas. Until an extension with 132,000 feddan the reduction in allocation follows the reduction in area more or less linearly for the canals serving the old lands. A further expansion causes a relative higher share of the total supply to be diverted to the old lands, due to a disproportional fall in the official reuse in this area.

Without extension (reference run) the calculated maximum official reuse amounts to 622 million m^3 annually. With an extension of 132,000 feddan (+7%) the reuse comes down to 553 million m^3 (-11%), and with the maximum extension of 350,000 feddan (+19%) the reuse equals 448 million m^3 (-28%). Therefore this sharp fall in official reuse cannot be seen separately from the heavy cut in the Nile water quota, both seriously endangering the crop water supply and leaching requirements in the old lands. Fortunately, the absolute quantities of official reuse are not that high when compared to an annual Nile water supply of 10,310 million m^3.

The annual farmers' uptake from the irrigation canals increases with 4% from 7,775 million m^3 for the reference run to 8,092 million m^3 for the strategy with an extension of 350,000 feddan. The net agricultural area, however, increased with more than 17%, clearly showing the adverse effects for the individual farmers in the old lands.

The irrigation system losses fall from 2,697 million m^3 for the reference run until 2,216 million m^3 (-18%) for the strategy with an extension of 350,000 feddan as a result of a more efficiently operated irrigation system.

The lower crop drainage and the lower losses from the irrigation system cause lower discharges in the drainage system. Having less water available in the canals immediately affects the quantities withdrawn for reuse.

The official reuse is pressed most severely, and goes down with 28% for the maximum extension with 350,000 feddan as mentioned before.

The unofficial reuse on the other hand drops with only 3%, from 1,133 million m^3 for the reference till 1,103 million m^3 for the maximum extension, which also underlines its importance to keep the crop water supply on an acceptable level.

As a consequence of the lower irrigation water losses and crop drainage, the simulated total discharge at the drainage canal outfalls goes down considerably, from

4,265 million m^3 for the reference till 3,537 million m^3 (-17%) for the maximum extension with 350,000 feddan.

Crop reaction

Differences in the evapotranspiration as simulated for the various crops are considered to be indicative for the changes in crop production. All crops cultivated in the old lands also occur in the reclaimed desert areas, except rice.

The total evapotranspiration of almost all individual crops shows an increase for each extension taken into production. The best performance, expressed in terms of a relative increase in seasonal evapotranspiration related to the relative areal expansion, is obtained with the winter crops, notably long and short berseem and wheat. The relative increase in evapotranspiration of these three crops follows the relative areal expansion quite closely, or even overtakes the latter in the case of long berseem. Most probably the higher evaporative demand in the desert areas causes higher evapotranspiration rates, apparently hardly being limited by water or salinity stress.

Summer crops perform less well. Their relative increase in evapotranspiration lags substantially behind the relative increase in net cultivated area. Among them, maize shows the best performance with a 21% higher total evapotranspiration placed against a 26% higher cropped area for an extension with 350,000 feddan. The production of rice, with its unchanged area, will go down as a result of a 5% drop in the evapotranspiration.

In most cases irrigation water shortages occurring during summertime can be hold accountable for the low response in evapotranspiration of the summer crops. Holding on a fixed allotment of irrigation water for the Eastern Nile Delta, the potential of supplementing this quantity with drainage water during the summer season should be investigated (higher official reuse).

Problems are faced with the vegetables in the reclaimed desert areas. High initial soil salinities around the 5.7 mmho·cm^{-1} impede plant growth, and a major part of the accumulated salts should be flushed first from the top soil.

Despite a substantial fall of the average soil salinity till around 3 mmho·cm^{-1} in most reclaimed areas, the evapotranspiration of summer vegetables in the total area reaches only 3% above the reference value 8 years after the first reclamation started (or the year in which the maximum extension was realized). In fact, this situation is even more critical since the area cultivated with summer crops has been enlarged with not less than 32%. Clearly, the reclaimed areas are barely able to offset production losses in the old lands caused by water shortages and a salinization of the top soil. Notwithstanding an intensive leaching of the soil in the reclaimed areas, salinity problems will continue to afflict production of these salt sensitive crops.

At first sight it seems recommendable to exclude the vegetables from the cropping pattern in the reclaimed desert areas. However, the application of more sophisticated methods as for instance sprinkler or drip irrigation may lift the vegetable production considerably. Such equipment offers a much higher leaching efficiency, and may even be a prerequisite for growing vegetables. In fact, sprinkler irrigation is already used in these areas on a large scale.

Generally, crop production in the old lands will decline as a direct result of the fixed Nile water allotment for the total area, leading to water and/or salinity stress conditions for the crops. Production in the reclaimed areas should compensate for these losses, and should yield a reasonable extra quantity in relation to their actual area for being economically attractive.

It appears from the model simulations that an expansion of the arable land may indeed raise the country's crop production. The simulations show an 11% higher aggregated (all crops) evapotranspiration after the last extension has been taken into production, i.e. after 8 years. Confronting the 11% with the 17% expansion of the total net cropped area, the conclusion can be drawn that the reclaimed areas perform quite well. The more so because the aggregated evapotranspiration in the old land goes down with more than 5%, which can be largely compensated by an increase in evapotranspiration in the reclaimed desert areas.

The simulations also reveal that the aggregated evapotranspiration can be maintained during a period of 50 years in the total area, despite a small increase in average soil salinity, mainly concentrated in the old lands.

5.4 Local water management strategies

5.4.1 Introduction

Measures related to water management can be implemented on different levels. First, the authorities have the option to interfere in the total available amount of irrigation water for the region. Next to this option they also have the possibility to change the allocation of the water with respect to time.

On a lower level, the internal distribution can be adapted in such a way that the supply follows the agricultural demand more closely, both in time and in space, reducing losses and thus improving the system efficiency. Although falling within the scope of the underlying report these options are not considered.

A strategy put forward by the Reuse Steering Committee concerned measures on the lowest level as schematized in the SIWARE model. For this level, i.e. the agricultural calculation unit, the following two options will be treated:

- a prohibition to use the small diesel pumps for lifting water from the irrigation canals for field irrigation;
- a total ban on the use of small diesel pumps for lifting water from irrigation as well as drainage canals.

The use of small capacity, movable diesel pumps is common practice nowadays in Egypt's irrigated agriculture. When the current trend continues, and fuel prices remain low, the water-wheel (sakkia) powered by animal force will soon become obsolete. Apparently the first farmers who replaced their sakkias by pumps saved a considerable amount of time and became more flexible in their planning. As with so many innovations, however, benefits tend to decrease when larger numbers become involved. The higher capacity together with the higher lifting head of the pumps have introduced a less uniform water distribution pattern over the area. As a result, farmers with plots located at the tail-ends of the irrigation canals were the first to feel the adverse effects, forcing them to irrigate during night hours. Step by step the consequences were felt in upstream areas, first affecting the flexibility of the investment with respect to the input (operating hours), and later on also with respect to the output (lifted quantity).

Nowadays, the economic returns of the investment will no longer be the only consideration. Farmers along the tail-ends may be forced to replace their sakkias for sheer agricultural survival. The expectations are that water shortages will appear more frequently because farmers having sufficient water at their disposal are tempted to withdraw more than their equal share of the supply, thus facing other farmers downstream with shortages. Low waterlevels and the lack of water during certain periods of the day will necessitate the use of pumps. When the downstream situation deteriorates too much, farmers will turn to the drainage canals when these are situated adjacent to their plots. For lifting water from this source they do not have any other choice then using diesel pumps. Applying substantial amounts of drainage water may cause an increase in soil salinity, which may result in lower crop yields.

The idea behind the Steering Committee's request is that, although the use of the small pump may be an improvement for the individual farmer, the effects for the whole population of farmers will be adverse when nothing will be done to limit the capacity and the lifting head. The use of sakkias has the advantage that it automatically re-introduces a continuous (24 hours) irrigation uptake by farmers. Moreover, the total capacity of the sakkias has been designed in such a way that it is in accordance with the total supply under control of the Ministry of Public Works and Water Resources.

Although it is possible to eliminate the pumps in the input data of the SIWARE model package entirely, the effects are expected to be small. The point being that for the calibration and validation runs of the SIWARE model package the maximum required uptake capacity has been provided by means of sakkias. At the same time this capacity has been augmented by adding a small number of diesel pumps to cover emergency situations as for instance low waterlevels. When these situations do not occur, being the case for the larger part of the year, sakkia capacity is sufficient to handle the demand for water, and pumps will be superfluous. Since reliable data on type and numbers of working irrigation tools are lacking, as well as the actual quantitative effects on the irrigation water distribution, it is difficult to predict how much the real improvements will be after elimination of the diesel pumps. Simulations can only show how the distribution, and related output results as evapotranspiration, quantity and salinity of drainage water, etc., could have looked like before the introduction of the pumps.

A factor which will have a considerable influence on the results is the scale. In the model approach it has been assumed that the water distribution within the calculation unit is uniform. The units themselves range from 2,000 to 40,000 feddan, with an average size of 15,750 feddan, while each unit is served by only one imaginary distributary canal. In reality the average area served by a distributary canal lies around 6,000 feddan. From this difference it will be clear that model calculations are not able to give a good perception of the non-uniformity in the water distribution caused by pumps. This non-uniformity will be mainly concentrated within the schematized calculation units. Simulations, however, can give an idea what the reciprocal effects on the distinguished units will be with a more uniform abstraction pattern over the day.

Prohibiting the unofficial reuse of drainage water will have a pronounced effect on crop yields, soil salinity, official reuse, etc. A combination made up by the elimination of the diesel pumps for lifting both irrigation and drainage water has been regarded feasible, because a more uniform water distribution may set aside the need for using drainage water. Although there will always be farmers facing shortages, such a strategy deserves attention if it were only for a better control of the whole agricultural system. The problem with a non-uniform distribution of irrigation water within the calculation unit, as occurs in reality, has been circumvented by using an over-irrigation factor of for instance 1.25 in the reference simulations when determining the required amounts of unofficial reuse.

In the various paragraphs the effects of the two strategies will be discussed. They are mainly confined to changes in irrigation and drainage discharges and salinities, evapotranspiration, and the long term consequences on evapotranspiration and soil salinity. As a reference, the cropping pattern and water supply for 1988 have been used. The allocation to the intakes of the 6 command canals has been calculated proportional to the official Ministry of Public Works and Water Resources allocation water duties, corrected for official reuse of drainage water, groundwater use, rainfall, and potable and industrial process water. The initial conditions with respect to soil salinity and soil moisture content have been acquired from a 100 year run, so that the reference for the long strategy runs would be a horizontal line (equilibrium) for the model salinity output variables, facilitating the interpretation of the results. In total six runs have been carried out and examined, the two aforementioned strategies with their reference, and two long term runs. In the last paragraph the results obtained will be discussed.

5.4.2 Changes in the supply and discharge system

5.4.2.1 The irrigation system

Predictions with respect to changes in the supply and discharge system can be provided by 3 short term runs, i.e. a reference and 2 strategy runs. The runs have been numbered as follows:

#0 - reference run with diesel pumps, with unofficial reuse, and
$Q_{Nile\ supply,1988} = 10{,}310$ million $m^3 \cdot yr^{-1}$;

#1 - strategy without diesel pumps and without unofficial reuse;

#2 - strategy without diesel pumps only.

Changes in the irrigation supply system can be related to the following factors:

- allocation and distribution;
- actual farmers' uptake;
- spillway and conveyance losses.

Allocation and distribution

The total amount of Nile water diverted to the Eastern Nile Delta remains fixed on the value for 1988 for both strategies. The allocation to the different intakes is distributed proportionally to the individual canal demand, according to the Ministry of Public Works and Water Resources allocation water duties, during each 10 day period. This distribution takes into account the local available amounts of official reuse, groundwater and rainfall, as well as additional demands for potable and industrial process water. Among these 'correction' factors only the official reuse can vary, because the discharges of the various pump stations will depend on the quantities of water available in the drainage canals. Generally, each strategy will simulate different drain discharges.

Contrary to the allocation procedure, which is quite straightforward, the water distribution is a more dynamic process. Where the water allocation will only be affected by changes in the official reuse, the internal water distribution in the area will also depend on the number and type of the irrigation tools. Next to this dependance on the irrigation tools, the farmers' uptake and system losses are directly linked to the internal distribution in the modelled area.

For both the water allocation and distribution the feed-back effects through the official reuse have been accounted for by running the complete SIWARE model for a number of iteration steps. After each simulation, the contents of the file with the reuse pump station discharges are updated with values regarding the actual simulated flows in the drainage canal system, or a fixed percentage thereof.

Table 35 shows higher reuse discharges for the strategy without diesel pumps and unofficial reuse (#1) when compared to the reference run (#0). Obviously, the absence of unofficial reuse in the catchments of reuse pump stations causes higher drain discharges, which will increase the amounts available for official reuse. The total yearly official reuse goes up with 8.5%, from 630 to 684 million m^3, for this strategy.

The elimination of the diesel pumps alone (#2) results in lower discharges of the reuse pump stations, i.e. 538 million m^3 or -14.6%. Most likely lower losses from the irrigation system, caused by a better distributed abstraction pattern over the day of the sakkias, result in lower available quantities in the drainage canals at the pump station sites.

Farmers' uptake

The quantity of water lifted by farmers from the distributary canals will depend on:

- the supply to the distributary canal;
- the number and type of the irrigation tools;
- the farmers' water requirements.

Table 35. The monthly supply to the Eastern Nile Delta with Nile water, and the calculated monthly quantities of official reuse and irrigation uptake by farmers.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

(all quantities expressed in 10^6 m^3)

month	Nile supply	official reuse			irrigation uptake		
		(#0)	(#1)	(#2)	(#0)	(#1)	(#2)
jan	314	46	52	38	284	264	263
feb	453	29	35	27	226	223	221
mar	759	47	55	45	511	560	557
apr	886	52	55	43	647	686	683
may	582	35	39	27	489	515	508
jun	1,480	49	62	40	1,118	1,089	1,116
jul	1,420	62	72	52	1,317	1,292	1,314
aug	1,524	69	72	59	1,265	1,201	1,244
sep	1,199	79	75	65	807	842	846
oct	453	62	60	51	335	307	306
nov	540	47	48	43	328	345	343
dec	701	55	58	48	462	490	489
tot	10,310	630 (ref.)	684 (+8.5%)	538 (-14.6%)	7,788 (ref.)	7,810 (+0.3%)	7,888 (+1.2%)

The supply to the distributary canal is part of the aforementioned dynamic process in the irrigation canal system. The inflow depends on quite a number of variables, upstream as well as downstream of the distributary canal intake. Among those are the water allocation to the main intakes of the command canal system, official reuse of drainage water, the discharge to other distributary canals, the irrigation system losses, the uptake by farmers and the losses from the distributary canal under consideration, etc.

Since the official reuse is the only parameter on the supply side which should be adjusted by an iteration procedure, it has been tried to establish a relation with the uptake. The reused quantities, however, amount to 7-8% of the total Nile water supply. Moreover, reuse pump stations only serve part of the Eastern Nile Delta, and when the supply exceeds the local demand the water will be partly spilled to the drainage system. Therefore a change of say 10% in 7-8% of the total supply will be hardly noticeable in the farmers' uptake. This view is supported by the year totals of table 35, where no relation can be found between the official reuse and the irrigation uptake columns. Other factors like an improved water distribution, in relation to a change in the number and type of the irrigation tools, are more likely to explain differences in the farmers' uptake.

Banning the use of diesel pumps for lifting water from the distributary canals will result in a more uniform abstraction pattern over the day for two reasons. The first is that the capacity and lifting head of the remaining sakkias are lower, resulting in a higher number of operating hours to meet the farmers' water requirements. The second reason is that the maximum number of daily operating hours has been increased to 24 for both strategies.

Simulation results make clear that, apart from the summer season, the amounts lifted from the irrigation canals are higher for both strategies as illustrated in tables 35 and 36. The year totals of the tables may differ slightly, because table 35 holds values for the complete modelled area, whereas table 36 is related to the study area only with 13% less net area.

Table 36. Average seasonal farmers' uptake from the irrigation system within the study area.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

strategy	farmers' uptake (mm·day^{-1})				
	winter	spring	summer	autumn	year
#0	1.8	2.9	7.0	3.0	3.5
#1	2.0	3.2	6.7	3.1	3.5
#2	2.0	3.1	6.9	3.1	3.6

The better distributed abstraction pattern over the day without the diesel pumps also results in a spatial water distribution which follows the farmers' requirements more closely. Figure 97 shows the yearly irrigation water supply to the different calculation units in the study area for the reference run and the two strategies. Generally, a shift in the supply will occur. Lower quantities of irrigation water will be diverted to the units upstream, close to the intakes along the river Nile (south-west), and higher quantities will be supplied to the units downstream of the canal system (north-east).

For all simulation runs the yearly average deviation between farmers' uptake and farmers' water requirements have been calculated for the total area. The average deviation using the Ministry of Public Works and Water Resources (MPWWR) water allocation duty instead of the farmers' requirements has been added between brackets. For the reference run (#0) the average yearly deviation equals to 21.6% (35.2%). For the strategy without diesel pumps and unofficial reuse (#1) the average deviation reduces till 19.0% (32.5%), and for the strategy without the pumps only (#2) the deviation hovers in between at 20.6% (31.6%).

The presented deviations between the farmers' uptake and the MPWWR duty are higher than for the farmers' requirements. This can logically be explained by the fact that the MPWWR duty is used on a higher level, i.e. for the irrigation water distribution, and that the farmers' requirements directly govern the uptake on the lowest level.

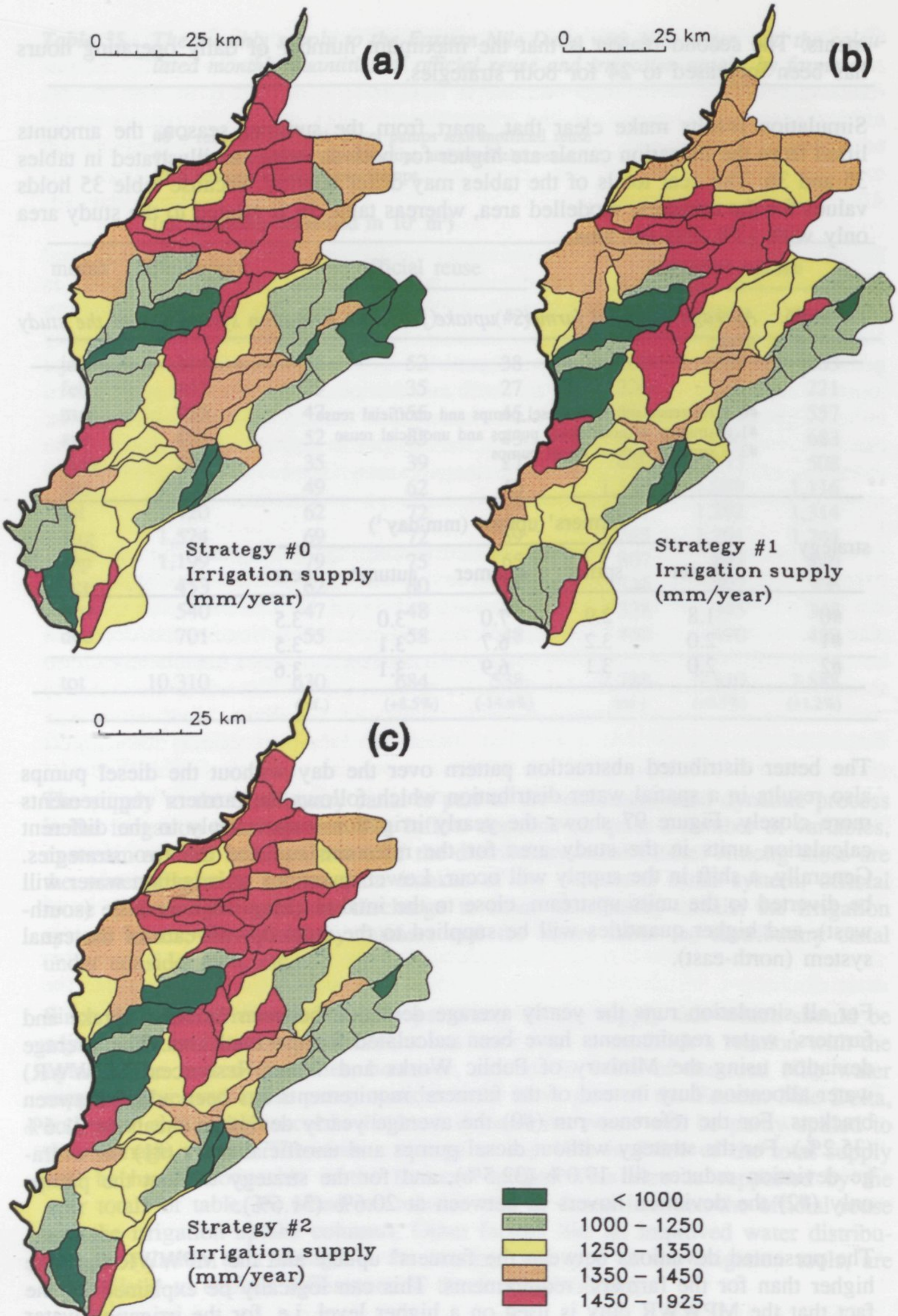

Fig 97. Spatial distribution of the yearly irrigation water supply to the agricultural calculation units in the study area for the reference run and both strategies.

Although the differences are not that large, all strategies score better than the reference. The first percentages imply that the strategy without diesel pumps and unofficial reuse (#1) gives the best performance with respect to the farmers' uptake. Such a comparison, however, should be interpreted cautiously because of the variations in the calculated farmers' rice water requirements for the different strategies. This will not be the case for the MPWWR duty, and here the strategy without diesel pumps (#2) produces the best results.

Notably, the farmers' uptake during the summer season is lower for both strategies (tables 35 and 36). A number of reasons can be considered. Foremost among them is the already mentioned calculated rice water requirements. The spatial variability of these requirements, due to hydrological and climatic conditions, will not differ among the various strategies, but the iteration procedure necessary to obtain a correct estimation of the official reuse will cause other changes. Depending on the salinity of the crop water supply, which includes the uptake from the irrigation canals, groundwater abstraction, and unofficial reuse, the rice water requirements may show a large variation. Low salinities will lead to lower requirements, whereas high salinities will require larger amounts of water in order to maintain a favourable salinity of the standing water layer. Obviously, the uptake from the irrigation canals will depend on the water requirements during the rice growing season.

The strategy without diesel pumps and unofficial reuse (#1) will have a much better salinity of the irrigation water and therefore a lower average rice water requirement, i.e. around 6,500 $m^3 \cdot feddan^{-1}$ for the growing season. The reference run (#0) and the strategy without pumps (#2) will require around 7,400 $m^3 \cdot feddan^{-1}$. This is directly reflected in the farmers' uptake during the months June, July and August (table 35), and the summer column of table 36.

The small decrease in the uptake during summer for the strategy without the diesel pumps (#2) cannot be explained by differences in the farmers' rice water requirements. The irrigation water salinity will hardly deviate from the reference values. In this case the combination of a lower maximum uptake capacity and the use of the 1988 cropping pattern appears to be unprofitable. The 1988 cropping pattern shows a concentration of rice in a northerly belt with an extensive maize area upstream, i.e. in the southern and central part of the Eastern Nile Delta. For both crops the calculated, spatially variable farmers' water requirements can diverge considerably from the fixed allocation crop water duty used by the Ministry of Public Works and Water Resources.

In chapter 4 it has been established that the calculated, average farmers' water requirements for rice are lower and for maize higher when compared to the Ministry of Public Works and Water Resources crop duties. With an actual (and modelled!) water distribution based on the MPWWR duties, and an uptake largely controlled by the farmers' water requirements, the lack of diesel pumps (lifting head!) will lead to a lower gift for the maize crop. As a consequence, more water will be available for the rice, where spillway losses will increase when the actual farmers' water requirements for this crop are lower than the MPWWR duty. The net result will be a slightly lower farmers' uptake during the summer for the strategy without diesel pumps (run #2, table 36), despite a better distributed water allocation to the crops according to the MPWWR duties.

Summarizing it can be concluded that on a monthly basis the irrigation uptake can be up to 8% higher for either strategy. On a yearly basis, however, the differences are restricted to a margin of 0.3 and 1.3% respectively, caused by the lower calculated rice water requirements related to the improved irrigation water salinity, and the restricted farmers' uptake capacity during summer in combination with differences between the calculated crop water requirements and the MPWWR duties (table 35).

Losses

Losses are the positive difference between irrigation water supply and farmers' uptake during a certain time interval. The largest component of these losses is made up by the spillway releases within the calculation units and at the tail-ends of the irrigation canals. Apart from mis-matches between supply and demand, spillway losses can also be induced by the inertia of the system, which can vary strongly because of seasonal variations in the growth of water plants.

Considering the total yearly spillway losses (table 37), two observations can be made:

- these losses are lowest when the small diesel pumps are eliminated, but the unofficial reuse remains permitted (strategy #2);
- elimination of the diesel pumps results in a shift of these losses from the spillways within the calculation units to the tail-ends of the command canals (both strategies #1 and #2).

Table 37. Yearly spillway losses within the calculation units, spillway losses at the tail-ends of the command canals, conveyance losses of the command canals, and the total losses from the irrigation canal system in the Eastern Nile Delta.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

(all quantities expressed in 10^6 m^3)

strategy	spillway losses	tail-end losses	conveyance losses	total losses
#0	2,065 (ref.)	290 (ref.)	303 (ref.)	2,658 (ref.)
#1	1,649 (-20.1%)	618 (+113%)	327 (+7.9%)	2,595 (-2.4%)
#2	1,573 (-23.8%)	468 (+61%)	324 (+6.9%)	2,366 (-11.0%)

One of the reasons for the lower spillway losses obtained with the strategy without the diesel pumps (#2) is the lower total irrigation water supply, caused by a decrease in the official reuse (table 35). This cannot explain the full reduction, nor does it explain why also the total losses in the strategy without diesel pumps and unofficial reuse (#1) show a decrease, where official reuse discharges are higher and rice water requirements are lower. The only explanation could be that the total losses and their shift in location, from calculation units to tail-ends, are interrelated.

Spillway losses within the agricultural calculation units appear to be very sensitive for the daily abstraction pattern. The use of diesel pumps will result in large fluctuations of the waterlevel in the distributary canals, and a low uptake during night hours will substantially increase spillway losses. With the introduction of night irrigation in both strategies, the distinction between day and night disappears, and the withdrawal will be spread more smoothly over the day, hence minimizing losses. Since surplus irrigation water should be released from the irrigation system, only the tail-ends of the main irrigation canals can serve as an additional escape.

Also the lack of withdrawal capacity in upstream areas, together with the observed discrepancies between the allocation water duties used by the Ministry of Public Works and Water Resources and the calculated farmers' requirements, will cause unused water to flow in the direction of the canal tail-ends. Especially during peak periods in the summer, the absence of diesel pumps in maize areas, with their low allocation duty and high crop water requirements, will result in a shift of water to the tail-ends.

In principle, the shift in location of the spillway losses, from the calculation units internally to the tail-ends of the irrigation canals, can be considered as beneficial. It does not only contribute to lower losses, but, apart from the summer season, also promotes an irrigation water distribution which matches the demand more closely (fig 97). Water which is not withdrawn from a distributary canal located upstream, can now be utilized in downstream agricultural areas.

Table 38. Yearly external uptake from the irrigation canals for potable and industrial process water in the Eastern Nile Delta.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

strategy	external uptake (10^6 m^3)
#0	502 (ref.)
#1	593 (+18.1%)
#2	598 (+19.1%)

One of the side-effects of the higher tail-end losses is that waterlevels in the main irrigation system will increase for both strategies, thus adding to the conveyance losses (table 37) and the uptake for sanitation and industrial process water (table 38). This will diminish part of the advantage gained. Nevertheless, the net result will be an increase in the farmers' uptake during the major part of the year (tables 35 and 36).

Notably, the tail-end losses for the strategy without diesel pumps and unofficial reuse (#1) exceeds by far similar losses for the other simulation runs (table 37). The aforementioned much lower farmers' rice crop water requirements, together with the downstream location of the rice areas, can explain this phenomenon. The Ministry of Public Works and Water Resources allocation water duty for rice is

Table 39. Different components of the yearly irrigation water supply to the crops together with the total crop supply and the crop drainage in the Eastern Nile Delta.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

(all quantities expressed in 10^6 m^3)

strat.	farmers' uptake	unoff. reuse	groundwater	total supply	crop drainage
#0	7,788 (ref.)	1,131 (ref.)	379	9,298 (ref.)	2,859 (ref.)
#1	7,810 (+0.3%)	0 (-100%)	379	8,189 (-11.9%)	2,170 (-24.1%)
#2	7,888 (+1.3%)	1,028 (-9.1%)	379	9,295 (-0.0%)	2,897 (+1.3%)

Table 40. Yearly official reuse, unofficial reuse, and the sum of both in the Eastern Nile Delta.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

(all quantities expressed in 10^6 m^3)

strategy	official reuse	unofficial reuse	total reuse
#0	629 (ref.)	1,131 (ref.)	1,760 (ref.)
#1	683 (+8.6%)	0 (-100%)	683 (-61.2%)
#2	537 (-14.6%)	1,028 (-9.1%)	1,566 (-11.0%)

Table 41. Yearly Nile water supply, total drainage discharge, and the percentage of the Nile water supply which is not discharged to the Mediterranean Sea in the Eastern Nile Delta ('system efficiency').

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

(all quantities expressed in 10^6 m^3 and the 'system efficiency' in %)

strategy	Nile water supply	total drainage discharge	'system efficiency'
#0	10,310	4,230 (ref.)	59
#1	10,310	4,622 (+9.3%)	55
#2	10,310	4,244 (+0.3%)	59

with its 8,800 $m^3 \cdot feddan^{-1}$ considerably higher than the average farmers' requirements of a mere 6,500 $m^3 \cdot feddan^{-1}$, thus giving way to higher tail-end losses. Also spillway losses in the rice areas will increase.

Less fluctuation in the waterlevel of a distributary canal feeding an agricultural unit will not only cause lower spillway losses, but will also contribute to a better internal water distribution in the unit. The scale used for modelling is almost a factor three higher than the real area served by a distributary canal. Therefore no answers can be given for the irrigation water distribution within the agricultural calculation unit considered, although improvements can certainly be expected on this level.

5.4.2.2 The drainage system

In the water balance of the drainage canal system, the crop drainage shows a large difference between the reference run and the strategy without diesel pumps and unofficial reuse (table 39). This can be directly related to the absence of the unofficial reuse. The total crop water supply is composed of the irrigation uptake, unofficial reuse, and groundwater abstraction. Since the groundwater abstraction does not change in the strategies considered, it will be clear that the total available amount for irrigation in the strategy without diesel pumps and unofficial reuse (#1) will be lowest, hence resulting in the lowest drainage rates.

Table 39 makes clear that a decrease of almost 12% in the total crop water supply is followed by a twofold decrease of 24% in crop drainage for the strategy without diesel pumps and unofficial reuse (#1). This high reduction in the drainage rate indicates that severe crop water shortages may have occurred. The somewhat higher crop drainage simulated by the strategy without diesel pumps only (run #2, table 39) can be attributed to the higher irrigation water supply in winter, spring, and autumn (tables 35 and 36).

The aforementioned shift in the irrigation water losses, from spillways to tail-ends, also has repercussions for the drainage system. Spillway water originating from the calculation units are more or less diffusely released to the drainage canals, whereas losses from the canal tail-ends are spilled at a limited number of locations. The number of these tail-ends will not exceed the number of irrigation canals, and the majority will be located in the northern part of the modelled area, close to the Coastal Lakes and the Mediterranean Sea. This implies that by shifting losses from the spillways to the tail-ends, the possibilities for both official and unofficial reuse are reduced. Banning the use of diesel pumps for irrigation purposes (#2) shows a drop of 14.6% in the official and a drop of 9.1% in the unofficial reuse (table 40).

As a yardstick for the system efficiency the percentage of the Nile water supply which is not discharged to the Coastal Lakes or the Mediterranean Sea can be taken. Table 41 shows that the present system, i.e. with diesel pumps and permitted unofficial reuse (#0) and the strategy without the diesel pumps (#2) are on the same level. The 'system efficiency' for the strategy without diesel pumps and unofficial reuse (#1) is noticeably lower, indicating that, on the short term, the prohibition of the unofficial reuse leads to a less efficient use of water.

Whether the crop production will follow this 'yardstick for system efficiency' remains questionable. The net effect of a better functioning irrigation system for both strategies, in combination with a better irrigation water salinity (lower reuse quantities), may result in a higher crop production, even despite a decrease in the system efficiency.

5.4.3 Crop reaction

5.4.3.1 Short term effects

The crop production is, within certain limits, linearly related to the crop evapotranspiration. Because the evapotranspiration is standard output in the SIWARE model package, indicative remarks for the crop production can be based on this variable. The relation between crop production and evapotranspiration has been explained extensively in paragraph 4.4.3.

In table 42 the figures for the relative evapotranspiration are arranged for both strategy runs relative to the reference run. In the same table a distinction has been made between summer crops, winter crops, perennial trees, and the aggregated value for all the crops.

The two major variables exerting their influence on changes in the evapotranspiration are the net quantity of irrigation water given to the crop and the soil salinity under the crop. Changes in the top soil salinity are strongly governed by the amount of irrigation water available for leaching and the salinity of the irrigation water. However, for simulations as short as one year major changes in the soil salinity are unlikely to occur. Therefore the most important factor controlling the evapotranspiration is the net quantity of irrigation water, which is composed of:

- uptake from the irrigation canals;
- unofficial reuse;
- groundwater abstraction.

Generally, it can be expected that crops sensitive for water shortages will suffer in their transpiration when the unofficial reuse component is lacking. Under similar conditions, crops which are sensitive for salt will slightly profit from the reduced salt content of the water supply, because the unofficial reuse and the groundwater abstraction are the largest contributors to the crop water salinity. The amount and salinity of the groundwater component have been assumed constant throughout the various simulations.

Previously it has been shown that, despite a better distribution over the Eastern Nile Delta, the yearly irrigation uptake for the strategy without diesel pumps and unofficial reuse (#1) was in the same order of magnitude as for the reference run (#0). The seasonal variations were such that during winter the quantities withdrawn from the canals were slightly higher and during summer slightly lower (tables 35 and 36). The lower farmers' uptake in summer have been fully attributed to the lower requirements of the rice crop for this strategy. Other summer crops profit

Table 42. Short term relative evapotranspiration for the summer crops, winter crops, perennial trees, and the aggregated value for all the crops in the Eastern Nile Delta with the reference values set at 100.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps

crop	evapotranspiration (%)		
	run #0	run #1	run #2
winter crops			
- long berseem	100	97	101
- wheat	100	95	100
- winter vegetables	100	98	101
- short berseem	100	94	100
summer crops			
- rice	100	99	100
- cotton	100	93	99
- maize	100	96	99
- summer vegetables	100	97	100
deciduous trees	100	97	100
aggregated value	100	96	100

from the improved water distribution. The unofficial reuse, however, has been eliminated in the strategy without diesel pumps and unofficial reuse (#1), resulting in a lower irrigation gift to all the crops. On the other hand, due to the absence of the unofficial reuse, the average salinity of this water improves from 445 $g{\cdot}m^3$ for the reference run till 356 $g{\cdot}m^3$.

Examining the relative evapotranspiration values in table 42 for the strategy without diesel pumps and unofficial reuse (#1), it turns out that all crops suffer from water shortages. The increase in uptake from the irrigation canals over the year, together with the reduced salinity of the crop water supply, is unable to offset evapotranspiration losses caused by the absence of the local unofficial reuse.

Notably, the rice crop performs relatively well with respect to its evapotranspiration for the strategy without diesel pumps and unofficial reuse (#1). On the other hand, drought resistant crops like wheat and cotton clearly do not display their advantage (table 42). This difference stems from the calibrated irrigation priority ranking of the farmers when watering their crops (table 6). A similar classification can be observed in the evapotranspiration figures of table 42 under water shortage conditions (run #1).

The reduced salt content of the crop water supply in the strategy without diesel pumps and unofficial reuse (#1), together with the relative high irrigation priority, also favours the extremely salt sensitive vegetables. Summer vegetables, and especially winter vegetables, show relative low reductions in evapotranspiration when compared to the other crops (table 42).

However, considering that not a single crop is able to surpass the reference evapotranspiration for the strategy without diesel pumps and unofficial reuse (#1), it can be concluded from table 42 that banning the use of diesel pumps for lifting water from the irrigation canals and the drainage canals does not offer a realistic alternative when crop yields should be maintained at the current level or when authorities aim for an increase.

From the strategy without diesel pumps only (#2), it can be said that the results in terms of evapotranspiration are very close to the reference run (table 42). Following the same trend in the irrigation water uptake by farmers (tables 35 and 36), the evapotranspiration for the winter crops is somewhat higher and for the summer crops slightly lower (table 42). The aggregated value for all considered crops does not differ from the reference run (#0).

During the summer season the simulated irrigation water uptake by farmers turned out to be slightly lower for the strategy without diesel pumps (#2). This has been ascribed to the specific cropping pattern during 1988 and the difference between the calculated farmers' crop water requirements and the Ministry of Public Works and Water Resources water duties when distributing the irrigation water. As a result of these factors, rice receives water in excess on the account of maize, which could only be compensated partially by additional uptake capacity in the maize areas. However, the strategy without diesel pumps (#2) lacks this capacity.

A far more serious restriction for the evapotranspiration of the summer crops is the reduced availability of water in the drainage canals. Due to the shift in irrigation water losses, from the spillways within the calculation units to the spillways at the tail-ends of the irrigation canals, less water will be available in the upstream areas. Consequently, less water can be reused unofficially by farmers (table 40) to cover local shortages likely to occur in summertime.

Table 42 shows that among the summer crops both maize and cotton are negatively affected in their evapotranspiration for the strategy without diesel pumps (#2) when compared to the reference run (#0). For these crops the combination of local water shortages and their intermediate or low irrigation priority ranking leads to a reduced evapotranspiration.

The cultivated rice area is located downstream (fig 59a). Extra irrigation water will be available for the rice (mostly at the expense of the maize crop), when surplus uptake capacity is missing in maize areas as stated before. Besides, part of the additional tail-end losses of the irrigation canals will be available for unofficial reuse to supplement local shortages. Finally, the highest irrigation priority when the available water has to be distributed over the crops decides in favour of the rice. Model simulations therefore produce a value equal to the reference evapotranspiration for the strategy without diesel pumps (run #2, table 42). It should be realized, however, that during the summer period peak demands occur, in combination with an extremely tight water supply, and substantial improvements will be difficult to realize.

Also the summer vegetables show their ability to maintain an evapotranspiration rate equal to the reference run (table 42, run #2). A relative moderate decline of the evapotranspiration under water shortage conditions and, above all, a high irrigation priority ranking determines the fate of this crop.

Salinity considerations are of minor importance. The average salinity of the crop water supply improves from 445 g·m^{3} for the reference run till 440 g·m^{3} for the strategy without diesel pumps (#2). For the individual crops, the salinity moves within a range of 0-3% below the reference crop water salinities, which hardly leads to noticeable changes in the soil salinity, and thus to changes in the evapotranspiration. Only rice and vegetables are affected to some extent by the soil salinity under the existing reference conditions.

For both strategies it appears that the unofficial reuse is a vital source of water to supplement locally occurring shortages of irrigation water. Neither strategy offers such improvements in the irrigation water distribution that the need for unofficially reusing large amounts of drainage water can be set aside. Summing up the total annual crop water supply, the strategy without diesel pumps and unofficial reuse (#1) arrives at a 10.6% lower value when compared to the reference run (#0). Also the strategy without diesel pumps only (#2) yields a 1% lower value, mainly affecting some summer crops, but not the aggregated evapotranspiration for all the crops.

Simulations performed with the present model schematization of the Eastern Nile Delta cannot predict how much the evapotranspiration rate of the different crops will increase as a result of an improvement in the water distribution within a calculation unit. It is very well conceivable that at this level the effects are much larger than on the inter-unit scale. Although it seems unlikely that the crop production of the strategy without diesel pumps and unofficial reuse (#1) will be able to surpass the reference, the strategy without the diesel pumps only (#2) may yield values way ahead of the reference run.

5.4.3.2 Long term effects

Long term effects are related to changes in soil salinity. When the cropping pattern remains unchanged, the availability and the salt content of the irrigation water have a major impact on a salinization or desalinization of the soil. Also the upward seepage from the deep aquifer can contribute to a considerable extent, especially in those areas where high groundwater salinities prevail. The salt content of the top soil will have a distinct influence on the crop production.

Two long runs have been carried out for a period of 50 years. They have been numbered as follows:

- #3 for the strategy without diesel pumps and unofficial reuse (#1);
- #4 for the strategy without diesel pumps only (#2).

In figure 98 the average soil salinity in the Eastern Nile Delta is given during a period of 50 years for both strategies. Due to the much lower salinity of the irri-

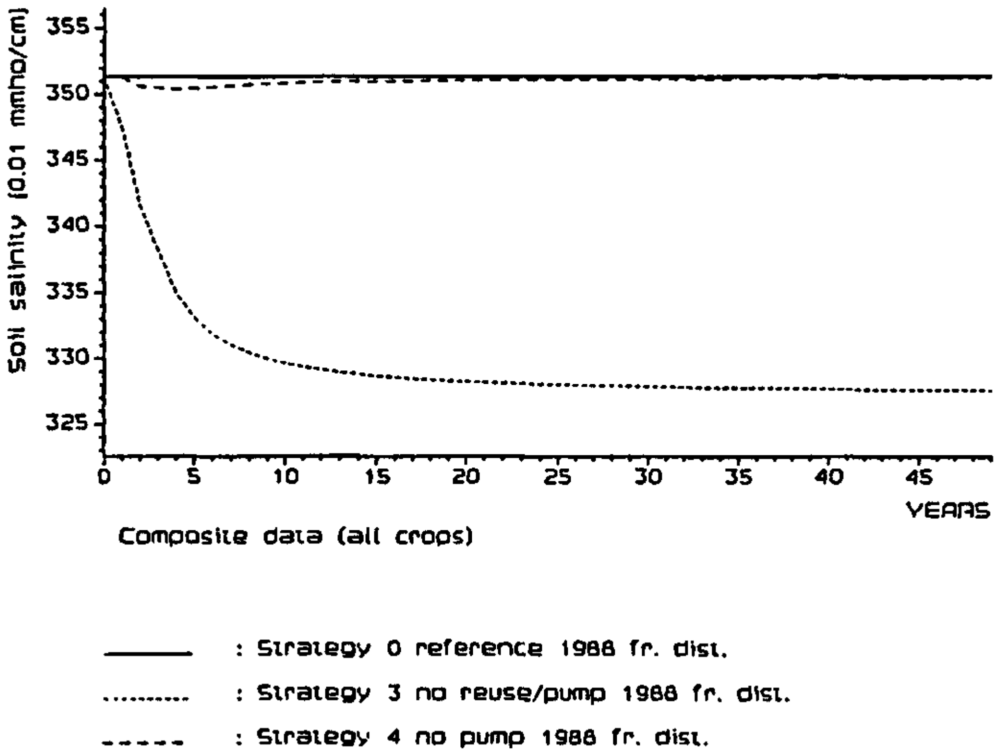

Fig 98. Development of the average soil salinity in the Eastern Nile Delta with time.

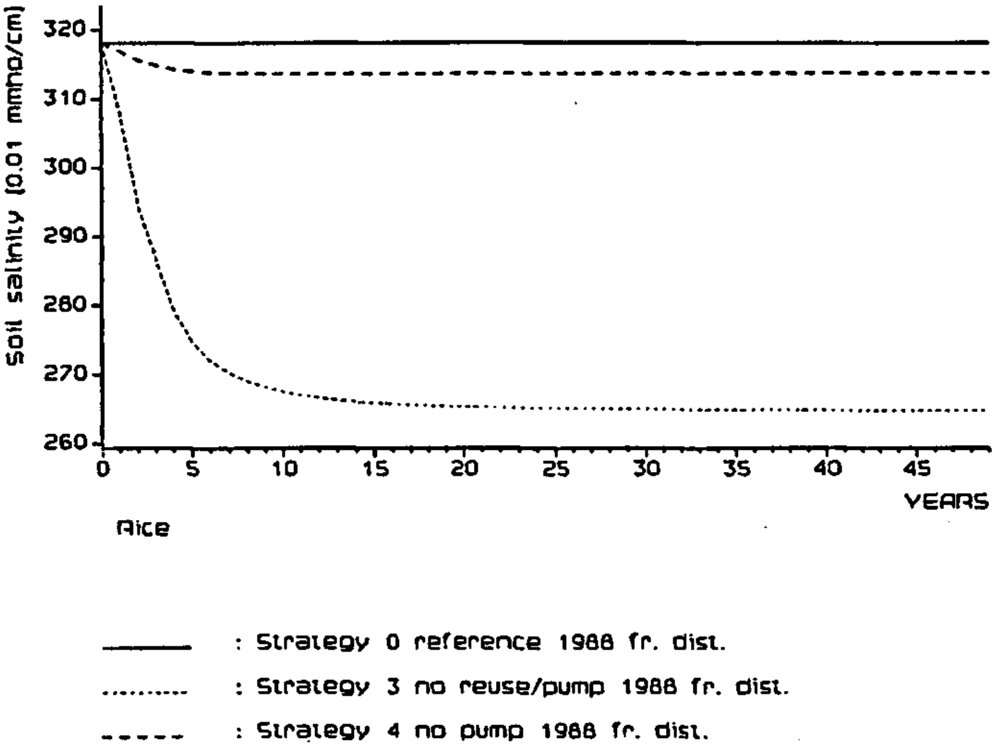

Fig 99. Development of the average soil salinity under rice in the Eastern Nile Delta with time.

gation water, when not mixed with the more saline unofficial reuse and with unchanged leaching fractions, the long term average soil salinity for the strategy without diesel pumps and unofficial reuse (#3) decreases from 3.51 mmho·cm^{-1} to 3.28 mmho·cm^{-1}, or almost 7%. The gap between both values is bridged for 90% within a time-span of approximately 9 years. The soil salinity found for the strategy without diesel pumps only (#4) remains more or less the same as for the reference run (#0), i.e. 3.50 mmho·cm^{-1}.

Table 43. Long term relative evapotranspiration for the summer crops, winter crops, perennial trees, and the aggregated value for all the crops in the Eastern Nile Delta with the reference values set at 100.

#0 = reference run with diesel pumps and unofficial reuse
#3 = long term strategy without diesel pumps and unofficial reuse (50 yr.)
#4 = long term strategy without diesel pumps (50 yr.)

crop	evapotranspiration (%)		
	run #0	run #1	run #2
winter crops			
- long berseem	100	97	101
- wheat	100	95	101
- winter vegetables	100	99	101
- short berseem	100	94	100
summer crops			
- rice	100	101	100
- cotton	100	94	99
- maize	100	96	99
- summer vegetables	100	98	100
deciduous trees	100	97	99
aggregated value	100	97	100

Table 43 presents the long term evapotranspiration values for the individual crops, as well as the aggregated value for all the crops combined. Only minor changes can be detected for the winter crops for either strategy when compared to the values as given in table 42. Apart from the vegetables, the average soil salinities under the winter crops do not indicate salinity stress. Locally, of course, hazardous conditions may occur. The winter vegetables profit from the lower salt content of the crop water supply in the strategy without diesel pumps and unofficial reuse (#3), and show an increase of 1% in the evapotranspiration (tables 42 and 43, runs #1 and #3). A similar increase in the strategy without diesel pumps only (#4) for wheat is deceptive, because it concerns only a rounding-off matter here.

The long term evapotranspiration of the summer crops shows significant improvements for the strategy without diesel pumps and unofficial reuse (#3). Comparing tables 42 and 43 (runs #1 and #3) reveals an increase for all the crops except maize. The lower salinity of the crop water supply caused by the absence of the unofficial reuse provides better conditions for the crop transpiration.

Notably, rice performs best with a raise of 2% for the strategy without diesel pumps and unofficial reuse (#3). Moreover, rice appears to be the only crop which can overcome the loss of the unofficial reuse in terms of evapotranspiration when compared to the reference run (#0), be it only after 50 years (table 43). Figure 99 shows an intensive soil desalinization under rice when irrigating with a better irrigation water quality. After only 7 years, 90% of the ultimate soil salinity value can be reached, which is faster then the aforementioned 9 years for the composite value. Higher evapotranspiration rates are therefore already to be expected after a few years.

Although the elimination of the diesel pumps, combined with prohibiting the unofficial reuse, has a favourable effect on the soil salinity and thus on crop production on the long term, it is not sufficient to offset the shortages in crop water supply. For all crops, except rice, the long term evapotranspiration values are lower when compared to the reference run (table 43). Like the conclusion drawn

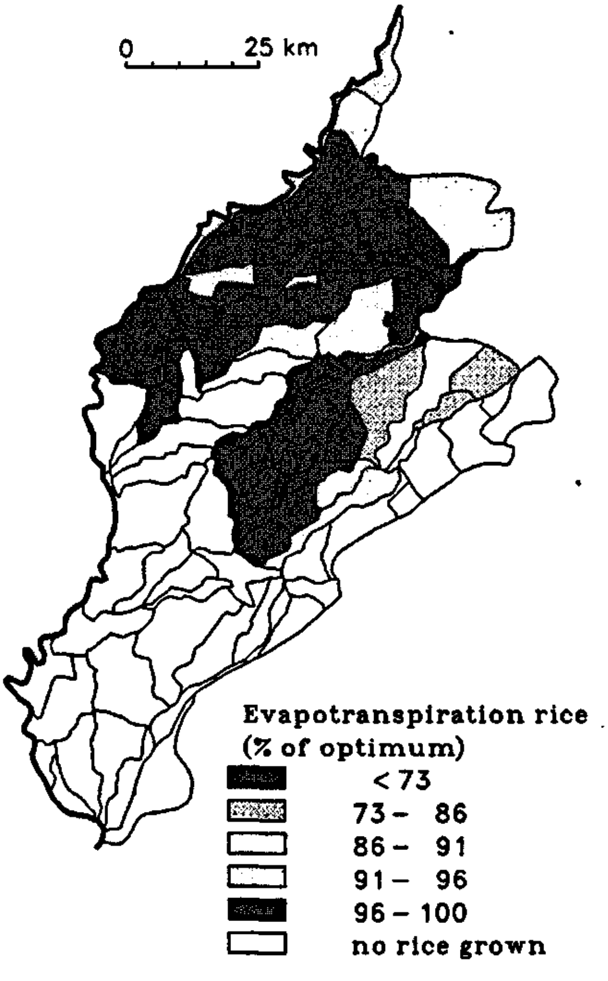

Fig 100. Spatial distribution of the relative evapotranspiration of rice for the reference run.

based on the short term evapotranspiration figures, the strategy without diesel pumps and unofficial reuse (#1/#3) does not offer a suitable alternative for the present local water management practices.

As has been observed for the winter crops, the long term evapotranspiration for the summer crops does not deviate from the values obtained with the short term simulations for the strategy without diesel pumps only (tables 42 and 43, runs #2 and #4). Since it has been established that the crop water salinity is only affected to a minor extent, no long term effects on the evapotranspiration are to be expected.

5.4.3.3 Spatial distribution

All evapotranspiration values given, either in table 42 or in table 43, are averages for the complete Eastern Nile Delta as schematized for the model simulations. Local conditions may cause large variations, which is clearly illustrated in figure 100 showing the spatial distribution in the evapotranspiration of rice for the reference run (#0).

In case the spatial variability in the evapotranspiration for a certain strategy is higher than for the reference run (#0), then this strategy can be excluded as undesirable. A good indicator is given by the standard deviation of the spatially distributed evapotranspiration. In table 44 both the average value and the standard deviation are tabulated for the reference, the short, and the long term aggregated evapotranspiration. Like figure 100, table 44 only provides information concerning the study area, and not the complete Eastern Nile Delta. Furthermore, all calculations are based on evapotranspiration values relative to the optimum evapotranspiration, and not relative to the reference run (#0).

Table 44. The average value and the standard deviation of the spatially distributed evapotranspiration for the reference run and all the performed strategies.

#0 = reference run with diesel pumps and unofficial reuse
#1 = strategy without diesel pumps and unofficial reuse
#2 = strategy without diesel pumps
#3 = long term strategy without diesel pumps and unofficial reuse (50 yr.)
#4 = long term strategy without diesel pumps (50 yr.)

strategy	evapotranspiration (%)	
	average value	standard deviation
#0	88.5	11.0
#1	85.1	9.9
#2	88.4	10.4
#3	85.8	9.3
#4	88.8	9.8

The average, short term aggregated relative evapotranspiration for the strategy without diesel pumps (#2) hardly differs from the reference run (#0), as was also the case for the complete Eastern Nile Delta. The standard deviation, however, appears to be significantly lower with 10.4% against 11.0% for the reference run (#0). Long term results (#4) even indicate a clear superiority of this strategy for both average value and standard deviation. It should be denoted, however, that these conclusions only hold for the study area, which constitutes around 87% of the total net area.

In terms of standard deviations merely, the strategy without diesel pumps and unofficial reuse (#1) performs best with 9.9% against 11.0% for the reference run (#0). Nevertheless, the more than 3% lower value for the average evapotranspiration leaves this strategy as uncompetitive, which is in accordance with previously found results. Despite small improvements, the strategy without diesel pumps and unofficial reuse (#3) remains also unattractive in the long run with an average relative evapotranspiration of 85.8% against 88.5% for the reference run (#0).

5.4.4 Conclusions

Two (local) water management strategies have been simulated with the SIWARE model package. One strategy concerned a complete elimination of the small diesel pumps used by farmers, implying that the water has to be lifted again from the irrigation canals with the traditional sakkia (water-wheel). When farmers do no longer have motorized pumps at their disposal, they also lack the means to withdraw water from the drainage canals in substantial amounts (unofficial reuse). Moreover, an elimination of the diesel pumps will also re-introduce a continuous irrigation uptake (24 hours) by farmers during irrigation-on periods, which better corresponds with the supply controlled by the Ministry of Public Works and Water Resources. The other strategy only considered a prohibition to use the pumps for lifting water from the irrigation canals.

For the allocation of irrigation water to the main command canals, the total amount of Nile water for 1988 has been taken and distributed proportionally to the Ministry of Public Works and Water Resources allocation water duty in the area served by each canal during a certain period. This procedure takes into account the locally available amounts of official reuse, groundwater, rainfall, and the locally required quantities of municipal and industrial water.

In order to compare and justify the simulation results, a reference run has been performed under similar conditions as for 1988. Initial conditions for soil moisture content, soil salinity, etc. were obtained from the same run after a period of 100 years. It has been assumed that conditions with respect to salt would be in an equilibrium state by then.

For both strategies, the short term (1 year) effects on the flows in the irrigation and drainage system, the irrigation water salinity, and the evapotranspiration have been quantified. The long term (50 years) effects on evapotranspiration and soil salinity have also been considered. The conclusions will comprise all these simulation results.

Irrigation and drainage system

Simulations show a better match between the farmers' water requirements and the farmers' irrigation water uptake after the elimination of the diesel pumps. As a consequence, the uptake will be higher during the major part of the year, and increases from 7,788 million m^3 annually for the reference simulation to 7,810 (+0.3%) for the strategy without diesel pumps and unofficial reuse. The strategy without diesel pumps comes up with 7,888 million m^3 (+1.3%).

Considering the farmers' uptake during the summer season, however, both strategies show a small decrease. For the strategy without diesel pumps and unofficial reuse the 3% fall in uptake can largely be explained by the farmers' rice water requirements, which drop considerably (-12%) as a result of the improved salinity of the irrigation water.

For the strategy without diesel pumps only, the 1% lower uptake during the summer appears to be the result of a combination of the 1988 cropping pattern, and the discrepancies between the Ministry of Public Works and Water Resources allocation crop water duties and the calculated farmers' crop water requirements. In 1988 the rice area was concentrated in a northerly belt, while extensive maize areas were located in the southern and central part of the Eastern Nile Delta. Furthermore, the farmers' requirements have been calculated lower for rice and higher for maize compared to the Ministry of Public Works and Water Resources allocation duties. When additional lifting head is not provided by the presence of diesel pumps, it is easily conceivable that maize will be under-irrigated and that spillway losses will increase in rice areas. Simulations using the cropping pattern of previous years most probably would have produced better results, although it must be commented that during the summer season the whole agricultural system is operated very efficiently and further improvements will be difficult to realize.

Total yearly irrigation system losses to the drainage canals and the groundwater aquifer fall from 2,658 million m^3 for the reference simulation to 2,595 million m^3 (-2.4%) for the strategy without diesel pumps and unofficial reuse. The strategy without diesel pumps arrives at a 2,366 million m^3 (-11.0%).

The absence of the diesel pumps also results in a shift in the location of the irrigation water losses. The smoother irrigation water abstraction pattern during the day of the sakkias (24 hour irrigation) causes higher spillway losses at the tail-ends of the irrigation command canals on the account of the spillway losses within the agricultural calculation units. The same shift in these losses results in a somewhat higher uptake of potable and industrial process water, caused by the higher waterlevels in the irrigation system.

The official and unofficial reuse from the drainage canals are also affected by differences in the quantity and the location of the irrigation water losses. The total yearly reuse drops from 1,760 million m^3 for the reference simulation to 683 million m^3 (-61%) for the strategy without diesel pumps and unofficial reuse. For the strategy without diesel pumps only, the fall is less dramatic with -11% till 1,566 million m^3.

Crop water supply and salinity

The crop water supply is the accumulated result of the farmers' uptake from the irrigation canals, local groundwater abstraction, and unofficial reuse of drainage water.

The total yearly crop water supply decreases from 9,298 million m^3 for the reference simulation to 8,189 million m^3 (-12%) for the strategy without diesel pumps and unofficial reuse. This reduction implies that the absence of unofficial reuse cannot be compensated by a higher farmers' uptake, since the groundwater abstraction remains constant throughout the various simulations.
For the strategy without diesel pumps, the lower amount of unofficial reuse is almost fully compensated by a higher farmers' uptake from the irrigation canals, resulting in an almost equal crop water supply as for the reference simulation of about 9,295 million m^3 annually.

Both strategies benefit from the different mixing ratio of the less saline irrigation water and the more saline unofficial reuse. The average salinity of the crop water supply goes down from 445 $g{\cdot}m^3$ for the reference simulation to 365 $g{\cdot}m^3$ for the strategy without diesel pumps and unofficial reuse. For the strategy without diesel pumps only, the outcome is less impressive with 440 $g{\cdot}m^3$.

Evapotranspiration

Effects of changes in the crop water supply, and the accompanying salinity, are reflected in the evapotranspiration.

Aggregated yearly values shows a decrease for the strategy without diesel pumps and unofficial reuse, where all crops are affected. Only rice gives an evapotranspiration close to the reference value. Taking the reference evapotranspiration at 100%, the strategy without diesel pumps and unofficial reuse comes up with an aggregated evapotranspiration of 96%, whereas the strategy without diesel pumps remains at 100%. Therefore a combined elimination of diesel pumps and unofficial reuse cannot be considered as a realistic alternative.

For the strategy without diesel pumps only, the evapotranspiration of the summer crops cotton and maize is negatively affected due to the used cropping pattern, the discrepancies between the calculated farmers' crop water requirements and the Ministry of Public Works and Water Resources allocation crop water duties, and especially lower rates of unofficial reuse. Some winter crops perform better, notably the vegetables and the long berseem, as a result of the improved irrigation water distribution.

Long term effects

Long term effects are mainly related to changes in the soil salinity. Simulations for the Eastern Nile Delta indicate a drop in the average soil salinity from 3.51 $mmho{\cdot}cm^{-1}$ to 3.28 $mmho{\cdot}cm^{-1}$ (-7%) for the strategy without diesel pumps and unofficial reuse after a period of 50 years. The much lower salinity of the crop water supply can be hold responsible. For the long term strategy without diesel pumps only, the result is close to the reference soil salinity, i.e. 3.50 $mmho{\cdot}cm^{-1}$.

The effects after 50 years in terms of evapotranspiration show that the strategy without diesel pumps and unofficial reuse still cannot compete with the reference simulation, despite improved soil conditions. Half the crops, with the emphasis on the summer crops and rice in particular, are able to increase their evapotranspiration when compared to the short term reference values, but not to such an extent that they can surpass the reference values.

Long term evapotranspiration rates for the strategy without diesel pumps cannot recover from the lower water supply to the summer crops. The more so because the irrigation water salinity, and thus the soil salinity, hardly shows improvements for this strategy. Also the winter crops remain unaffected on the long term, and therefore the aggregated evapotranspiration value stays equal to the reference value.

Spatial distribution evapotranspiration

Analyzing the spatial distribution of the aggregated relative evapotranspiration over the study area reveals the lowest standard deviation for the strategy without diesel pumps and unofficial reuse. However, the much lower average, aggregated relative evapotranspiration leaves this strategy as uncompetitive.

More interesting is the spatial variability in evapotranspiration obtained for the strategy without diesel pumps only. Here the average values are on a comparable level as for the reference simulation, but the standard deviation comes up with somewhat lower values. This indicates a more even distribution of the aggregated relative evapotranspiration over the area with less dips, which is also socially more acceptable for the farmers.

The long term simulations show, despite small improvements for either strategy, no significant deviations from the above mentioned trends.

Recommendations

The various simulations carried out for the Eastern Nile Delta show that the unofficial reuse of drainage water is a flexible, and, above all, indispensable source to supplement locally occurring shortages of irrigation water. Prohibiting the unofficial reuse is therefore likely to have adverse effects on the crop water supply and thus on the crop production.

Taking away the flexibility in the water management system by eliminating the unofficial reuse should not only be discouraged, but also single-sided improvements in the irrigation system by banning the diesel pumps as irrigation tools should be accompanied by further measures to minimize spillway losses. Therefore investigations into the disparities between the water duties used by the Ministry of Public Works and Water Resources, when allocating and distributing the irrigation water, and the calculated farmers' water requirements should provide the knowledge to arrive at substantial lower spillway losses to offset the reduced amounts of reuse. Also the use of a more uniform cropping pattern, instead of the segregated rice and maize cultivation, is likely to cut down spillway losses.

Following the reduced crop water supply, the strategy without diesel pumps and unofficial reuse also does not offer an alternative for the present situation in terms of evapotranspiration. When crop yields should be maintained at the current level or when authorities aim for an increase, the simulations made clear that this lies outside physical reality for both the short and the long term.

The strategy in which the diesel pumps have been eliminated for lifting water from the irrigation canals, but where the unofficial reuse remains permitted, presents itself as an alternative which could be considered. However, peak demands occurring in summer are difficult to meet with the available amounts of irrigation water and the reduced uptake capacity of the farmers.

Improvements in the water distribution for the strategy without diesel pumps in the summer cannot be established on the inter-calculation unit scale, given the specific cropping pattern of 1988 and the Ministry of Public Works and Water Resources allocation water duties. An optimum distribution, in relation to significantly lower spillway losses, can only be pursued after further examination of these two factors. Nevertheless, improvements are certainly to be anticipated on the intra-calculation unit scale. Application of the SIWARE model package on a single calculation unit is likely to confirm this.

The implementation of strategies prohibiting the use of diesel pumps will meet formidable obstacles. The use of diesel pumps is widely spread nowadays. Since it seems that the unofficial reuse remains necessary to maintain at least the present evapotranspiration rates, diesel pumps are also needed to provide enough lifting head for withdrawing water from the deeper excavated drainage canals.

The unlimited access of the diesel pumps to the irrigation canals on the other hand should be prevented. Therefore farmers should be persuaded to lift their irrigation water from the original sakkia sump, which is connected with the canal by means of a fixed diameter pipe. In this way both the lifting head and the uptake capacity can be limited, and shortages occurring in the irrigation system will be spread more uniformly over the whole area. In case their water requirements can still not be met, farmers should have the possibility to turn to the drainage canals. However, implementation of such a practice will require enforcement by a rigid control system.

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