TRAINING MANUAL SIWARE MODEL

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

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

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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.

REUSE OF DRAINAGE WATER PROJECT

TRAINING MANUAL SIWARE MODEL

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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.
30 (Main Report)	Analysis of Water Management in the Eastern Nile Delta, S.T. Abdel Gawad, M.A. Abdel Khalek, D. Boels, D.E. El Quosy, C.W.J.Roest, P.E. Rijtema, M.F.R.Smit, Reuse of Drainage Water Project, 1991.

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PREFACE

This manual is meant to be a guide for a 2-month duration training course concerning the SIWARE (SImulation of Water management in the Arab Republic of Egypt) model to be held twice in Wageningen, the Netherlands, from August until October respectively from October until December. The course should provide the trainees with insight in both model concepts and practical model application. Consequently, the manual consists of three parts:

- Part I dealing with the model concepts
- Part II dealing with the practical model application
- Part III containing exercises concerning both concepts and application

During the course lectures are given, exercises are made and discussed, and a case study is performed on a part of the Eastern Nile Delta. The basic set-up of the course is to provide the trainees with some theoretical backgrounds on a certain topic and subsequently make them apply the acquired knowledge directly, either through the exercises or in the case study. The appendix contains a tentative program.

It should be noted that this document is not a model manual. When applying the model one is therefore referred to the 'User's guide for program package SIWARE Version 1.0', 1988 by D. Boels, C.W.J. Roest and M.F.R. Smit. Reuse report 27. Reuse of drainage water project. Drainage Research Institute, Cairo and DLO Winand Staring Centre, Wageningen, Netherlands.

PART I: MODEL CONCEPTS

1 INTRODUCTION

Part I is structured similar to the SIWARE model itself. Following the pathway of the irrigation water from its main inlet 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, treated in the submodel DESIGN (chapter 1);
- 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, treated in the submodel WDUTY (chapter 2);
- the water distribution within the irrigation command areas resulting in a supply to the agricultural fields and operational losses to the drainage system, treated in the submodel WATDIS (chapter 3);
- the water losses from the area to the atmosphere through evaporation and transpiration, to the aquifer through leakage and seepage, and to the river/sea through the drainage system, treated in the submodel REUSE (chapter 4).

The part of the REUSE submodel dealing with field water application, infiltration, irrigation losses etc. is called FAIDS (section 4.1). FAIDS is also available as a field-scale water management model on a stand-alone basis and is therefore treated quite extensively.

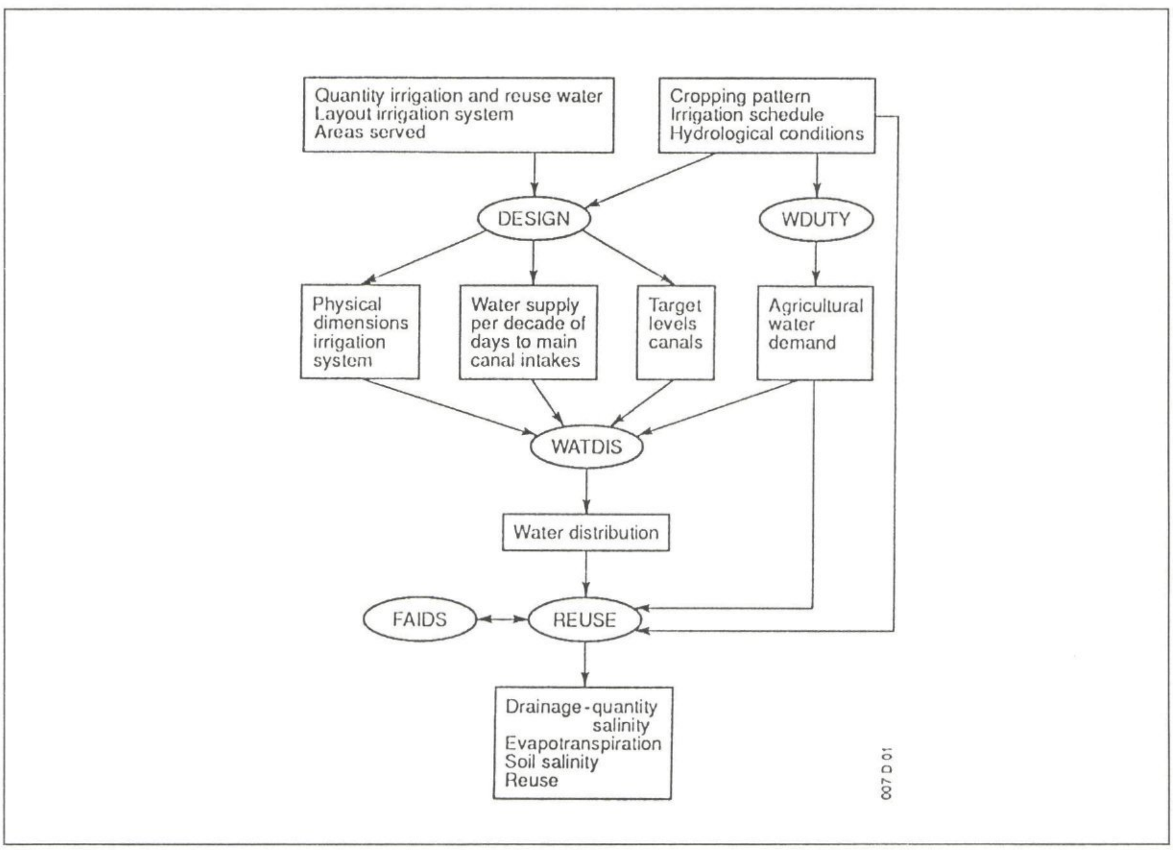


Figure 1: Schematization of the SIWARE simulation model, its submodels and required in- and output.

2 DESIGN OF THE WATER DISTRIBUTION SYSTEM (DESIGN)

2.1 General

With the program package SIWARE the evapotranspiration and drainage from all crops are calculated throughout the Nile Delta. These calculations can only be performed when the supplied quantity of water to the crops through time is known. In addition the quantity and quality of the generated drainage water at different locations can only be calculated correctly when also the operational losses released from the irrigation canals into the drainage canals are known. These data can basically be obtained in two ways:
- by measurements in the actual system;
- by calculations based on hydraulic principles and known water management practices.

The first option is only feasible when an existing situation is analyzed. The second option has to be used when the effects of future changes in water management have to be assessed. One might think in this case of extending the irrigated area or increasing groundwater use or drainage water reuse.

In order to perform such calculations the expected water distribution in the Nile Delta should be known. This distribution is mainly determined by the hydraulic properties of irrigation canals and the water allocation policy. Since it is virtually impossible to determine the actual dimensions of the system in the field, the program DESIGN designs a system, based on the existing layout, and the design criteria as were used by the Ministry of Public Works and Water Resources (MPWWR). It also determines the water allocation to the different canals given a certain total supply, according to the practice of the MPWWR. As a result a virtual water supply system is created which can be expected to respond to changes in water supply, water uptake etc., in a similar way as the real system. The subprogram WATDIS calculates the actual water distribution to the different subareas in the Nile Delta. DESIGN provides WATDIS with the following data:
- dimensions of irrigation canals (bed width, bed slope, bank slopes, bed roughness);
- dimensions of control structures;
- intake rates of main canals per each 10-day period;
- target water levels up- and/or downstream of control structures.

2.2 Design of irrigation canal systems

2.2.1 System description

An irrigation canal system is defined as a number of main canals for the distribution of irrigation water. Each main canal includes only one main intake and several branch canals. Control structures like weirs, orifices are functional components of the system. The required quantities of water for the area served are continuously supplied through the main intakes at preset rates at preset time moments. The distribution of available water resources among the main canal intakes is called water allocation and is subject to allocation procedures and policies.

The supply to branch canals is also continuous and the rate is controlled by maintaining certain preset water levels downstream of the canal intake. These water levels should be maintained during a certain period and are called target water levels. They are determined prior to the real distribution for a given discharge (water requirement in downstream areas) and downstream flow characteristics of the branch canal.

A branch canal of a main canal is called a first (high) order canal. A branch of a first order canal is called a second (low) order canal. The lowest order canal considered is a (hypothetical) distributary which serves a certain subarea. The supply to such an area is considered continuous and the distribution of water is assumed uniform.

When the most downstream part of a canal is not connected with a lower order canal, a tailend escape is present to prevent flooding of adjacent areas. Excess water is diverted to a drainage canal.

In certain situations canals may be used to supply water to an other main canal system. This affects the canal dimensions and water allocation of both main canal systems.

Basically the DESIGN submodel has not been developed for operational purposes. For this reason rotation is not implemented. The boundaries of the sub-areas are chosen in such a way that rotation takes place within this subarea in order to maintain a continuous supply. Such subareas are referred to as distributary areas or calculation units. Canals inside these units are represented in the model by a reservoir with a certain storage capacity and a spillway for water level control. Spilled water is diverted to drainage canals. This spillway represents the numerous spills at the end of the so called meskaas, the lowest order irrigation canals. Irrigation water is withdrawn from the (hypothetical) reservoir by farmers through lifting. In Egypt the sakkia and diesel pumps are mainly used. The capacity of these lifting tools depends on the lifting head and the total irrigation capacity depends on the area grown with rice.

Reuse of drainage water is implemented through pumping stations which lift drainage water from drainage canals and deliver it to irrigation canals. Drainage water is an official source for providing a certain area with irrigation water. These pumping stations are treated in the DESIGN submodel as an external irrigation water source which provides known water quantities to a certain irrigation canal. The presence of a reuse pumping station has consequences for the required conveyance capacity of the canals upstream of the mixing location.

2.2.2 Design criteria

Irrigation canal systems are designed to convey certain quantities of water and to facilitate the required distribution of water. The conveyance capacity of canals is based on a discharge rate which occurs with a certain probability. The control features of structures should allow a proper control of water levels or discharge rates in a certain range of minimum and maximum discharge.

A main canal system serves a certain area where a certain quantity of water is required. This quantity will vary with respect to time depending on the activities which require water. The maximum quantity of water that the irrigation canals should be able to convey is determined by the maximum demand for (additional) water in the area served. Demand for water comes from:

- Agriculture.
  Determining factors are the cropping pattern and the water requirements of different crops.
- Municipal water requirements.
  With respect to this requirements the number of inhabitants and the average water use per capita play a dominant role.
- Industrial water use.
  Industries use water for cooling, processes and cleaning. The requirements are determined by the type, capacity and number of factories in the area served.
- Navigation.
  In certain canals a minimum waterdepth is required for navigation. This waterdepth can be maintained through a certain minimum discharge. When this discharge exceeds the downstream water requirements the excess will most probably be spilled to a drainage canal.
- Conveyance and operational losses.
  Water is lost through evaporation and leakage. These losses are called conveyance losses. When the supply rate exceeds the uptake rate, for instance during night time when farmers do not use the full capacity of their irrigation tools, the water levels in the irrigation system rise. With water levels above tail-end escape levels, part of the excess is spilled to a drainage canal. The spilled quantities are called operational losses.

The sources for irrigation water in the Nile Delta of Egypt are:

- Nile water.
  Water from this source originates from the Nile basin and is stored in Lake Nasser. Through the High Dam a full control of water releases is implemented. As an average a total quantity of about 85 billion cubic meter of water is annually available of which Egypts' share is 55 billion cubic meter according to the water treaty between Egypt and Sudan.
- Ground water.
  In the southern parts of the Nile Delta groundwater of good quality is available. The ground water reservoir is recharged by canal infiltration (conveyance losses) which has a good quality and regional leakage from irrigated lands with a moderate quality. Groundwater abstraction is practiced locally at relatively low rates, which makes it sustainable.
- Rain.
  Small amounts of rainfall in the northeast and northwest coasts and the Nile Delta (about 150 mm annually), decreasing to the south (30 mm in Cairo).
- Drainage water.
  Drainage water is a mixture of drainage water from irrigated land, industrial and municipal releases and operational losses from irrigation canals. When this mixture has a moderate salinity, it is suitable for reuse, provided that it does not contain toxic components. The quantities of available drainage water are determined by the total irrigation water supply, the cropping pattern and other water releasing activities. The determination of these quantities is one of the reasons that the SIWARE model has been developed.

Table 1 shows the sources and water requirements in the Eastern Nile Delta.

Table 1: Demands for water in the Eastern Nile Delta and available resources (1986)

Demand	Quantity (10^6 m^3)	Sources	Quantity (10^6 m^3)
Agriculture	10,175	Nile	11,645
Municipal & industry	587	Re-use (pumps)	925
Conveyance losses	342	Reuse (local)	1,163
Tail end losses	342	Groundwater	379
Spill losses	2655	Rainfall	4

For designing purposes a good estimate of the total maximum demand has to be made. As a rule of thumb the demand is related to the area served. The design characteristics of irrigation canals in Egypt are listed in table 2. The maximum discharge rate for the smaller canals is based on a maximum demand for water when rotation occurs. The major canals, serving areas of 200,000 feddan or more have been designed for half of the maximum demand. These canals convey water on a continuous basis to areas where rotation occurs.

Table 2 Design characteristics for irrigation canals in Egypt

Area served (fed.)	Maximum disch. ($m^3.s^{-1}$)	Water depth (m)	Bed width (m)	Bed slope $10^{-5}m.m^{-1}$	Maximum velocity ($m.s^{-1}$)
< 750	0.435	0.86	1.0	13.0	0.284
1000	0.57	0.88	1.5	12.0	0.284
2000	1.175	1.14	2.0	11.0	0.322
5000	2.958	1.57	3.5	9.0	0.375
10,500	6.090	1.91	6.0	8.0	0.419
14,100	8.178	2.07	7.0	7.0	0.438
20,500	11.89	2.24	9.0	7.0	0.461
25,000	14.79	2.41	10.0	7.0	0.484
32,500	18.84	2.50	12.0	7.0	0.498
200,000	58.0	3.17	27.0	5.9	0.60
400,000	116.0	3.55	45.0	5.5	0.67
600,000	174.0	3.76	61.0	5.3	0.71
800,000	232.0	3.91	76.0	5.2	0.74

For practical applications, the design characteristics have been described as functions of the area served. The following functions have been derived from table 2:

$$Q_{min} = 5.8 * 10^{-4} A_s$$

$$Q_{min} = 2.1 * 10^{-4} A_s$$

$$H_{max} = \frac{8.5 * 10^{-4}}{\frac{0.0124}{A_s^{0.403}} + 1.5 * 10^{-4}}$$

$$S_o = 10^{-5} * (\frac{69.377}{A_s^{0.314}} + 4.0)$$

$$W_b = 8.68 * 10^{-2} A_s^{0.439} + 10.5 * 10^{-4} A_s^{0.842} - H_{max}$$

$$C_{chezy} = 21.3957 * A_s^{0.0698}$$

Where: Q_{max} = peak design discharge ($m^3.s^{-1}$);
A_s = area served (feddan);
Q_{min} = minimum design discharge ($m^3.s^{-1}$);
H_{max} = water depth at maximum design discharge (m);
S_0 = bed slope ($m.m^{-1}$);
W_b = bed with of canal (m);
C_{chezy} = Chezy constant.

The dimensions of control structures (orifices or weirs) which are calculated in the DESIGN submodel are the following:

- the (effective) width;
- the difference in bed height upstream and downstream of the structure;
- In addition for weirs the minimum crest height and for orifices the maximum orifice opening is calculated.

The difference in bed height upstream and downstream of an orifice is determined in such a way to assure the best possible control. The required static head for a discharge, q, per unit width through the opening of an (submerged) orifice is derived from:

$$\Delta h = (\frac{q}{C})^2 * (\frac{1}{h_g})^2$$

Where: Δh = static head (m);
q = discharge per unit width of structure ($m^2.s^{-1}$);
h_g = height opening orifice (m);

C = constant.

The most sensitive control is obtained when the first derivative of Δh with respect to h_g equals -1:

$$\frac{\partial}{\partial h_g}(\Delta h) = (\frac{q}{C})^2 * (-2) * h_g^{-3} = -1$$

From this equation the relationship between static head and discharge is solved:

$$\Delta h = (\frac{q}{2 * C})^{\frac{2}{3}}$$

For a given design-discharge and pertaining waterdepths upstream and downstream of the structure, the optimum value for the difference in bed level, Δb, is determined with:

$$\Delta b = h_d + \Delta h - h_u$$

Where: Δb = difference in bed level upstream and downstream control structure (m);
h_u = water depth downstream structure (m);
h_d = water depth upstream structure (m).

The minimum crest height of a weir is calculated for a maximum discharge and a water depth that exists at that moment in the upstream canal section. The minimum crest height is calculated from:

$$h_{w,min} = H_{max} - (\frac{q}{C_w})^{\frac{2}{3}}$$

Where: q = discharge per unit width ($m^2.s^{-1}$);
C_w = constant.

The width of the hypothetical spill, W_s, inside the calculation unit is a function of the area of the calculation unit, A_d, and hypothetical length of the hypothetical meskaa, L_d. These functions are:

$$L_d = 0.5 * \frac{(0.4 + 2.33 * 10^{-4} A_d^{0.559}) * A_d * 42.0}{A_w}$$

Where: L_d = total length of canals inside calculation unit (m);
A_d = area calculation unit (feddan).

The total length and the wetted surface per unit length of the canals in the calculation unit determine the conveyance losses.

$$A_w = \frac{H_{max} + H_{min} + 2.6}{2.0}$$

Where : A_w = wet area of irrigation canals inside calculation unit per unit length of the canals ($m^2.m^{-1}$);

The spill height, h_s, is a function of the maximum water depth, H_{max}, and maximum discharge per unit width, q_{max}. The maximum discharge equals the design-maximum supply rate to the calculation unit. The water depth, H_{max}, is equal to the maximum water depth in a canal that serves a similar area. The hypothetical width of the spill is:

$$W_s = \frac{A_d}{3750.0} + 2.73 * 10^{-3} * L_d$$

Where: W_s = hypothetical width of representative spill in calculation units (m);
H_{min} = waterdepth at minimum design discharge (m).

The crest height of the hypothetical spill is at least equal to the minimum water depth, H_{min}. When the difference between the maximum water depth and the static head that is required for discharging the maximum discharge over the spill is more than the minimum water depth, the higher value is selected. The effective width of weirs and orifices is set to 0.8 times the bed width of the canal.

2.2.3 Design procedure

The design procedure starts with identifying the calculation units. For this purpose the irrigation districts are subdivided into smaller areas according to a number of criteria:
- supply continuous, rotation within the boundaries of calculation units;
- uniform soil type;
- uniform salinity distribution in deep aquifer;
- uniform vertical resistance of clay cap;
- uniform drain depth and -spacing;
- uniform landuse;
- uniform climatical conditions;
- respecting the boundaries of irrigation districts;
- irrigation water supply through only one major canal;
- produced drainage water to be released to one major drainage canal.

The size of each calculation unit is determined.

In the next step the major irrigation canals are identified. The intakes of main canals and of the calculation units, control structures and the reuse pumping stations are located. For design purposes the average expected supply rate of reuse stations has to be known. The canals are subdivided into a number of sections. The coordinates of all relevant locations (control structures, reuse pumping stations and nodes of the canal sections) are obtained from a map.

The length of each canal section is calculated from the coordinates in the nodal points.

Starting in the most downstream canal section the area served by each node is calculated by adding all areas served. The area which is intended to be irrigated with drainage water downstream of a certain node, is subtracted from the area served in all upstream nodes. If a certain other irrigation canal delivers water to the canal under consideration a similar procedure is followed. The areas served in all upstream nodes of the canal section which receives water are decreased with the area served through the feeder. The area served in all upstream nodes of the feeder is increased with the area served by the feeder which area belongs to that other main canal system. The area served by branch canals is added to the area served in the upstream nodes of the connected canal. Through this procedure the area served by each nodal point is obtained.

The canal dimensions and bed slopes in each node are determined with the design formulae. DESIGN determines only relative bed heights. The height in a certain node is calculated from the bed height in the previous node, the length of the canal section and the bed slope. The differences in bed level at control structures are calculated for a maximum and minimum discharge. The required water depths are obtained through the determination of the backwatercurve upstream and downstream of the control structure. The larger one of the two solutions for the difference in bed levels is selected.

An example is given in Tables 3 and 4. In Table 3 the numbers of the different nodes of Bouhia canal are given together with their coordinates and the presence of distributary intakes and control structures. Table 4 gives the canal dimensions for the Bouhia canal resulting from the procedure described above.

2.3 Management of the irrigation system

The management of the system includes the determination of the quantities of water to be supplied at different time moments to the main canal intakes (allocation) and the calculation of settings of control structures or the target water levels to realize a fair water distribution. In this approach the quantity of available water is known.

2.3.1 Water allocation

Water allocation is defined as the distribution of available quantities of water among main intakes according to certain rules. This means that with given water consuming activities in different areas, the required (additional) water quantity is determined which will be supplied to each main canal system during certain periods.

The activities which require water have been listed in the previous text. The municipal and industrial water use will not vary significantly during the year, while the crop water requirements which depend largely on crop type and development and weather conditions will show a wide variation. For the Nile Delta the Ministry of Public Works and Water Resources has prepared tables for the average water requirement of each crop per ten daily period. In

Table 3: Location of nodes Bouhia canal and its structures

node number	X-coordinate (km)	Y-coordinate (km)	Remark
1	116.00	88.25	intake
2	117.01	92.44	
3	119.84	95.13	
4	122.43	97.31	distributary 37
5	122.50	100.00	distributary 29
6	122.68	102.39	head regulator
7	125.21	106.10	distributary 30
8	128.55	107.96	distributary 32
9	128.55	108.60	
10	128.00	109.25	distributary 24
11	129.68	110.57	head regulator
12	132.39	112.86	distributary 31
13	132.87	115.50	head regulator
14	136.25	117.74	
15	137.50	118.50	distributary 25
16	138.66	119.21	head regulator
17	141.00	119.55	
18	143.00	119.90	tail end, weir

Table 5 these requirements have been summarized for the major crops on a monthly basis. Instead of the average crop water requirements from Table 3, optionally local requirements for each calculation unit (to be obtained through WDUTY submodel) can be applied. The water demands in a certain calculation unit are determined from the crop water requirements and the area grown with different crops. The areas of different crops, the total crop water requirements, the ground water use and optionally the total rainfall in a calculation unit are transferred to the canal node where the intake of the calculation unit is located.

To allocate water the demands and the sources (ground water, reused drainage water and rain) at the main canal intakes have to be known. The procedure to get this information includes the determination of demands and sources in each node. Then a summation procedure similar to the one for designing canals is applied. Conveyance losses are considered as a water demand. Canal leakage is a function of the wet area, drain depth in the adjacent agricultural area, clay cap thickness, vertical hydraulic conductivity and the water pressure in the deep aquifer. Parameters for this function are calculated for each canal section and applied in a formula for conveyance losses by leakage. Evaporation is added and an estimate of the conveyance losses is obtained. The losses are added to the demand for water in the considered node.

Table 4: Dimensions Bouhia canal.

Node number:	Area served (feddan):	Remarks:	Bed width (m):	Bed level (m):	Chezy constant ($m^{½/s}$):
1			20.7	5.31	46
2			20.7	5.05	46
3			20.7	4.81	46
4	134880		20.7	4.60	46
5	112480		18.2	4.43	46
6		Head regul.	18.2	4.28	46
7	91210		15.7	3.59	46
8	85050		15.0	3.34	45
9			10.9	3.30	45
10	53860		10.9	3.25	45
11		Head regul.	10.9	3.10	45
12	32620		7.7	2.70	42
13		Head regul.	7.7	2.50	42
14			4.8	2.16	40
15	16500		4.8	2.05	40
16		Head regul.	4.8	1.95	40
17			4.8	1.35	40
18		Tail end	4.8	1.20	40

If a certain canal also supplies water to another main canal system, a fraction of the total demand and sources in the canal node in the receiving main canal system is transferred to the node of the feeder canal. This fraction is the ratio of the area served by the feeder over the total area served downstream of the node in the other main canal system. The demand and sources in both canal systems are adjusted similar to the design procedure in such cases.

The summation procedure ends at the intake of each main canal system. For each distinguished period (ten days) the totals of the different demands are determined. In a similar way also the totals of the area of different crops, the total groundwater use, the total quantity of reused drainage water and (optionally) the total quantities of rainfall are determined for each main canal system.

The total quantity of available water which originates from different sources is allocated to the different main canal intakes according to the demands. In principle the allocation should be equal to the demands. When, however, the demands exceed the availability, decisions have to be made on which kind of activity will receive less water than required. If it has been decided to reduce the irrigation water supply, two options are available: the areas of different crops are adjusted in order to match demands with the allocation or the crop water demands

Table 5: Crop water duties according to the Ministry of Public Works and Water Resources ($m^3.fed^{-1}$)

Month	Long bers.	Wheat	Short bers.	Veget	decid trees	maize	rice	cot-ton
Jan	340	172	-	290	202	-	-	-
Feb	340	172	-	294	197	-	-	349
Mar	676	349	-	584	340	-	-	323
Apr	756	328	-	706	542	-	-	302
May	210	-	-	794	546	-	181	416
Jun	-	-	-	668	617	340	2255	655
Jul	-	-	-	130	613	651	1781	756
Aug	-	-	-	-	588	613	2629	378
Sep	-	-	-	-	491	706	1953	-
Oct	55	-	286	533	391	378	-	-
Nov	302	176	592	706	239	-	-	-
Dec	378	403	769	794	197	-	-	-
Total	3058	1600	1646	3200	4964	2688	8800	3179

will be met to a certain extent only while the cropped areas remain unchanged. In the latter case the available water quantity can be distributed proportionally with the demands, or water can be supplied to certain crops according to their demands on the account of the supply to other crops.

A number of options for water allocation are included in DESIGN:
- allocation is set equal to the demands, in this case DESIGN calculates the total supply (= total demand);
- allocation is proportional with the demands;
- a (selectable) part of the available quantity is allocated proportional to the demand, the remaining part is allocated to certain crops ('key-crops') according to their demands;
- a (selectable) part of the available quantity is allocated proportional to the demand, the remaining part is allocated proportional to the area served.

To obtain the actual quantity of water which will be supplied to a main canal intake, the allocated quantity is reduced with the quantity of water which is available in the area itself: groundwater, drainage water and effective rainfall.

2.3.2 Water distribution control

The objective of water distribution control is to realize a fair distribution of irrigation water. Two types of control can be distinguished. The first control is based on pre-setting of required discharge rates or target water levels and assumes steady state conditions during each distinguished time period. The second type is based on manipulation of control structure settings according to the pre-set discharge rates or target waterlevels in order to realize the intended water distribution. The first type of control is included in DESIGN and the second one in WATDIS, where deviations from the average situations have to be compensated.

For the determination of control structure settings or target water levels the following assumptions have been made:

- the water allocation rule is applicable at all levels;
- irrigation water uptake by farmers is continuous;
- steady state conditions within the time step (follows from assumption 2);
- no tailend losses occur;
- constant supply rate of drainage water for reuse during the time step;
- drainage water is only used downstream of the mixing location;
- groundwater is directly applied to the fields.

Based on the supplied water quantities to the main canal intakes, the required discharge in each canal node during each time period is calculated. The corresponding water depth in each canal node is calculated, starting with the most downstream node where the waterdepth is set equal to the crest height of the tailend escape. Assuming steady state conditions, water depths in upstream nodes are calculated. When in a certain node a control structure is present the downstream water depth is calculated according to the described procedure. The upstream water depth is by definition set equal to the maximum water depth. The calculated downstream water level is the target water level. The required structure setting is calculated for the known static head and discharges. The DESIGN submodel finally provides a table with target water levels upstream and downstream of control structures and optionally the required structure setting (crest height or gate opening).

2.4 Options for application of DESIGN

The DESIGN submodel can be applied for simulation purposes and provides the WATDIS submodel with the required input data.

Potentially DESIGN could also be used for planning purposes on a national scale for the water allocation to the Irrigation Directorates. The procedure to implement such an application is to define the interface between the agricultural Markaz and the Irrigation Districts. This interface should specify which areas of an Irrigation Districts belong to a certain Markaz. Also the irrigation main canal systems have to be defined. Data on cropped areas can be obtained from the Markaz and with a pre-processing program which is available in the SIWARE model, the total areas of different crops in the Irrigation Districts can be calculated. The DESIGN submodel could calculate the total areas of different crops per main canal intake. Based on the official or average crop water requirements in different regions, the total crop water requirement per main canal intake can then be calculated with DESIGN. For given quantities of available Nile water, groundwater, drainage water and data on industrial and municipal water requirements in different Irrigation Districts, the DESIGN submodel could calculate the quantities of irrigation water which will be supplied to the different main canal intakes. In the same procedure, required discharge rates to intakes of the major lower order canals can be calculated.

A second potential application of DESIGN is its use as a tool for designing irrigation canal systems. With a planned layout of the canals with known area served downstream different relevant canal nodes, the dimensions can be determined according to the design criteria in Egypt. The definite locations of control structures have to be chosen by the designer, based on the information obtained from the DESIGN submodel.

3 FARMERS IRRIGATION WATER DEMAND (WDUTY)

In irrigated agriculture it is common to calculate water requirements of crops based on potential evapotranspiration of a reference crop, to multiply these rates with appropriate crop factors, and to allow for a certain amount of leaching. By taking into account the available soil moisture in the rooting depth of crops between field capacity and wilting point and allowing soils to dry out to a certain degree, the irrigation interval is determined. Having thus established the irrigation amounts and irrigation frequencies of individual crops, field irrigation management an operation systems can be determined.

In reality crop water requirements depend on much more factors and circumstances. Egyptian farmers in the Nile Delta are supposed to irrigate their fields by lifting (freely available) irrigation water from small meskaa canals. These canals are supplied with water on a rotational basis. Since individual farmers are free to withdraw the amount of water they need, or which they can manage to withdraw, actual farmers water demand determines to some extent the distribution of irrigation water among farmers.

For model simulations with the SIWARE model it is therefore important to make good estimates of actual crop water requirements during all crop growth stages.

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 crops are 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 cropping pattern, be it accompanied by corresponding changes in water supply due to changed total demand for water or not, will result definitely in changes in drainage water quantity and salinity and seasonal distribution of both.

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 farmers behavior with respect to the amounts of water they consider necessary for irrigating their crops. These quantities may deviate considerably from official water requirement figures used by the Ministry of Public Works and Water Resources for the official water allocation strategy.

Farmers demand for irrigation water depends on initial soil moisture conditions in the field. Farmers will try to maximize the quantity of irrigation water given to 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 official water requirement and 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 farmers demand for irrigation water influences water distribution, this demand is calculated with the model WDUTY, before water distribution is simulated. For each calculation unit in the Eastern Nile Delta and for each irrigation turn of each crop, the quantity of water, farmers will use under the conditions of unlimited supply of irrigation water, is calculated. In this procedure, hydrological conditions for each calculation unit are taken into account. Initial moisture conditions prior to each irrigation are simulated using the evapotranspiration and drainage modules developed for the REUSE model.

Almost 70% of irrigation water provided to fields by irrigation is used for evapotranspiration and 30% is lost by leaching and subsequent drainage, and leakage to the aquifer. Since the majority of irrigation water provided is used for evapotranspiration, this process plays a key role in the determination of water requirements of crops.

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

In the simulation of the actual evapotranspiration the approach of Rijtema (Rijtema and Abou Khaled, 1975) has been used. In this approach, evapotranspiration is considered potential, until in the plant a critical leaf water suction is reached, at which plant stomata are closing and reduction starts. In the model this critical leaf water potential is translated into a fraction of total available soil moisture, 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 evapotranspiration model accounts for salinity effects through the osmotic potential and also takes the capillary flux into the root zone into account.

Since 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 crop development data such as crop height and relative soil cover for different stages in the growing season 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.

It should be noted that WDUTY is using the FAIDS submodel which will be described in the next chapter. When called by WDUTY, FAIDS assumes an ample water supply to determine the farmers demand. For normal on-farm water management simulation, FAIDS is called by REUSE and the actual water supply is used in order to calculate the amount and the salinity of the generated drainage water. Since the FAIDS model will also be available as a stand-alone one dimensional water management model, its description will be somewhat more extensive.

The main and foremost factor affecting crop water requirements is the actual evapotranspiration rate. This rate, in turn, is influenced by a number of factors which play an important role in irrigated agriculture:

- climatologic parameters, such as net radiation, wind velocity, relative humidity, temperature, etc.;
- soil characteristics, such as soil moisture retention curve, unsaturated hydraulic conductivity, soil salinity, etc.;
- hydrological circumstances, such as drain depth, drain distance, entrance resistance of drains, saturated hydraulic conductivity, piezometric head, etc.;
- crop characteristics, such as crop height, soil cover, rooting depth, growing period and crop development, internal plant resistance against water transport, suction in plant leaves at which stomata are closing, etc.;
- irrigation frequency.

The second aspect influencing crop water requirements concerns irrigation water losses during field application, which are influenced by:

- irrigation method: basin irrigation, furrow irrigation, sprinkling, drip irrigation, etc.;
- field dimensions: length and width of basins;
- soil characteristics: cracking behavior, infiltration rate, surface roughness, initial soil moisture content, etc.;
- geo-hydrological circumstances;
- leaching fraction;
- crop characteristics: resistance of crops against prolonged ponding, etc;
- irrigation stream size.

3.1 Evapotranspiration

Rijtema and Abou Khaled (1975) distinguished three climatological zones in the Nile Delta in Egypt: the Coastal region, the Central Delta region, and the Desert Delta region. On the basis of standardized long term average meteorological data for these regions, these authors calculated mean monthly atmospheric evaporative demands, as a function of crop height and soil cover fraction. These data have been recalculated to potential evapotranspiration per 10-day periods. In Table 6 the data for the Coastal Delta region are presented as an example.

Reduction factors of evaporative demand for incomplete soil cover by crops, according to Rijtema and Abou Khaled (1975), are given in Table 7. These factors account for evaporation of soil without plant cover for medium dry bare soil conditions. For rice the maximum evaporative demand is calculated as the weighted average of both crop transpiration and open water evaporation.

Table 6: Mean atmospheric evaporative demand and open water evaporation (E_o) Coastal Delta region (mm.day^{-1})

10-day period	crop height (m)										
	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	E_o
1	1.10	2.29	2.90	3.21	3.45	3.67	3.85	4.03	4.16	4.25	1.66
2	1.30	2.45	3.08	3.39	3.65	3.87	4.06	4.25	4.37	4.47	1.78
3	1.44	2.63	3.28	3.60	3.86	4.08	4.28	4.48	4.61	4.70	2.06
4	1.62	2.89	3.57	3.91	4.19	4.43	4.63	4.84	4.97	5.08	2.29
5	1.82	3.14	3.86	4.23	4.52	4.77	4.99	5.21	5.35	5.46	2.37
6	2.09	3.40	4.14	4.51	4.80	5.06	5.28	5.50	5.65	5.76	2.87
7	2.41	3.82	4.63	5.03	5.35	5.64	5.88	6.12	6.28	6.40	3.23
8	2.76	4.27	5.12	5.55	5.89	6.19	6.44	6.70	6.87	7.00	3.56
9	3.12	4.57	5.42	5.85	6.19	6.49	6.75	7.00	7.17	7.30	3.95
10	3.41	4.80	5.63	6.04	6.38	6.67	6.92	7.17	7.33	7.46	4.32
11	3.75	5.10	5.93	6.34	6.68	6.97	7.21	7.46	7.63	7.75	4.61
12	4.18	5.46	6.30	6.72	7.05	7.35	7.60	7.85	8.02	8.14	5.11
13	4.56	5.71	6.51	6.91	7.23	7.51	7.75	7.99	8.15	8.28	5.54
14	4.95	5.96	6.75	7.14	7.46	7.73	7.97	8.20	8.36	8.48	6.11
15	5.28	6.23	6.98	7.36	7.66	7.93	8.15	8.38	8.53	8.64	6.29
16	5.55	6.46	7.20	7.57	7.87	8.13	8.35	8.58	8.73	8.84	6.60
17	5.81	6.64	7.36	7.71	8.00	8.25	8.47	8.69	8.83	8.94	7.04
18	6.01	6.89	7.61	7.97	8.26	8.51	8.73	8.95	9.09	9.20	7.09
19	6.23	7.10	7.82	8.19	8.48	8.73	8.95	9.17	9.31	9.42	7.37
20	6.32	7.21	7.94	8.30	8.59	8.84	9.06	9.28	9.42	9.53	7.64
21	6.23	7.10	7.81	8.16	8.45	8.69	8.91	9.12	9.26	9.37	7.37
22	6.00	6.84	7.52	7.86	8.13	8.37	8.57	8.78	8.91	9.01	7.08
23	5.74	6.61	7.29	7.64	7.91	8.15	8.35	8.56	8.70	8.80	6.89
24	5.43	6.39	7.09	7.44	7.72	7.96	8.17	8.38	8.52	8.62	6.67
25	5.10	6.17	6.92	7.30	7.60	7.87	8.09	8.32	8.47	8.58	6.06
26	4.70	5.82	6.60	7.00	7.31	7.58	7.82	8.05	8.21	8.33	5.74
27	4.26	5.32	6.07	6.45	6.75	7.02	7.25	7.47	7.62	7.74	5.12
28	3.77	4.73	5.42	5.77	6.05	6.29	6.50	6.70	6.84	6.95	4.60
29	3.19	4.13	4.77	5.09	5.35	5.57	5.76	5.95	6.08	6.18	4.07
30	2.83	3.80	4.45	4.78	5.04	5.26	5.46	5.65	5.78	5.88	3.54
31	2.42	3.33	3.95	4.27	4.52	4.74	4.93	5.12	5.24	5.34	3.01
32	1.86	2.77	3.33	3.61	3.84	4.03	4.20	4.37	4.48	4.56	2.24
33	1.42	2.44	3.00	3.28	3.51	3.70	3.87	4.04	4.15	4.23	2.19
34	1.14	2.16	2.72	3.01	3.23	3.43	3.60	3.77	3.88	3.97	1.90
35	1.01	2.08	2.67	2.96	3.19	3.40	3.57	3.75	3.87	3.95	1.47
36	1.06	2.23	2.85	3.16	3.41	3.62	3.81	3.99	4.12	4.21	1.53

Table 7: Reduction factor of evaporative demand for incomplete soil cover percentage

soil cover percentage	Coastal Delta region		Central Delta region		Desert Delta region	
	winter	summer	winter	summer	winter	summer
0	0.27	0.32	0.28	0.38	0.25	0.29
10	0.34	0.40	0.35	0.47	0.32	0.38
20	0.41	0.47	0.43	0.54	0.39	0.45
30	0.49	0.55	0.50	0.62	0.47	0.52
40	0.57	0.63	0.58	0.69	0.55	0.61
50	0.67	0.72	0.66	0.78	0.65	0.70
60	0.78	0.82	0.78	0.86	0.76	0.80
70	0.86	0.89	0.87	0.91	0.85	0.88
80	0.94	0.95	0.94	0.96	0.93	0.94
90	1.00	1.00	1.00	1.00	1.00	1.00

The calculation method of readily available soil moisture according to Rijtema and Abou Khaled (1975) has been adapted to account for the osmotic suction in the soil solution due to dissolved salts. The following relation between leaf water suction, crop transpiration, and soil physical conditions can be given:

$$\psi_l = E(r_{pl} + \frac{b}{k}) + \psi_s + \psi_{os}$$

where: ψ_l = leaf water suction (bar);
E = evapotranspiration rate (mm.day^{-1});
r_{pl} = crop resistance for water flow from root surface to sub-stomatal cavities (bar.day.mm^{-1});
b = geometry and activity factor of the root system (bar);
ψ_s = mean soil matrix suction in root zone (bar);
k = unsaturated hydraulic conductivity at soil water suction ψ_s (mm.day^{-1});
ψ_{os} = mean osmotic suction in crop root zone at soil water suction ψ_s (bar).

The dependence of the osmotic pressure on total solute concentration is given by the Van 't Hoffs' equation:

$$\psi_o = \frac{n\,R\,T}{V}$$

where: ψ_o = osmotic pressure (bar);
n = number of moles (mol);
V = volume (m^3);
R = gas constant;
T = absolute temperature (°K).

This equation is valid for an ideal solution of non-dissociating substances. For a completely dissociating salt, like NaCl, both ions Na^+ and Cl^- contribute to the osmotic pressure. In the soil solution several ions have to be accounted for. Especially at high concentrations, formation of complexes of separate ions becomes important (Abdel Khalek and Blömer, 1984). For computing the osmotic pressure, it is therefore necessary to evaluate the total molality of all ions and complexes together. In the model approach, the Cl^- ion has been selected as a tracer ion, because it is not involved in precipitation and dissolution processes, dissociation and association reactions, nor in adsorption. The Cl^- concentration in soil solution will be known at all times as an output of the salinity sub-model.

For all water samples collected from the drainage system in the Eastern Nile Delta during 1980 through 1983 the model COMPLEX (Abdel Khalek and Blömer, 1984) has been used to calculate the total molality of cations, anions and complexes together. By curve fitting of the computed (ψ_o) against Cl^- concentrations the following empirical relation for the Eastern Nile Delta has been found (Fig. 2):

$$\psi_o = 0.1409\ [CL^-]^{0.7903}$$

where: $[Cl^-]$ = Cl^- concentration ($eq.m^{-3}$).

The osmotic suction at actual soil moisture content is assumed inversely proportional to this actual soil moisture content:

$$\psi_{os} = \frac{\theta_{ma}+\theta_{wp}}{\theta_a+\theta_{wp}}\ \psi_o$$

where:
- ψ_{os} = mean osmotic suction in the crop root zone at actual soil moisture fraction, θ_a (bar);
- ψ_o = osmotic suction at field capacity (bar);
- θ_a = available soil moisture fraction ($m^3.m^{-3}$);
- θ_{ma} = maximum available soil moisture fraction ($m^3.m^{-3}$);
- θ_{wp} = soil moisture fraction at wilting point ($m^3.m^{-3}$).

The crop resistance (r_{pl}) for water flow increases with depletion of available soil moisture. Taking a minimum value of 0.5 $bar.day.mm^{-1}$ at field capacity and a maximum value of 3.60 at wilting point, the following relationship is implicitly assumed:

$$r_{pl} = 0.613\ \ln\ \psi_s + 1.493$$

Using the empirical relationships given by Rijtema and Abou Khaled (1975) for (ψ_s), (k) and (b), and introducing the relations for (ψ_{os}) and (r_{pl}) in the general equation, the following relation between (E) and (θ_a) can be derived:

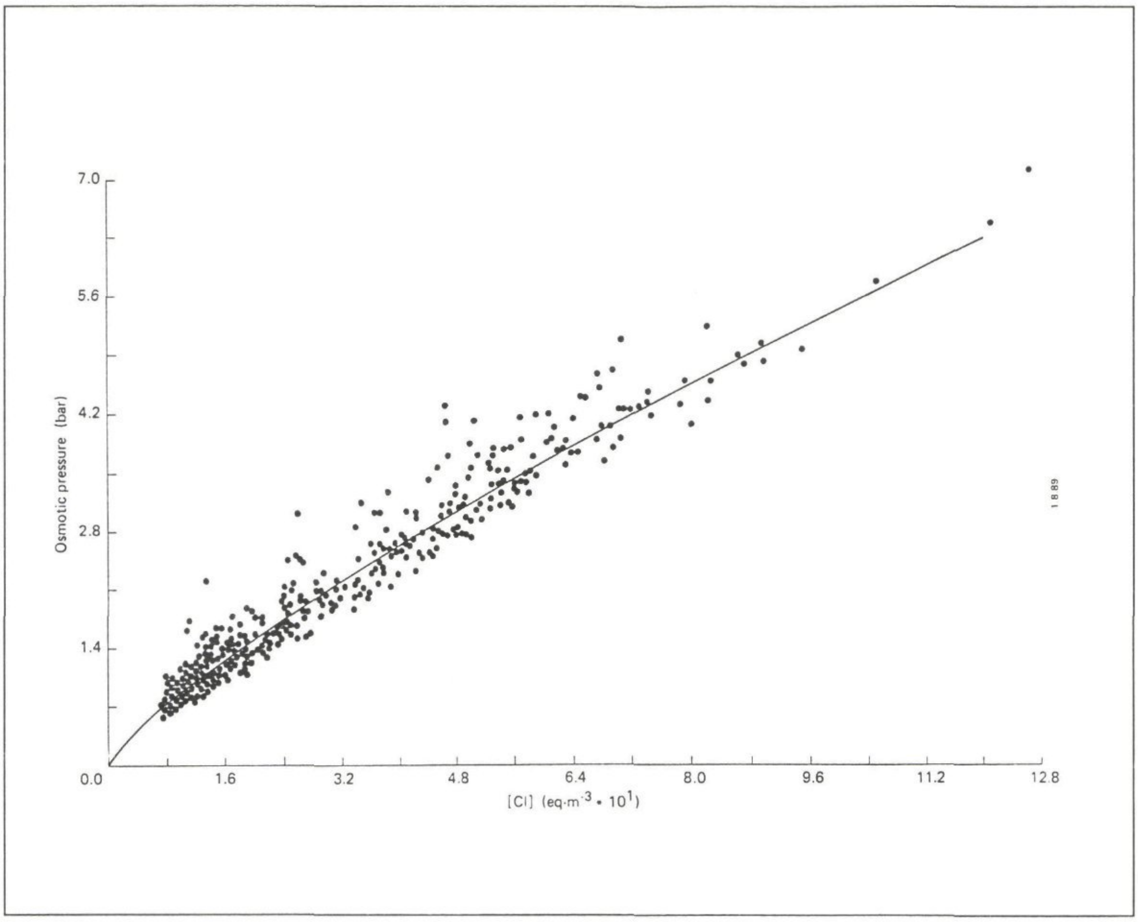


Figure 2: Empirical relation between osmotic pressure (bar) and Cl^- concentration

$$\psi_l = E\left(3.60 - 0.613\,\alpha\,\theta_a + \frac{0.1275}{d_w\,a'}\,e^{-1.4\,\alpha\,\theta_a}\right) + 16\,e^{-\alpha\,\theta_a} + \psi_o\,\frac{\theta_{fc}}{\theta_a + \theta_{wp}}$$

where:
- α = soil type dependent constant;
- d_w = effective root zone depth (mm);
- a' = constant ($mm.day^{-1}$);
- θ_{fc} = soil moisture fraction at field capacity ($m^3.m^{-3}$)

This equation is used to compute the critical available soil moisture fraction (θ_c) at which stomata start to close, by substituting the critical leaf water potential (ψ_c) for (ψ_l) and the maximum evaporative demand (E_m) for the transpiration rate (E). Due to the complex nature of the equation the solution is found by trial and error. Once the value of θ_a (= θ_c) has been found, the parameter (a) can be calculated as the ratio between (θ_c) and (θ_{fc}). Parameter (a) gives the fraction of total available soil moisture, which is available under plant stress conditions only, and fraction (1-a) is the readily available soil moisture.

Based on an analysis of the solutions found for this equation for different soil types and evaporative demands, a simplified function has been developed to calculate this parameter (a).

In table 8 data used for the analysis of water management in the Eastern Nile Delta are given.

Table 8: Data on critical leaf water suctions (ψ_c) used for the model simulations for a number of crops

crop	critical leaf water suction, ψ_c (bar)
cotton	13
wheat	10
maize	7
berseem	7
vegetables	5
rice	5

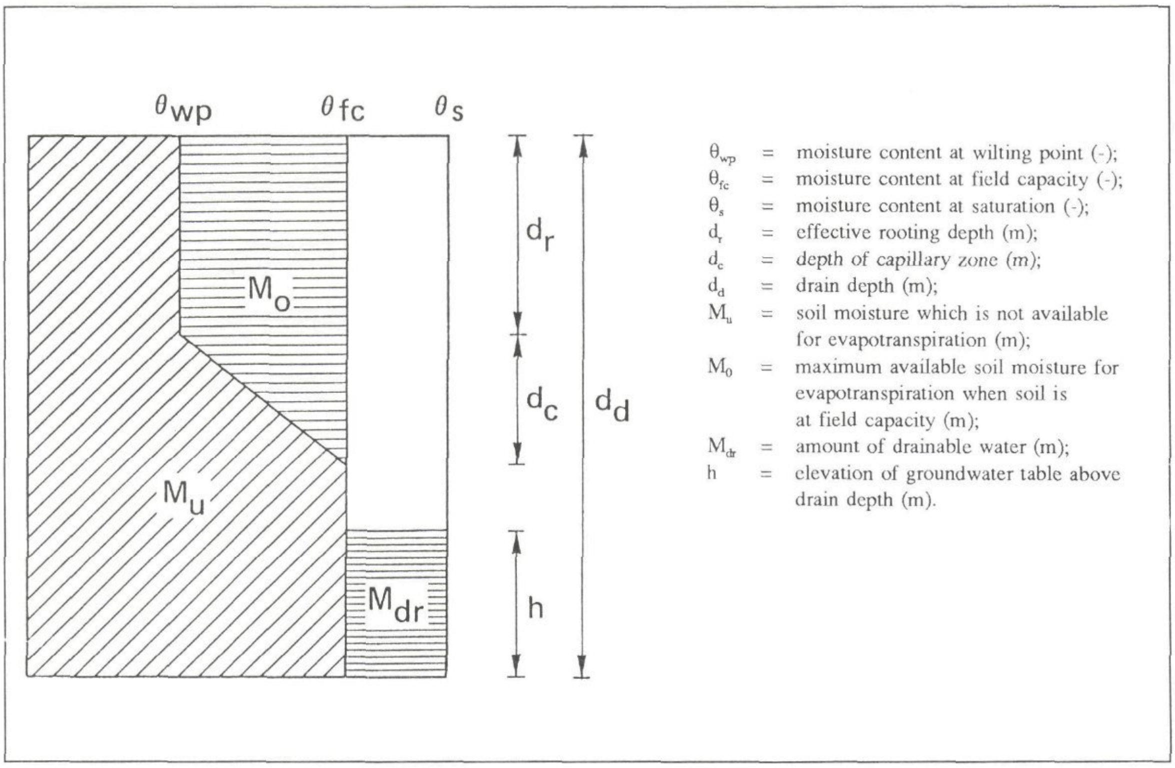


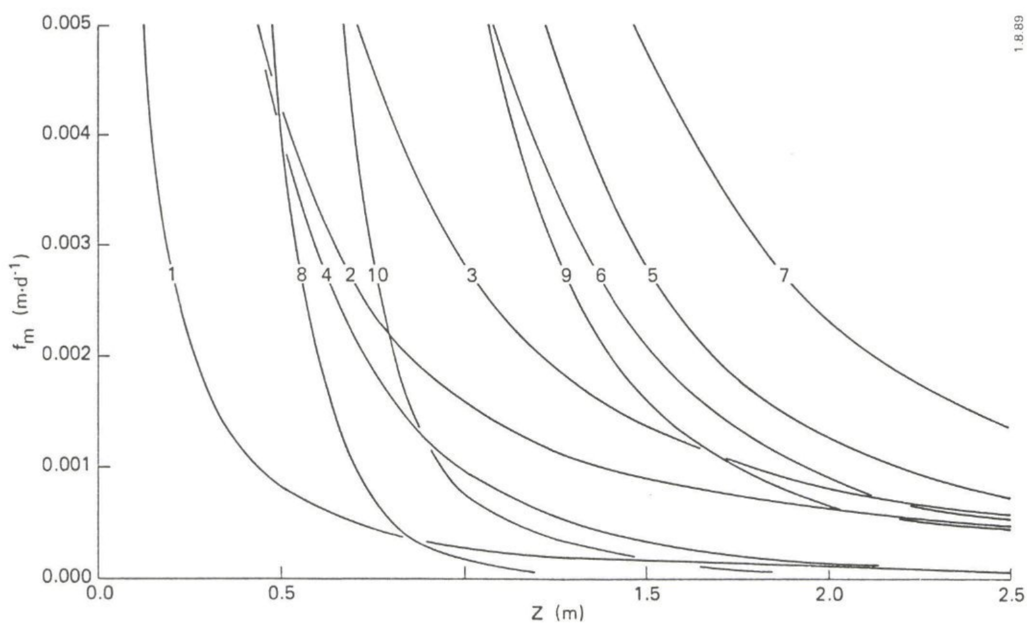
Figure 3: Schematization of the soil profile

3.2 Capillary contribution

During and immediately after irrigation, a moisture front can be observed in the soil profile. During the evapotranspiration cycle, soil moisture depletion normally starts at the top of the soil profile where root density is largest and upon prolonged evapotranspiration plant roots deplete also deeper layers. Simultaneously, upward unsaturated groundwater flow from wet soil layers to (partly) depleted upper soil layers takes place. In the schematization used for the WDUTY model an uniform moisture profile with depth is assumed in the root zone (Fig 3).

This effective root zone is the upper soil layer which contains roughly 80% of the plant roots. The maximum quantity of water which can be withdrawn by plant roots is the amount available between field capacity and wilting point. Below the effective root zone depth half of this quantity is assumed to become available through vertical unsaturated groundwater flow. The depth of the zone below root zone, which is assumed to contribute, is called the capillary zone. This zone has been defined on the basis of a steady state flux of about 0.5 mm.day^{-1} during an average irrigation interval of about 14 days.

In the presence of high groundwater tables, the possibility exists that also a capillary flux from saturated groundwater contributes to evapotranspiration. This capillary flux depends on the depth of groundwater below root zone and on the soil moisture suction in the crop root zone. The capillary flux can be assumed to attain its maximum value when the soil moisture fraction in the crop root zone is at wilting point. The relation between maximum capillary flux and distance to waterlevel has been reported by Rijtema (1969) for a number of standard soils (Fig 4).



1	=	basin clay	2	=	silty clay	3	=	silty clay loam
4	=	clay loam	5	=	sandy clay loam	6	=	loam
7	=	silt loam	8	=	sandy loam	9	=	loamy fine sand
10	=	medium fine sand						

Figure 4:** **Relation between maximum capillary flux f_m (m/day) and distance to groundwater table Z (m), assuming a soil moisture suction in the root zone at permanent wilting point

For actual computations these curves have been approximated by simplified relations. The required groundwater depth for estimation of the maximum capillary rise flux is obtained by solving the water balance of the drainable water reservoir (Fig 2):

$$\mu \frac{dh(t)}{dt} = -(f_d + f_l + f_m)$$

where: μ = drainable porosity ($m^3.m^{-3}$);
$h(t)$ = groundwater table elevation above drain level at time t (m);
f_d = drainage flux ($m.day^{-1}$);
f_l = leakage/seepage flux ($m.day^{-1}$);
f_m = maximum possible capillary flux, given the depth of water table ($m.day^{-1}$).

By assuming initially for drainage and leakage fluxes values associated with the initial waterlevel (immediately after irrigation), this water balance equation is used to calculate the average ground-water level during the time step. Generally, this takes only a few iterations. The estimated average groundwater level is then used for estimation of the maximum capillary rise flux.

3.3 Soil moisture balance

Considering the irrigation interval of crops, two separate sub-periods can be distinguished:
- supply of irrigation water to fields and distribution of this water across fields including occurrence of losses;
- subsequent period until the next irrigation event, during which crops withdraw water from the soil, capillary flow may contribute to crop transpiration and sub-surface drainage and leakage/seepage to the aquifer may take place.

For this second period mentioned all sinks and sources from the soil moisture reservoir have been treated and the soil moisture balance can be drafted. Immediately after irrigation the soil moisture which is available for evapotranspiration is known. Based on the two flux components which influence this available soil moisture in the period following irrigation, i.e. evapotranspiration flux and capillary flux, the mass balance for available soil moisture can be formulated:

$$\frac{dM(t)}{dt} = -E_r(t) + f_c(t) \qquad with \qquad M(t) = M(t_0) \qquad if \;\; t = t_0$$

where: $M(t)$ = soil moisture, available for evapotranspiration (m);
$M(t_o)$ = initial available soil moisture (m);
$E_r(t)$ = actual evapotranspiration rate at time t ($m.day^{-1}$);
$f_c(t)$ = capillary flux at time t ($m.day^{-1}$).

Depending on occurrence of crop stress conditions actual evapotranspiration may be equal to atmospheric demand, or be reduced due to closure of stomata in plant leaves. Considering a certain fraction (1 - a) of the maximum available soil water (M_o) to be available without crop stress conditions (Rijtema and Abou Khaled, 1975) the actual evapotranspiration rate can be approached by one of the following three relations:

$$E_r(t) = E_m \qquad if \quad M(t) > aM_0$$

$$E_r(t) = \frac{M(t)}{aM_0} E_m \qquad if \quad 0 < M(t) < aM_0$$

$$E_r(t) = 0 \qquad if \quad M(t) \leq 0$$

where: a = fraction of maximum available soil water which is still available for evapotranspiration when reduction starts (-);

E_m = maximum evaporative demand ($m.day^{-1}$);

M_o = maximum soil moisture which is available at field capacity (m).

Depending on soil moisture suction in the root zone and water table depth, the capillary flux is assumed inversely proportional to the soil moisture available for evapotranspiration:

$$f_c(t) = (1 - \frac{M(t)}{M_0})$$

By substituting the equation for actual evapotranspiration rate and the equation for the capillary flux into the mass balance equation, three solutions for the soil moisture balance equation during the period between two irrigations are found:

- maximum evapotranspiration:

$$\frac{dM(t)}{dt} = f_m - E_m - \frac{f_m}{M_0} M(t)$$

- reduced evapotranspiration:

$$\frac{dM(t)}{dt} = f_m - \frac{1}{M_0} (\frac{E_m}{a} + f_m) M(t)$$

- zero evapotranspiration:

$$\frac{dM(t)}{dt} = f_m - \frac{f_m}{M_0} M(t)$$

The third solution is an exceptional one because it is only valid for conditions of a negative available soil moisture (M(t) < 0). In practice, this may occur when crops are harvested after depleting the soil moisture reservoir. This means that the root zone depth decreases, the capillary zone shifts upward in the soil profile (Fig 2), and the available soil moisture can become negative. In this case the equation describes the increase of soil moisture due to capillary fluxes from the saturated groundwater.

The three equations can be written in a generalized form:

$$\frac{dM(t)}{dt} = B - A\ M(t)$$

where: A = lumped parameter with dimension (day^{-1});
B = lumped parameter with dimension ($m.day^{-1}$).

The general solution for the soil moisture reservoir gives an exponential depletion of this reservoir:

$$M(t) = \frac{B}{A} + (M(t_0) - \frac{B}{A})\ e^{-At}$$

Ponding of fields will occur during leaching and during growth of rice. During the ponding period, with a standing water layer on the field, available soil moisture in the plant root zone can be assumed constant. Any water, used by rice for transpiration, will be replenished from the standing water layer reservoir by infiltration. This means that the mathematical formulation of the evapotranspiration flux is not governed by the soil moisture balance in this case, but by the standing water layer balance. During ponding leaching will take place and, additional to replenishing the evapotranspiration rate, also this leaching flux infiltrates into the soil.

In case of ponding, the general solution for soil moisture given above, is applied in the model to the standing water layer reservoir. In this case the capillary flux obviously equals zero, and for the leaching flux (drainage) the equations derived by Ernst (1962) are applied.

3.4 Irrigation water application

In the WDUTY model the water content of the soil moisture storage reservoir at the timing of the next irrigation is evaluated by the approach given above. In other words, the soil moisture deficit relative to field capacity is known. This deficit, increased with a certain leaching fraction gives the net crop water requirements at crop level.

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 water depth. Both the advance function, as well as total infiltration of water, is determined to a large extent by the cracking characteristics of Egyptian clay soils in the Nile Delta. Losses of water through soil cracks to the drainage system during ponding of field plots (rapid drainage) is taken into account. The time period during which this rapid drainage occurs is calculated based on the swelling speed of 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.

Farmers lift irrigation water from irrigation canals using sakkias or diesel pumps. Lifted water is conveyed to fields through small field canals (merwaas). The common field irrigation method in the Nile Delta of Egypt is either furrow or basin irrigation. Irrigation water losses can be defined as those quantities of applied irrigation water which cannot be used by agricultural crops for evapotranspiration purposes. Four types of irrigation water losses can be distinguished:

- seepage losses from field canals;
- surface drainage of excess irrigation water applied by farmers;
- subsurface drainage losses by horizontal movement of applied irrigation water through soil cracks into the (sub)surface drainage system (rapid drainage);
- subsurface drainage of water which has leached the soil below the crop root zone to the saturated system.

The amount of irrigation water losses is dependent on many factors, among which:

- infiltration characteristics of the soil;
- quantity of irrigation water applied;
- capacity of pump or sakkia used;
- size (width and length) of field plots.

Infiltration characteristics of heavy clay soils in the Nile Delta of Egypt depend to a large extent on swelling and shrinking behavior of these soils. Development of soil cracks not only affects infiltration rates, but also increases horizontal hydraulic permeability considerably. Due to this higher horizontal permeability, irrigation water is lost to the drainage system. Infiltration rates generally decrease with time. After prolonged infiltration the rate approaches a constant value, which is often referred to as basic infiltration rate.

The phenomenon of a high initial infiltration rate, which decreases with time, is more pronounced in heavy textured soils with a swelling and shrinking behavior due to rapid drainage through cracks. This high drainage rate for a short duration has an adverse effect on application efficiency. The duration of this rapid drainage is limited due to swelling of clay soils and closure of cracks. The hydraulic conductivity of cracked top soils, which may be very high at the start of field irrigation, will decrease gradually upon closure of these soil cracks.

Conveyance losses from field channels, called "merwaas", which are at or above field surface, are computed in the model. Given a certain soil type, depth of water table and hydraulic radius of the field channel, seepage losses depend mainly on the distance between irrigation tool and plot which is irrigated. These factors are accounted for in the simulation model.

For a more detailed description of the field application process see section 4.1 on the FAIDS model. The outcome of this approach is an expression for the location of the waterfront at any time during field irrigation (see section 4.2.11). This solution is basic for determining the gross water requirements of crops.

Farmers are managing irrigation water on field level. They will try to maximize crop production, and therefore have the following (sometimes conflicting) objectives during field irrigation:

- supply sufficient water to crops;

- avoid crop yield depressions due to plant stress;
- provide sufficient leaching in order to avoid adverse salinity effects on crops;
- limit the ponding period of fields in order to avoid damage to crops due to limitations in oxygen supply to crop roots (anaerobic conditions).

In the model approach relative priorities have been assigned to these farmers' objectives. It has been assumed that he will give highest priority to avoiding plant stress due to water shortage. This means, that he will continue with irrigation for a limited period of time beyond maximum ponding period at the head of the field, if the end of field has not yet been wetted. At the moment the waterfront reaches the end of field, the standing water layer still has to infiltrate into the soil. Consequently, the infiltration opportunity time at the head of field, associated with the characteristic time at which the waterfront reaches the end of field (T_e) can be calculated as:

$$t_i = T_e + \frac{h_0}{I_t}$$

where: t_i = infiltration opportunity time at head of field if the sakkia operation is stopped when the waterfront reaches the end of field (s)
h_0 = depth of water flowing over the field (m)
I_t = gross infiltration flux ($m.s^{-1}$)

Prolonged ponding of agricultural fields will cause oxygen deficiency in the crop root zone and thereby cause crop damage. If the infiltration opportunity time at the head of field is less than the maximum admissible ponding period, farmers are assumed to continue supplying water to satisfy leaching requirements of crops:

$$T_d = T_e + \frac{I_t L}{q_0} (t_p - t_i) \qquad if \quad t_1 \leq t_p$$

where: t_p = maximum allowable ponding time without crop damage due to anaerobic conditions in the root zone (s);
T_d = required sakkia operation time to meet the farmers' demand (s);
L = Length of the field;
q_0 = discharge per unit width of field ($m^2.s^{-1}$).

This equation is valid for the condition that the end of field is reached with the sakkia is still in operation while the maximum ponding period allowed is not exceeded. If this condition is not fulfilled, farmers have to choose between two alternatives. They can stop irrigation at such a time that the maximum ponding period is not exceeded at the head of field. This means that he accepts loss of crop yield at the tail of field, due to an insufficient supply of water. The alternative is that he continues sakkia operation until the end of field is reached. In this case he accepts a loss of crop yield at the head of field due to deficient oxygen conditions. In the model approach, farmers' demand for water in this case has been defined in between both approaches. Farmer are assumed to accept some damage at the upstream side due to prolonged saturation and some damage downstream due to drought. Under these conditions, it is assumed that the sakkia operation time required to satisfy the farmers demand is the average of both operation times (operation time associated with maximum ponding period, and operation time associated with reaching the end of field):

$$T_d = \frac{1}{2} (t_p - \frac{h_0}{I_t} + T_e) \qquad if \quad t_p \leq t_i$$

The gross farmers' demand for water for one irrigation turn is now assessed in the model by multiplying the required sakkia operation time with net sakkia capacity.

Rice is grown under wet conditions. Farmers maintain a standing water layer on fields in order to suppress weed growth in rice crops. Consequently, farmers have a number of priorities when irrigating their rice crop. The first and foremost priority is to saturate the soil, if this is not yet the case when he starts field irrigation. His second priority will be to add water to the initial standing water layer on rice fields until it reaches a sufficiently high level to provide water to the rice crop until the next irrigation turn. His third concern will be the salinity of the standing water layer. If irrigation water supply is sufficient, he will try to refresh this water layer until its salinity reaches a satisfactory low level. In practice, farmers have a fourth objective, which is important during the first period of the rice growing season. Due to incomplete soil cover of rice crops during early growth stages, the temperature of the standing water layer may rise to above 30 °C, and become harmful for crop development. Water requirements for temperature control of standing water in rice fields has not been taken into account in the model formulation, however.

Based on the salinity of the mixture of the original standing water layer on rice fields and salinity of added irrigation water, farmers will try to dilute the standing water layer. A certain concentration factor (f_a), with which the irrigation water salinity has to be multiplied, can be defined to assess the allowed maximum initial quality of the standing water layer. This allowed (or desired) maximum initial salinity is then given by the following equation:

$$c_a \leq f_a \, c_{ir}$$

where: c_a = maximum allowed (desired) initial salinity (Cl^- concentration) of the standing water layer ($eq.m^{-3}$);
f_a = empirical factor, depending on irrigation interval, irrigation water quality, and salt resistance of the rice crop;
c_{ir} = Cl^- concentration of irrigation water ($eq.m^{-3}$).

The basic irrigation water quality of the river Nile can be characterized by its electrical conductivity of about 0.33 $mmho.cm^{-1}$. Accepting an initial conductivity of twice this basic quality ($f_a \approx 2$), means that with depletion of 80% of standing water until the next irrigation, its salinity will remain below 3 $mmho.cm^{-1}$, which may be considered as a threshold value for yield depression of rice (Morsi et al., 1978).

If the concentration of the standing water layer after topping up of the initial standing water layer is above this threshold, farmers are assumed to continue field irrigation until the standing water layer concentration is lowered till this critical concentration. Assuming complete mixing of incoming irrigation water with water on rice fields, the following balance equation can be drafted:

$$h_m^* \frac{dc(t)}{dt} = f_s \, (c_{ir} - c(t))$$

where: h_m^* = maximum allowable standing water layer on rice fields (m);
$c(t)$ = Cl^- concentration of standing water layer at time t ($eq.m^{-3}$);
f_s = q_o / L = surface drainage flux ($m.s^{-1}$);
L = length of field plot (m)

The solution of this balance equations results in an exponential decreasing standing water layer salinity:

$$c(t) = c_{ir} + (c_e - c_{ir}) \, e^{-\frac{f_s}{h_m^*} t}$$

where: c_e = salinity (Cl^- concentration) of the standing water layer after topping up ($eq.m^{-3}$).

The duration of this surface drainage from rice fields can now be solved by substitution the desired salinity (c_a) for c(t) and solving for time:

$$T_s = \frac{h_m^*}{f_s} \ln\left(\frac{c_e - c_{ir}}{c_{ir} \, (f_a - 1)}\right)$$

where: T_s = required duration of surface drainage of rice fields to obtain the desired salinity of the standing water layer (s).

The gross farmers' demand for water for one irrigation turn of a rice field can now be assessed based on the concentration after topping up the standing water layer, adding the amount of water to saturate the soil and to attain the desired ponding depth on rice fields:

$$I_d = (S_d + h_m^* - h_i) \frac{Q_0}{Q_n} \qquad if \quad c_e \leq f_a \, c_{ir}$$

$$I_d = (S_d + h_m^* - h_i + T_s \, f_s) \frac{Q_0}{Q_n} \qquad if \quad c_e > f_a \, c_{ir}$$

where: I_d = gross rice irrigation requirements (m);
S_d = saturation deficit of the soil (m);
h_i^* = rice fields initial standing water layer (m);
Q_o = irrigation tool capacity ($m^3.s^{-1}$).

3.5 Model results

Several factors influence crop water requirements. The most sensitive factors appeared to be crop characteristics:

- growing period and crop development (height, soil cover, rooting depth);
- irrigation frequency;
- maximum allowed ponding period, or admissible infiltration opportunity time.

For the first estimate of these data extension pamphlets of the Ministry of Agriculture have been used. These pamphlets recommend planting/sowing dates, irrigation frequencies, and agronomic measures such as fertilizer use etc. For the regional application of the SIWARE model the fact that planting and sowing takes place during a certain period, during which the area occupied by a certain crop increases gradually, has to be taken into account. These periods have been subjected to calibration. The same holds true for irrigation frequency and number of irrigations which are given to different crops. The simulated output of the SIWARE model appeared to be very sensitive for small changes in irrigation pattern of individual crops and changes in planting date of crops. The final results of the crop model input parameters are given in Table 9.

Other important crop parameters are crop development: rooting depth, soil cover, crop height and maximum ponding period (Table 10). These parameters affect the evaporative demand of the crop canopy to a great extent, and are consequently important for crop water requirements. In the models, the rooting depth of crops given in Table 10 may be limited by drain depth. Maximum rooting depth, considered in the model, is restricted to 25 centimeter less than 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 9: Calibrated growing period and irrigation pattern of 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 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)

Table 10: Calibrated crop development characteristics and maximum ponding period for 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 bers	20 (10 dec)	70 (1 jan)	30 (1 jan)	12/6
wheat	120 (1 may)	100 (1 apr)	40 (1 feb)	7
short bers	40 (15 apr)	100 (1 feb)	30 (20 nov)	12
wint veg	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 veg	30 (1 jun)	75 (1 jun)	30 (20 may)	5

Crop water requirements calculated with the model WDUTY are spatially distributed. The official water allocation duty used by the Ministry of Public Works and Water Resources for water allocation to main canal intakes and internal water distribution do not differentiate between distinguished regions in the Nile Delta. Large differences are consequently found between the Ministry of Public Works and Water Resources figures and those simulated by WDUTY, which are influenced by climatic, soil, and hydrological conditions (table 11).

Table 11: Comparison of allocation water duties used by the Ministry of Public Works and Water Resources and crop water requirements calculated with the model WDUTY for the main field crops in the study area ($m3.feddan^{-1}$)

main field crop	allocation duty MOPWAWR	water requirements WDUTY model	variation water requirements relative to allocation duty
long bers	3,060	2,800	-40% - + 40%
wheat	1,600	2,130	-15% - + 55%
short bers	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%
total	6,560	7,720	-20% - + 50%

4 WATER DISTRIBUTION (WATDIS)

Crops in the Nile Delta are almost exclusively supplied with water from Nile origin. Only a narrow belt along the Mediterranean coast receives a 100 to 200 mm rainfall on annual basis. Since the major part of this water falls in the months December and January, when crop water demands are low, rainfall contributes only modestly to the total requirements.

Nile water is diverted to the Delta from its apex, just north of Cairo, where the river bifurcates into the Rosetta and Damietta branch. A substantial part of the area, however, is also served by canals receiving their water further northwards from the branches themselves. From each intake onwards, water is distributed by means of a hierarchical canal system. The main command canals, comprising up to 3 or 4 orders, are under a continuous supply regime controlled by the Ministry of Public Works and Water Resources (MPWWR). Distributary canals, branching off from any order main command canal, are on the other hand under rotation. Depending on the season, a distributary may receive water during a limited on-period, whereas the supply is blocked during the off-period. Farmers are supposed to lift their required quantity of irrigation water from the latter canals.

Almost all canals in the Nile Delta are separated by control structures. Unlike the Fayoum depression where the weir type is predominant, in the Delta with its relative mild surface slope towards the sea mostly movable undershot gates are found. Control over the water distribution is exercised by means of maintaining preset up- and/or downstream waterlevels. These target levels are computed from downstream water requirements and calibrated stage-discharge relation of structures. After tabulating by the local offices of the Ministry of Public Works and Water Resources, the results are handed over to the gate operators in charge.

At various locations in the Delta pump stations are present lifting water from the drainage canals and discharging it into irrigation command canals. Where present, the MPWWR reduces the irrigation water allocation for the canals in question. A similar procedure is followed for areas partially irrigated with groundwater and areas with an amount of precipitation worth considering. Such a method, as a matter of fact, not only affects the water allocation at the main intakes of the Delta, but also the internal water distribution in the area itself.

This section considers the major aspects of the irrigation water distribution in the Nile Delta. It also aims to elucidate the reasons for building the hydraulic simulation model WATDIS and the approach followed during development. At the same time it discusses most of the basic assumptions, as well as those aspects which were not included in the model.

4.1 Model development

Next to the establishment of a monitoring network in the major drainage canals in the Nile Delta, the Reuse of Drainage Water Project phase I had as second objective to develop a mathematical simulation model covering the whole agricultural cycle in the area.

A major question during model formulation was: how much irrigation water is actually lifted by the farmers from the irrigation canals? A number of reasons supported the idea that the

amount of water farmers require does not always comply with the amount the Ministry of Public Works and Water Resources allocates for them. The major reasons are:
- spatial variability of the farmers' water requirements;
- spillway and tail-end losses;
- conveyance losses;
- human interference.

- Spatial variability of water requirements
One of the most incumbent necessities urging the use of a hydraulic model stemmed from the observation that actual farmers' water requirements may deviate considerably from the allocation duties listed by the Ministry of Public Works and Water Resources. The latter duties are, for practical reasons, considered to be uniform over the Nile Delta. This implies that farmers growing similar crops at any location are assumed to have the same requirements, independent of local hydrological conditions, evaporative demand, leaching conditions, etc.

Research showed that for rice the actual water requirements may vary between 4,000 m^3 and 13,500 m^3 per feddan for the growing season (Abdel Gawad et al., 1991). It is easily conceivable that for other crops also a wide range may exist.

When locally the water allocated differs from the water required, a new hydraulic equilibrium has to be found. Under the regime of maintaining target levels downstream at inlet structures of distributary canals, a higher uptake by farmers will lead to a drop in the waterlevel forcing the gate operator to open the gate further in an effort to reach again his prescribed level. Since numerous distributary canals are connected to a command canal, actions of farmers and gate operators will have a distinct influence on the flows in the latter canal. The interaction between the various elements of the hydraulic system is envisaged to have a major effect on the farmers' uptake, thus requiring the use of a hydraulic computational model.

- Spillway and tail-end losses
Most irrigation canals in the Nile Delta release their excess water to the nearest drain in their vicinity. Spillways are usually installed as a safety precaution against human errors in the irrigation system's operation and against natural causes as for instance intensive, heavy rainfall. In most cases however, spill water in the Nile Delta is the direct result of:
- a mismatch between the amount allocated by the Ministry of Public Works and Water Resources and the actual farmers' water requirements as discussed under the previous item;
- farmers' preference for day irrigation and the use of high capacity lifting tools.

Without doubt farmers strongly prefer to irrigate their fields during daytime. Although the number of irrigation hours has been reduced considerably since the introduction of the small movable diesel pumps, farmers can hardly be persuaded to work during the night.

A more balance abstraction pattern from distributary canals could be obtained if the uptake capacity would be better distributed over the day. Sudden heavy demands provoke a more erratically behavior in maintaining target levels at the inlet gates of distributary canals, thus resulting in considerable spillway losses at the tail-ends of these canals when the demand drops again. Since inlet gates are adjusted about three times daily, and in many cases less, these losses cannot be neglected. In fact, the MPWWR accounts for this phenomenon when allocating water to the intake of command canals. However, for practical reasons, these compensations are a fixed percentage of the total allocation, not considering local circumstances. It seems reasonable to assume that the recent trend of replacing the traditional sakkia (water wheel) by small diesel pumps has lead to significantly higher spillway losses.

Because spillway losses, either occurring at tail-ends of distributary canals or at tail-ends of a command canals, are currently not monitored by any authority, only a hydraulic computational model can provide an estimation. At the same time the model can quantify the effects on the farmers' uptake. It may be clear that such an approach calls for a well perceived modeling of the expected farmers' and gate operators' behavior.

- *Conveyance losses*
As is the case for spillway and tail-end losses, leakage from irrigation canals is accounted for by the Ministry of Public Works and Water Resources, be it again as a fixed percentage of the total allocation at command canal intakes.

Conveyance losses depend on the variable water depth in the canal, the piezometric level of the deep groundwater, and the resistance of the mainly vertical flow profile. Canals close to the fringes of the Nile Delta, with lighter textured soils, will undoubtedly show higher losses than canals excavated in the heavy clay soils of the Delta itself. It may be expected therefore that these losses will show a distinct spatial distribution.

Notwithstanding the minor quantities of water involved, farmers locally may have slightly more or slightly less water available than intended by the Ministry of Public Works and Water Resources. These deviations can only be predicted, although roughly, by a hydraulic model.

- *Human interference*
The influence of the human factor has already been discussed previously under other items. It may be clear that the actual farmers' water requirements cannot always be met with the allocated amounts of the Ministry of Public Works and Water Resources.

The lifting tools at the farmer's disposal and his behavior with respect to the timing for irrigation may also decide to what extent he will be able to satisfy his demand. The latter factors are strongly interwoven with the gate operation at the intakes of the distributary canals, the second human element involved.

Through the command canal, the combined effects of these human actions will propagate to other distributary canals. Estimation of such effects requires the application of a hydraulic model.

It may be concluded that for a more accurate calculation of the farmers' uptake the use of a hydraulic model is indispensable. Specific matters as the expected behavior of farmers and gate operators should be taken into consideration in the formulation.
For these reasons a relative simple hydraulic model called WATDIS has been developed. Its simplicity having as additional asset that the mathematical approach followed allowed for large timesteps, thus limiting the considerable computation time for solving large and intricate canal schemes.

4.2 Basic principles and mathematics of the WATDIS model

The Water Distribution model has basically been designed to serve input requirements of the SIWARE model. To improve its versatility however, also a stand-alone option has been built in. Figure 1 shows the elementary input. On the output side, the following main aspects of the water distribution are computed:

- actual irrigation water uptake from distributary canals by farmers;
- spillway losses at tail-ends of command canals and at tail-ends of distributary canals;
- conveyance losses to the deep groundwater (or conveyance gains from the deep groundwater);
- flows from one section to the other in the command canal system.

The last item is a prerequisite for calculating the salinity of the water at locations where pump stations discharge drainage water into the irrigation system. These calculations are carried out in the REUSE model.

To arrive at such output, WATDIS has to perform a number of computations for the canal system in which the following components can be distinguished:

- command canals subdivided into sections;
- distributary canals;
- control structures;
- pump stations.

- *Command canals*

Command canals are subdivided into sections of reasonable length, i.e. varying between say 0.5 km and 10.0 km. Each section, except for the first and the last, has an open connection with previous and next sections through which water can enter or leave. Sections are made up by two nodal points with x and y coordinates.

The dimension of the cross section (trapezoidal) as well as the bottom elevation are given. The flow of water from one section to another is calculated with the Chezy formula, assuming steady state conditions during a timestep (eq.1). Therefore also the Chezy coefficient should be provided.

$$Q = C_{Chezy}\, A\, \sqrt{R\, s} \qquad (1)$$

where:

where:	C_{Chezy}	=	Chezy coefficient in ($m^{1/2} \cdot s^{-1}$);
	A	=	wetted cross section in (m^2);
	R	=	hydraulic radius in (m);
	s	=	slope in hydraulic head in (-).

To facilitate an easy calculation scheme, the equations can be linearized under the condition that the variation in water depth between two adjacent sections remains limited during a timestep.

Assuming that the flow is linearly dependent on the difference in hydraulic head and bearing in mind that:

$$s = \frac{(h_j - h_{j+1} + b_j - b_{j+1})}{\Delta l} \tag{2}$$

where: h_j = water depth in section j in (m);
b_j = bottom level in section j in (m);
Δl = longitudinal distance between both section centres in (m).

yields an equation of the following shape:

$$Q = C^* \, (h_j - h_{j+1} + b_j - b_{j+1}) \tag{3}$$

$$\textit{where:} \quad C^* = \frac{C_{Chezy} \, A \, \sqrt{R}}{\Delta l \, \sqrt{s}}$$

The first three terms of C^* can be averaged out over the two adjacent sections j and j+1 according to:

$$C^* = \frac{C_j \, h_j + C_{j+1} \, h_{j+1}}{2 \, \Delta l \, \sqrt{s}}$$

where: $C_j = C_{Chezy,j} \cdot A_j \cdot \sqrt{R_j}$
$C_{j+1} = C_{Chezy,j+1} \cdot A_{j+1} \cdot \sqrt{R_{j+1}}$

Once the equation for continuity (3) has been determined, the result can be substituted in the volume balance (eq.4).

$$\frac{\Delta V_{j,t}}{\Delta t} = Q_{j-1,j,t} - Q_{j,j+1,t} - Q_{j,t} \tag{4}$$

where: $V_{j,t}$ = volume of water in section j at time t in (m^3);
Δt = timestep in (s);
$Q_{j-1,j,t}$ = flow from section j-1 to section j in ($m^3 \cdot s^{-1}$);
$Q_{j,j+1,t}$ = flow from section j to section j+1 in ($m^3 \cdot s^{-1}$);
$Q_{j,t}$ = sink or source term for section j in ($m^3 \cdot s^{-1}$).

When $V_{j,t}$ is replaced by $S_{j,t} \cdot h_{j,t}$, in which S represents the wet surface area of section j, and the flow terms Q by their relevant expressions according to equation (3), then a set of N linear first order differential equations is obtained for each single canal with N sections.

Solving this set of equations in the conventional way would put limits on the timestep used. An alternative is to integrate equation (4) for $h_{j,t}$, although the water depths in the neighboring sections are not yet known for time $t+\Delta t$. The latter problem has been solved by assuming that both $h_{j-1,t}$ and $h_{j+1,t}$ will vary linearly with time according to:

$$h_{j+1,t,av} = (1 - \alpha_{j+1})\, h_{j+1,t0} + \alpha_{j+1}\, h_{j+1,t+\Delta t} \tag{5}$$

where: $h_{j+1,t,av}$ = average approximated water depth in section j+1 in (m);
$h_{j+1,t+\Delta}$ = water depth in section k+1 at time t=t+Δt in (m);
α_{j+1} = iteration variable of section j ($0 \leq \alpha_{j+1} \leq 1$).

Substituting equation (5), and evidently a similar expression for $h_{j-1,t,av}$, into the continuity equation (3) for $h_{j+1,t}$ and $h_{j-1,t}$ and subsequently filling in the volume balance equation (4), results after integration in the final set of linear equations.

It was found that for solving this set of equations a threefold iteration procedure, yielding new approximations for the variable α_j, virtually eliminated balance deviations. Results were already considered acceptable after only 2 steps. Moreover, since the solution has been obtained analytically, no more constraints were placed on the size of the timestep.

Contrary to for instance the full Saint-Venant equation for hydraulic flow, the velocity head has been neglected in the followed approach. It was felt that for model applications using unlined canals with flow velocities of not more than 0.7 $m \cdot s^{-1}$ the contribution of this factor could be disregarded. On the other hand, it should also be remarked that going after high accuracies would be a spilled effort since only small amounts of actual data on hydraulic canal properties are available.

When schematizing a command canal into sections, care should be taken as not to end up with too large segments at branchings and head (or cross) regulators. The mathematical approach only warrants relative accurate calculations when the difference in hydraulic head between two sections is not too much.

Resistances can be accounted for by varying the conductance term C_{Chezy} in the continuity equation whenever data are available. Under most conditions the value ranges between 30 and 60 $m^{1/2} \cdot s^{-1}$.

- Distributary canals

Distributary canals are considered as quadrangular shaped canals serving a so-called distributary unit. Within the unit's area the distribution of irrigation water is regarded diffuse, i.e. all farm plots receive the same amount of water.

Although conflicting with reality, it is assumed that distributary canals are served by command canals on a continuous basis. Since the schematized distributary canals are only hypothetical, such an assumption is only justified by fixing a lower threshold for the applicable scale. In practice this means that a minimum number of existing distributary canals have to be combined.

Farmers lift their water requirements directly from canals using either small diesel pumps with a maximum estimated capacity of 50 $l \cdot s^{-1}$ or sakkias (water wheels) with a maximum estimated capacity of 25 $l \cdot s^{-1}$. Any combination of those tools can be used as input, although it is anticipated that nowadays the diesel pumps have rendered the sakkias obsolete.

At the end of each canal the presence of a spillway connected to the nearest drain has been considered.

For the distributary canal no flow computations are carried out, since the abstraction pattern is assumed diffuse. Therefore a simple volume balance suffices (eq. 6):

$$\frac{\Delta V_{l,t}}{\Delta t} = Q_{in j,t} - Q_{up,l,t} - Q_{sp,l,t} - Q_{l,t} \tag{6}$$

where:
- $V_{l,t}$ = volume of water present in canal l at time t in (m^3);
- Δt = timestep in (s);
- $Q_{in,j,t}$ = intake from section j of the command canal in ($m^3 \cdot s^{-1}$);
- $Q_{up,l,t}$ = uptake from distributary canal l by farmers in ($m^3 \cdot s^{-1}$);
- $Q_{sp,l,t}$ = spillway losses at tail-end of canal l in ($m^3 \cdot s^{-1}$);
- $Q_{l,t}$ = sink or source term for canal l in ($m^3 \cdot s^{-1}$).

$V_{l,t}$ can be replaced by $S_{l,t} \cdot h_{l,t}$, in which the wet surface area of distributary canal l is represented by $S_{l,t}$.

The middle two terms on the right hand side of equation (6) can be written as linear functions of the water depth $h_{l,t}$ as follows (eqs. 7 and 8):

$$Q_{up,l,t} = n_s\,(b_s\,h_{l,t} + a_s) + n_p\,(b_p\,h_{l,t} + a_p) \tag{7}$$

where:
- n_s = number of sakkias in operation depending on farmers' water requirements (input) and daily and seasonal irrigation intensity distribution;
- b_s and a_s = operation constants for sakkias related to lifting head in ($m^2 \cdot s^{-1}$) and [$m^3 \cdot s^{-1}$] respectively;
- n_p = number of pumps in operation, see $n_{s;;}$
- b_p and a_p = operation constants for pumps related to lifting head in ($m^2 \cdot s^{-1}$) and ($m^3 \cdot s^{-1}$) respectively.

$$Q_{sp,l,t} = B_{s,l}\,h_{l,t} + A_{s,l} \tag{8}$$

where $B_{s,l}$ and $A_{s,l}$ are spillway constants in [$m^2 \cdot s^{-1}$] and [$m^3 \cdot s^{-1}$] respectively.

It should be denoted that spillways, generally constructed as broad crested weirs, do not discharge linearly with the waterlevel. Hence, the appropriate power function can only be accurately described when a number of intervals are defined for linearization.

The first term on the right hand side requires special consideration since flows from command canals not only depend on waterlevels in distributary canals, but also on waterlevels in the command canals themselves (eq. 9):

$$Q_{in j,t} = B_{str j}\,h_{av j,t} - B_{str j}\,h_{l,t} + A_{str j} \tag{9}$$

where: $B_{str,j}$ = constant for the inlet structure of the distributary canal in ($m^2 \cdot s^{-1}$);
$A_{str,j}$ = constant for the inlet structure of the distributary canal in ($m^3 \cdot s^{-1}$);
$h_{av,j,t}$ = weighted average water depth in the command canal section j in (m).

Inlet structures of distributary canals are constructed as submerged orifices with a typically non-linear discharge relation. Therefore, like spillways, both constants are only defined within the range of each appropriate interval where the linear relation reflects the power function accurately enough.

After substituting all linear relations, the volume balance of equation (6) can be solved analytically for $h_{1,t}$. New constants $B^*_{str,j}$ and $A^*_{str,j}$ can be derived so that the discharge to the distributary canal will have the following shape:

$$Q_{in,j,t} = B^*_{str\,j}\; h_{av,j,t} + A^*_{str\,j} \tag{10}$$

The linear equation (10) can be incorporated in equation (4) for the volume balance of the relevant canal section. Finally, solving the water depth in this section gives the discharge to the distributary canal.

- *Control structures*
In the WATDIS model the following basically different hydraulic control structures are distinguished:
- weirs (short or broad crested);
- gates (undershot type for head and diversion regulators).

In each section of the command canal system only one structure may be present, which is good practice because the linearization procedure applied does not allow for large drawdowns of the waterlevel compared to adjacent sections.

The flow to lower order command canals can be regulated by short crested weirs. In the Nile Delta this type is not in use for such purposes. The model accounts, however, for short crested weirs equipped with rectangular control sections.

Spillways at the end of the command canals are considered to be broad crested. The same type, also equipped with rectangular control sections, is supposed to be present at the tail-ends of distributary canals.

The general stage-discharge relation for weirs is given by:

$$Q_t = C_d\, C_v\, \frac{2}{3} \left(\frac{2}{3}\, g\right)^{0.5} W_{str}\, (h_t - h_0)^{1.5} \tag{11}$$

where: Q_t = discharge in ($m^3 \cdot s^{-1}$);
C_d = discharge efficiency coefficient
~ 1.0 to 1.25 for short crested weir;
~ 0.848 for broad crested weir;
C_v = velocity correction coefficient
~ 1.0 to 1.1 for short and broad crested weirs;

W_{str} = structure width in (m);
h_t = upstream water depth in (m);
h_0 = crest height above bottom level in (m);
g = gravity constant in ($m \cdot s^{-2}$).

Because of the non-linearity of equation (11) a threefold interval has been defined depending on the difference between h_t and the variable crest height h_0. Linear approximations within these intervals are considered to follow the power function close enough.

For short crested submerged weirs an approach has been used distinguishing between a free discharge component and a submerged component. The total discharge reads with $(C_d \cdot C_v)_{free}$= 1.05 and $(C_d \cdot C_v)_{submerged}$= 0.63 (see gates):

$$Q = W_{str} \; (1.79 \; (H_1 - H_2)^{\frac{3}{2}} + 2.795 \; H_2 \; (H_1 - H_2)^{\frac{1}{2}}) \tag{12}$$

where: H_1 = $h_{up,t}$ - $h_{0;}$
H_2 = $h_{down,t}$ - Δb - $h_{0;}$
Δb = difference in bottom level up- and downstream (m);
h_0 = crest height above bottom level in (m).

Unlike freely discharging weirs a double fourfold interval is required for describing the discharge relation of equation (12) in linear terms.

The model also provides the possibility to input 10-daily upstream target levels for any type of weir. These levels, when defined, should be maintained as good as possible by lowering or raising the crest height of the weir according to:

$$h_{0,new} = h_{0,old} + (h_{up,target} - h_{up,t}) \tag{13}$$

where: $h_{0,new}$ = new crest height of the weir in (m);
$h_{0,old}$ = old crest height of the weir in (m);
$h_{up,target}$ = pre-defined upstream target level in (m);

The discharge of irrigation water to lower order command canals in the Nile Delta is regulated by undershot gates. Also the flow to distributary canals is controlled by these diversion structures. Under normal conditions gates are submerged.

At several locations head or cross regulators can be found. These structures are mainly erected to prevent too high flow velocities in the command canals in order to keep bottom and side slope scour under control. Sometimes hydraulic conditions are such that head regulators or diversion regulators discharge under free flow. When the downstream waterlevel does not influence discharges the equation reads as follows:

$$Q_t = C_d \; C_v \; (2g)^{0.5} \; A_{str} \; (h_{up,t} - h_0)^{0.5} \tag{14}$$

where: Q_t = discharge in ($m^3 \cdot s^{-1}$);
C_d = discharge efficiency coefficient

~ 0.85;
C_v = velocity correction coefficient
~ 1.0 to 1.07;
A_{str} = cross section of gate opening in (m^2);
$h_{up,t}$ = upstream water depth in (m);
h_0 = height of centre of gate opening above bottom level at upstream side in (m);
g = gravity constant in ($m \cdot s^{-2}$).

Under normal conditions, i.e. with submerged gates, the discharge equation for head and diversion regulators can be given as:

$$Q_t = C_d\, C_v\, (2g)^{0.5}\, A_{str}\, (h_{up,t} - h_{do,t} - \Delta b)^{0.5} \tag{15}$$

where: C_d = discharge efficiency coefficient
~ 0.61;
C_v = velocity correction coefficient
~ 1.0 to 1.07;
$h_{up,t}$ = upstream water depth in [m]
$h_{do,t}$ = downstream water depth in [m]
Δb = difference in bottom level between up- and downstream in (m).

Both equation (14) and (15) are linearized in four intervals. Which interval applies depends for the free flowing condition on the actual gate opening multiplied with the difference between the actual upstream water depth and the actual centre height of the gate opening above canal bottom. For the submerged case the actual centre height should be replaced by the downstream water depth minus the difference in bottom level between up- and downstream.

Target level control can be exercised by adjusting gate opening(s). Ten daily pre-defined levels at either upstream, downstream, or at both sides of the structure can be given. The general equation reads:

$$H_{new} = \alpha_c\, H_{old} \tag{16}$$

where: H_{new} = new height of the gate opening in (m);
H_{old} = old height of the gate opening in (m);
α_c = control factor in (-).

For upstream target level control the following expression for α holds:

$$\alpha_{c,up} = \left(1 - \frac{(h_{up,target} - h_{up,t})}{MAX(h_{up,target}, h_{up,t})}\right)^{0.5} \tag{17}$$

where: $\alpha_{c,up}$ = upstream control factor in (-);
$h_{up,target}$ = upstream target level in (m);
$h_{up,t}$ = upstream water depth at time t in (m);

and for downstream control:

$$\alpha_{c,do} = (1 + \frac{(h_{do,target} - h_{do,t}}{MAX(h_{do,target}, h_{do,t})})^{0.5} \tag{18}$$

where: $\alpha_{c,do}$ = downstream control factor in (-);
$h_{do,target}$ = downstream target level in (m);
$h_{do,t}$ = downstream water depth at time t in (m).

whereas for two sided target level control equation (19) can be applied:

$$\alpha_c = 1 - (\frac{h_{up,target} - h_{up,t}}{MAX(h_{up,target} - h_{up,t})} - \frac{h_{do,target} - h_{do,t}}{MAX(h_{do,target}, h_{do,t})})^{0.5} \tag{19}$$

- Pump stations:
Two types of pump stations are included in the model approach, namely agricultural and reuse pump stations. The first withdraws water from an irrigation canal section using the following linear expression:

$$Q_{ps} = - B_{ps,j}\ h_{j,t} - A_{ps,j} \tag{20}$$

where: $Q_{ps,t}$ = uptake by pump station in ($m^3 \cdot s^{-1}$);
$B_{ps,j}$ = pump station constant in ($m^2 \cdot s^{-1}$);
$A_{ps,j}$ = pump station constant in ($m^3 \cdot s^{-1}$).

Reuse pump stations are supposed to discharge their drainage water directly into a section of an irrigation command canal independent of the waterlevel in the latter canal according to:

$$Q_{rps,t} = + A_{rps,j} \tag{21}$$

where: $Q_{rps,t}$ = discharge of reuse pump station in ($m^3 \cdot s^{-1}$);
$A_{rps,j}$ = reuse pump station constant in ($m_3 \cdot s^{-1}$).

5 REUSE OF DRAINAGE WATER (REUSE)

The REUSE model fulfills the following basic functions:
- distribution of irrigation water supplied to one calculation unit among the different crops;
- calculate the amount and the salinity of the drainage water generated for the different crops in the all calculation units (FAIDS submodel);
- add up these values to calculate the total amount of drainage water in the different sections of the drainage system;
- simulate the effects of reuse of drainage water, both official (i.e. through a government operated pumping station) and un-official (i.e. by the farmers from drains in the vicinity of the plots);
- simulation of crop succession after crop harvesting, at the onset of the next growing season.

Section 4.2 describes the FAIDS submodel. Since the FAIDS submodel is also available as a stand-alone field scale model it is rather extensive compared to the sections dealing with the other functions of reuse (4.1 and 4.3 till 4.5).

5.1 Distribution of irrigation water among crops

It is physically impossible to include in the REUSE submodel all the field plots in a certain calculation unit. To overcome this deficiency a representative (hypothetical) plot is defined for each major crop. Irrigating such a plot requires only a short time period compared to the length of an irrigation interval which depends on the type of crop. Since in the submodel only few field plots are present, irrigation is not continuously needed but occurs at different time moments, depending on the irrigation intervals of the field crops. No irrigation water is required in the FAIDS submodel during the time periods between two successive irrigations. The supply of irrigation water to a calculation unit, however, is continuous. In order to cope with this discrepancies, the total quantity of irrigation water which is supplied during a period between two successive irrigations is allocated to the field crops. The total quantity of allocated irrigation water to a certain crop during a certain irrigation interval is supplied to that crop at the beginning of the considered interval. A similar procedure is followed to determine the quantity of available drainage water from local sources: available drainage water during the period between two successive irrigations is used for irrigation at the beginning of such an interval.

The quantity of irrigation water for a certain calculation unit is passed to the REUSE submodel by the WATDIS submodel and is the combined result of farmers irrigation practice and the capacity of the irrigation tools. The groundwater abstraction is added to this quantity which is distributed among the different crops according to the local crop water requirements as has been determined in advance by the WDUTY submodel. This requirement represents the quantity which farmers will supply to their crops when sufficient irrigation water is available and when the irrigation intervals are fixed. This pre- determined demand, may be lower than the actual water demand when crops during the preceding irrigation interval have been under-irrigated. Under these conditions the soil moisture deficit is higher than was assumed in the WDUTY model. Similar situations are also likely to occur in downstream parts of relatively large calculation units, where most probably the irrigation water distribution is non-uniform. To cope with these deviations, the REUSE submodel assumes a certain percentage over-irrigation whose magnitude, however, is unknown and has to be determined through model calibration. When the (adjusted) demand exceeds the supply, farmers may decide to apply additional drainage water. If the available quantity of irrigation water is still 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 REUSE submodel a certain percentage of the supply is assumed to be distributed proportional to the crop water requirements. This percentage has been calibrated at about 75% for the Eastern Nile Delta. The remaining percentage of the irrigation supply is given to the crops, according to the (farmers) irrigation priority sequence (table 13).

Table 12. Irrigation priority ranking of the main crops in the Eastern Nile Delta, in Summer and Winter period

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

5.2 Field water management (FAIDS)

Basically the FAIDS submodel functions according to the same principles as described for WDUTY. The main difference is that the water supply serving as input for FAIDS is the result of the WATDIS submodel -i.e. after confronting the farmers demand resulting from WDUTY with the allocated volumes resulting from DESIGN- whereas in WDUTY an ample water supply is assumed. Obviously another difference is the fact that the purpose of WDUTY is to determine farmers demand while the purpose of FAIDS is to calculate the volume and the salinity of the generated drainage water.

5.2.1 Description of different modules

Five separate modules are distinguished in FAIDS:
- on-farm irrigation module IRREFF;
- redistribution of salts in the root zone module REDIS;
- evapotranspiration module EVA;
- drainage module DRAGE;
- salinity module SAMIA.

Following is a brief explanation of each of the modules:

On-farm irrigation module IRREFF
On-farm irrigation starts with lifting 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 traditional sakkias. Water is spread over the field and some of this water evaporates, some of it runs off from tail-ends of plots 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 water infiltrates into the soil, of which a part will be converted into evapotranspiration through abstraction by plant roots and an other part will pass through the soil and will be collected by field drains. 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 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 Egyptian clay soils in the Nile Delta. Losses of water through the soil cracks to the drainage system during ponding of field plots are taken into account. The time period during which this rapid drainage occurs is calculated based on the swelling speed of the soil. The capacity of the sakkia or diesel pump, the basic infiltration rate, the plot characteristics, the drainable porosity, 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 soil moisture content, groundwater depth, and volumes of water lost from the field tail-ends (surface drainage), by leakage from merwaa field irrigation channels (conveyance losses), and by rapid drainage through cracks to the drainage system.

Redistribution of salts in the root zone module REDIS

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

In the simulation model this process has been formulated in a simplified way. For vertical water fluxes through the soil elements a leaching efficiency of 100% is assumed, and for vertical water flow through cracks a leaching efficiency of 0% (no leaching). Consequently, the initial irrigation water salinity is assigned to horizontal fluxes from cracks into soil elements. For the simulation of salt removal with rapid drainage through 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 infiltrating water into 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 in-flowing water with soil moisture is considered. Out-flowing concentrations equal 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 groundwater, i.e. soil water stored in the drainable porosity, and the quantities of salts lost through tail-end losses of merwaas, surface drainage, and rapid drainage through soil cracks.

For salinity calculations the chloride ion has been selected because this element is neither retained in the soil by adsorption processes nor involved in precipitation reactions. Based on 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 soil moisture the actual evapotranspiration rate may be reduced due to increased soil moisture potential as well as on the osmotic potential of accumulated salts. In this process 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 a certain critical leaf water suction is reached. At this suction 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 from below the root zone into account. For the capillary flux ten different soil types are considered.

Since 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 crop development data such as crop height and relative soil cover for different stages in the growing season maximum rates are calculated.

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 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 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 piezometric head in the aquifer is the driving force for discharge to (leakage) and from (seepage) the aquifer. For the calculation of 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 volumes of drain discharge and seepage/leakage flows. In each soil layer complete mixing of incoming water fluxes with 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 updating of 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, leakage flux salinity and the updated salinity of both saturated and unsaturated soil layers.

5.2.2 Schematization

Simulation models, such as FAIDS, are simplified reproductions 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, frequently limit the equivalence between simulation model and reality.

To facilitate the calculation process, the Eastern Nile Delta to which the SIWARE model has been applied, has been schematized into sub-areas. These sub-areas, also referred to as calculation units, should be uniform with respect to soil, hydrological, climatic, and water supply conditions. Within calculation units each crop is represented by one typical (average) field plot.

Each representative agricultural field has in principle three dimensions: length, width, and depth. Assuming such a field to be uniform over the width, it can be schematized in two dimensions only.

During field irrigation, water is applied at the upstream end of the field and the waterfront is proceeding to the downstream end. During advance of the waterfront, its speed is slowed down due to infiltration into the soil in the flooded part of the field. Consequently, the amount of water infiltrated at the upstream end of the field will generally be more than the amount at the downstream end. Also leaching will be higher at the upstream end, resulting in a higher water table immediately after irrigation.

In the FAIDS model the field irrigation process is formulated as a two-dimensional process, assuming processes uniform over the width of the field. For evapotranspiration, drainage and leakage/ seepage processes which take place after irrigating the land, the field is schematized to one dimension only (depth). This means that the agricultural field is schematized to a single soil profile with assumed uniform properties in all horizontal directions. The initial moisture content in the root zone following field irrigation, which may be at field capacity at the upstream end of the field and lower at the downstream end is taken as the average to this purpose. The same procedure is followed for the initial water level.

During and immediately after irrigation, a moisture front can be observed in the soil profile. During the evapotranspiration cycle, soil moisture depletion normally starts at the top of the soil profile where root activity is largest and upon prolonged evapotranspiration plant roots deplete also deeper layers. Simultaneously, upward unsaturated groundwater flow from wet soil layers to (partly) depleted upper soil layers takes place. In the schematization used for the FAIDS model the effective root zone depth is considered. This is the upper soil layers containing roughly 80% of the roots. In this zone an uniform moisture profile with depth is assumed (Fig. 5). The maximum quantity of water which can be withdrawn by plant roots is the amount available between field capacity and wilting point.

Below the effective root zone for a restricted depth, half the quantity of soil moisture stored between field capacity and wilting point is assumed to be available for evapotranspiration. This depth is called the capillary zone (d_c) and has been defined on the basis of a steady state flux of about 0.5 mm.day^{-1} during the normal irrigation interval of about 14 days.
The common field irrigation method in the Nile Delta of Egypt is either furrow or basin

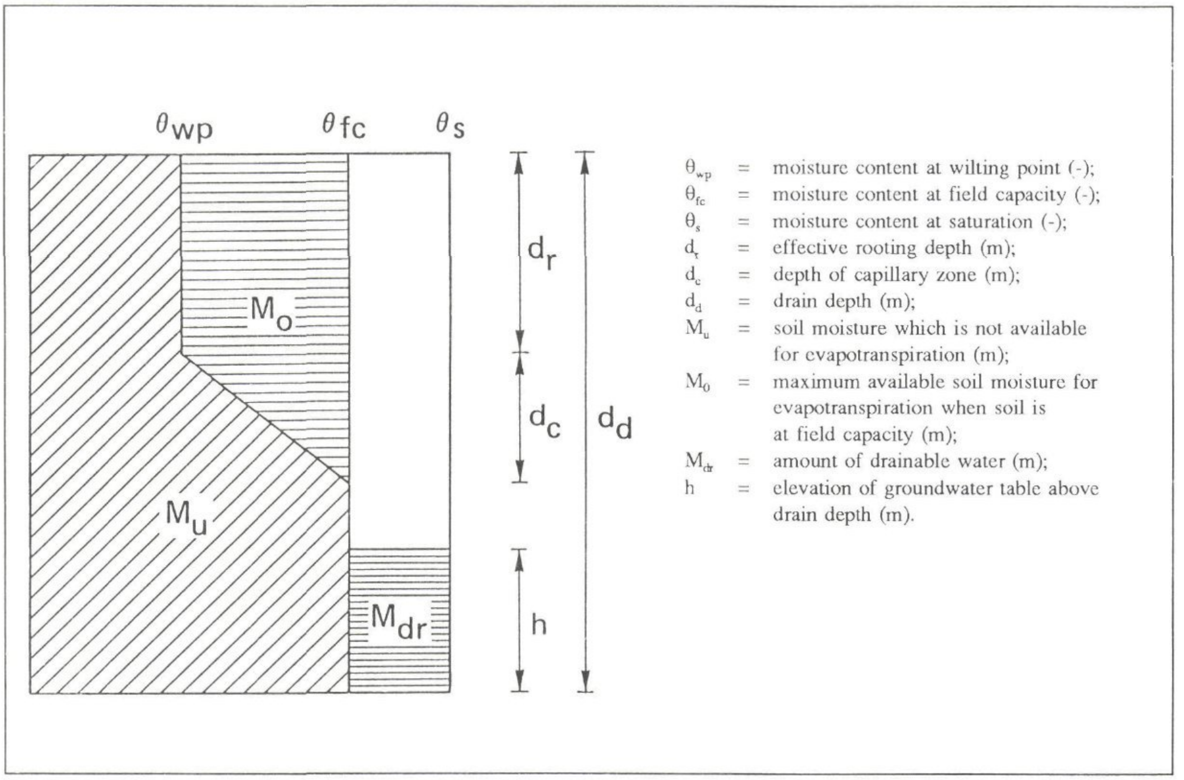


Figure 5: Schematization of soil profile

irrigation. Irrigation water losses can be defined as those quantities of applied irrigation water which cannot be used by agricultural crops for evapotranspiration purposes. Four types of irrigation water losses can be distinguished:
- seepage losses from field canals;
- surface drainage of excess irrigation water applied by farmers;
- sub-surface drainage losses by horizontal movement of applied irrigation water through soil cracks into the (sub)surface drainage system;
- subsurface drainage of water which has leached the soil below the crop root zone, to the saturated soil system.

The amount of irrigation water losses is dependent on many factors, amongst which:
- infiltration characteristics of the soil;
- quantity of irrigation water applied;
- capacity of the pump or sakkia used;
- size (width and length) of the field plot.

5.2.3 Infiltration

The rate of infiltration of water into the soil generally decreases with time. This is due to the fact that larger soil pores are filled with water first and smaller pores are filled next, at a much slower rate. After some time of continued infiltration the rate of infiltration approaches a constant value. This value is often referred to as the basic infiltration rate.

In soils which exhibit a swelling behavior on wetting and a shrinking behavior on drying, the phenomenon of a decreasing infiltration rate is dominated by the presence of soil cracks. When irrigating such cracked soils by surface irrigation methods, these cracks fill immediately with water. For this reason, in the FAIDS model infiltration has been formulated as an instantaneous filling of soil cracks, followed by a basic infiltration rate rather than formulating a decreasing infiltration rate with time.

5.2.4 Soil cracks

During the shrinking process of soil aggregates, the volume of these elements decreases. As a consequence the dry bulk density of these soil elements increases as a function of the soil moisture fraction (Reeve et al., 1980; Roest et al., 1992):

$$\rho(\theta) = \rho_0 + \kappa(\theta - \theta_s)$$

where: $\rho(\theta)$ = dry bulk density of soil aggregates ($ton.m^{-3}$);
ρ_o = dry bulk density (minimum) of soil structure elements at field capacity ($ton.m^{-3}$);
κ = slope dry bulk density relation with soil moisture fraction of soil aggregates ($ton.m^{-3}$);
θ = soil moisture fraction of soil aggregates ($m^3.m^{-3}$)

In ripened soils, as prevailing in the Nile Delta, shrinkage is a reversible process and extends uniformly in all directions. This means that an unit volume of soil decreases equally in size in horizontal as well as in vertical direction. The dry bulk density therefore relates directly to the shrinkage of these elements. For the mathematical description of infiltration of applied water into soil cracks, the subsidence of the soil due to shrinkage should not be included in the crack volume. For a unit soil volume it follows then (Fig. 6):

$$v_c = 1 - (1 - \epsilon)^2$$

where: v_c = volume fraction of soil cracks for a unit soil layer ($m^2.m^{-2}$);
ε = relative one-dimensional shrinkage ($m.m^{-1}$)

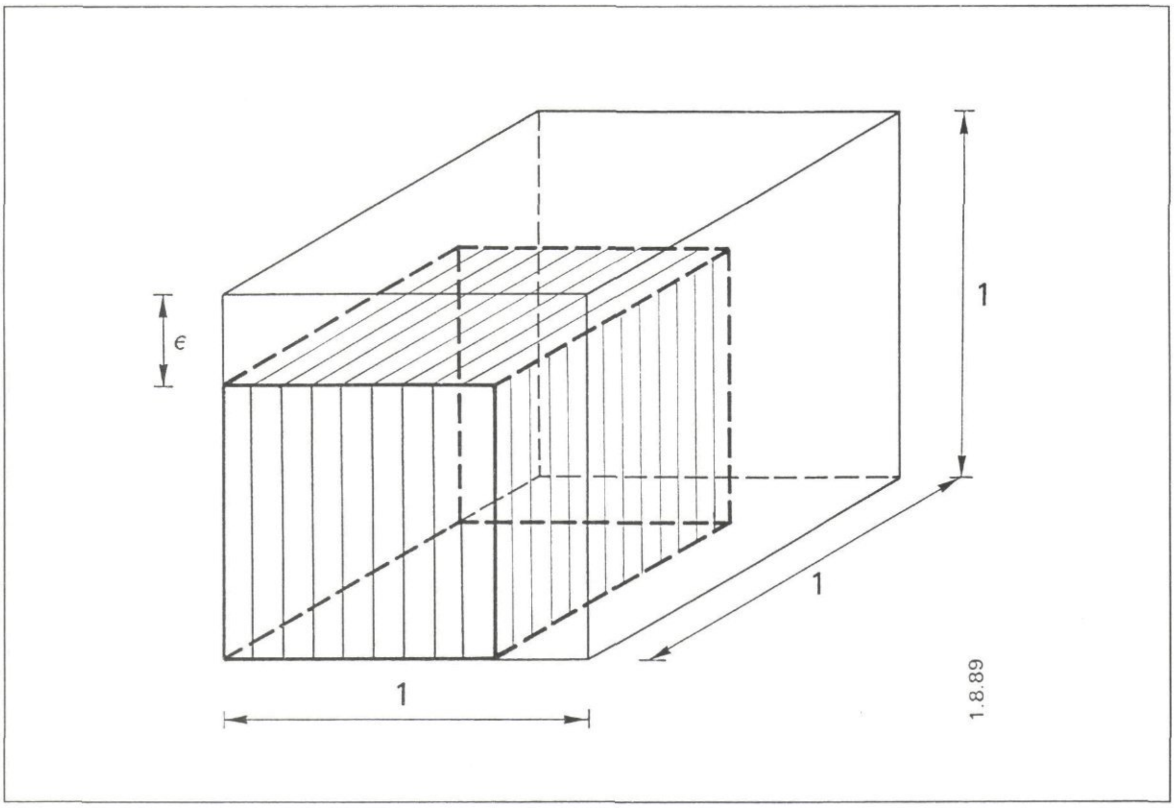


Figure 6: Size of a soil element with unit dimension (1) before shrinkage and dimension (1-ε) after shrinkage

A linear relation of the soil moisture fraction with depth from soil surface till the depth of moisture extraction is assumed. Using the relation between dry bulk density and soil moisture fraction, and the relation between the unit crack volume and one-dimensional shrinkage the following relation for the crack volume can be derived:

$$V_c = \int_0^D \{1 - (\frac{\rho_0 + \kappa(\theta_s - \theta_m)(\frac{z}{D} - 1)}{\rho_0})^{-\frac{2}{3}}\} \, dz$$

where: V_c = crack volume ($m^3.m^{-2}$);
D = total depth of soil moisture extraction zone below (subsided) soil surface

(m);
θ_m = soil moisture fraction at soil surface ($m^3.m^{-3}$);
z = depth below (subsided) soil surface (m)

5.2.5 Drainage through cracks

During field irrigation of heavy clay soils the application efficiency is negatively influenced by a high drainage rate for a short duration immediately after irrigation. The duration of this rapid drainage is limited due to swelling of the clay soils and closure of cracks, which are present during irrigation. The hydraulic conductivity of the cracked top soil, which may be very high at the start of field irrigation, will decrease gradually upon closure of these soil cracks.

The actual duration of the rapid drainage phenomenon is influenced by the initial moisture status of the soil, the infiltration rate of irrigation water into soil structural elements, the crack geometry, and the drainage system characteristics of the field considered.

For horizonal movement of water through cracked top soils, the hydraulic permeability of this cracked soil has to be assessed. Basically, this hydraulic permeability relates to the hydraulic radius of cracks. For laminar flow conditions the hydraulic conductivity will be proportional to the square of the hydraulic radius. If turbulent flow conditions prevail (which may be the case in large soil cracks), the hydraulic conductivity will be proportional to the square root of the hydraulic radius of soil cracks. Since no detailed measurements are available on flow conditions through soil cracks, in the present approach a linear relationship between hydraulic conductivity and crack size is assumed.

Because the crack volume is proportional to the air fraction in the soil, the average hydraulic conductivity in the cracked top soil can be given by the following equation:

$$k_r = N \kappa \frac{\theta_s - \theta_0}{2}$$

where: k_r = hydraulic permeability of cracked top soil ($m.day^{-1}$);
N = empirical constant (appr. 0.24);
θ_s = soil moisture fraction at saturation ($m^3.m^{-3}$);
θ_o = average soil moisture fraction in the top soil prior to field irrigation ($m^3.m^{-3}$)

The drainage rate through cracked topsoil and unsaturated sub-soil to the drainage system can be described using the drainage resistance. In our case, two parallel resistances can be defined (Fig. 7):

$$C_r = \omega L + \frac{L^2}{8 k_r h_0}$$ for top soil drainage

$$C_d = \omega\ L + \frac{L^2}{8\ k\ D} \qquad \text{for subsoil drainage}$$

where: C_r = drainage resistance of cracked top soil (days);
h_o = initial groundwater level in cracks above uncracked subsoil (m);
C_d = subsoil drainage resistance (days);
ω = entrance resistance of drains (day.m^{-1});
k = hydraulic permeability of the subsoil (m.day^{-1});
D = thickness of layer below drain level contributing to drainage flow (m)

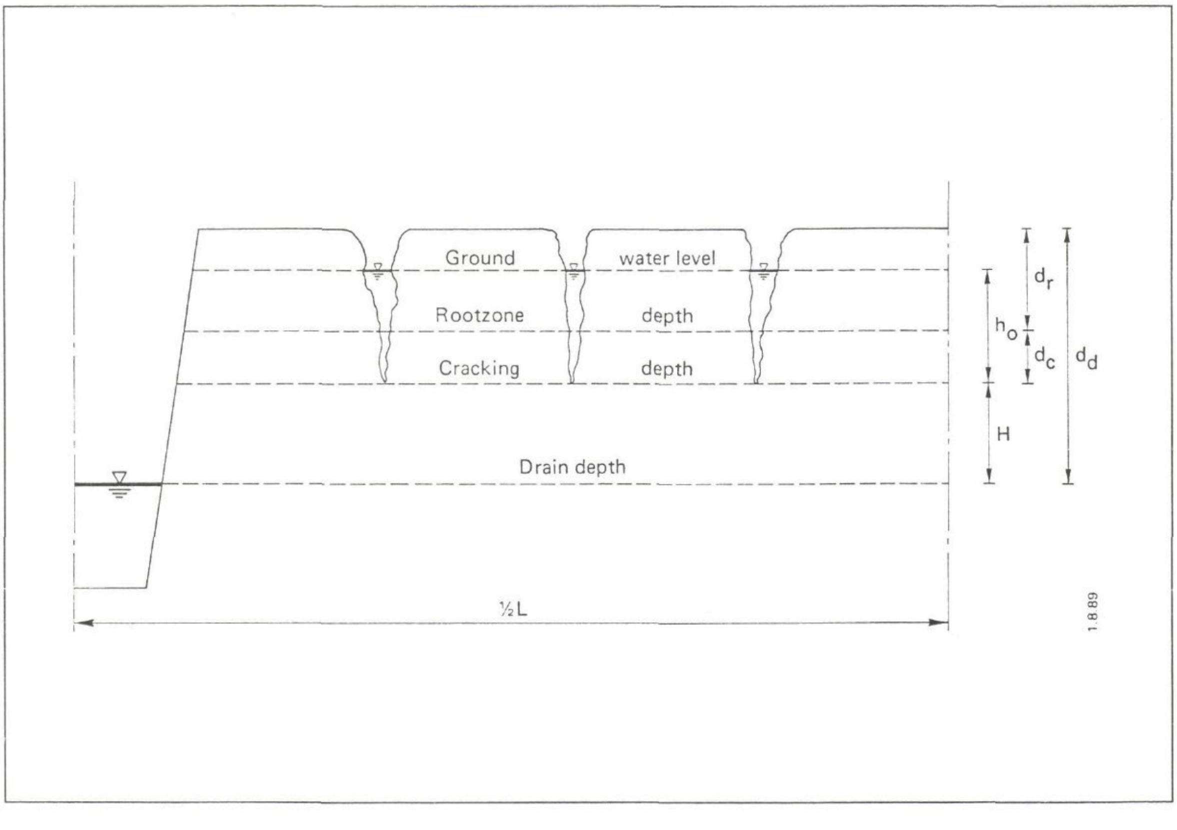


Figure 7: Definition sketch of the parameters determining the phenomenon of rapid drainage through cracks

The duration of this drainage flux through soil cracks is limited. As soon as cracks are filled with irrigation water, infiltration into soil elements starts. During infiltration, these elements will swell and cracks diminish in size. The general equation for the horizontal soil moisture flux in unsaturated soil can be given as:

$$\frac{\partial\theta(x,t)}{\partial t} = - \frac{\partial}{\partial x} \{D(\theta) \frac{\partial\theta(x,t)}{\partial x}\}$$

with: $D(\theta) = k(\theta) \frac{\partial\psi}{\partial\theta}$

where: t = time (days);
k(θ) = unsaturated hydraulic conductivity ($m.day^{-1}$);
ψ(x,t) = soil matrix potential (m);
x = horizontal distance in the infiltration flux direction (m);
D(θ) = diffusivity ($m^2.day^{-1}$);
∂ψ/∂θ = slope of moisture retention curve

This equation describes infiltration of water from soil cracks into soil aggregates. As soon as these soil elements reach field capacity, soil cracks are closed and the rapid drainage process stops. Generally soil aggregates will be small (say a few cm). Under Egyptian conditions, they have sizes ranging from 15 to 30 cm upon initial drying of the soil (Bakr, personal communication). If the drying process continues, smaller cracks develop in these elements, thereby creating smaller soil aggregates with characteristic sizes of 2 to 5 cm. Since the rapid drainage flux takes place mainly through larger cracks (smaller ones close very fast upon irrigation), 25 cm has been chosen as the characteristic size of soil structure elements in the FAIDS model.

Introduction of the average diffusivity value for the practical soil moisture range, the average soil moisture fraction in soil structure elements, and after simplification the time dependent drainable porosity in cracked top soil can be derived:

$$\mu(t) = \frac{V_c}{d_r + d_c} \frac{\theta_s - \theta(t)}{\theta_s - \theta_a}$$

where: μ(t) = average drainable porosity in cracked top soil during and immediately after irrigation ($m^3.m^{-3}$);
θ_a = initial average soil moisture fraction in soil aggregates ($m^3.m^{-3}$)

Using these relations the equation for the rapid drainage flux can be derived, after some simplifications:

$$f_r(t) = h(t) \{\frac{1}{C_r} + \frac{1}{C_d}\} + \frac{H}{C_d} = -\bar{\mu} \frac{dh(t)}{dt}$$

where: $f_r(t)$ = rapid drainage flux ($m.day^{-1}$);
h(t) = waterlevel in cracks (m);
$\bar{\mu}$ = average drainable porosity during the rapid drainage phenomenon ($m^3.m^{-3}$);
V_c = crack volume ($m^3.m^{-2}$);
H = thickness uncracked sub-soil above drain level (m).

This equation is used in the model to compute the amount of rapid drainage. By solving the equation for a waterlevel of zero, the maximum time period of rapid drainage is calculated first:

$$T = \frac{C_d\, C_r}{C_d + C_r} \frac{\mu_0\, L_s^2}{4\, \bar{D}\, T} \{1 - e^{-\frac{4\bar{D}}{L_s^2} T}\} \ln \{\frac{H\, C_r + h_0\, (C_d + C_r)}{H\, C_r}\}$$

where:
- T = duration of rapid drainage (days);
- μ_o = initial drainable porosity in the cracked topsoil at the start of field irrigation ($m^3.m^{-3}$);
- L_s = characteristic size of soil aggregates (m);
- $\bar{D}$ = average diffusivity ($m^2.day^{-1}$)

After solving this equation for time (T), the average rapid drainage flux is computed in the model and added to the basic infiltration rate for waterfront advance simulation.

5.2.6 Irrigation advance

For the calculation of the net stream size reaching field plots, conveyance losses in the merwaa are accounted in the model. For the hydraulics of water movement over the field surface the Manning equation is used in the model, considering the field as a wide rectangular channel. For crops grown on ridges, such as cotton or tomatoes, a correction factor for the wetted width of fields, (α) has been introduced. For furrow irrigation this factor is smaller than one.

During advance of irrigation water over the field soil cracks are filled with irrigation water and infiltration of water into soil aggregates takes place. In heavily cracked soils, soil cracks act as a shunt to the drainage system during field irrigation. As a consequence, drains will be discharging. Taking this rapid drainage flow through soil cracks into account, the discharge over the field surface at any distance (x) can be formulated as follows:

$$q_x = q_0 - (I_s + \frac{f_r}{\alpha})\, x \qquad \text{if } x \leq x_f$$

$$q_x = 0 \qquad \text{if } x > x_f$$

where:
- q_x = discharge per unit wetted field width at distance x ($m^2.s^{-1}$);
- q_o = discharge per unit width of field ($m^2.s^{-1}$);
- I_s = basic infiltration rate ($m.s^{-1}$);
- f_r = drainage rate through cracks ($m.s^{-1}$);
- α = fraction of wetted field width (-);
- x = distance from head of field (m);
- x_f = location of waterfront (m).

For irrigation advance simulation the average ponding depth mid-way between up- and downstream side of plots is considered. The waterfront is slowed down both due to building up this water layer, as well as by filling of soil cracks with irrigation water. Taking into account that also below the ridges in between furrows cracks are filled with water, the velocity of the waterfront is formulated as follows:

$$v_a = \frac{dx}{dt} = \frac{q_0 - I_t\, x}{h_0 + \frac{V_c}{\alpha}}$$

where: v_a = advance speed of waterfront during field irrigation ($m.s^{-1}$);
x = distance of waterfront, measured from head of field (m);
t = time elapsed after start of field irrigation (s);
I_t = $I_s + f_r/\alpha$ = gross infiltration flux ($m.s^{-1}$);
h_o = average ponding depth (m).

This equation is solved in the FAIDS model and gives the location of waterfront during field irrigation. Now the infiltration opportunity time and irrigation water losses can be computed.

5.2.7 Irrigation water losses

During the irrigation ponding period, infiltration of water into the soil takes place. Water which infiltrates below the crop root- and capillary zone is considered here as subject to sub-surface drainage. For the mathematical formulation, a distinction has to be made between two cases. If the waterfront reaches the end of the field within the net sakkia operation period (T_n), the time elapsed since the start of sakkia operation till the field falls dry, is given by the following equation:

$$t_e = T_e + \frac{h_0}{I_t} + \frac{q_0(T_n - T_e)}{I_t\, L} \qquad \text{if } T_n \geq T_e$$

where: t_e = elapsed time between start of irrigation and field falling dry (s);
T_e = time required for waterfront to reach end of field (s);
T_n = net sakkia operation time, excluding the operation time required for surface drainage losses (s);
L = length of field plot (m).

If the waterfront does not reach the end of the field within the sakkia operation period, it has been assumed in the present simplified approach, that the location of waterfront is fixed. Remaining water on the (wetted part of) the field is assumed to infiltrate. Under Egyptian conditions, the magnitude of this quantity (h_o) varies from 10 to 35 mm and is in the same order of magnitude as irregularities of the soil surface. With these conditions and assumptions, the time elapsed since start of field irrigation till the field falls dry can be calculated with:

$$t_e = T_n + \frac{h_0}{I_t} \qquad \text{if } T_n < T_e$$

The infiltration opportunity time at any distance (x) is now obtained by deducting the advance time of waterfront from the total time until the field falls dry:

$$t_i(x) = t_e - \frac{x}{v_a}$$

where: $t_i(x)$ = infiltration opportunity time at distance x (s).

The net infiltration volume per unit area is obtained by multiplying the basic infiltration rate with the infiltration opportunity time and adding this quantity to the crack volume:

$$V_i(x) = \alpha\ I_s\ t_i(x) + V_c = \alpha\ I_s\ t_e + V_c - \frac{I_s}{v_a}\ \alpha\ x$$

where: $V_i(x)$ = net recharge of soil moisture during field irrigation at location x (m);
V_c = crack volume ($m^3.m^{-2}$);
v_a = advance speed of waterfront during field irrigation ($m.s^{-1}$)

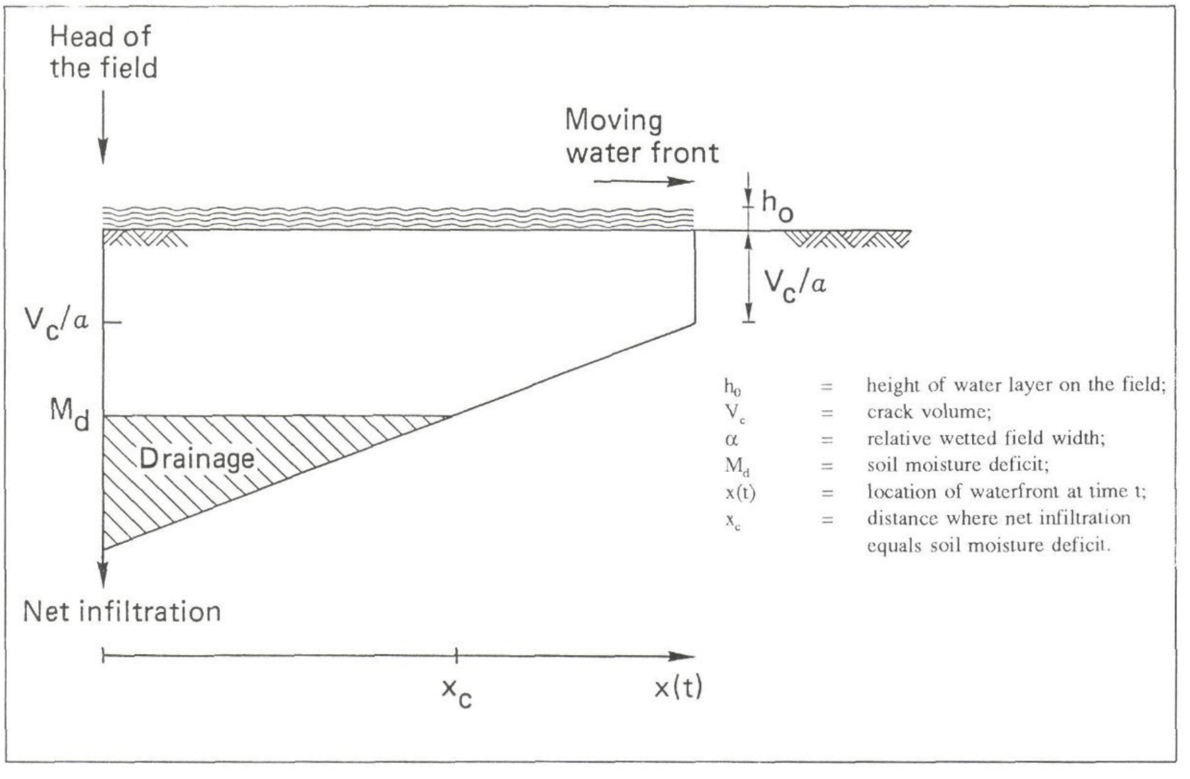


Figure 8: Definition sketch of surface irrigation and subsurface drainage losses

Sub-surface drainage losses will occur if the net infiltration volume is larger than the soil moisture deficit. Defining the distance (x_c) as the location where both quantities are equal, sub-surface drainage losses can be identified in the reach upstream of this location (fig 8). The characteristic distance (x_c) is found by taking the net infiltration equal to the soil moisture deficit and solving for (x):

$$x_c = v_a \{t_e + \frac{V_c - M_d}{\alpha\ I_s}\}$$

where: x_c = distance where net infiltration equals soil moisture deficit (m);
M_d = soil moisture deficit below field capacity (m)

The total subsurface drainage is then found by integrating the difference between net infiltrated volume and soil moisture deficit over the distance (x_c) and dividing by L:

$$V_d = \frac{1}{L} \int_0^{x_c} \{V_i(x) - M_d\} dx = \frac{x_c}{L} \{\alpha\ I_s\ t_e + V_c - M_d - \frac{\alpha\ I_s}{2\ v_a} x_c\}$$

where: V_d = subsurface drainage losses (m)

The total rapid drainage volume during the ponding period is obtained by multiplying the infiltration opportunity time with the rapid drainage flux:

$$V_r = \frac{1}{L} \int_0^{x_e} \bar{f}_r\ t_i(x)\ dx = \bar{f}_r \frac{x_e}{L} \{t_e - \frac{x_e}{2\ v_a}\}$$

where: f_r = average rapid drainage flux ($m.day^{-1}$);
V_r = actual volume of rapid drainage (m);
x_e = final location of waterfront (m).

The total net recharge of soil moisture (available for evapotranspiration) can now be calculated as the difference between total field irrigation and irrigation water losses:

$$I_n = I_g - V_{cl} - V_d - V_r$$

where: I_n = average recharge of soil moisture available for evapotranspiration (m);
I_g = gross irrigation gift (m);
V_{cl} = conveyance losses from merwaa (m).

5.2.8 Vertical soil moisture distribution

In the FAIDS model, field irrigation has been considered as a two-dimensional process. The upstream side of plots normally receive more water than downstream parts. Subsequent evapotranspiration and drainage processes are considered one-dimensional only. The vertical soil moisture distribution for different soil layers has therefore to be averaged. In the root zone an uniform vertical soil moisture distribution is assumed. For the capillary zone below, the moisture content is assumed to increase linearly till field capacity at the lowest position of the soil moisture extraction zone (Fig. 9).

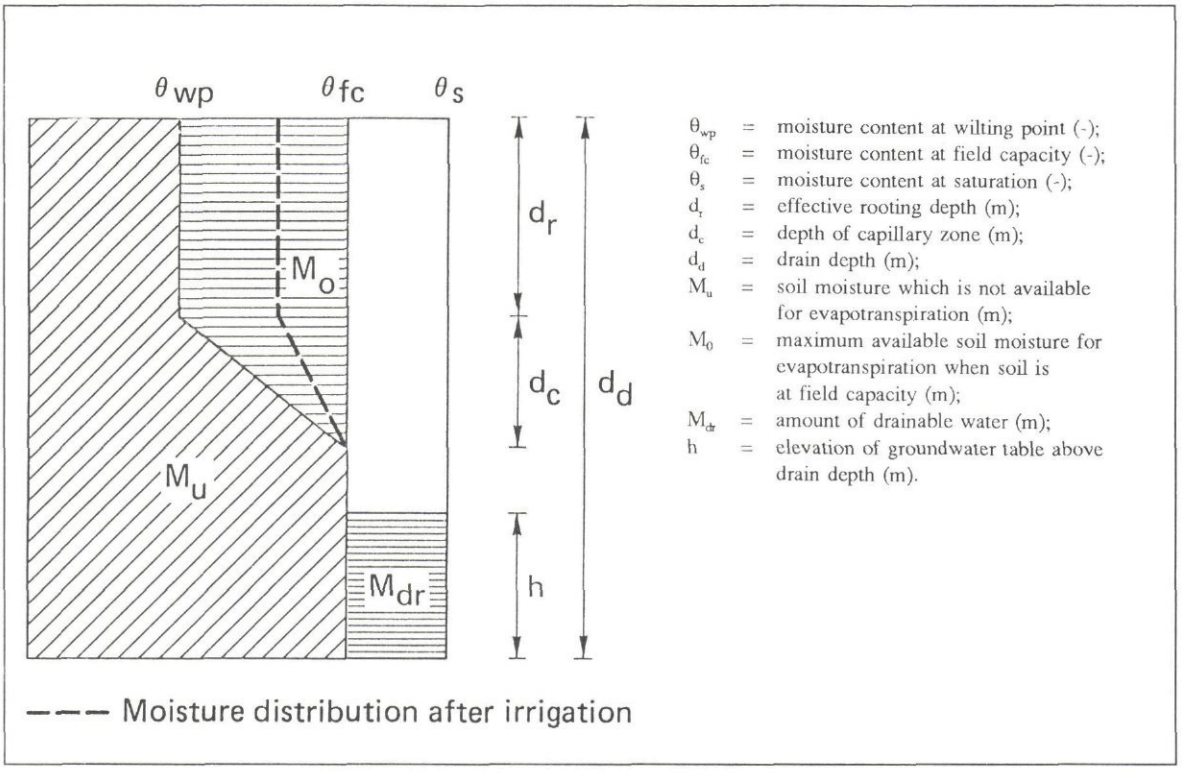


Figure 9: Vertical soil moisture distribution (average for irrigation plot) after irrigation

5.2.9 Evapotranspiration

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

Immediately after irrigation the available soil moisture for evapotranspiration is known. Considering also a capillary flux, the mass balance for available soil moisture can be formulated:

$$\frac{dM(t)}{dt} = -E_r(t) + f_c(t)$$

where: $M(t)$ = soil moisture, available for evapotranspiration (m);
$M(t_o)$ = initial available soil moisture (m);
$E_r(t)$ = actual evapotranspiration rate at time t ($m.day^{-1}$);
$f_c(t)$ = capillary flux at time t ($m.day^{-1}$).

Depending on the occurrence of crop stress conditions, actual evapotranspiration may be equal to the atmospheric demand, or be reduced due to closure of stomata in plant leaves. Considering a certain fraction (1 - a) of the maximum available soil water (M_o) to be available without crop stress conditions (Rijtema and Abou Khaled, 1975), the actual evapotranspiration rate can be approached by the following three relations:

$$E_r(t) = E_m \qquad \text{if} \quad M(t) > a\,M_0$$

$$E_r(t) = \frac{M(t)}{a\,M_o}\,E_m \qquad \text{if } 0 < M(t) \leq a\,M_0$$

$$E_r(t) = 0 \qquad \text{if} \quad M(t) \leq 0$$

where: a = fraction of maximum available soil water which is still available for evapotranspiration when reduction starts (-);
E_m = maximum evaporative demand ($m.day^{-1}$);
M_o = soil moisture which is available at field capacity (m).

The maximum evaporative demand (E_m) is determined by meteorological factors and crop stage of development (crop height and soil cover fraction). Since 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 crop development data such as crop height and relative soil cover for different stages in the growing season maximum rates are calculated according to Rijtema and Abou Khaled (1975).

When in plants a certain critical leaf water suction is reached, plant stomata start to close and reduction of crop transpiration begins. In the model formulation this critical leaf water potential is translated into a fraction of total available soil moisture, which is available for transpiration without reduction. Since each crop has its own characteristic critical leaf water potential, this fraction is different for each crop.

This fraction readily available soil moisture (a) depends also on the resistance of the plant for water transport from soil to the leaves, soil moisture suction characteristics, osmotic pressure in the soil water solution due to salinity, and on the maximum evaporative demand.

Depending on soil moisture suction in the plant root zone and water table depth, the capillary flux is assumed inversely proportional to the available soil moisture:

$$f_c(t) = f_m\,\{1 - \frac{M(t)}{M_0}\}$$

where: f_m = maximum possible capillary flux, given the depth of the groundwater table ($m.day^{-1}$).

The theoretical maximum capillary flux (f_m) is based on the depth of groundwater and a root zone which is at permanent wilting point. See Fig. 4 for some curves for standard soils.

By substituting the equation for actual evapotranspiration and the equation for the capillary flux in the mass balance equation, three solutions for the soil moisture balance equation are found, which are implemented in the model (See paragraph 3.4).

5.2.10 Drainage

Drainage of non-rice crops

For the simulation of drainage the resistance against flow to the drainage system is based on the theory of Ernst (1962) and discharge is simulated by a linear relation between water table depth above 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 clay cap and vertical hydraulic permeability. The difference between water table depth and piezometric head in the aquifer is the driving force for discharge to (leakage) and from (seepage) the aquifer. For calculation of the drainage hydrograph the balance equation of the drainage reservoir is solved.

During field irrigation both the unsaturated and the saturated soil moisture reservoirs are refilled to a certain degree. Distribution of applied irrigation water over both reservoirs depends on the soil moisture deficit before irrigation, the crack volume of the soil, and the quantity of irrigation water applied. The quantity of drainable water has been defined for the soil system above drainage depth:

$$M_{dr}(t) = \mu \; h(t)$$

where:
- $M_{dr}(t)$ = quantity of drainable water (m);
- μ = $\theta_s - \theta_{fc}$ = drainable porosity ($m^3.m^{-3}$);
- θ_s = soil moisture fraction at saturation ($m^3.m^{-3}$);
- θ_{fc} = soil moisture fraction at field capacity ($m^3.m^{-3}$);
- $h(t)$ = height of groundwater level above drain depth at time t (m).

Four water fluxes from the saturated groundwater system have been considered for the drainable soil water balance: drainage flux, leakage/seepage flux to the aquifer, capillary rise flux, and evapotranspiration flux during ponded conditions. Based on these fluxes, the mass balance equation for the drainable water reservoir can be formulated as follows:

$$\mu \frac{dh(t)}{dt} = -f_d(t) - f_l(t) - f_c - E_r$$

where:
- μ = drainable porosity for non ponded conditions, and unity in case of ponding ($m^3.m^{-3}$);
- $f_d(t)$ = drainage flux ($m.day^{-1}$);
- $f_l(t)$ = leakage/seepage flux ($m.day^{-1}$);
- f_c = capillary rise flux ($m.day^{-1}$);
- E_r = evapotranspiration flux ($m.day^{-1}$)

For the mathematical description of drain discharges, head losses due to restricted permeability of the soil are considered concentrated at the location of drains. Neglecting vertical and horizontal flow through the saturated part of the soil above drainage level, and assuming equidistant, parallel drains, the total drainage resistance can be given as (Ernst, 1962):

$$C_d = \omega\, L + \frac{L^2}{8\, k\, D}$$

where: C_d = drainage resistance (days);
ω = entrance resistance of drains ($day.m^{-1}$);
L = drain distance (m);
k = saturated soil permeability ($m.day^{-1}$);
D = depth of layer participating in horizontal drainage (m)

The drainage flux is positive when the groundwater table is above drainage depth and zero when the groundwater level is below drainage depth (no infiltration from drains assumed):

$$f_d(t) = \mu\, \frac{h(t)}{C_d} \qquad \text{if} \quad h(t) \geq 0$$

$$f_d(t) = 0 \qquad \text{if} \quad h(t) < 0$$

The leakage/seepage flux is positive in case of leakage (ground-water level above aquifer piezometric head) and negative in case of seepage (aquifer pressure above groundwater level) and is related to groundwater level and aquifer piezometric head:

$$f_l(t) = \frac{h(t) - h_{aq}}{C_{aq}}$$

where: h_{aq} = aquifer piezometric pressure above drain level (m);
C_{aq} = vertical resistance for leakage/seepage (days)

Evapotranspiration, directly from the saturated groundwater reservoir is assumed only under ponding conditions (water on the land surface). Both evapotranspiration and capillary fluxes have been assessed in the evapotranspiration module.

By substitution of the appropriate relations for fluxes, three solutions of the water mass balance are found. All three can be reduced to the general form:

$$\frac{dh(t)}{dt} = B - A\, h(t)$$

where: A,B = lumped parameters with resp. dimension (day^{-1}) and ($m.day^{-1}$)

The solution of this equation gives an exponential relation for groundwater depth:
Both drainage volume and leakage/seepage fluxes are computed in the model by substituting this equation in the flux equations and integration over the time step.

$$h(t) = \frac{B}{A} + \{h(t_0) - \frac{B}{A}\}e^{-At}$$

Drainage of rice

Land preparation for rice cultivation by Egyptian farmers starts with a dry tillage, crumbling large soil elements into finer ones. This dry crumbling procedure is followed by dry land levelling. By this technique small soil particles fall into cracks, which are at this time of the year maximally developed. During the succeeding pre-irrigation the dry soil swells and becomes more compacted than prior to land preparation. Mathematically, the reduction in permeability, associated with a higher soil compaction, is represented by a shallow resistance (puddled layer).

When under these conditions a standing water is present on the field, the groundwater level in the drainage and seepage/leakage flux equations has to be replaced by the piezometric head at drain level. The infiltration of water from the standing water layer follows from the difference in hydraulic head and the resistance of the puddled layer:

$$f_i(t) = \frac{h^*(t) + d_d - h_p(t)}{C_p}$$

where: $f_i(t)$ = infiltration flux at soil surface (m.day^{-1});
$h^*(t)$ = height of standing water layer (m);
d_d = drainage depth (m);
$h_p(t)$ = piezometric head at drain depth (m);
C_p = resistance of puddled layer (days).

The infiltration flux must be equal to the sum of drainage and leakage/seepage flux, under the condition that the piezometric head at drain level is positive. Under this condition the following relation for piezometric head is found:

$$h_p(t) = \frac{\frac{h_{aq}}{C_{aq}} + \frac{h^*(t) + d_d}{C_p}}{\frac{1}{C_{aq}} + \frac{1}{C_d} + \frac{1}{C_p}}$$

Upon continued infiltration from the standing water layer, the piezometric head may become negative and the infiltration flux at soil surface equals the leakage/seepage flux (the drainage flux is zero). Under this condition the piezometric head is given by the following relation:

$$h_p(t) = \frac{\dfrac{h_{aq}}{C_{aq}} + \dfrac{h^*(t) + d_d}{C_p}}{\dfrac{1}{C_{aq}} + \dfrac{1}{C_p}}$$

Based on the assumption that water used for transpiration by the plant canopy is extracted by plant roots from the first few centimeters of saturated soil above the puddled layer, the water balance of the standing water layer is drafted and solved in the model in analogy with the drainable water balance.

5.2.11 Salts

Salt transport in the soil

During and immediately following irrigation, water moves downward through the soil to the water table. During this downward transport, dilution, mixing of salts in various layers, and leaching of top layers occurs. Excess irrigation water causes also a leaching of salts from the saturated soil system to drains.

Water losses through evapotranspiration may reverse the flow direction, and water moves up from the water table by capillary rise. Evapotranspiration removes pure water from the soil, leaving salts behind, since salt uptake by plants is negligible.

Quantity and quality of drainage water, as well as salinization of the unsaturated zone, are also dependent on quantity and quality of the seepage water arriving from the groundwater aquifer.

Although cation exchange between soil and soil water can play an important role, particularly in alkaline soils, it has not been taken into consideration in the FAIDS model. The same holds true for dissolution and precipitation of salts. As a consequence the chloride ion has been taken as a tracer. This Cl^- concentration appears to be related to the total dissolved salts and to the electrical conductivity

Three different situations must be considered for transport of salts in soil systems:
- recharge of soil moisture deficit and subsequent salt distribution in the unsaturated zone, following irrigation (module REDIS);
- redistribution of salts in the unsaturated zone, between two irrigations, as affected by evapotranspiration and capillary flow (module SAMIA;
- leaching of salts from the saturated zone as affected by excess irrigation water, seepage and drainage (module SAMIA).

The basic model used for calculation of transport of salts is obtained by subdividing the soil profile into a number of layers. Through the boundary of each layer transport of salts takes place by mass transport of water.

For Egyptian clay soils a moisture deficit dependent crack volume is introduced, which acts as a bypass with horizontal infiltration in each layer during irrigation. For very heavy clay soils in the northern part of the Nile Delta these cracks most probably are the major vertical transport path for irrigation water. Part of the water in cracks moves horizontally towards the drainage system and leaches part of the salts, which have accumulated on crack surfaces. In order to account for this leaching, part of the water flowing through cracks to drains will be considered as passing through the soil matrix.

Soil layer water balance

For each distinguished soil layer, the general water balance equation can be formulated as follows:

$$\Delta t \{f_i(n-1,n) + f_i(n+1,n) + \alpha(n)\, f_r(n) + f_{cr}(n) - f_0(n,n+1) +$$

$$- f_o(n,n-1) - \alpha(n) f_r(n) - f_d(n) - f_e(n)\} + V(n,t_0) - V(n,t) = 0$$

where:

Δt	=	time step length (days);
$f_i(n-1,n)$	=	inflow from layer n-1 ($m.day^{-1}$);
$f_i(n+1,n)$	=	inflow from layer n+1 ($m.day^{-1}$);
$\alpha(n)\ f_r(n)$	=	effective leaching flux by rapid drainage ($m.day^{-1}$);
$\alpha(n)$	=	fraction of rapid drainage flux which is assumed to pass through the soil (-);
$f_r(n)$	=	rapid drainage flux through soil cracks adjacent to layer n ($m.day^{-1}$);
$f_{cr}(n)$	=	inflow from soil cracks ($m.day^{-1}$);
$f_o(n,n+1)$	=	outflow to layer n+1 ($m.day^{-1}$);
$f_o(n,n-1)$	=	outflow to layer n-1 ($m.day^{-1}$);
$f_d(n)$	=	outflow to drainage system ($m.day^{-1}$);
$f_e(n)$	=	transpiration flux ($m.day^{-1}$);
$V(n,t_o)$	=	moisture volume at start of time step ($m^3.m^{-2}$);
$V(n,t)$	=	moisture volume at end of time step ($m^3.m^{-2}$)

Depending on the situation which has to be analyzed, one or more of the flux components in this equation are zero.

Part of the rapid drainage flux through cracked top soils is assumed to pass through the soil matrix, to account for leaching of accumulated salts at the surface of soil cracks. This leaching fraction is assumed to be related to the crack volume per layer:

$$\alpha(n) = \epsilon\ \{1 - 0.8\ \frac{V_c(n,t_0)}{V_{fc} - V_{wp}}\}$$

where:

ε	=	leaching fraction when the soil is not cracked, i.e. when the soil is at field capacity (-);
$V_c(n,t_o)$	=	crack volume of layer n (m);
V_{fc}	=	moisture volume of layer (n) at field capacity (m);
V_{wp}	=	moisture volume of layer (n) at wilting point (m).

Given the boundary fluxes at the top and/or bottom of the unsaturated soil system, the outflow from each unsaturated soil layer is evaluated in the model. The vertical soil moisture distribution according to figure 6 is respected during this procedure. The rapid drainage flux per soil layer, as well as infiltration of water from cracks into soil aggregates is taken proportional to the initial crack volume per soil layer. Discharge to, or from, the bottom of the unsaturated soil system is taken to, or from, the drainable water reservoir. This reservoir forms the top boundary for the saturated soil system. Here, the drainage flux is taken proportional with depth. At the bottom boundary the seepage/leakage flux is used as an input. The outflow from each saturated and unsaturated soil layer is computed in the model from the general water balance equation.

Salt transport

For the transport of salts in the soil, complete and continuous mixing of incoming fluxes with soil water present in each identified soil layer is assumed. The transport and conservation equation can then be written as follows:

$$\frac{d\{V(n,t)\ c(n,t)\}}{dt} = \sum f_i\ c_i - \sum f_o\ c_o$$

where: $c(n,t)$ = concentration in layer n ($eq.m^{-3}$);
$\sum f_i\ c_i$ = total incoming flux of material ($eq.day^{-1}$);
$\sum f_o\ c_o$ = total outgoing flux of material ($eq.day^{-1}$)

For salt transport all water fluxes are assumed constant within the time step. As a consequence the moisture volume in each soil layer changes linearly with time. In this equation all incoming fluxes have to be identified on the basis of concentrations. These concentrations are assumed constant within the time step in the model. Based on these assumptions and simplifications the general form of the conservation equation can be formulated:

$$\frac{d\{c(n,t)\}}{dt} + \frac{A}{V(n,t_0) + \Delta V\ t}\ c(n,t) = \frac{B}{V(n,t_0) + \Delta V\ t}$$

with:

$$A = \Delta V + \sum f_o - f_e(n)$$

$$\Delta V = \frac{V(n,t_0+\Delta t) - V(n,t_0)}{\Delta t}$$

$$B = \sum f_i\ c_i$$

where: A = lumped parameter with dimension ($m.day^{-1}$);
ΔV = rate change of the moisture volume per soil layer ($m.day_{-1}$);
t = variable time between t_o and $t_o+\Delta t$ (days);
Δt = time step length (days);
B = lumped parameter with dimension ($eq.day^{-1}$).

Based on critical values for the parameters (A) and (ΔV), the following solutions of this equation are used in the model:
- for $\Delta V \neq 0$ and $A \neq 0$:

$$c(n,t) = \frac{B}{A} + \{c(n,t_0) - \frac{B}{A}\} \{\frac{V(n,t_0) + \Delta V t}{V(n,t_0)}\}^{-\frac{A}{\Delta V}}$$

- for $\Delta V = 0$ and $A \neq 0$:

$$c(n,t) = \frac{B}{A} + \{c(n,t_0) - \frac{B}{A}\} e^{-\frac{A\,t}{V(n,t_0)}}$$

- for $\Delta V \neq 0$ and $A = 0$:

$$c(n,t) = c(n,t_0) + \frac{B}{\Delta V} \ln \{\frac{V(n,t_0) + \Delta V\, t}{V(n,t_0)}\}$$

- for $\Delta V = 0$ and $A = 0$:

$$c(n,t) = c(n,t_0) + \frac{B\, t}{V(n,t_0)}$$

Due to the fact that in the model salt transport is treated layer by layer, the flow direction of water has to be followed. By integration of the above equations the average outflowing flux concentration is therefore determined first, before the next layer can be computed. A special algorithm in the model determines the calculation sequence.

Drainage salinity
The concentration of drainage water is calculated for each time step as the average of the saturated solute concentration of the layers below drain depth:

$$\hat{c}_d = \frac{1}{n_s} \sum_{1}^{n_s} \hat{c}(n)$$

where: $\hat{c}_d$ = drainage water concentration (eq.m^{-3});
n_s = number of saturated soil layers (-);
$\hat{c}(n)$ = average concentration of soil layer n (eq.m^{-3})

The concentration of the rapid drainage water flux is obtained by multiplying the leaching fraction of the rapid drainage flux with the average unsaturated salinity and the remaining part with the irrigation water salinity:

$$\hat{c}_r = \frac{1}{V_r} \sum_{1}^{n_u} [\alpha(n)\, f_r(n)\, \hat{c}(n) + \{1 - \alpha(n)\}\, f_r(n)\, c_{ir}]$$

where: $\hat{c}_r$ = average concentration of rapid drainage discharge (eq.m^{-3});
V_r = rapid drainage losses (m);
n_u = number of unsaturated soil layers (-);
c_{ir} = concentration of irrigation water (eq.m^{-3})

Drainage salinity rice fields

For rice fields, the salinity of the standing water layer is also considered. For salt computations, this reservoir is treated identical to soil layers (complete and continuous mixing).

Rice plants extract soil moisture from soil layers with plant roots and, by diffusion, material will move upward to the standing water. In the model approach for regional application, this diffusion is accounted for by assuming transpiration to take place from the standing water layer (in addition to evaporation of open water when soil cover is incomplete).

Under rice field conditions, flow to the drainage system through the unsaturated soil system has to be taken into account. Soil layers above drain level are generally well structured and completely ripened. This means that (horizontal) saturated hydraulic permeability of these layers may be much higher than in less good structured soil layers below drain level. In order to account for this phenomenon, part of the drainage flux is assumed to pass through soil layers above drain level directly to drains.

Drainage water salinity for rice field conditions is calculated in the model with the following relation:

$$\hat{c}_d = \frac{\alpha_f}{n_u} \sum_{1}^{n_u} \hat{c}_u(n) + \frac{1 - \alpha_f}{n_s} \sum_{1}^{n_s} \hat{c}_s(n)$$

where: α_f = fraction of drainage discharge which flows through layers above drain level (-);
$\hat{c}_u(n)$ = average soil moisture salinity in the unsaturated soil layer n (eq.m^{-3});
$\hat{c}_s(n)$ = average soil moisture salinity of the saturated soil layer n (eq.m^{-3})

5.3 Generated volumes of drainage water

Drainage from a certain field plot through cracks (so called fast drainage), surface or subsurface drainage, starts at a high rate directly after irrigation and decreases when time elapses. The total area of a certain crop is not irrigated at the same time moment during a certain irrigation interval but increases when irrigation proceeds and so does the area producing drainage water. The rate of drainage water production in a certain calculation unit at a certain time moment is the summation of the drainage water production rate of individual field plots which already have been irrigated. It can be proven that the drainage water production in a calculation unit per unit area and per day by a certain crop during one irrigation interval is equal to the average daily drainage production on one individual field plot per unit area during that irrigation interval. This allows the use of only one representative field plot for each crop in the REUSE submodel. In the real situation, however, field plots which are irrigated at the end of an irrigation interval produce drainage water in the succeeding interval. This causes a lag time between irrigation supply and drainage water production. This lag time depends on the effective or drainable porosity, drain depth, drain spacing, soil type and leakage or seepage conditions. The most important factor, however, is the draindepth (Fig. 10).

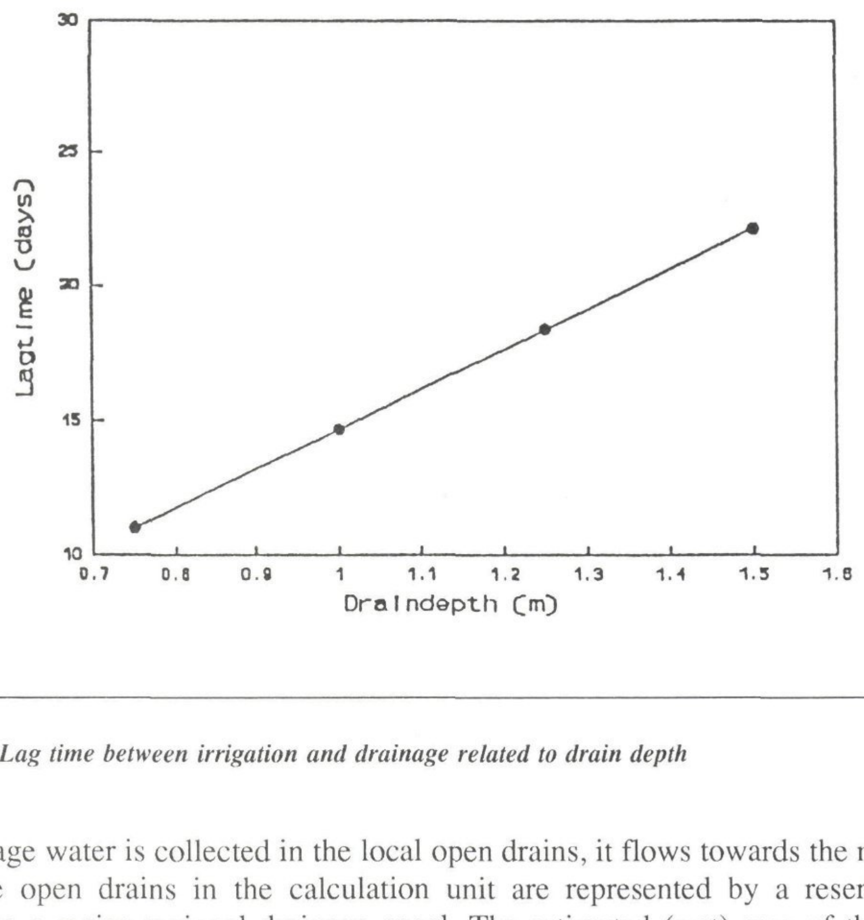


Figure 10: Lag time between irrigation and drainage related to drain depth

Once drainage water is collected in the local open drains, it flows towards the major drainage canals. The open drains in the calculation unit are represented by a reservoir which is connected to a major regional drainage canal. The estimated (wet) area of this reservoir is about 3% of the irrigated area in the Eastern Nile Delta. The outlet of the reservoir to the major drain is considered as a canal with a certain flow resistance. Its characteristics are a hydraulic slope which is equal to the bed slope and dimensions which are functions of the drained area. These functions are similar to those for irrigation canals be it that maximum design-discharge is reduced by 50%.

When a certain time has elapsed drainage water which was released to the reservoir is released to the regional major drainage canal. It is proved that the lag time is a function of the size of the reservoir (table 13).

Table 13: Lag time between release of drainage water to local drains and release to regional major drains

Area calculation unit (fed.)	Lag time (days)
2,000	0.2
4,000	0.6
5,000	0.8
10,000	1.5
15,000	2.0
25,000	3.0

The submodel accounts for the total of the aforementioned lag times when drainage water from the calculation units is released to the major drainage canals.

The drainage canal system is considered as a collecting and transferring system for drainage water. In the REUSE submodel drainage canals are decomposed in sections. The discharge in each section is the sum of the discharge in the upstream section plus the discharge from a connected calculation unit. Canal leakage or seepage is also included. Spillway and tailend losses are added to the corresponding section. Reuse of drainage water through pumping stations or local pumps, is treated as a reduction of the discharge and salt load with a certain quantity. For the salinity calculations in drainage canal sections all sources of drainage water are assumed to mix completely.

5.4 Reuse of drainage water

Reuse of drainage water has been implemented in the REUSE submodel on two levels: 1- through pumping stations which feed irrigation canals (regional reuse) and 2- through stationary or movable pumps which deliver drainage water directly to the fields (local reuse).

Decisions for regional reuse are taken and implemented by the authorities. Once the stations are in operation, the expected quantities of drainage water are considered as irrigation water. For planning purposes a relationship should be available between the quantity of supplied irrigation water to certain regions, the cropping pattern and the quantity of available drainage water for reuse. In the REUSE submodel available quantities are calculated. The expected quantities have been used in the water allocation procedure in the DESIGN submodel and are adjusted by the REUSE submodel when the discharge in the corresponding drainage canal section is insufficient. The REUSE submodel keeps record of detected deviations and writes them to a special message file.

The REUSE submodel recognizes two main sources for local reuse: the local minor drainage canal system which conveys drainage water from the calculation unit itself, and the major regional drainage canal system, which conveys drainage water from upstream areas. Because only a limited area is located close enough to drainage canals, only a fraction of the total available drainage water quantity can be used. This fraction, however, is unknown and has to be determined through model calibration. A further limitation of local reuse of drainage water is caused by the non-continuity of irrigation (only by day-time) whereby the potential reuse is reduced with about 50%. Decisions to reuse drainage water locally are made by the farmers.

Reuse obviously has its effect on the irrigation water salinity downstream of the pumping station. Irrigation water supplied to the intakes of main irrigation canals has a known salinity (Nile water quality), which changes at two levels:
- downstream of reuse pumping stations and;
- in the calculation units when locally drainage water is reused.

When local drainage water is applied in reality, it is in general not diluted through mixing with fresh water. However, by assuming linear relationships between salinity of irrigation water and salt effects, the salinity of irrigation water supplied to the crops can be determined by blending the different supplied irrigation water quantities.

Prior to the updating of irrigation water salinity downstream of the mixing locations (reuse pumping stations) the discharge and salinity in the drainage canal section which provides drainage water to the pumping station have to be known. The drainage water releases from different calculation units have therefore been determined according to a certain sequence. The REUSE submodel starts simulations for calculation units which are connected to the most upstream sections of the drainage canal system and which are irrigated with pure Nile water. The simulations proceed in a downstream direction. In the meanwhile the discharge and salinity of drainage water in the drainage canals are updated. The sequence is interrupted when a reuse pumping station withdraws drainage water from a certain section or when a connected calculation unit is irrigated with a mixture of drainage water and irrigation water of which the salinity still has to be determined. If available, the requested quantity of drainage water is withdrawn from the drainage canal section and released to a certain irrigation canal. Trough a special algorithm, assuming complete and instantaneous mixing, the salinity of the irrigation water which already was supplied to downstream calculation units through the WATDIS submodel is updated. After this update the calculation of drainage water releases from calculation units is resumed till similar conditions are met (an additional reuse station) and a new update is required.

5.5 Simulation of crop succession

Succession of crops is determined by many factors: the area to be grown with a certain crop, optimization of the profits, avoiding of plant diseases or salinity hazards. A crop rotation which is suitable for the prevention of salinization starts with a crop which is susceptible for salinity and requires relatively large quantities of water (eg. rice) and ends with a crop which requires limited quantities of water and is less susceptible to relatively high salinities. The soil salinity increases during such a crop rotation. Crop succession in the REUSE submodel is considered as a farmers decision. The submodel represents this decision through two considerations:
- the areas of crops which have to be grown are respected and;

- a preference for a certain crop above other crops to be grown after a preceding crop. These preferences are listed in Table 14.

Table 14. Crop succession preference for the main crops. 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)

Crop succession starts at the moment when a certain crop is harvested. The area occupied by such a crop will then become available for following crops according to the preferences in Table 14. If the available area of the preceding crop for the following crop is (more than) sufficient, the procedure stops. In the other case, the complete area of the preceding crop is occupied and the additional required area is withdrawn from the area of a crop that has a second preference as preceding crop. The new hypothetical field plot is composed of parts of the field plots of preceding crops. Soil salinity, moisture distribution and average groundwater table for the new plot are recalculated as weighted averages of these entities of the preceding plots. In the crop succession procedure the possibility that the area grown with the new crop increases gradually with respect to time is taken into account.

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PART II: MODEL APPLICATION

1 INTRODUCTION

Apart from the model concepts treated in part I, the course focusses on the practical aspects of model application. Starting with the spatial schematization (chapter 1) a brief overview of all the neccessary input data is given (chapter 2). In chapter 3 some aspects of the practical model execution have been described. Chapter 4 deals with analysis and presentation of output. In chapter 5 and 6 respectively calibration/validation and running different scenarios are treated.

2 SPATIAL SCHEMATIZATION

The first activity that should be carried out when preparing input data for the SIWARE model is the spatial schematization i.e. the division of the study area into calculation units (or distributary areas). A calculation unit is considered homogeneous with respect to cropping pattern, hydrological circumstances etc. Calculation of the different terms of the water balance takes place for the different crops present in the unit. Subsequently the results are aggregated into the terms of the water balance of the complete unit. The surface irrigation water entering a calculation unit is assumed to originate from one source (i.e. a canal node) and its drainage water is assumed to be discharged into one section of the drainage system. Consequently a calculation unit has the five following characteristics:
- supplied with irrigation water from one single irrigation canal;
- release of drainage water to one single drainage canal;
- situated within the boundaries of a drainage catchment;
- situated within the boundaries of an irrigation district;
- input data as for instance soil paramaters, climatical parameters, cropping pattern, etc. can be considered as uniform within the unit.

Schematization starts with preparing a map of the relevant irrigation and drainage canals and the boundaries of the study area. On a copy of this map, the main canals (first order), the second and all relevant lower order irrigation canals are highlighted. Branches which serve a relatively small area can be considered as distributaries, even if they again have branch canals (a distributary is a feeder of a calculation unit).

Now a map of the calculation units can be prepared. A copy of the map with the irrigation and drainage system is required. Boundaries of canal command areas, irrigation districts and drainage catchments have to be added. When supply of irrigation water is on a rotational basis, the boundaries of the calculation units should be chosen in such a way, that at least one complete rotation lies within its boundaries. Under these conditions, the supply to such calculation units is continuous. Since boundaries of canal command areas do not coincide with the boundaries of drainage catchment areas, it may occur that a certain area receives irrigation water from one source, but releases its drainage water into different drainage catchment areas. In those cases, the calculation units should be subdivided into smaller units where each unit lies in only one drainage catchment. The calculation units have to be subdivisions of irrigation districts.

The location of the intake of the canal which feeds a calculation unit is indicated on the map. To each calculation unit a number is assigned. The gross arcreage of these calculation units has to be determined. For this purpose a planimeter can sucessfully be used. The percentage of the area under irrigation has to be known. When no such data are available, satellite images can be used to obtain this information.

3 INPUT DATA PREPARATION

Input data can be divided in two groups; time independent and time dependent input data. A brief description of the different input data is given below. However, for a description of the different input files and their format one is referred to the manual of the SIWARE model.

3.1 Time independent input data

The main time independent input data are the following:
- Irrigation system data;
- Drainage system data;
- Data on hydrological circumstances;
- Data on cropping pattern;
- Crop development data;
- Data on soil physical properties;
- Data on the initial conditions;
- Irrigation management data;
- Data to control the process.

- Irrigation system data
The input data on the layout of the irrigation system are given as coordinates of nodes. The distance between two nodes should be roughly between 0.5 and 5 km. For each node its coordinates should be given, its elevation (for future program development), and information about the water level control structures (e.g. head regulator, distributary intake) present.

- Drainage system data
Since the drainage system is simply represented by a sequence of reservoirs without storage capacity the input data consist basically of the sequence in which the different sections are connected and the calculation unit releasing its drainage water into that section. The input file also contains information on the sequence in which the discharges in the different sections should be simulated. The discharge in a certain section can only be simulated after the discharge in all sections upstream and its branches has been determined. Supplemental irrigation with drainage water from a certain section in a certain calculation unit (unofficial reuse) should also be inputted.

- Data on hydrological circumstances
In order to calculate all the water flows, seepage or leakage from or into canals, leakage or seepage from or into the aquifer, etc. data on resistances, depth to the aquifer, aquifer conductivity etc. are needed. They can generally be obtained from hydrogeological maps.

- Data on cropping pattern
The area grown with different crops in different administrative districts can be obtained from the Ministry Of Agriculture (MOA). An alternative would be the analysis of satellite images. This requires detailed field data on different crops ("ground truth"). If these data are not sufficient the results will be rather unreliable. The MOA data are generally presented on the basis of agricultural districts. In order to transform these data to data per calculation unit a file should be created indicating the fraction of the area of a certain unit belonging to a

certain agricultrual district (MARKAZ.INTERFACE). These fractions can be obtained by combining a map of the agricultural districts with one of the calculation units using any GIS package.

The following example serves to illustrate how the cropping pattern and subsequently the average crop water requirements are determined for a calculation unit, based on data per agricultural markaz:

The area of a calculation unit is divided among three agricultural markaz (resp 40, 50 and 10 %). Now the following table can be created:

Table 15: Cropping pattern for three markaz and and the derived cropping pattern for the calculation unit in % of the total area

Crop:	Markaz 1 (40 %)	Markaz 2 (50 %)	Markaz 3 (10 %)	Calculation unit area
Long Berseem	10	30	35	22.5
Short berseem	20	15	20	17.5
Wheat	20	25	30	23.5
Winter veget.	30	20	10	23.0
Decid. trees	20	10	5	13.5
Maize	40	50	55	46.5
Rice	0	5	10	3.5
Cotton	40	35	30	36.5
Total	200	200	200	200

The last column in Table 15 is calculated as the average of the three preceding columns weighed by the relative area shared with the concerning markaz. For example for wheat:

$(0.4 * \underline{20}\ \%) + (0.5 * \underline{25}\ \%) + (0.1 * \underline{30}\ \%) = \underline{23.5}\ \%$

The described procedure is performed automatically by the program CREATCD. It uses the files MARKAZ.INTERFACE and MARKAZ.CR* (containing the MOA data) as input.

-Crop development data
Also data are needed specifying when a certain crop is seeded/planted, when it reaches full soil cover, rooting depth etc.

- Data on soil physical properties
To be able to calculate the different fluxes in the soil, the model needs the soil physical properties such as the moisture content at saturation, field capacity and wilting point, and the parameters describing function of the maximum capillary flux as a function of the watertable depth input. Data on the swelling and shrinkage properties of the different soil types are also

needed. They can be determined through laboratory tests using samples of the representative soils in the area. All these data should be prepared for each distinguished soil type. A small data base with about 10 soil types is available for the model.

- Data on initial conditions

When starting a model application, certain initial conditions regarding soil moisture and salinity and groundwater table are required. Estimation of the initial status of soil moisture conditions and salinity from the literature or by field observations is virtually impossible (30 or more calculation units with 5 winter crops and 20 soil layers per crop results in about 40,000 initial data). As an alternative an initial estimate has been made followed by a simulation run of about 30 years, using data of an average year. The soil and watertable conditions at the end of this run are considered as initial conditions. 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.

- Irrigation management data

Another important type of input data are the parameters describing the human factor in the irrigation management such as the daily irrigation water abstraction, capacities of irrigation tools and the farmers' preference regarding irrigation of certain crops when water shortage occurs.

- Data to control the process

Different options can be chosen for a certain run of the model. Also some of the input and output files that the program will read from or write to can be specified. All this information is stored in a few special input files.

3.2 Time dependent input data

The following main time dependent data have been distinguished:

- Maximum evapotranspiration
- Water supply
- Groundwater extraction
- Regional reuse of drainage water

- Maximum evapotranspiration

The maximum evapotranspiration is calculated per 10-daily period according to the Rijtema approach. The data have to be entered in a file for different crop heights. When different climatological zones are distinguished within the study area, a file should be created for each zone. In addition to these maximum evapotranspiration rates, reduction factors should be entered depending on the soil cover percentage and the seaaon. A small data base with these data for three climatological zones in the Nile Delta is available for the model.

- Water supply

Data on water supply to the main canal intakes into the study area should be available to the model on a monthly or 10-daily basis.

- *Groundwater extraction*
Data on the quantity and salinity of the extracted groundwater for irrigation purposes should be obtained on calculation unit basis.

- *Regional reuse of drainage water*
Data on the quantities of drainage water officially reused by means of government operated pump stations should be entered in a file.

4 MODEL EXECUTION

When all the input files have been prepared according to the guidelines given in the User Manual, the model can be executed. This part deals with some practical aspects of this model execution.

4.1 Interactive/non-interactive model execution

When using a mainframe computer a program can be run interactively and non-interactively.

- *Interactive execution*
When starting executing of a program interactively, it will begin using the Central Processing Unit (CPU) to execute its different commands. During model execution the terminal from which the program execution was started is not available for other work untill the program terminates. Under VAX/VMS a program is executed by typing after the prompt:

$ run "program name"

- *Non-interactive execution*
Another option is to execute a program non-interactively. The user starts the execution of the program in the 'background" through another "session". This is done by using a so called command file, usually with the extension "COM". The command file contains the command lines in exactly the same format as if they had been entered directly from the terminal. Once a command file has been created it can be submitted to a so called "batch-queue" using for example the following command (VAX/VMS):

$ submit/queue=LUCTOR$SLOWBATCH "command file name"

Subsequently the commands in the command file will be executed in sequence. In the mean time the user can continue working normally on the terminal. When the execution of the program (the "job") is finished, a message is sent to the screen.

4.2 Creating command files

A command file can be created using any kind of editor that can produce an ASCII text-file. Under VAX/VMS the editor EDT is normally used. Following is an example of a command file that could be used to run the different sub programs of the SIWARE model:

```
$ COPY PERIOD.86 PERIOD.TXT
$ RUN WDUTY
$ RUN DESIGN
$ RUN WATDIS
$ RUN REUSE
$ COPY REUSE.MESSAGE REUSE.86
$ PURGE
```

First the file PERIOD.86 is copied to the file PERIOD.TXT (a file controlling the input; see user's manual). Then the different submodels are executed. After running REUSE the file REUSE.MESSAGE (containg information on the reuse of drainage water) is copied to the file REUSE.86. Finally the purge command deletes old versions of the different data transfer files.

A command line in an existing command file can be disabled by entering a character in the position directly after the $-sign.

5 OUTPUT ANALYSIS AND PRESENTATION

5.1 Output files

The principal outputfiles produced by the model package are:
- BALIRR.*
  containing data on the irrigation water balance on a monthly basis;
- BALDRN.*
  containing data on the drainage water balance on a monthly basis;
- BALTOT.*
  containing data on the water and salt balance of both the irrigation and the drainage water on a monthly basis;
- BALDELT.*
  containing data on water and salt balance components for each distributary;
- DRNDS.*
  containing the discharge and the salinity in the different sections of the drainage system. The file is produced to be used by the program CPALL (See section 5.3). Data for individual sections can also be retrieved from this file using INSPECT (See section 6.2);
- SCDATA.*
  containing all output data on distributary basis in a special format to be used by the Interactive Comparative Display System (ICDS) for presentation of output data (See section 5.3);
- REUSE.MESSAGE
  containing data on the availability and the actual use of drainage water for irrigation purposes. This file can be used to adapt the design capacities of future reuse pumping stations when running different scenarios.

The extension * generally refers to a certain year for which the program has been applied (e.g. 86).

5.2 Post-processing of output data

Some small programs have been developed to process the output data of the model. A brief decription of each of them is given below:

- WDBAL
  A small program which produces an outputfile containing the different components of the irrigation water balance. It uses only the output files of the WATDIS submodel. The output file is called OUTBAL.DAT. Since the REUSE submodel already produces outputfiles with the same information it is mainly only used when WATDIS is executed on a stand-alone basis.

- INSPECT
  A program to retrieve data on discharge and salinity for one section of the drainage system from the file DRNDS.*. It is particularly useful when the user wants to include a possible future reuse pumping station in the model. Using INSPECT one obtains information on the discharge and salinity in the drain at the tentative location.

- READOUT

  This program reads information from the file OUTQLT. one of the outputfiles of WATDIS containing data on discharge, water levels and salinities in the different nodes of the canal system per 10-daily period. This file is unformatted and not directly accessible using a normal editor. READOUT extracts, for a certain canal section specified by the user, these data and writes them to an output text file READOUT.OUT on a monthly basis. Like INSPECT this program is meant to be a tool when planning an additional reuse pump station. The water allocation for an area downstream of a certain node in the canal system can now be estimated.

5.3 Graphical presentation

For a proper analysis and presentation of the model results graphical output is indispensable. When comparing future developments assuming different scenarios graphical output is also an important tool for decision support. Basically two different types of graphical output can be distinguished:
- Graphs showing the change of certain output data through time.
- Maps showing the spatial distribution of some output data.

The first type of graphical output is especially useful during the calibration/validation of the model (See chapter 6), but also for decision support. The second type is mainly used for output analysis and decision support.

Three ways of producing graphical output are available in combination with the SIWARE model:
- The program CPALL can be used to create graphs of drain discharge, salinity and total salt load through time for a certain section of the drainage system. This type of output is mainly used during calibration/validation. CPALL reads information from three files:
  * The file CALIB.* contains the measured discharge and salinity for certain locations in the open drainage system on a monthly basis.
  * The file DRNDS.* contains the simulated discharge and salinity for all the sections defined in the drainage system on decade basis.
  * The file VIEW.DAT contains the information on the locations and sections to be read from the two previous files and subsequently combined into one graph. CPALL uses the SIMPLOT package, a "toolkit" containing modules with various graphical functions. For information on the use of SIMPLOT one is referred to the SIMPLOT user's guide.
- The program PW is similar to CPALL and is used to plot irrigation water discharges through time for specified canal nodes. PW is mainly used for calibration of the WATDIS model. PW reads the WATDIS outputfile OUTCAC.ext containing the calculated discharges and salinities. The other inputfile needed by PW is OUTCAM.ext containing the measured values.
- The Interactive Comparative Display System (ICDS) is used to produce maps with the different output data on distributary basis. The main input file SCDATA.* is automatically produced by SIWARE. For further information on this extensive program one is referred to Report 14 of the DLO Winand Staring Centre, "Interactive comparative display system for analyzing results of environmental modeling" by P.E.V. van Walsum.

6 CALIBRATION/VALIDATION

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 different components of the regional SIWARE model package. For a correct validation of these models, field data on input and output of each relations included in the models should be collected. By comparing observed and simulated output of each relation model validity can be proven. A complete coverage of all relations considered requires, however, an enormous field research effort and is therefore not possible.

Collection of sufficient and 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* can been used instead in order to obtain more accurate model results. During this procedure measured output (water allocation, water distribution, drainage discharge and salinity) is used as a yardstick for changing input data between certain ranges. Values giving best results are then finally selected. Accurate results for circumstances for which data have been calibrated, does not automatically mean that 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. The latter process is the *validation* of the model.

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

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

For the first two levels of comparison (water allocation and distribution) observations of the Ministry of Public Works and Water Resources can be used. Drainage water discharge and salinities have been monitored by the Drainage Research Institute on drainage catchment scale.

6.1 Calibration procedure

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 defining the water management strategy, such as cropping pattern, allocation water duties and water supply data;
- model input parameters determining 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 system behaviour model input data are subject to calibration. This means that values of such model input parameters are changed in order to fit model simulation results with field observations. Model input parameter calibration can be justified by any one of the following reasons:
- limited knowledge about certain model parameters;
- uncertainty about exact values of model input parameters;
- spatial variability of model parameters within assumed uniform calculation units.

The main model input parameters which can be 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.

Theoretically, before calibrating the model a so called sensitivity analysis should be carried out. By changing all parameters one by one and subsequently analysing the output the user can find out the extent of the effect of a certain change. The "sensitivity" of the model to changes in the value of a certain parameter is determined. Within the scope of the current training course however, a simpler procedure, basically of trial and error, is followed.

Certain initial values for the different parameters have already been provided. According to the sequence given above these values are changed one by one i.e. multiplied or divided by a certain factor. After each change, the model is run and the resulting output is compared with measured data (drain discharge and salinity) using the program CPALL for all locations where both simulated and measured data are available. At the bottom of the graphs also the 'average monthly deviation' deviation' is indicated. 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. Whenever a certain change results in an improvement (i.e. decrease in deviation) of the output the change is maintained.

A certain criterion should be established beforehand that should be matched in order to make the result of the calibration procedure acceptable. When calibrating the model for the complete Eastern Nile Delta the following criteria were used for the 'average monthly deviation':

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

6.3 Validation

After finishing calibration, the model should still be validated using a different data set than the one used for calibration. Again the program CPALL can be used to display the results of the comparison between measured and simulated data.

The purpose of model 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 reliablilty 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.

Given the limited time and data availability for the study area no validation will take place within the scope of this training course.

7 RUNNING SCENARIOS

One of the main reasons to develop the SIWARE model was to create a tool to support the selection of certain water management measures/strategies. The underlying thought is that, when calibrated and validated properly, the model will respond to imaginary changes in water management, cropping pattern etc. in a similar manner as the actual system. Consequently it can be used to assess the effects of possible management measures/strategies on the water and salt balance which, in their turn, effect crop production. By simulating different management alternatives (scenarios) a better foundation for certain decisions can thus be created. However, it is important to keep in mind that when running scenarios not too much value should be attached to the actual values of model output. When analysing model output for different scenarios one should focus on the differences in trends between them.

When using the model as a tool for the analysis of possible management scenarios the user should adress the following questions:

- *Can the posed question be answered using the SIWARE model?*
  It is quite conceivable that a certain issue is at stake, which is not included in the model formulation. If, for instance, decisions makers want to have an indication about the effect of an increase of groundwater extractions on water pressures in the aquifer underneath the Nile Delta, the SIWARE model can simply not be used. Also in many cases an unequivocal answer can not be given. The answer to the question "How much drainage water can be reused?" depends for instance mainly on the level of yield reduction one is willing to accept as a result of increased soil salinities. However, using the model one could get an indication about the extent of these reductions related to different reuse levels. Although this is evidently very important information, it does not answer the queston.

- *Which input data have to be changed in order to simulate the proper scenario?*
  A list should be prepared containing all input data that should be changed also indicating the way in which they should be changed.

- *For what period should the model be run?*
  The user should judge in advance what the character of the expected effects of the changes mentioned under (ii) will be. If these effects are long-term effects, such as salinization, the model should be run for an extended period.

- *How can the resulting model output be translated into an answer to the original question?*
  The output data that will be the most interesting to decision makers will be water use efficiency and data related to crop production such as soil salinity and relative evapotranspiration. As explained above, in most cases an unambiguous answer can not be given. It is the model user's task to translate relevant model output in expected trends that can serve as a foundation for certain decisions in water management.

PART III: EXERCISES

EXERCISES

Two groups of four engineers are trained each consisting of members of the open drains division of the Drainage Research Institute, part of the Water Research Center (WRC-DRI) and the Irrigation Department of the Ministry of Public Work and Water Resources (MPWWR-ID). The first group consists of:
- Dr. Ahmed Morsi (WRC-DRI)
- Eng. Akram El Ganzouri (WRC-DRI)
- Eng. Essam Khalifa (WRC-DRI)
- Eng. Gamal El Kasar (MPWWR-ID)

The second group consists of:
- Eng. Adel Abdel Rasheed (WRC-DRI)
- Eng. Ashraf El Sayed (WRC-DRI)
- Eng. Amr El Shafi (WRC-DRI)
- Eng. Ragab Abdel Azim (MPWWR-ID)

For the exercises each group is split up in two groups of two persons each. Per sub-group the exercises are performed and the results discussed between groups and with trainers. Some of the exercises concern practical model applications, others deal with theoretical backgrounds of the model. The order in which they are presented is roughly in accordance with the course agenda.

Exercise 1:

The 5 characteristics of a calculation unit:

- supplied with irrigation water from one single irrigation canal;
- release of drainage water to one single drainage canal;
- located within the boundaries of a drainage catchment;
- located within the boundaries of an irrigation district;
- input data as for instance soil paramaters, climatical parameters, cropping pattern, etc. can be considered as uniform within the unit.

It should also be kept in mind that a large difference in areas should be avoided and that a unit should not be made too small.

- Prepare a map with the irrigation canals drawn in blue and the drainage canals drawn in red;
- Put a transparent on this map and draw:
  - the outer boundaries;
  - the 3 (three! --> check situation at Wadi pump station) drainage catchments;
  - all irrigation districts (check when necessary with trainers);
  - the calculation units.

Finally, the results of both groups will be discussed together under the supervision of ir Boels. The possibility exists that the training will be continued with more than one schematization, so that it can be decided from SIWARE simulation results which one is the best.

Exercise 2:

Draw the boundaries of the calculation units on your map solely based on the given irrigation and drainage canals.

Exercise 3:

Draw the major command canals on a separate transparency in such a way that:
- each schematized calculation unit can be served by a command canal;
- the nodes for command canal intakes, side-branch intakes, distributary canal intakes, and all control structures are marked;
- all command canals end with a spillway.

Digitize (with line command) the irrigation command canals taking into consideration that:
- the distance between 2 successive nodes is as large as possible, but not more than 10 km;
- the minimum distance between 2 successive nodes is not less than 0.5 km.
- all marked nodes for the various structures are included.

Prepare file CNSYST.** using the digitized coordinates under the format as dexcribed in the manual;

Exercise 4:

Prepare the cropping pattern for each schematized calculation unit starting from Markaz data as obtained from the Ministry of Agriculture and enter these data in file CD**.TXT.

Exercise 5:

Prepare the hydrological data per calculation unit, but only those parameters related to the irrigation water distribution (DESIGN/WATDIS):
- distributary number (item 1);
- code for climatic region (item 2);
- soilcode (item 4);
- saturated hydraulic conductivity (item 5);
- resistance claycap (item 9);
- water pressure in the deep aquifer (item 11);
- chloride concentration in the deep aquifer (item 12);
- gross area of the calculation unit (item 14);
- thickness claycap (item 18);
- fraction of area under cultivation (item 20);
- official fraction of cultivated area under rice (item 21).

Use the existing file HD88.TXT and update above listed parameters for the schematized calculation units. Leave all other input parameters as they are and, finally, delete all records containing irrelevant data.

Exercise 6:

Prepare the files with the water supply data and the non-agricultural use of water;
- water supply --> at intakes of irrigation command canals, reuse pump stations, and groundwater abstraction (files IRQUAN.**, INTIPU.** and GRWUSE.DAT);
- non-agricultural use --> municipal and industrial uptake (file NAGRUS.**).

Exercise 7:

Prepare in cooperation with the trainers the files with general input data (not spatially or time distributed) GENERAL.TXT, GENINP.TXT, and DISRULE.TXT.

Exercise 8:

Prepare in cooperation with the trainers the program execution/option files PERIOD.TXT d REUSE.SEL.

Exercise 9:

a) Given a basin clay soil with the following properties:
   $\theta_{fc} = 0.52\ m^3/m^3$
   $\theta_{wp} = 0.32\ m^3/m^3$
   $\alpha\ = 20$
   $a'\ = 0.00045$

   At field capacity the Cl^- concentration in the soil moisture is 40 eq/m^3. What is the osmotic pressure ?

b) The soil dries out till $\theta = 0.42\ m^3/m^3$ as a result of crop transpiration. What will be the osmotic pressure in the soil?

c) On this soil a berseem crop is grown. In the first week of March the crop is 40 cm high, the soil cover is 90 % and the effective rootzone depth is 300 mm.

   Determine the critical available soil moisture fraction at which the stomata start to close. (Suggestion: use LOTUS-123)

d) Answer question c) for a wheat crop, 90 cm high with 100 % soil cover.

e) Answer questions c) and d) assuming an initial CL^- concentration of 10 eq/m^3 at field capcity.

Exercise 10:

Show in a graph how the depletion of the soil moisture reservoir would take place if the general soil moisture balance equation would read:

$$\frac{dM(t)}{dt} = -B$$

or if it would read:

$$\frac{dM(t)}{dt} = -A\ M(t)$$

Exercise 11:

What will happen to the waterfront advance speed if:
- the sakkia is replaced with a diesel pump with a higher capacity;
- the soil is drier;
- the basic infiltration rate increases.

Exercise 12:

On day 1 a rice plot is covered with a standing water layer (h_{max}) of 0.20 m with an Electrical Conductivity (EC) of 1.2 mmho/cm. On day x 10 cm has evaporated and 5 cm has infiltrated.

a) What is the EC of the standing water layer on day x?

b) What will be the EC of the standing water layer after topping it up till h_{max} again using irrigation water with an EC of 0.8 mmho/cm ?

c) Given the discharge of the diesel pump used is 40 l/s, the width of the field is 20 m, the length is 50 m and assuming $f_a = 1.5$, how much longer will the farmer have to irrigate to obtain a salinity of the water in the standing layer, lower than the critical concentration?

Exercise 13:

A farmer irrigates his wheat crop using a sakkia. The following data are given:
- The sakkia is operated for 1 h and 20 minutes, with a discharge of 20 l/s.
- The waterfront reaches the end of the field after 1 h and 10 minutes.
- Field width = 20 m, field length = 50 m
- h_0 = 20 mm, M_d = 0.105 m and V_c = 0.10 m^3/m^2
- The gross infiltration flux = 5 * 10^{-6} m/s

a) Give an expression for the advance speed of the waterfront as a function of x (the distance from the upstream end of the field).

b) Give the advance speed of the waterfront halfway between the upstream and the downstream end of the field. (approximating the average speed)

c) Give an expression for the infiltration opportunity time as a function of x.

d) What will be the net infiltration volume 20 m from the upstream end of the plot (in mm)?

e) At what distance from the upstream end of the plot the net infiltration volume equals the soil moisture deficit M_d ?

f) Calculate the total subsurface drainage losses.

Exercise 14:

Assume a (theoretical) situation were the unsaturated soil moisture reservoir is depleted by crop evapotranspiration without capillary flux. a=0.4, E_m=0.006 m/day, M_0=0.09 m.

a) Derive an expression for E_r as a function of time for $0 \leq M(t) \leq aM_0$.

b) Draw a graph showing the actual evapotranspiration rate through time.

Exercise 15:

Given a ponded rice plot with the following hydrological characteristics:
- C_{aq} = 500 days, C_d = 50 days, C_p = 100 days
- h_{aq} = 80 cm above drain depth, d_d = 1.00 m

At a certain moment the depth of the standing water layer is 20 cm. Calculate the piezometric head at drain depth.

Exercise 16:

Give a simplified version of the general water balance equation for a situation where a crop is grown on a sandy soil and the watertable depth is below drain depth during the time step.

Exercise 17:

Consider an unsaturated soil layer at field capacity of 0.25 m thickness and an initial CL^- concentration of 5 eq/m^3. The transpiration flux from this layer is 0.003 m/day and a capillary flux from the underlaying layer of 0.001 m/day with an average CL^- concentration of 10 eq/m^3 takes place. At field capacity the moisture fraction is 0.52 m^3/m^3.

a) Draft the daily water balance of this soil layer.

b) Draft the salt balance of this soil layer (differential equation).

c) Calculate the CL^- concentration in the soil moisture during a 10-day period.

Exercise 18:

Take the soil layer of the previous question and divide it into two layers of 0.125 m each. From both layers the transpiration flux is now 0.0015 m/day and through the bottom of the lower layer the capillary flux is entering the soil. Repeat question 9 for this situation.

Remarks: - Assume a uniform soil moisture distribution in the crop root zone.
- For question c) you should find the average concentration of the capillary flux entering the top layer.

Exercise 19:

Calibrate the input data given in section 5.2 by multiplying/dividing them by a certain factor and running the model again. Whenever a certain change results in an improvement of the output (use CPALL) it should be maintained.

Exercise 20:

For the water management in the Nile Delta many options are possible. The following two questions could possibly be asked by decision makers:

- Increase the official reuse of drainage water; indicate where this can be done for the study area, show how much Nile water can be saved, and find out what the limitations are.

- Increase the amount of groundwater use; how much Nile water can be saved for the study area?; what are the limitations?

Try to figure out within the group what should be done to implement such measures. Write down on paper what the most likely consequences will be. Ask yourself whether it is necessary to make simulation runs or whether these questions can be answered straightforwardly or cannot be answered at all.

When you decide to make model runs, adapt the calibrated data set for the study area in such a way that the model can answer these questions. Try also to assess the long term effects by running the model for 15 years.

Exercise 21:

The last question concerns a change in the cropping pattern. Suppose that farm-gate cotton prices raise considerably. As a result farmers will be tempted to grow more cotton. Therefore, increase all the areas currently cultivated with cotton in your study area by a factor 2. Try to assess the consequences before making the simulations and write them down on paper (do not forget the long term consequences!).

ANNEX: TENTATIVE PROGRAM

AGENDA week 1

day	subject
monday morning	General background on modelling
monday afternoon	Introduction VAX
tuesday morning	schematization (theory)
tuesday afternoon	computer practicing/schematization exercise
wednesday morning	DESIGN/schematization (theory)
wednesday afternoon	schematization test area
thursday morning	DESIGN/schematization (theory)
thursday afternoon	schematization test area
friday morning	WDUTY (theory)
friday afternoon	schematization test area

AGENDA week 2

day	subject
monday morning	input data preparation
monday afternoon	idem
tuesday morning	input data preparation
tuesday afternoon	digitizing maps
wednesday morning	input data preparation
wednesday afternoon	digitizing maps
thursday morning	WATDIS (theory)
thursday afternoon	input data preparation/digitizing maps
friday morning	WATDIS (theory)
friday afternoon	input data preparation/digitizing maps

AGENDA week 3

day	subject
monday morning	WATDIS (theory)
monday afternoon	input data preparation
tuesday morning	REUSE (theory)
tuesday afternoon	input data preparation
wednesday morning	REUSE (theory)
wednesday afternoon	input data preparation
thursday morning	input data preparation
thursday afternoon	calculation sequence theory
friday morning	input data preparation
friday afternoon	idem

AGENDA week 4

day	subject
monday morning	FAIDS theory
monday afternoon	FAIDS exercises
tuesday morning	FAIDS theory
tuesday afternoon	FAIDS exercises
wednesday morning	FAIDS theory
wednesday afternoon	FAIDS exercises
thursday morning	FAIDS theory
thursday afternoon	FAIDS exercises
friday morning	FAIDS theory
friday afternoon	FAIDS exercises

AGENDA week 5

day	subject
monday morning	excursion
monday afternoon	idem
tuesday morning	FAIDS theory
tuesday afternoon	input data processing
wednesday morning	FAIDS theory
wednesday afternoon	FAIDS exercise/input data processing
thursday morning	explanation ICDS
thursday afternoon	input data processing
friday morning	input data processing
friday afternoon	first run

AGENDA week 6

day	subject
monday morning	theory of calibration/validation
monday afternoon	calibration test area/output analysis
tuesday morning	calibration test area/output analysis
tuesday afternoon	idem
wednesday morning	theory of calibration/validation
wednesday afternoon	calibration test area/output analysis
thursday morning	calibration test area/output analysis
thursday afternoon	idem
friday morning	calibration test area/output analysis
friday afternoon	idem

AGENDA week 7

day	subject
monday morning	calibration test area/output analysis
monday afternoon	writing report
tuesday morning	calibration test area/output analysis
tuesday afternoon	writing report
wednesday morning	demonstration Remote Sensing
wednesday afternoon	writing of report
thursday morning	definition of managem. strategies
thursday afternoon	Translating strat. into model inp.
friday morning	writing of report
friday afternoon	translating strat. into model inp.

AGENDA week 8

day	subject
monday morning	preparation input extended reuse scenario
monday afternoon	idem
tuesday morning	output analysis extended reuse scenario
tuesday afternoon	discussion extended groundwater use scenario
wednesday morning	preparation input changed cropping pattern scenario
wednesday afternoon	idem
thursday morning	idem
thursday afternoon	output analysis changed cropping pattern scenario
friday	evaluation training course