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RE- USE OF DRAINAGE WATER

MODEL ANALYSIS

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Report of a mission to Egypt

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ADVISORY PANEL FOR LAND DRAINAGE IN EGYPT

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CONTENTS

Annex 1

1. INTRODUCTION

The present assignment was carried out in the framework of the activities of the Advisory Panel for Land Drainage in Egypt. This is a group of experts from Egypt and the Netherlands, established in 1976, on land drainage and related subjects to advice the Ministery of Irrigation of the Arab Republic of Egypt.

The establishment in the Drainage Research Institute (DRI) of an Open Drains Division made it possible in principle to plan a programme of systematic investigations of the drainage water in the Delta. In this connection the author was requested to carry out a consultancy to advice on:

- the outline and further formulation of a simulation model for predicting future trends in drainage water quality and water quantity;
- the collection of data required as input in such a model;
- the future actions to make the model operational.

Re-use of drainage water is a complex problem involving hydrometry, hydrology, soil physics, soil chemistry and water and soil management. Under the present conditions about 15 percent of the drainage water of suitable quality is re-used, but an enormous quantity of drainage water is still flowing unused to the sea. A portion of this water which has a low salinity could be re-used or be saved making irrigation water available for an additional area that can be reclaimed.

The mission was carried out in the period 11 January to 7 February 1981. The author had to rely on the assistance of the staff of DRI, and the Dutch team in this Institute. He is grateful to Dr. M. Hassan Amer, Director of the Institute, for the confidence placed in him by

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giving this assignment. The author had the benefit of intensive discussions with Dr. Mostafa El Gabaly, Dr. Mohamed Fahim and Dr.Mamdouh Ab El Hamid Fahmy, based on the questions given in annex 1. Efficient assistance was obtained from Dr. Samiah El-Guindi and Dr. Dia El Kousy, who where always found ready to supply the author with further information.

The author had regularly contact with Ir. H. van der Zel, leader of the Dutch team. The daily discussions with Ir. C.W.J. Roest, member of the Dutch team, who advices DRI on the subject of re-use of drainage water, were very fruitful.

2. AN OUTLINE OF A RE-USE MODEL

The re-use of drainage water is dependent on both quantity and quality of the drainage water. A complete re-use of all the drainage water is impossible, since a substantial portion must be conveyed outside the agricultural area. This follows from the overall water- and salt balance of the Delta. The supply of salts by the given irrigation water, by saline seepage and the possible further desalinization of reclaimed soils, results in an average salt content of the drainage water, that becomes finally so high, that the water is unsuitable for further agricultural use.

The low efficiency of the present irrigation system results in drainage water, which has a relatively good quality. The likely increase in the irrigation efficiency in future, reduces the volume of drainage water and results automatically in an increase in salinity or the drainage water.

Re-use of drainage water is only possible in specific locations, which are more of less limited in number, depending on the place where the drainage water becomes available.

Both the quantity and the quality of the drainage water depend on the efficiency of the irrigation system, the agricultural water use, the hydrological conditions and the chemical conditions of the soil. A re-use model that has to give answers to the effects of improved water management on quality and quantity of drainage water has to

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simulate the complete water management system in the Delta. Such a re-use model can be given by a number of sub-models, describing the various parts of the whole system. The scheme of such a re-use model is given in fig. 1.

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                    ┌─── 1. Supply System model (Susy)
                    │
                    ├─── 2. Use and Drainage model (Usdra)
                    │
   Re-use model ────┼─── 3. Salt Mixing Analysis model (Samia)
                    │
                    ├─── 4. Drain water Generation model (Drage)
                    │
                    └─── 5. Evaluation model (Eva)
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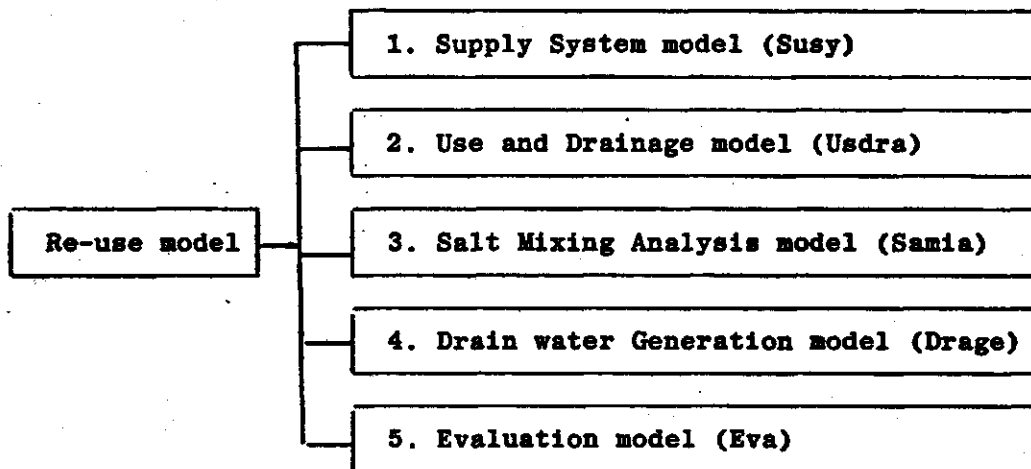
Fig. 1. Scheme of the re-use model

2.1. The supply system model

The Susy model can be described by the scheme given in fig. 2.

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        ┌─── Regional transport      conveyance
        │    main system             losses
        │
1 Susy ─┼─── Regional distribution   tail losses       2 Usdra
model   │    at farm level           spillway          model
        │
        └─── non-official
             re-use by farmers

        2 Usdra    4 Drage    4 Drage
        model      model      model
```

Fig. 2. Scheme of the Susy model

The model Susy has to describe quantitatively and qualitatively the regional transport of the irrigation water from the Delta Barrage into the Delta by the main canal system. Estimates have to be made of

the magnitude of the conveyance losses in the canal system. The second part has to calculate the regional distribution of the irrigation water in the distributaries and at farm level. In this part of the model also estimates of the spillway losses at the tail ends of the distributaries will be calculated. Both the calculated estimates of the conveyance losses and the spillway losses will be used as input data in the Drage model for the generation of the drain water. On the other hand will Susy be coupled with Drage and Usdra for the calculation of the non-official re-use by the farmers. Susy and Usdra will determine the need for re-use, while Drage determines the availability of drain water.

The Susy model has to quantify the local operational system. The applicability and the accuracy of this submodel depends strongly on the variability of the local operational systems. Sensitivity tests have to be performed beforehand to prove the possibilities of a certain standardization in local operation, based on assumed and empirical relations.

2.2. T h e   u s e   a n d   d r a i n a g e   m o d e l
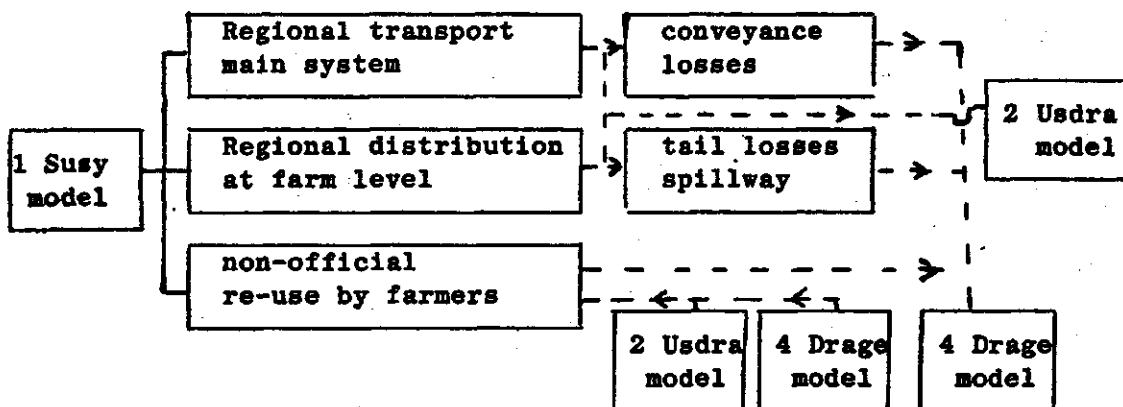
The Usdra model can be described by the scheme given in fig. 3.
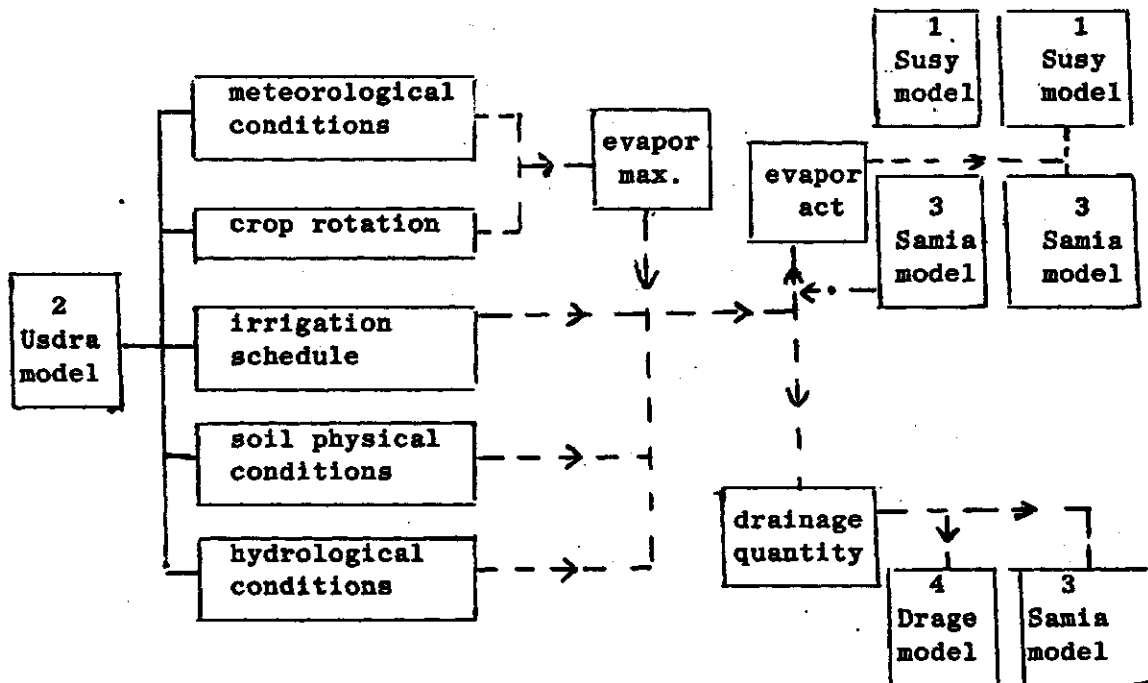

Fig. 3. Scheme of the Usdra model

The Usdra model has to calculate the maximum evaporative demand, using the data of the meteorological conditions in the Delta, crop rotation data, planting and harvesting data. Actual crop water use data are calculated, using that information in combinations with data of the irrigation schedule, the water availability, the soil physical conditions and the data of salt accumulation in the root zone, obtained from the model Samia. This information is also used in the Susy model for the calculation of the need of non-official re-use.

The model calculates also the quantity of drain water through the soil system with the information concerning the irrigation schedule, the field irrigation efficiency and the soil physical and hydrological conditions. This part of the Usdra model must be coupled with the Samia and Drage models.

2.2.1. Meteorological data

The available meteorological data can broadly be classified into two main groups. The first group includes the long-term mean values of some meteorological factors which have been observed during more than twenty years. The second group consists of data which have been measured during a much shorter period. In the present study the data collected by Rijtema and Aboukhaled (1975) can be used to describe the meteorological conditions in the various parts of the Niledelta. All calculations will be based on mean meteorological conditions.

2.2.2. Crop rotation

The main crop rotation in the Niledelta is given in table 1 for the southern, middle and northern part of the Delta. Though a large number of crops are grown in the Delta, only the major crops will be considered. The cropping pattern is based on the growth of a summer and a winter crop. A further intensification of the cropping pattern is not considered. In the southern delta no cultivation of rice is present; but a part of this area is used for vegetable production. In the northern part of the Delta rice becomes the predominant crop in summer, while occasionally barley is grown instead of wheat on saline soils.

Table 1.   The 3-years crop rotation in the southern, middle and
            northern part of the Delta, with summer and winter crops

Southern Delta	vegetables - berseem(long) - maize - berseem (short) - cotton - wheat
Middle Delta	rice - berseem(long) - maize - berseem(short - - cotton - wheat
Northern Delta	rice - berseem(long) - rice - berseem (short) - - cotton - wheat

Data have to be collected concerning the actual crop rotation in
different sub-areas.

2.2.3. Maximum evaporative demand

Previous investigations (Rijtema, 1965, 1969) have shown that real
evapotranspiration can be calculated using the combined energy balance
- vapour transport method. Rijtema and Aboukhaled (1975) used this
method for the calculation of the maximum evaporative demand for different
climatological regions in Egypt. The results of their calculations for
the Niledelta, as well as the reduction factors for partial soil cover
are given in table 2.

The results of these calculations, combined with the average
planting and harvesting data of the various crop results in a table
giving the contribution of the various crop in the total maximum eva-
poration demand. The calculated data are given in table 3. The first
two periods for rice concern nurseries, which take about 10% of the
rice acreage.

Table 2. Maximum evaporative demand and reduction factors for partial soil cover for the different zones of the Nile-delta

Southern Delta

Crop height cm	Mean monthly maximum evaporative demand E_{max} in mm.day^{-1}											
	J	F	M	A	M	J	J	A	S	O	N	D
0	1.1	1.7	2.9	4.0	5.1	5.9	6.3	5.7	4.6	3.3	1.9	1.0
10	1.7	2.6	4.3	5.6	7.6	8.8	8.2	6.8	5.6	4.5	2.5	1.7
20	2.1	3.1	5.2	6.6	9.0	10.4	9.4	7.6	6.4	5.2	2.9	2.1
30	2.3	3.4	5.6	7.1	9.6	11.1	10.0	7.9	6.7	5.6	3.1	2.3
40	2.5	3.6	6.0	7.5	10.2	11.7	10.5	8.3	7.0	5.6	3.3	2.5
50	2.6	3.8	6.3	7.8	10.7	12.2	10.9	8.5	7.3	6.1	3.4	2.7
60	2.8	3.9	6.5	8.1	11.1	12.7	11.3	8.8	7.5	6.4	3.7	2.8
70	2.9	4.1	6.8	8.4	11.5	13.1	11.7	9.0	7.7	6.6	3.7	2.8
80	2.9	4.2	6.9	8.6	11.7	13.4	11.9	9.1	7.9	6.7	3.8	3.0
90	3.0	4.3	7.1	8.7	11.9	13.6	12.1	9.3	8.0	6.8	3.8	3.0

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Reduction factor											
Winter	.31	.39	.47	.54	.63	.71	.81	.89	.95	1.00	1.00
Summer	.35	.43	.51	.59	.66	.75	.84	.90	.96	1.00	1.00

Middle Delta

Crop height cm	J	F	M	A	M	J	J	A	S	O	N	D
0	1.0	1.6	2.6	3.7	4.8	5.9	5.8	5.4	4.2	3.0	1.6	0.9
10	1.8	2.8	3.8	5.5	7.0	7.5	6.6	5.9	4.7	3.7	2.1	1.9
20	2.2	3.5	4.5	6.6	8.2	8.6	7.2	6.4	5.3	4.2	2.5	2.4
30	2.4	3.8	4.8	7.1	8.8	9.1	7.5	6.6	5.5	4.5	2.7	2.6
40	2.6	4.0	5.1	7.5	9.3	9.6	7.8	6.9	5.7	4.7	2.8	2.8
50	2.7	4.3	5.3	7.8	9.7	9.9	8.0	7.0	5.9	4.9	3.0	3.0
60	2.9	4.5	5.6	8.2	10.2	10.3	8.2	7.2	6.0	5.0	3.1	3.1
70	3.0	4.7	5.8	8.5	10.5	10.6	8.4	7.3	6.2	5.2	3.2	3.2
80	3.1	4.8	5.9	8.7	10.7	10.8	8.6	7.4	6.3	5.3	3.3	3.3
90	3.1	4.9	6.0	8.8	10.9	10.9	8.7	7.5	6.4	5.4	3.3	3.3

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Reduction factor	.28	.35	.43	.50	.58	.66	.78	.87	.94	1.00	1.00
Winter	.28	.35	.43	.50	.58	.66	.78	.87	.94	1.00	1.00
Summer	.38	.47	.54	.62	.69	.78	.86	.91	.96	1.00	1.00

Northern Delta

Crop height cm	J	F	M	A	M	J	J	A	S	O	N	D
0	1.3	1.8	2.7	3.7	4.9	5.8	6.2	5.7	4.6	3.2	1.9	1.1
10	2.5	3.2	4.3	5.1	6.1	6.7	7.1	6.6	5.8	4.2	2.8	2.2
20	3.2	4.0	5.2	6.0	6.9	7.5	7.8	7.3	6.6	4.9	3.4	2.8
30	3.5	4.4	5.6	6.5	7.3	7.9	8.2	7.7	7.0	5.3	3.7	3.1
40	3.8	4.7	6.0	6.8	7.7	8.2	8.5	8.0	7.3	5.5	3.9	3.3
50	4.0	4.9	6.3	7.1	8.0	8.4	8.8	8.2	7.6	5.8	4.1	3.5
60	4.2	5.1	6.5	7.4	8.2	8.6	9.0	8.4	7.8	6.0	4.3	3.7
70	4.4	5.4	6.8	7.6	8.4	8.9	9.2	8.6	8.1	6.2	4.4	3.9
80	4.5	5.6	7.0	7.8	8.6	9.0	9.3	8.8	8.2	6.3	4.6	4.0
90	4.6	5.6	7.1	7.9	8.7	9.1	9.4	8.9	8.3	6.4	4.7	4.1

Soil cover %	0	10	20	30	40	50	60	70	80	90	100
Reduction factor											
Winter	.27	.34	.41	.49	.57	.67	.78	.86	.94	1.00	1.00
Summer	.32	.40	.47	.55	.63	.72	.82	.89	.95	1.00	1.00

Table 3. Values of maximum evaporative demand (E_{max}) in $mm.day^{-1}$ for different crops in the Southern, Middle and Northern Delta

Period	Rice S/M/N	Maize S/M/N	Cotton S/M/N	Vegetables S/M/N	Berseem long S/M/N	Berseem short S/M/N	Wheat S/M/N
J1					2.0/2.1/2.3	2.4/2.0/2.3	2.0/ 2.1/2.4
J2					2.1/2.2/2.6	2.1/2.2/2.6	2.3/ 2.4/3.0
F1					2.9/3.4/3.7	2.9/3.4/3.7	3.6/ 4.0/4.7
F2					3.3/3.5/4.2	3.3/3.5/4.2	3.8/ 4.3/4.9
M1					4.8/4.2/4.8	4.8/4.2/4.8	6.4/ 5.5/6.3
M2	-/0.6/0.5		1.5/ 1.3/1.5		5.3/4.7/5.3		6.9/ 5.9/6.5
A1	-/0.9/0.8		3.5/ 3.4/3.1		6.3/6.3/5.8		8.1/ 8.3/7.4
A2			5.0/ 5.0/4.6		6.8/6.8/6.2		8.7/ 8.8/7.9
M1	-/0.6/0.5		10.2/ 6.3/7.7		8.8/8.0/6.7		11.0/10.0/8.0
M2	-/0.9/0.8		10.7/ 9.7/8.0		9.0/8.0/7.1		12.0/11.0/9.0
J1	-/9.0/7.9	3.5/3.0/2.7	13.6/10.9/9.1	6.2/ -/-			
J2	-/8.0/8.8	5.2/4.4/3.9	13.4/10.7/8.9	8.8/ -/-			
J1	-/8.0/8.8	10.1/7.6 8.3	12.3/ 8.9/9.6	9.6/ -/-			
J2		10.9/8.0/8.8	11.9/ 8.5/9.2	9.4/ -/-			
A1	-/7.5/8.9	8.3/7.5/9.0	9.5/ 7.7/9.1	7.8/ -/-			
A2	-/7.1/8.4	9.0/7.1/8.7	9.1/ 7.3/8.7	7.4/ -/.			
S1	-/6.5/8.2	8.2/6.6/8.5	8.2/ 6.8/8.5	6.6/ -/-			
S2	-/8.1/7.5	7.8/8.2/8.0	7.8/ 6.2/8.0	6.2/ -/-			
O1	-/5.7/8.7			5.5/ -/-		2.4/2.0/2.3	
O2	-/4.7/5.4			4.9/ -/-		3.6/3.1/3.4	
N1	-/3.5/4.8				0.9/0.8/1.0	3.0/2.5/3.5	
N2					1.8/1.5/2.0	2.7/2.4/3.2	
D1					1.8/1.8/2.2	1.9/1.9/2.4	1.0/ 0.0/1.1
D2					1.6/1.8/2.0	1.7/1.8/2.0	1.3/ 1.4/1.7

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2.2.4. Actual crop water use, a simplified aproach

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

$$E_{re} = E_{max} = - \frac{dM_t}{dt} \qquad\qquad M_t \geqslant aM_o \qquad (1)$$

$$E_{re} = \frac{M_t}{aM_o} \cdot E_{max} = - \frac{dM_t}{dt} \qquad\qquad M_t < aM_o \qquad (2)$$

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

E_{max} = maximum evaporative demand in $cm.day^{-1}$

M_o = maximum available soil moisture in cm

M_t = available soil moisture in cm at time t

a = fraction of remaining soil moisture at which the reduction in transpiration starts

Intagration of the first equation yields:

$$\int_{t=0}^{t=t'} E_{max} \, dt = - \int_{M_o}^{aM_o} dM_t \qquad (3)$$

or:

$$t' = (M_o'/M_o - a) \, M_o \, E_{max}^{-1} \qquad (3a)$$

provided that: $M_o' \geqslant aM_o$

M_o' is the amount of available moisture present in the soil after application of irrigation at time t = 0. If the irrigation interval $t_1 < t'$ than the soil moisture deficit at the end of the irrigation interval equals:

$$M_d = M_o - (M_o' + E_{max} \cdot t_1) \qquad (4)$$

where: ·

M_d = the soil moisture deficit at the end of the irrigation interval in cm

t_i = time length of the irrigation interval in days

When $t_i \geqslant t'$, the second equation must also be used.

Depending on the value of M_o', two different solutions are obtained.

When $M_o' > aM_o$:

$$\int_{t=t'}^{t} \frac{E_{max}dt}{aM_o} = - \int_{aM_o}^{M_t} \frac{dM_t}{M_t} \tag{5}$$

or:

$$\frac{E_{max}}{aM_o}(t-t') = - \ln \frac{M_t}{aM_o} \tag{5a}$$

or:

$$M_t = aM_o \exp\left[- \frac{E_{max}}{aM_o}(t-t') \right] \tag{5b}$$

Replacing t' by $(M_o'/M_o - a) M_o . E_{max}^{-1}$ yields for the soil moisture deficit at the end of the irrigation interval:

$$M_d = M_o \left(1 - a \exp\left[-\left\{ \frac{E_{max}t_i}{aM_o} - \frac{M_o'/M_o - a}{a} \right\} \right] \right) \tag{6}$$

Under the conditions of $M_o' \leqslant aM_o$ the solution of the differential equation becomes:

$$\int_{t=0}^{t} \frac{E_{max}dt}{aM_o} = - \int_{M_o'}^{M_t} \frac{dM_t}{M_t} \tag{7}$$

or:

$$M_t = M_o' \exp\left[- \frac{E_{max}t}{aM_o} \right] \tag{7a}$$

The soil moisture deficit equals in that case:

$$M_d = M_o - M_o' \exp\left[- \frac{E_{max}t_i}{aM_o} \right] \tag{8}$$

The real evapotranspiration can be calculated as:

$$E_{re} = \left\{ M_d - (M_o - M_o') \right\} t_i^{-1} \tag{9}$$

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The value of M_o' for the next interval equals when underirrigation is applied:

$$M_o' (T) = M_o - M_d (T - 1) + f \cdot I_T \qquad (10)$$

where: $M_o'(T)$ = the available soil moisture at the beginning of the Tth irrigation interval in cm

$M_d(T-1)$ = soil moisture deficit at the end of the interval T-1 in cm

f = the field irrigation efficiency

I_T = the gross irrigation gift at the beginning of the Tth irrigation interval in cm

The given equations describe the soil moisture deficit and the real evapotranspiration in terms of the soil profile by M_o, as its value depends on soil properties and rooting depth, the length of the irrigation interval t_i and the climatological conditions and the crop development by E_{max}.

The value of the coefficient a depends on the evaporative demand. It is well-known that under conditions of low evapotranspiration demand the available soil moisture can be almost completely depleted to wilting point without any reduction in transpiration, whereas the reduction at high demands already starts when the soil moisture content is still nearly at field capacity. So under conditions of low evaporative demand the factor a approaches zero, whereas it approaches 1.0, when the demand is very high. Values of the factor a have been calculated by Rijtema and Aboukhaled (1975) in relation to the value of E_{max}. These authors did not take into account the effect of soil salinity on the reduction in evapotranspiration.

The relation between the osmotic potential and the salt concentration in the soil by the average salt composition can be given by the expression:

$$\psi_{osm} = 0.041 \, c_o \cdot \theta_o \cdot \theta_t^{-1} \qquad (11)$$

where: ψ_{osm} = the osmotic potential in bars

c_o = the salt concentration in the rootzone immediately after irrigation in meq/liter at field capacity

θ_o = the volumetric soil moisture content in the rootzone at field capacity

θ_t = the volumetric soil moisture content in the rootzone at time t

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Adding the value of the osmotic potential to the procedure described
by Rijtema and Aboukhaled (1975) results in the calculated values of
a given in table 4 in their dependency on the soil salinity.

Table 4. The relation between the factor a, the maximum evaporative
demand (E_{max}) and the salt concentration in the rootzone at
field capacity

E_{max} cm.day^{-1}	Salt concentration at field capacity in meq/liter									
	0	10	25	50	75	100	125	150	175	200
0.1	.13	.15	.20	.26	.32	.39	.47	.59	.68	.80
0.2	.25	.27	.31	.37	.44	.51	.60	.68	.76	.84
0.3	.34	.36	.40	.46	.53	.59	.66	.73	.79	.86
0.4	.42	.44	.48	.53	.60	.65	.71	.76	.82	.87
0.5	.49	.51	.54	.60	.65	.70	.75	.79	.83	.88
0.6	.55	.56	.60	.64	.68	.73	.77	.81	.85	.89
0.7	.59	.61	.64	.68	.71	.75	.79	.83	.86	.90
0.8	.63	.65	.67	.71	.74	.77	.80	.83	.87	.90
0.9	.66	.67	.69	.73	.75	.78	.82	.84	.87	.90
1.0	.68	.70	.72	.75	.77	.80	.82	.85	.88	.91
1.1	.70	.71	.74	.76	.78	.81	.83	.86	.88	.91
1.2	.72	.73	.75	.77	.80	.82	.84	.87	.89	.91
1.3	.73	.74	.76	.78	.80	.82	.85	.87	.89	.92

Calculations showed that for practical application the relation
between a, the value of E_{max} and the salt concentration in the root-
zone can be considered as being independent of the soil type.

For the quantification of M_o, it is assumed that the toplayer
of 25 cm can be depleted to wilting point and in the deeper layers is
the extraction proportional with depth, with zero extraction at drain
depth.

The total amount of maximum available soil moisture equals the
depth integrated difference between the equilibrium moisture content

(at zero flux) and the moisture extraction for the assumed extraction pattern. The maximum depth of importance for moisture extraction by upward flux is considered to be 1.50 m. The soil characteristic given by Rijtema and Aboukhaled (1975) for respectively fine, medium and coarse textured soils can be used to calculate the value of M_o in relation to drain depth. As the depth of rooting also depends on drainage conditions, the value of M_o increase with increasing depth of drainage.

Calculated values of M_o for open field drains of 0.9 m depth, and tile drainage at respectively 1.25 m and 1.5 m are given in table 5.

Table 5. Values of M_o (cm) for fine, medium and coarse textured soils under different drainage conditions

Drainage conditions	Soil texture		
	fine	medium	coarse
open drains 0.9 m	11.2	8.0	4.2
tile drains 1.25 m	14.5	10.3	5.0
tile drains 1.50 m	17.0	12.1	5.5

2.2.5. Actual evapotranspiration and seepage flux

Evapotranspiration will be affected in regions with an influx of seepage water into the rootsystem. This situation is of particular importance when underirrigation is applied. In the present study it will be assumed that the contribution of seepage to evapotranspiration is proportionate to the soil moisture deficit.

Immediately after irrigation the seepage water is completely drained off, while in a completely exhausted soil the contribution of the seepage flux to the rootzone is determined as upper boundary by the maximum capillary rise f_c.

Under these assumptions the following relations hold:

$$E_{re} = E_{max} = -\frac{dM_t}{dt} + (1 - \frac{M_t}{M_o}) f_c \qquad M_t \geqslant aM_o \qquad (12)$$

and

$$E_{re} = \frac{M_t}{aM_o} \cdot E_{max} = -\frac{dM_t}{dt} + (1 - \frac{M_t}{M_o}) f_c \qquad M_t < aM_o \qquad (13)$$

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

E_{max} = maximum evaporative demand in $cm.day^{-1}$

M_o = maximum available soil moisture in cm

M_t = available soil moisture at time t in cm

a = fraction of remaining soil moisture at which the reduction in transpiration starts

f_c = maximum capillary rise to the rootzone in relation to depth of drainage in $cm.day^{-1}$

Integration of eq.(12) yields:

$$\int_{t=0}^{t'} dt = \int_{M_o}^{aM_o} \frac{-dM_t}{E_{max} - (1 - \frac{M_t}{M_o}) f_c} \qquad (14)$$

or:

$$t' = \frac{M_o}{f_c} \ln \left\{ \frac{E_{max} - (1 - \frac{M_o'}{M_o}) f_c}{E_{max} - (1 - a) f_c} \right\} \qquad (14a)$$

The remaining soil moisture volume at the end of the irrigation interval $t_1 < t'$ equals:

$$M_t = M_o \left[1 - \frac{E_{max}}{f_c} + \left\{ \frac{E_{max}}{f_c} - (1 - \frac{M_o'}{M_o}) \right\} \exp -\frac{f_c t'}{M_o} \right] \qquad (15)$$

For $0 < t_1 < t'$ the integrated value of the seepage contribution to evapotranspiration equals:

$$S_{E_1} = \int_0^t (1 - \frac{M_t}{M_o}) f_c \, dt \qquad (16)$$

or

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$$S_{E_1} = E_{max} \cdot t_1 - M_o \left\{ \frac{E_{max}}{f_c} - \left(1 - \frac{M_o'}{M_o} \right) \right\} \left\{ 1 - \exp\left(\frac{-f_c t}{M_o} \right) \right\} \quad (16a)$$

The total evapotranspiration equals in that case $E_{max} \cdot t_1$. When $t > t'$ the differential equation (13) must also be used. Integration of this equation yields:

$$M_t = \frac{aM_o}{E_{max} + af_c} \left[f_c + \left\{ E_{max} - (1-a) f_c \right\} \exp\left\{ - \frac{E_{max} + af_c}{aM_o}(t-t') \right\} \right] \quad (17)$$

The time integrated contribution of the seepage flux to evapotranspiration is given by the expression:

$$S_{E_2} = E_{max} t' - M_o \left\{ \frac{E_{max}}{f_c} - (1 - \frac{M_o'}{M_o}) \right\} \left\{ 1 - \exp\left(\frac{-f_c t'}{M_o} \right) \right\} +$$

$$+ (1 - \frac{af_c}{E_{max} + af_c}) f_c(t-t') - \frac{a^2 M_o f_c}{(E_{max} + af_c)^2} \left\{ E_{max} - (1-a)f_c \right\}$$

$$\left\{ 1 - \exp\left[- \frac{E_{max} + af_c}{aM_o} t \right] \right\} \quad (17a)$$

with t' equalling the value calculated with eq. (14a).

The total evapotranspiration equals under these conditions:

$$E \cdot t_1 = (M_o' - M_t) + S_{E_2} \quad (18)$$

For the conditions that $M_o' < aM_o$ for $t = 0$ integration of eq.(13) results in the following expression:

$$M_t = \frac{aM_o}{E_{max} + af_c} \left[f_c + \left\{ \frac{M_o'}{aM_o} (E_{max} + af_c) - f_c \right\} \exp\left[- \frac{E_{max} + af_c}{aM_o} \cdot t \right] \right] \quad (19)$$

The time integrated seepage contribution to evapotranspiration equals under these conditions:

$$S_{E_3} = \left\{ 1 - \frac{af_c}{E_{max} + af_c} \right\} f_c t - \frac{a^2 M_o f_c}{(E_{max} + af_c)^2} \left\{ \frac{M_o'}{aM_o} (E_{max} + af_c) - af_c \right\} \cdot$$

$$\cdot \left\{ 1 - \exp \cdot \left(- \frac{E_{max} + af_c}{aM_o} \cdot t \right) \right\} \quad (20)$$

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The total evapotranspiration equals in that case:

$$E.t_i = (M_o' - M_t) + S_{E_3} \tag{21}$$

2.2.6. Irrigation schedule

The farmers will get irrigation water available in the distributaries by a scheme of 5 days water, 10 days closed in winter. In areas without rice cultivation the scheme in 7 days water, 7 days closed in summer. In areas with rice cultivation the scheme during summer is 4 days water, 4 days closed. In particular in the early stages of the rice cultivation the standing water layers will be refreshed when the water temperature becomes above 35 ^{o}C. The irrigation system is closed for maintenance from January 15th to February 15th. A pre-irrigation treatment will generally be given for soil cultivation. The irrigation schedule and the irrigation gifts given in table 6 will be considered as the 'ideal' system.

Table 6. Number or irrigations applied and the 'ideal' quantity per irrigation gift (mm) for different crops on fine textured soils

Period	Rice	Maize	Cotton	Vege-tables	Berseem long	Berseem short	Wheat
J1	1x100				1x 50	1x 50	-
J2					1x100	1x100	1x100
F1					-	-	-
F2					-	-	-
M1			1x150		1x100		1x100
M2			-		1x100		1x100
A1			1x 50		1x100		1x100
A2			-		1x100		
M1			1x 75		1x100		
M2	4x 10	1x150	1x100	1x150			
J1	4x 5	-	1x100	2x 50			
J2	4x100	1x 65	1x125	2x 50			
J1	4x 50	1x 75	1x100	2x 50			
J2	2x100	1x 75	1x100	2x 50			
A1	2x100	1x 75	1x100	2x 50			
A2	2x100	1x100	1x100	2x 50			
S1	2x100	1x100		2x 50			
S2	2x100			2x 50			
O1				2x 50			
O2				1x 50	1x150	1x 50	
N1						1x 50	
N2					1x 50	1x 50	1x150
D1					1x 50	1x 50	-
D2					1x 50	1x 50	-
Year	1660	640	1000	1100	950	550	550

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A first calculation of actual evapotranspiration based on this schedule, assuming no additional losses due to irregular water distribution, gives for the meteorological conditions of the Middle Delta the data presented in tabel 7.

Table 7. Actual evapotranspiration in the Middle Delta by optimum distribution of the irrigation water E_{re} in mm.day^{-1}

Period	Rice	Maize	Cotton	Vege-tables	Berseem long	Berseem short	Wheat
J1					2.1	2.1	2.1
J2					2.2	2.2	2.4
F1					3.4	3.4	3.9
F2					2.5	2.5	2.1
M1					4.2	1.0	4.9
M2			1.3		4.7		5.7
A1			3.4		5.9		6.8
A2			4.8		6.2		2.1
M1			6.2		6.7		0.5
M2	0.6		6.4		2.1		0.1
J1	0.9	3.0	6.4	5.3			
J2	9.0	4.4	7.2	7.5			
J1	8.0	6.4	6.1	7.3			
J2	8.0	5.4	6.1	7.2			
A1	7.5	4.9	6.0	6.6			
A2	7.1	5.6	6.1	6.3			
S1	6.5	5.8	1.8	5.4			
S2	6.1	1.9	0.5	5.1			
O1	5.6			4.4		2.0	
O2	2.8			3.9		3.1	
N1	1.5				0.8	2.5	
N2					1.5	2.4	
D1					1.9	1.9	0.9
D2					1.8	1.8	1.4

Generally field efficiency is assumed to be 80%, but this figure must be considered as highly variable, depending upon the conditions of over- and underirrigation.

2.2.7. Precipitation

The amount of precipitation is small, compared with the amounts of irrigation water required. The mean monthly precipitation for the

Southern, Middle and Northern Delta is given in table 8. The data are the average figures of different meteorological stations in the Delta.

Table 8. Mean monthly precipitation in the Southern, Middle and Northern Delta in $mm.month^{-1}$

Region	J	F	M	A	M	J	J	A	S	O	N	D	Y
South	7.5	4.2	2.7	0.8	1.6	–	–	–	–	1.5	4.9	4.9	28.1
Middle	10.8	8.8	5.3	2.2	3.4	0.3	–	0.8	0.1	3.9	6.7	14.0	56.3
North	37.5	20.6	12.0	2.1	2.1	–	–	0.1	1.0	11.2	20.6	46.1	153.3

The precipitation will be proportionally added with the irrigation gifts. During the closed season the precipitation will be distributed over the calculation intervals.

2.2.8. Drainage water, quantity

The drainage water quantity produced during the irrigation interval (T) is the greatest value of the equations:

$$D_T = \left\{ f_s \cdot t_i - S_E \right\}_T + (1 - f) \cdot I_T \qquad f_s \cdot t_i \geqslant S_E \qquad (22a)$$

and

$$D_T = \left\{ f_s \cdot t_i - S_E \right\}_T + I_T - (M_o - M_{t(T-1)}) \quad f_s \cdot t_i \geqslant S_E \qquad (22b)$$

where: D_T = the drainage water quantity in cm produced during irrigation interval T

f_s = seepage flux in $cm.day^{-1}$

t_i = length of the irrigation interval in days

S_E = the seepage contribution to evapotranspiration in cm

I_T = the irrigation gift in cm at the beginning of irrigation interval T

f = the field irrigation efficiency

M_o = the maximum available soil moisture in cm

$M_{t(T-1)}$ = the available soil moisture in cm at the end of irrigation interval T-1

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The seepage flux f_s is negative when a leakage to the aquifer is present. In that case $S_E = 0$. The value of $D_T = 0$ when

$$f_s.t_i + (1-f) I_t^{'} \leqslant 0 \quad \text{or}$$

$$f_s.t_i + I_T - (M_o - M_{t(T-1)}) \leqslant 0$$

Irrigated rice fields require a deviating procedure, as in that case one has to deal with drainage of ponded fields.

2.3. The salt mixing analysis model
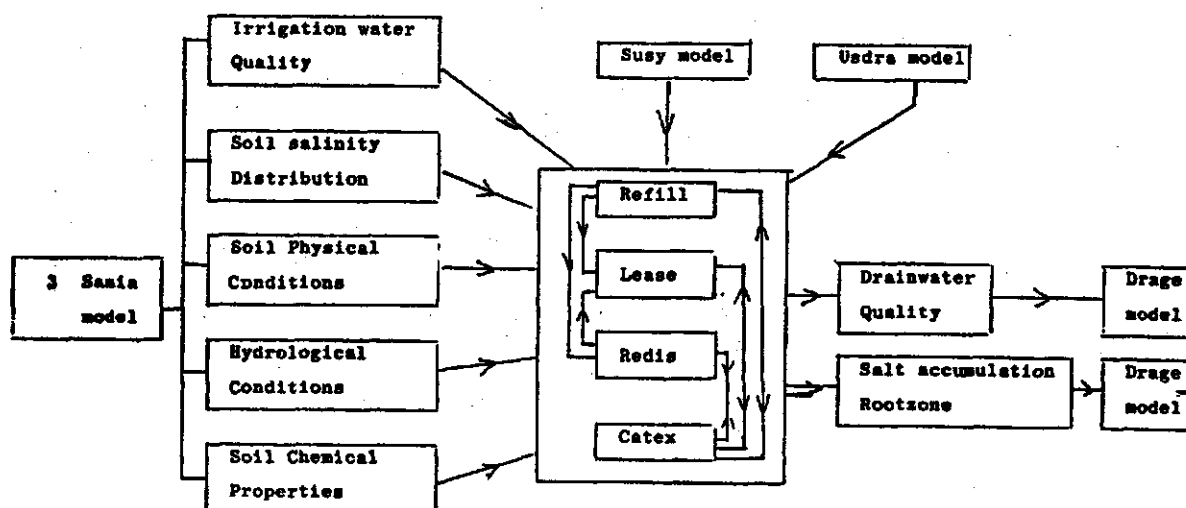
The scheme of the Samia model is given in fig. 4.

Fig. 4.   Scheme of the Samia model

The Samia model has a very complex character, as it deals with non-steady downwards and upwards transport of water and salts. More-over, the model deals with the exchange of cations with the soil system. The model has to run at each timestep two or three times, depending on the chemical composition in the system.

In irrigated areas a water table exists at some depth below the ground surface with a condition of unsaturation above it. During and immediately following periods of rainfall or irrigation, water moves downwards through the soil to the water table. During this downwards transport a refilling of the moisture deficit in the unsaturated

zone takes place. During this process the dilution, mixing of salts in the various layers and leaching of the top layers takes also place. Thise whole process will be described and be calculated in the submodel Refill. The excess water causes also a leaching out of salts from the soil system to the drains. The quantity and the quality of the drain-water is also dependent on the quantity and quality of the seepage water from the groundwater aquifer. This part of the process is described in the submodel Lease. The water losses through evapotranspiration may reverse the direction of flow, so the 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 neglicible, salts accumulate in the rootzone of the soil. This process is described in the submodel Redis.

An important part of the Samia model is the cation exchange between the soil and the water. This process will be described in the submodel Catex. This submodel must always be used in combination with one of the submodels Refill, Lease and Redis to calculate the distribution between dissolved and adsorbed cations.

The Samia model is coupled with Susy and Usdra to get the input data for the submodels Refill and Lease. For the effect of salt accu-mulation on evapotranspiration the Usdra model has to be coupled with the submodel Redis. Finally, Lease gives the drainwater quality as input for the Drage model.

2.3.1. General approach

For the transport of salts in the soil system three different situations must be considered:

- the refilling of the moisture deficit in the different layers;
- the leaching of salts under conditions of irrigation excess water and the generation of the drain water quality;
- the redistribution of salts in the soil profile between two irriga-tions due to evapotranspiration.

The basic model to be used for the calculation of the transport of salts either as downward movement due to refilling and leaching,

or upward movement due to seepage inflow and evapotranspiration, can be obtained by subdividing the soil profile in a number of layers. Through the boundary of each layer transport of salts take place by mass transport of water. It is assumed that in each layer a complete mixing of the water present in the layer and the incoming water takes place. It is also assumed that exchange of cations adsorbed at the soil system and those present in the soil solution can be considered at the end of each time step. Under these conditions the ion-balance of the soil solution can be written for the n^{th} layer as:

$$L_n \theta_n \, dc_n(t) = \left[f_d \, c_{(n-1)}(t) - f_d c_n(t) \right] dt \qquad (23)$$

where: L_n = thickness of the n^{th} layer in cm

θ_n = volumetric moisture content of layer n

f_d = Darcian flux in cm.day^{-1}

c_n and c_{n-1} = ion concentration in layer n and n-1 in meq.l^{-1}

t = time in days

Substituting $A_n = (L_n \theta_n)^{-1}$ and rearranging eq.(23) gives:

$$\frac{d}{dt} \left[c_n(t) \right] + A_n f_d c_n(t) = A_n f_d c_{(n-1)}(t) \qquad (23a)$$

This equation can be solved under the boundary condition :

$$c_n(t) = c_n(t_0) \quad for \quad t = 0$$

Introduction of a constant moisture volume per layer ($L_n \theta_n$ = constant) gives: $A_0 = A_1 = A_2 \ldots\ldots\ldots\ldots = A_n$.

Integration of eq.(23a) results in that case in:

$$c_n(t) = c_i + \sum_{k=0}^{n} \left[c_k(t_0) - c_i \right] \left[A f_d t \right]^{n-k} \exp\left[-A f_d t \right] \left[1/(n-k)! \right] \quad (24)$$

where: c_i = concentration of the irrigation water in meq.l^{-1}

2.3.2. Downward movement in the unsaturated zone during refilling (Refill)

The model has a somewhat more complex character in the unsaturated zone, where moisture extraction by plant roots has created a soil

moisture deficit. This moisture deficit has to be replenished during irrigation. The procedure is simplified by dividing the unsaturated zone into layers with equal moisture volumes directly after refilling.

When the depth of the top layer equals L cm, then $L\Delta\theta_o$ cm of irrigation water is required to refill this layer. The time required for this moisture supply at mean infiltration flux f_d equals:

$$t_o' = (L_o\Delta\theta_o)/f_d \tag{25}$$

The concentration in this layer can be calculated after refilling with the equation:

$$c_o(t_o') = \frac{L_o\theta_o c_o(t_o) + L_o\Delta\theta_o c_1}{L_o(\theta_o + \Delta\theta_o)} \tag{26}$$

The refilling of the moisture deficit of the next layer (n=1) requires a time step $t_1' - t_0'$. This time step is defined by the equation:

$$t_1' - t_0' = L_1\Delta\theta_1/f_d \tag{27}$$

During this period a leaching of salts from the top layer takes already place. These salts are transported to the layer (n=1). The salt concentration of the water entering layer (n=1), however, is changing with time. The salt concentration of the water leaving the top layer can be derived from the general equation (24) and is given by:

$$c_o(t) = c_1 + \left[c_o(t_0') - c_1\right] \exp\left[-Af_d(t - t_0')\right] \tag{28}$$

where: $A = L_o(\theta_o + \Delta\theta_o)$

The mean concentration of the water used for refilling layer (n=1) is obtained by integration of eq.(28) and dividing this value by the time step $t_1' - t_0'$. This gives as expression for the mean concentration:

$$\tilde{c}_o = c_1 + \left[Af_d(t_1' - t_0')\right]^{-1}\left[c_o(t_0') - c_1\right]\left[1 - \exp\left\{-Af_d(t_1' - t_0')\right\}\right] \tag{28a}$$

The salt concentration in this layer (n=1) equals after refilling:

$$c_1(t_1') = \frac{L_1\theta_1 c_1(o) + L_1\Delta\theta_1 \tilde{c}_o}{L_1(\theta_1 + \Delta\theta_1)} \tag{29}$$

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The refilling of the moisture deficit of the n^{th} layer requires a time step $t_n' - t_{n-1}'$, which equals $L_n \Delta\theta_n . f_d^{-1}$. The mean salt concentration of the water entering this layer n is given by the general equation:

$$\tilde{c}_{n-1} = c_i + \frac{1}{t_n' - t_{n-1}'} \int_{t_{n-1}'}^{t_n'} \sum \left[c_k(t_{n-1}') - c_i \right] \left[A f_d (t - t_{n-1}') \right]^{(n-1)-k} .$$

$$. \exp\left[-A f_d (t - t_{n-1}') \right] \left[1/(n-1-k) ! \right] dt \qquad (30)$$

When the quantity of water required for refilling is small the calculation of $\tilde{c}_{n-1}$ can be linearized, which reduces the problem to:

$$\tilde{c}_{n-1} = \frac{1}{2} \left\{ c_{n-1}(t_{n-1}') + c_{n-1}(t_n') \right\} \qquad (31)$$

The concentration in the n^{th} layer becomes after refilling:

$$c_n(t_n') = \frac{L_n \theta_n c_n(o) + L_n \Delta\theta_n \tilde{c}_{n-1}}{L_n (\theta_n + \Delta\theta_n)} \qquad (32)$$

In the discussion of the moisture depletion by evapotranspiration it has been assumed that the soil moisture depletion was proportionally distributed with depth. Consequently the refilling in the salt model can also easily be described in terms of the soil moisture deficit and the irrigation gift. As a matter of convenience it is assumed that under conditions of underirrigation the irrigation water at the end of the refilling is distributed over the various layers of the unsaturated zone, proportionally to the moisture deficit of the layers. The quantity of water R used for refilling equals $f.I_n$ in case of underirrigation and M_d when adequate irrigation and over-irrigation has been applied. The deficit of each layer can be given by $b_n.M_d$, where b_n is a proportionate factor depending on the layer number. So refilling of each layer requires either a quantity $b_n.M_d$ or $b_n.f.I_n$. Values of facor b_n for an unsaturated zone divided up to 5 layers are given in table 9.

Table 9. Values of b_n for unsaturated zones of 1 to 5 layers

Layer number	Number of unsaturated layers				
	1	2	3	4	5
0	1.00	.667	.500	.400	.333
1		.333	.375	.334	.292
2			.125	.200	.208
3				.067	.125
4					.042

The summation of time steps multiplied by f_d can be expressed in terms of the amount of water used for refilling, so the whole procedure can be given in terms of the distribution of water quantities. The set of equations required for the calculation of the salt distribution after refilling are given in table 10.

2.3.3. Leaching and drainage water quality (Lease)

Application of excess irrigation water leads to a leaching of the unsaturated zone. Also in cases of underirrigation a certain quantity of leaching occurs dependent on the field irrigation efficiency. The leaching process can be described for all layers n both in the unsaturated and in the saturated zone by the general equation. The quantity of leaching water $(I_n - M_d)$ or $(1 - f)I_n$ equals $f_d \cdot t$, so the equation can be rewritten as:

$$c_n(t) = c_i + \sum_{k=0}^{n} \left[c_k(t_n') - c_i \right] \left[A(I-M_d) \right]^{n-k} \exp \left[-A(I-M_d) \right] \left[1/(n-k)! \right] \quad (33a)$$

or:

$$c_n(t) = c_i + \sum_{k=0}^{n} \left[c_k(t_n') - c_i \right] \left[A(1-f)I_n \right]^{n-k} \exp \left[-A(1-f)I_n \right] \left[1/(n-k)! \right] \quad (33b)$$

The values of $c_k(t_n')$ are the concentrations present in each layer at the end of the refilling period.

Both the quantity and the quality of the drainage water depend on the

Table 10

Review of equations used for salt transport during refilling

No influence or leakage to the aquifer

If $\zeta I \geqslant M_d \longrightarrow R = M_d$

$\zeta I < M_d \longrightarrow R = \zeta I$

1. Leaching and refilling unsaturated zone

Seepage from the aquifer

$R = \zeta I + S_E$ if $S_E \rangle (1 - \eta) I$ $R = I$

$R = M_d + S_E \lessgtr I$ (see 2, 3, 3, 3, 3.)

Concentration of inflow water of layer n during refilling

After refilling layer n	Concentration layer n		c_i
0	0	$c_o(t'_o) = \dfrac{\left[A^{-1} - b_o M_d\right] c_o(o) + b_o R c_i}{A^{-1}} = (1 - Ab_o M_d) c_o(o) + Ab_o R c_i$	
1	0	$c_o(t'_1) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_o) - c_i\right] \left[AR(b_1)\right]^{n-k} \exp\left[-AR(b_1)\right]\left[1/(n-k)!\right]$	$\bar{c}_o = c_i + \dfrac{1}{ARb_1}\left\{\left[c_o(t'_o) - c_i\right]\left\{1 - \exp\left[-ARb_1\right]\right\}\right.$
	1	$c_1(t'_1) = (1 - Ab_1 M_d) c_1(o) + Ab_1 R \bar{c}_o$	
2	0	$c_o(t'_2) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_o) - c_i\right]\left[AR(b_1 + b_2)\right]^{n-k} \exp\left[-AR(b_1 + b_2)\right]\left[1/(n-k)!\right]$	
	1	$c_1(t'_2) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_1) - c_i\right]\left[AR b_2\right]^{n-k} \exp\left[-AR b_2\right]\left[1/(n-k)!\right]$	$\bar{c}_1 = \tfrac{1}{2}\left\{c_1(t'_1) + c_1(t'_2)\right\}$
	2	$c_2(t'_2) = (1 - Ab_2 M_d) c_2(o) + Ab_2 R \bar{c}_1$	
3	0	$c_o(t'_3) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_o) - c_i\right]\left[AR(b_1 + b_2 + b_3)\right]^{n-k} \exp\left[-AR(b_1 + b_2 + b_3)\right]\left[1/(n-k)!\right]$	
	1	$c_1(t'_3) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_1) - c_i\right]\left[AR(b_2 + b_3)\right]^{n-k} \exp\left[-AR(b_2 + b_3)\right]\left[1/(n-k)!\right]$	$\bar{c}_2 = \tfrac{1}{2}\left\{c_2(t'_2) + c_2(t'_3)\right\}$
	2	$c_2(t'_3) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_2) - c_i\right]\left[AR b_3\right]^{n-k} \exp\left[-AR b_3\right]\left[1/(n-k)!\right]$	
	3	$c_3(t'_3) = (1 - Ab_3 M_d) c_3(o) + Ab_3 R \bar{c}_2$	
4	0	$c_o(t'_4) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_o) - c_i\right]\left[AR(b_1 + b_2 + b_3 + b_4)\right]^{n-k} \exp\left[-AR(b_1 + b_2 + b_3 + b_4)\right]\left[1/(n-k)!\right]$	
	1	$c_1(t'_4) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_1) - c_i\right]\left[AR(b_2 + b_3 + b_4)\right]^{n-k} \exp\left[-AR(b_2 + b_3 + b_4)\right]\left[1/(n-k)!\right]$	$\bar{c}_3 = \tfrac{1}{2}\left\{c_3(t'_3) + c_3(t'_4)\right\}$
	2	$c_2(t'_4) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_2) - c_i\right]\left[AR(b_3 + b_4)\right]^{n-k} \exp\left[-AR(b_3 + b_4)\right]\left[1/(n-k)!\right]$	
	3	$c_3(t'_4) = c_i + \sum\limits_{k=0}^{n} \left[c_k(t'_3) - c_i\right]\left[AR b_4\right]^{n-k} \exp\left[-AR b_4\right]\left[1/(n-k)!\right]$	
	4	$c_4(t'_4) = (1 - Ab_4 M_d) c_4(o) + Ab_4 R \bar{c}_3$	

influx from and the outflux to the deep groundwater aquifer of the Delta. Three situations must be considered in the model:

- the groundwater aquifer has no influence;
- a leakage of shallow groundwater to the groundwater aquifer, with a mean yearly flux $- f_s$, expressed in $cm.day^{-1}$;
- a seepage from the deep groundwater aquifer to the phreatic water with a mean yearly flux f_s, expressed in $cm.day^{-1}$.

2.3.3.1. No effect of the groundwater aquifer

The flow to the drains can be considered schematically as a combination of horizontal and vertical fluxes. The scheme for the proposed model is given in fig. 5.
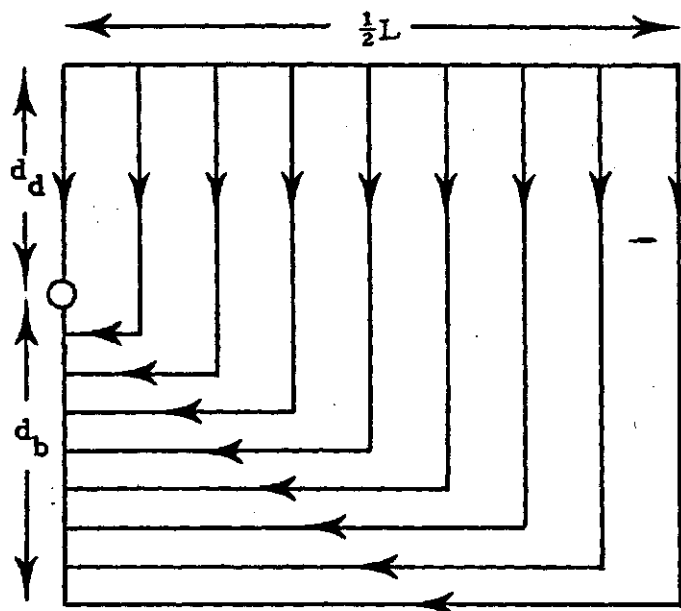
Fig. 5. Schematic flux pattern under the condition no influence of the aquifer

The vertical upward flux to the drain is neglected, as its effect is extremely small in the ultimately calculated result. Dividing half of the drainspacing ($\frac{1}{2}\ell$) in m parts, gives for the vertical pathway a length of: $L_v = d_d + (1 - k/m).d_b$

where:

Table 10 Review of equations used for salt transport during refilling

No influence or leakage to the aquifer

If $L1 \geq M_d \longrightarrow R = M_d$

$\quad L1 < M_d \longrightarrow R = L1$

1. Leaching and refilling unsaturated zone

After refilling layer n	Concentration layer n
0	$c_0(t_0') = \dfrac{[A^{-1} - b_0 M_d] c_0(o) + b_0 R c_1}{A^{-1}} = (1 - Ab_0 M_d) c_0(o) + Ab_0 R c_1$
0	$c_0(t_1') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_0') - c_1][AR(b_1)]^{n-k} \exp\left[-AR(b_1)\right] [1/(n-k)!]$
1	$c_1(t_1') = (1 - Ab_1 M_d) c_1(o) + Ab_1 R \tilde{c}_0$
0	$c_0(t_2') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_0') - c_1][AR(b_1 + b_2)]^{n-k} \exp\left[-AR(b_1 + b_2)\right] [1/(n-k)!]$
1	$c_1(t_2') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_1') - c_1][AR b_2]^{n-k} \exp\left[-AR b_2\right] [1/(n-k)!]$
2	$c_2(t_2') = (1 - Ab_2 M_d) c_2(o) + Ab_2 R \tilde{c}_1$
0	$c_0(t_3') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_0') - c_1][AR(b_1 + b_2 + b_3)]^{n-k} \exp\left[-AR(b_1 + b_2 + b_3)\right] [1/(n-k)!]$
1	$c_1(t_3') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_1') - c_1][AR(b_2 + b_3)]^{n-k} \exp\left[-AR(b_2 + b_3)\right] [1/(n-k)!]$
2	$c_2(t_3') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_2') - c_1][AR b_3]^{n-k} \exp\left[-AR b_3\right] [1/(n-k)!]$
3	$c_3(t_3') = (1 - Ab_3 M_d) c_3(o) + Ab_3 R \tilde{c}_2$
0	$c_0(t_4') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_0') - c_1][AR(b_1 + b_2 + b_3 + b_4)]^{n-k} \exp\left[-AR(b_1 + b_2 + b_3 + b_4)\right] [1/(n-k)!]$
1	$c_1(t_4') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_1') - c_1][AR(b_2 + b_3 + b_4)]^{n-k} \exp\left[-AR(b_2 + b_3 + b_4)\right] [1/(n-k)!]$
2	$c_2(t_4') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_2') - c_1][AR(b_3 + b_4)]^{n-k} \exp\left[-AR(b_3 + b_4)\right] [1/(n-k)!]$
3	$c_3(t_4') = c_1 + \sum\limits_{k=0}^{n} [c_k(t_3') - c_1][AR b_4]^{n-k} \exp\left[-AR b_4\right] [1/(n-k)!]$
4	$c_4(t_4') = (1 - Ab_4 M_d) c_4(o) + Ab_4 R \tilde{c}_3$

Seepage from the aquifer

$R = L1 + S_E \quad$ if $S_E > (1 - f)$ if $R = 1$

$R = M_d + S_E \leq 1 \quad$ (see 2.2.3.3.)

Concentration of inflow water of layer n during refilling

c_1

$\tilde{c}_0 = c_1 + \dfrac{1}{AR b_1}\left\{c_0(t_0') - c_1\right\}\left\{1 - \exp\left[-AR b_1\right]\right\}$

$\tilde{c}_1 = \tfrac{1}{2}\left\{c_1(t_1') + c_1(t_2')\right\}$

$\tilde{c}_2 = \tfrac{1}{2}\left\{c_2(t_2') + c_2(t_3')\right\}$

$\tilde{c}_3 = \tfrac{1}{2}\left\{c_3(t_3') + c_3(t_4')\right\}$

The two-dimensional flux pattern can be considered as a one-
-dimensional case due to the model used for the flux pattern.

The concentration of the drainage water equals in this case the
mean concentration present in the layers n between

$$n = A (d_d.\theta_d) \quad \text{and} \quad n = A (d_d.\theta_d + 2.d_b.\theta_b)$$

2.3.3.2. Drainage combined with leakage to the deep aquifer

In those cases that leakage to the deep sand aquifer cannot be
neglected the calculation scheme must be adapted. The flux f_s (negative)
to the aquifer will be taken as a constant with time. The flux pattern
as shown in fig. 6 will be considered.
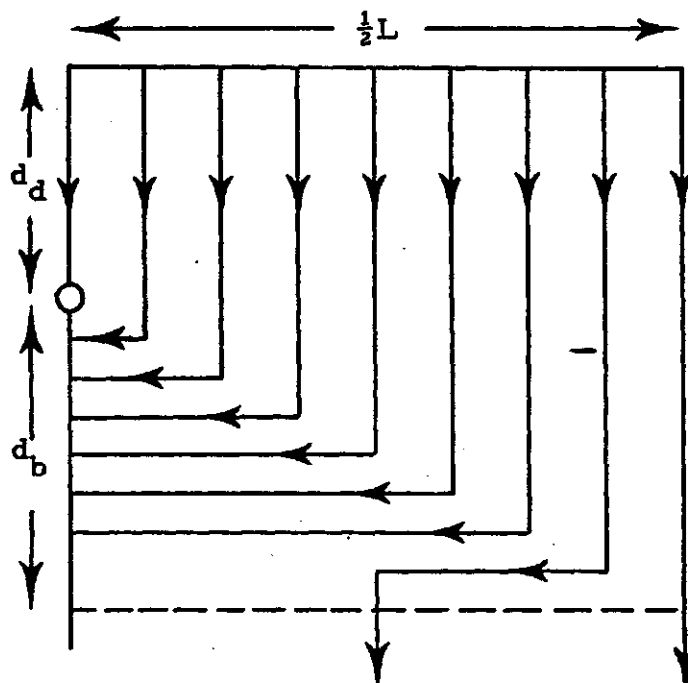
Fig. 6. Schematic flux pattern with leakage to the sand aquifer

The vertical flux component is divided in a flux to the aquifer
and one to the drain system. The part of the flux participating in the
leakage flux is at the greatest distance from the drain. The flux to
the drain is again schematically calculated as a combination of the
vertical and horizontal flux. The area of the landsurface participating
in the drainage flux can be given by the expression: $\frac{1}{2}$. $(1 - \alpha).\ell$,
where α is the greatest value of the two expressions:

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L_v = the length of the vertical pathway

d_d = depth of drainage

d_b = depth of drainage flux barrier (maximum = $\frac{1}{4}\ell$)

k varies form 0 at a distance $\frac{1}{2}\ell$ to m for a pathway above the drain.

The horizontal length of each pathway becomes:

$$L_h = \frac{1}{2}\ (1 - k/m)\ .\ell \tag{34}$$

The ratio between the horizontal flow velocity of the drainage water and the vertical one depends on the drain distance and the depth of the drainage barrier. This relation can be given as:

$$f_h = \frac{\ell}{2d_b}\ .\ f_v \tag{35}$$

The general differential equation (23) gives the same solution when the product $A.f_d$ is taken as a constant. The given relation for horizontal and vertical flux determines also the relation between A_v and A_h by the expression:

$$A_h = \frac{2d_b}{\ell}\ .\ A_v \tag{35a}$$

or:

$$L_n\theta_n)_h = \frac{\ell}{2d_b}\ .\ (L_n\theta_n)_v \tag{35b}$$

The number of layers n to be considered from the soil surface to the drain for each value of k can be given by the expression:

$$n = \frac{d_d\ \theta_d}{L_n\ \theta_n} + \frac{(1 - k/m)d_b\ \theta_b}{L_n\ \theta_n} + \frac{\frac{1}{2}\ (1 - k/m)\ell\ \theta_b}{(\ell/2d_b)\ .\ (L_n\ \theta_n)} \tag{36a}$$

or:

$$n = A\left\{ d_d\ \theta_d + 2\ (1 - k/m)\ d_b\ \theta_b\right\}\quad d_b \leqslant \frac{1}{4}\ell \tag{36b}$$

where: d_d = drain depth in cm

θ_d = volumetric soil moisture fraction above drain depth

d_b = depth of drainage barrier in cm below drain depth

θ_b = volumetric soil moisture fraction below drain depth

The flux pattern in the saturated zone must be adapted when seepage from the aquifer is present. Fig. 7 gives a schematic presentation of the two situations that must be considered in that case.
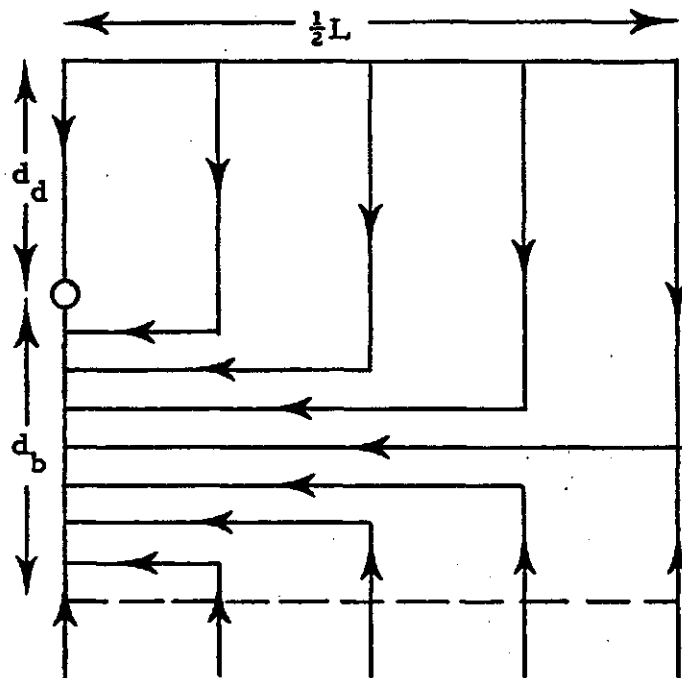

Fig. 7. Schematic flux pattern with seepage from the aquifer

The saturated zone is divided into two regions with different flux patterns. In the top part the discharge of the net irrigation excess takes place. The net irrigation excess can be given by the greatest value of the expressions:

$$D_I = (1-f) \; I - S_E$$

or:

$$D_I = (I-M_d) - S_E$$

In the bottom part the discharge pattern of the seepage is given. The depth of the separation between both fluxes depends on the ratio α, where α is given by:

$$\alpha = \frac{D_I}{D_I + f_s t_i}$$

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$$\alpha = \frac{-f_s t_i}{(1-f) I} \quad \text{or} \quad \alpha \leq \frac{-f_s t_i}{I - M_d}$$

When $\alpha > 1$, take $\alpha = 1$.

For the drainage flux the following expressions can be derived:

- vertical pathway length : $L_v = d_d + (1 - k^*/m^*) (1 - \alpha) d_b$

- horizontal pathway length: $L_h = \frac{1}{2} (1 - \alpha)(1 - k^*/m^*) \ell$

with k^* equalling 0 at distance $(1 - \alpha)\ell$ and equaling m^* above the drain.

The number of layers to be considered for the drainage flux is given by the expression:

$$n = A \left\{ d_d \, \theta_d + 2 (1 - \alpha)(1 - k^*/m^*) \, d_b \right\} \qquad (37)$$

When α varies from irrigation interval to interval the drainage concentration can be approximated by taking the mean value of the concentration in the layers with n between:

$$n = A_n (d_d \, \theta_d) \quad \text{and} \quad n = A_n \left\{ d_d \theta_d + 2 (1 - \alpha) \, d_b^\theta \, b \right\}$$

The number of layers into account varies with the value of α.

2.3.3.3. Drainage combined with seepage from the deep aquifer

The proposed model describes the discharge of the excess irrigation water $(1-f)I$ as a constant flux during the irrigation interval. The large variation in discharge rate between the one at the beginning of the irrigation interval and at the end will not be taken into account. Moreover, the quantity S_E, that reaches the rootzone during the irrigation interval, will in the quality model also be considered as a constant flux, with a relatively good quality. In the refill model in table 10 the value of S_E is considered as a temporary storage in the unsaturated zone. In terms of the model discharge it indicates that the discharge of the irrigation excess will be reduced by this procedure. In all those cases that the value of S_E is greater than the irrigation excess a small quantity of seepage water will pass the depth of drainage and will be transported to the rootzone.

the model redis and will pass the boundary between the saturated and the unsaturated zone. The layers participating in the drain water production are the layers between n_{max} and $n_{max}-n$. The value of $n_{max}-n$ is given by:

$$n_{max}-n = 2A.(1-\beta).d_b\theta_b \quad \text{with} \quad \beta=D_I/f_s.t_i$$

The concentration in these layers can be calculated again with eq.(39). The concentration of the drain water can be approximated as the average concentration of the layers concerned.
The concentration of the inflow in the unsaturated zone will be calculated as the concentration in the layer $n_{max} - n = 2 A.d_b\theta_b$.

2.3.4. Redistribution of salt in the unsaturated zone (Redis)

Due to evapotranspiration a redistribution of salts in the unsaturated soil is present during the irrigation interval. As the actuel evapotranspiration depends on the salt concentration in the rootzone, underirrigation may cause salt accumulation in the rootzone during the vegetation period. The process of salt redistribution and salinization of the rootzone can be described by the general differential equation for layer n as:

$$\left\{ \frac{1}{A} - (f_o - f_i) t \right\} \frac{dc_n(t)}{dt} = f_i \tilde{c}_{n+1} - f_o c_n (t) \qquad (40)$$

where: $a = (L_n\theta_n)^{-1}$

f_o = outflow from layer n in cm.day^{-1}

f_i = inflow into layer n in cm.day^{-1}

c_{n+1} and c_n = concentration in layer n+1 and n, respectively

It has been assumed in the Usdra model that the quantity of soil moisture extracted from the different layers of the unsaturated zone was proportional with depth. So the flux at the boundaries of each layer can be given as:

$$f_i = f_{n+1,n} = \left(1 - \sum_{0}^{n} b_n \right).(E_{re} - \bar{f}_c) + \bar{f}_c$$

$$f_o = f_{n,n-1} = \left(1 - \sum_{0}^{n-1} b_n \right).(E_{re} - \bar{f}_c) + \bar{f}_c$$

The seepage flux has its influence to the depth of drainage when $\alpha \leqslant 0$. The following expressions for the drainage pattern of the net irrigation excess D_I can be derived:

- length vertical pathway : $L_v = d_d + (1 - k/m)\alpha\, d_b$

- horizontal pathway : $L_h = \frac{1}{2} \cdot (1 - k/m) \cdot \ell$

The number of layers to be considered for the discharge of D_I can be given by the expression:

$$n = A \left\{ d_d\,\theta_d + 2\,\alpha(1 - k/m)\,d_b \right\}$$

The salt concentration in these layers can be given by the equation:

$$c_n(t) = c_i + \sum_{k=0}^{n} \left[c_k(t'_n) - c_i \right]\left[AD_I \right]^{n-k} \exp\left[- AD_I \right]\left[1/(n-k)! \right] \quad (38)$$

The concentration of this part of the drain water can be approximated as the average concentration of the layers between $n = A\,(d_d\,\theta_d)$ and $n = A\,(d_d\theta_d + 2\,d_b\theta_b)$.

The seepage flux has an opposite direction of flow, starting from the deepest layer to shallower ones. The layer numbering has to be transformed. This can simply be done by the introduction of the maximum layer number $n_{max.} = A.\,(d_d\theta_d + 2\,d_b\theta_b).$ —

The total number of layers participating in the discharge of the seepage equals:

$$n_{max} - n = 2A\,(1 - \alpha).\,d_b\theta_b$$

The concentration in the participating layers can be calculated with the equation:

$$c_{(n_{max}-n)} = c_s + \sum_{k=0}^{n_{max}-n} \left[c_k(t_0) - c_s \right]\left[Af_s t_1 \right]^{(n_{max}-n-k)} \exp\left[-Af_s t_1 \right]\left[1/\left\{(n_{max}-n)-k\right\}! \right]$$

$$(39)$$

where c_s equals the concentration of the seepage influx.

The concentration of this part of the drain water can be approximated as the average concentration of the layers between n_{max} and $n_{max} - n$. When D_I becomes negative, the seepage flux takes place in the whole saturated zone. However, part of this seepage flux will be used in

2.3.5. Chemical processes in the soil (Catex)

Salinization of a soil profile is defined as an increase in the concentration of salts in, and eventually precipitation of salts from the soil solution. Aside from their influence on the concentration of the soil solution, the addition of salts to the soil profile may also lead to an alteration in the composition of the exchange complex. The salinization and desalinization processes are accompanied with a gradual adjustment in the composition of the adsorption complex. The final exchangeable sodium fraction of the soil complex composition depends on the reduced concentration ratio of Na^+ and Ca^{2+} in the soil solution. This reduced ration is given the name Sodium Adsorption Ratio (sar) and is given by the expression:

$$sar = \frac{[Na^+]}{\sqrt{\frac{1}{2}\{[Ca^{2+}]+[Mg^{2+}]\}}} = \frac{[c^+]}{\sqrt{\frac{1}{2} c^{2+}}} \qquad (46)$$

The name indicates that the sar determines the composition of the adsorption complex. The relation between sar and the exchangeable sodium fraction (ES) can be given by the expression:

$$ES = \frac{0.015 \ sar}{1 + 0.015 \ sar} \qquad (47)$$

The concentration c^+ and c^{2+} can be expressed as function of sar and $c_n(t)$ by the equations:

$$c_n^+ (t) = \frac{sar^2}{4} \left\{ -1 + \sqrt{1 + \frac{4}{sar^2} c_n(t)} \right\} \qquad (48)$$

and

$$c_n^{2+} (t) = \frac{1}{2} c_n(t) + \frac{sar^2}{4} \left\{ 1 - \sqrt{1 + \frac{4}{sar^2} c_n(t)} \right\} \qquad (49)$$

where: $c_n(t)$ = salt concentration in layer n at time t in $meq.l^{-1}$

$c_n^+(t)$ = salt concentration of monovalent cations in layer n at time t in $meq.\ l^{-1}$

$c_n^{2+}(t)$ = salt concentration of divalent cations in layer n at time t in $meq.l^{-1}$

sar = sodium adsorption ratio in $(m \ mol.l^{-1})^{1/2}$

It is assumed that the total quantity of cations adsorbed by the soil complex is very large compared with the change in the cation

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Equation (40) can be solved for the n^{th} layer when the concentration of the inflow from the $(n+1)^{th}$ layer is constant during the irrigation interval.

Rearranging equation (40) gives:

$$\frac{dc_n}{f_1 c_{n+1} - f_o c_n(t)} = \frac{d\,t}{\left\{\frac{1}{A} - (f_o - f_1)\,t\right\}} \qquad (40a)$$

Integration yields:

$$c_n(t) = f_1/f_o\ c_{n+1} + \left\{c_n(t_o) - f_1/f_o\ c_{n+1}\right\}\left\{1 - A(f_o - f_1)t\right\}^{\frac{f_o}{f_o - f_1}} \qquad (41)$$

The mean concentration in layer n over the irrigation interval will be used to calculate the salt accumulation in the layer n-1. The mean concentration can be calculated with the expression:

$$\bar{c}_n(t) = (f_1/f_o)c_{n+1} + \frac{1}{A(2\,f_o - f_1)}\left\{c_n(t_o) - (f_1/f_o)c_{n+1}\right\}\left[1 - \left\{1 - A(f_o - f_1)t\right\}^{\frac{2f_o - f_1}{f_o - f_1}}\right] \qquad (42)$$

The procedure described by the equations (41) and (42) can be repeated for each layer. It must be realized that with a value of $\bar{f}_c = 0$, the concentration of the layer n remains constant over the considered irrigation interval.

The toplayer requires a special solution, as an outflow of water is present, but the salts remain in that layer.

This is given by the differential equation:

$$\left\{\frac{1}{A} - (f_o - f_1)\,t\right\}\frac{dc_o(t)}{dt} = f_1\ \bar{c}_1 \qquad (43)$$

Rearranging gives:

$$\frac{dc_o(t)}{f_1\ \bar{c}_1} = \frac{dt}{\left\{\frac{1}{A} - f_o - f_1\right\}t} \qquad (44)$$

Integration of this equation results in:

$$c_0(t) = c_0(t_o) - \frac{f_1}{f_o - f_1}\ \bar{c}_1\ \ln\left\{1 - A(f_o - f_1)\,t\right\} \qquad (45)$$

This value can be used as the initial value $c_0(t_o)$ of the next irrigation interval in the refill model. The time integrated value of $c_0(t)$ must be taken into account in the evaluation model Eva in the analysis of the effect of integrated salinity on crop yield

system controls the maximum concentration of Ca^{2+}, conversely the presence of solid phase carbonates in the soil will stabilize the actual concentration of the cations in the soil solution. An approach of the precipitation or dissolution of $CaCO_3$ in the model system can be obtained with the aid of the reaction equations. Expressing the total concentration of dissolved CO_2 as H_2CO_3 gives the reaction equation:
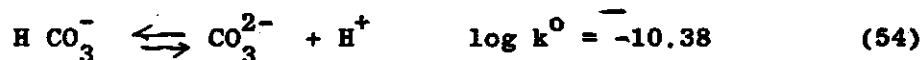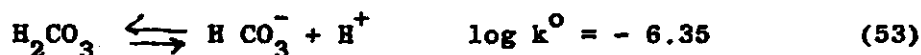
$$CO_2(g) + H_2O \rightleftharpoons H_2CO_3 \qquad \log k^o = -1.46 \qquad (52)$$
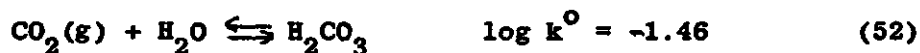
The activity of CO_2-gas is here expressed in terms of the gas pressure P in bar.
In general terms one finds:

$$- \log [H_2CO_3] = 1.46 - \log P_{CO_2} \qquad (52a)$$

The carbonic acid molecules entertain protolysis reactions according to:

$$H_2CO_3 \rightleftharpoons H CO_3^- + H^+ \qquad \log k^o = -6.35 \qquad (53)$$

$$H CO_3^- \rightleftharpoons CO_3^{2-} + H^+ \qquad \log k^o = -10.38 \qquad (54)$$

Combining these equations results in:

$$- \log [HCO_3^-] = 7.81 - \log P_{CO_2} - pH \qquad (53a)$$

and

$$- \log [CO_3^{2-}] = 18.14 - \log P_{CO_2} - 2 pH \qquad (54a)$$

In the applied approach it is assumed that only calcite is present in the solid carbonate in the soil system. The dissolution reaction of calcite can be given as:

$$CaCO_{3(s)} \rightleftharpoons Ca^{2+} + CO_3^{2-} \qquad \log k^o_{SO} = -8.35 \qquad (55)$$

or

$$- \log [Ca^{2+}] = 8.35 + \log [CO_3^{2-}] \qquad (55a)$$

Combining the equations (53a), (54a) and (55a) gives also the expression:

composition of the soil solution of a considered layer n during the timestep t. Under these conditions ES(t) $\approx$ ES(t$_o$), which results in sar(t) $\approx$ sar(t$_o$). So a first approach of the concentrations of the monovalent and divalent cations in the soil solution at time t can be obtained using the value of sar (t$_o$).

The mass balance equations of the nth layer can in that case be given as:

$$\tilde{c}^+_{n-1} \ f_i t - \tilde{c}^+_n \ f_o t = c^+_n(t) \left[L_n \theta_n\right]_t - c^+_n (t_o) \left[L_n \theta_n\right]_{t_o} +$$

$$+ \left\{ES(t) - ES(t_o)\right\} \left\{\frac{CEC}{100} \ L_n \rho_n\right\} \qquad (50)$$

and

$$\tilde{c}^{2+}_{n-1} \ f_i t - \tilde{c}^{2+}_n \ f_o t = c^{2+}_n (t) \left[L_n \theta_n\right]_t - c^{2+}_n(t_o) \left[L_n \theta_n\right]_{t_o} +$$

$$+ \left\{ES(t) - ES(t_o)\right\} \left\{\frac{CEC}{100} L_n \rho_n\right\} + \Delta\left[CaCO_3\right]_s \qquad (51)$$

where: c^+ $= \frac{1}{2}\left\{c^+(t_o) + c^+(t)\right\}$ in meq.l^{-1}

c^{2+} $= \frac{1}{2}\left\{c^{2+}(t_o) + c^{2+}(t)\right\}$ in meq.l^{-1}

f_i = incoming flux in cm.day^{-1}

f_o = outgoing flux in cm.day^{-1}

$L_n \theta_n$ = moisture volume of layer n in cm

CEC = cation exchange capacity in meq per 100 g of soil

$\frac{CEC}{100} L_n \rho_n$ = cation exchange capacity of layer n in meq.

$\Delta\left[CaCO_3\right]_s$ = change in solid calcite concentration

c^+ and c^{2+}, as well as $c^+_n(t)$ and $c^{2+}_n(t)$ are as a first approach calculated with the assumption sar(t) equals sar(t$_o$), leaving ES(t) as the only unknown factor, which can be calculated from the equations. When ES(t) differs too much drom ES(t$_o$) an iterative procedure must be used to obtain a better approach of ES(t).

The presence of CO_2-gas in soil systems delimits the maximum possible concentration of many cations in the soil. The most abundant one of the cations forming carbonates with low solubility is the Ca^{2+}-ion and accordingly many soils contain solid calcium carbonates. While the local pressure of CO_2-gas in the soil, together with the pH of the soil

$$\log \left[CaHCO_3^+ \right] = 3.24 - pH \tag{61}$$

For the calculation of the total quantity of Ca present in the soil solution when calcite is present the equations (57a), (60) and (61) can be used, giving:

$$\left[Ca^{2+} \right] + \left[CaCO_3^o \right] + \left[CaHCO_3^+ \right] = \frac{10^{-8.35} + 10^{1.98 - pH}}{\left[CO_3^{2-} \right]_+ \left[HCO_3^- \right]} +$$

$$+ 10^{-5.15} + 10^{3.24 - pH} \tag{62}$$

An other Ca-course can be present in many soils under arid conditions in gypsum. In some soils gypsum may be already present in the sedimentary deposits. It can also be formed by the precipitation of calcium and sulphate during salinization. So also information regarding the gypsum content of the soils is important. The composition of a solution saturated with respect to gypsum is defined by equation (63) giving:

$$CaSO_4 \cdot 2 H_2O_{(s)} \rightleftharpoons Ca^{2+} + SO_4^{2-} + 2 H_2O \quad \log k_{SO}^o = -4.61 \tag{63}$$
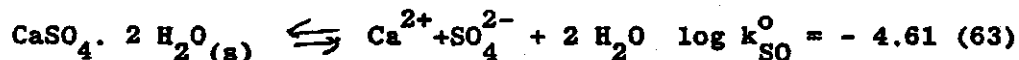
or

$$\left[Ca^{2+} \right] = \frac{10^{-4.61}}{\left[SO_4^{2-} \right]} \tag{63a}$$

As with the carbonates the soluble complex is involved. The formation reaction of the uncharged ion-pair $CaSO_4^o$ reads:

$$Ca^{2+} + SO_4^{2-} \rightleftharpoons CaSO_4^o \quad \log k^o = 2.31 \tag{64}$$

In a system where also solid gypsum is present the concentration of $CaSO_4^o$ is constant. The numerical value of the equilibrium constant equals $10^{-2.29}$.

So in a system in equilibrium with solid gypsum the total Ca-concentration can be given as:

$$\left[Ca^{2+} \right] + \left[CaSO_4^o \right] = \frac{10^{-4.61}}{\left[SO_4^{2-} \right]} + 10^{-2.29} \tag{65}$$

The existence of long range electrostatic interactions between ions is the main reason for non-ideal behaviour of these ions in solutions.

$$- \log \left[Ca^{2+} \right] = pH - 1.98 + \log \left[HCO_3^- \right] \tag{56}$$

or

$$\left[Ca^{2+} \right] \left[CO_3^{2-} \right] = 10^{-8.35} \tag{55b}$$

and

$$\left[Ca^{2+} \right] \left[HCO_3^- \right] = 10^{-1.98 - pH} \tag{56a}$$

Adding together gives

$$\left[Ca^{2+} \right] \left[\left[CO_3^{2-} \right] + \left[HCO_3^- \right] \right] = 10^{-8.35} + 10^{1.98 - pH} \tag{57}$$

or

$$\left[Ca^{2+} \right] = \frac{10^{-8.35} + 10^{1.98 - pH}}{\left[CO_3^{2-} \right] + \left[HCO_3^- \right]} \tag{57a}$$

Equation (57a) gives the Ca^{2+} concentration in $mol.l^{-1}$ at saturation in relation to the concentration of CO_3^{2-}, HCO_3^- and pH.

So far the solubility of calcite has been discussed with respect to the Ca^{2+}-ion only. In actuality the ion-pairs $CaHCO_3^+$ and $CaCO_3^o$ should also be considered. Whenever calcite is present in the soil system the ion activities of the relevant ion-pairs are ultimately determined by this solid phase. The reaction equations for both ion-pairs can be given as:

$$Ca^{2+} + CO_3^{2-} \rightleftharpoons CaCO_3^o \qquad \log k^o = 3.20 \tag{58}$$

and

$$Ca^{2+} + HCO_3^- \rightleftharpoons CaHCO_3^+ \qquad \log k^o = 1.26 \tag{59}$$

or
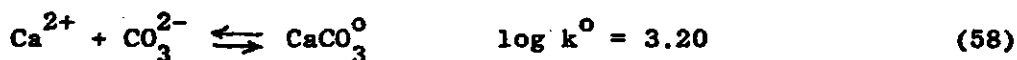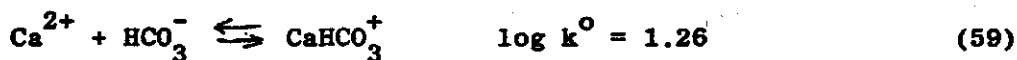
$$- \log \left[Ca^{2+} \right] - \log \left[CO_3^{2-} \right] + \log \left[CaCO_3 \right] = 3.20 \tag{58a}$$

and

$$- \log \left[Ca^{2+} \right] - \log \left[HCO_3^- \right] + \log \left[CaHCO_3^+ \right] = 1.26 \tag{59a}$$

Combination of the equation (55a) and (58a) gives:

$$\log \left[CaCO_3^o \right] = -5.15 \tag{60}$$

As long as solid calcite is present in the soil the concentration of $CaCO_3^o$ remains constant.

Combination of the equations (56) and (59a) gives:

The calculation of the final concentrations requires possibly an iterative procedure. The calculation of the HCO_3^-, the CO_3^{2-} and tho SO_4^{2-} concentrations requires separate runs of the submodels Refill, Lease and Redis.

The precipitation or dissolution of calcium can be approximated mathematically by the following set of equations:

$$(x - \Delta x)(y_1 - \Delta y_1) = C_1 \tag{69}$$

and

$$(x - \Delta x)(y_2 - (\Delta x - \Delta y_1) = C_2 \tag{70}$$

Both equations give as result:

$$\Delta y_1 = y_1 - \frac{C_1}{x - \Delta x} \tag{71}$$

and

$$\Delta x = \tfrac{1}{2}(x+y_1+y_2) - \tfrac{1}{2}\sqrt{(x+y_1+y_2)^2 - 4\left[x(y_1+y_2) - (C_1+C_2)\right]} \tag{72}$$

where: x = the Ca^{2+}-concentration in meq.1^{-1}

y_1 = the SO_4^{2-}-concentration in meq.1^{-1}

y_2 = the HCO_3^- + CO_3^{2-}-concentration in meq.1^{-1}

C_1 = 6.14 f_2^{-2}

C_2 = $(0.0011 + 10^{7.38-pH}) f_2^{-2}$

Δx and Δy_1 are positive un case of precipitation.
When under saturation exists, without the presence of solid gypsum equation (69) does not hold and Δy_1 equals zero. When no solid calcite is present equation (70) does not hold and Δy_1 equals in that case Δx. The equations (69) and (70) have no meaning when both solid phases are not present.
For soils with solid $CaCO_3$, the pH can be calculated by the equation:

$$pH = (p k_2 - p k_c) + p\left[\tfrac{1}{2}(Ca + Mg)\right] + p \, Alk \tag{73}$$

where $p \tfrac{1}{2}(Ca+Mg)$ and $p \, Alk$ are the negative logarithms of the equivalent concentrations of Ca + Mg and of the equivalent concentration of titrable base (CO_3^{2-} and HCO_3^-), respectively. pk_2 and pk_{so} are the negative logarithms of the second dissociation constant of H_2CO_3 and the solubility constant of $CaCO_3$ respectively, both corrected for ionic strength.

For this reason ion-activity should be used instead of ion-concentrations. The ion-activity can for practical purpose be given as:

$$a_i = f_i c_i \tag{66}$$

where: a_i is the ion-activity in $mol.l^{-1}$

f_i is the activity coefficient

c_i is the ion concentration in $mol.l^{-1}$

The activity coefficient can be calculated using the Davies equation:

$$- \log f_i = A z_i^2 \left(\frac{\sqrt{I}}{1 + \sqrt{I}} - 0.3 \, I \right) \tag{67}$$

where: f_i is the activity coefficient of ion i

A is constant, equalling 0.5085

z is valence of the ion considered

I is ionic strength

The ionic strength is given by the equation:

$$I = \tfrac{1}{2} \sum_i c_i z_i^2 \tag{68}$$

where: c_i is concentration of ion i in $mol.l^{-1}$

z_i is valence of ion i

At ionic strengths up to 0.5 $mol.l^{-1}$ the Davies equation agrees very well with experimental data. The activity coefficients of the uncharged ion-pairs $CaCO_3^o$ and $CaSO_4^o$ equal unity.

Correcting the reaction equations for ionic activity and expressing the concentrations in $meq.l^{-1}$ gives the following set of equations:

$$c_{Ca}^{2+} = \frac{10^6}{2f_2} \left\{ \frac{10^{-8.35} + 10^{1.98 - pH}}{2f_2 \, c_{CO_3}^{2-} + f_1 \, c_{HCO_3}^{-}} \right\} \tag{57b}$$

and

$$c_{Ca}^{2+} = \frac{10^6}{4 \, f_2^2} \left\{ \frac{10^{-4.61}}{c_{SO_4}^{2-}} \right\} \tag{63b}$$

The equations (57b) and (63b) give the maximum value of c_{Ca}^{2+} in a system with solid phases of calcite and gypsum.

In the model it is assumed that during the timestep under consideration over- or undersaturation of the soil solution is present, so precipitation or dissolution occurs at the end of the timestep.

2.4. The drainwater generation model

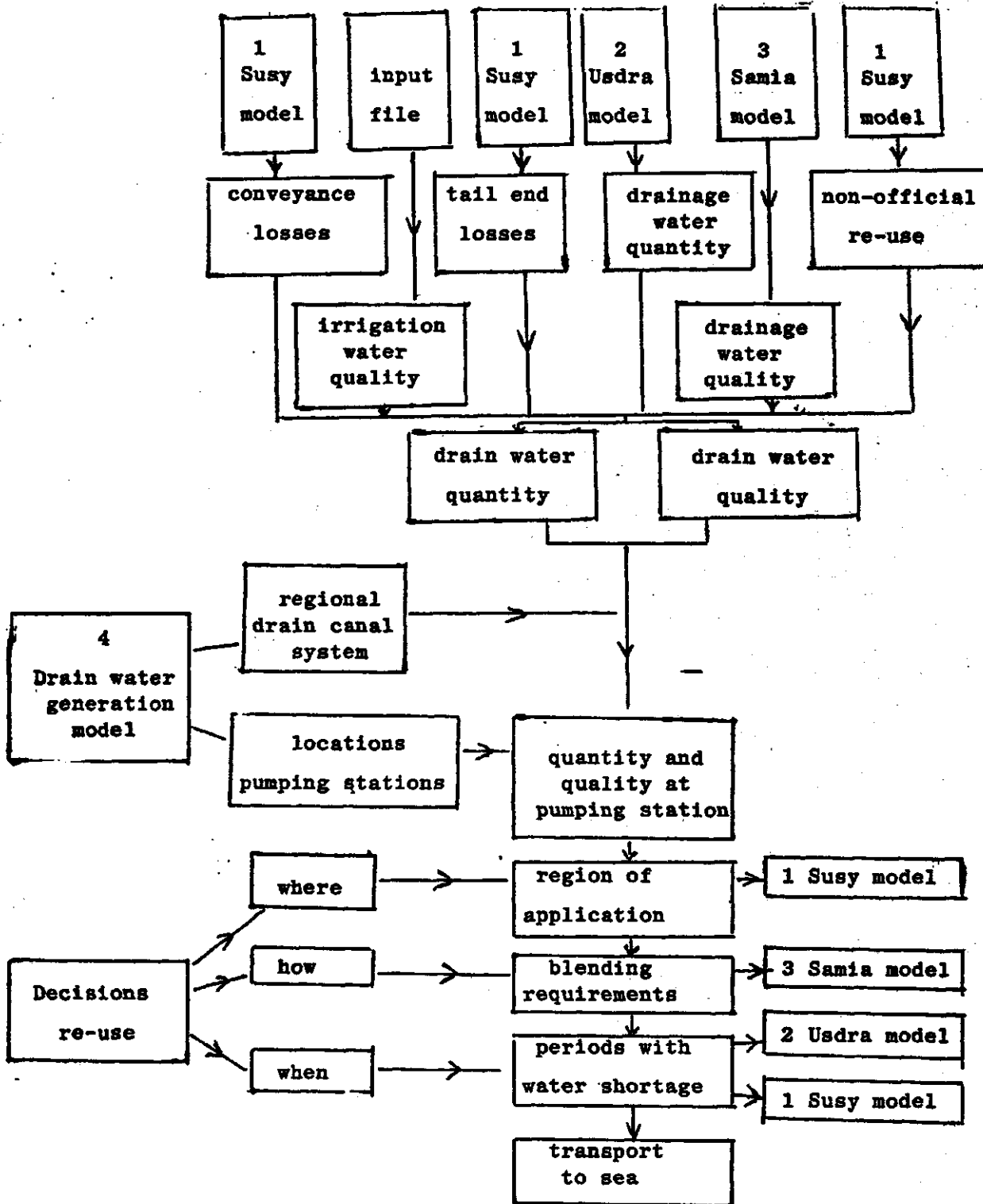The Drage model can be described by the scheme given in fig. 8.

Fig. 8. Scheme of the Drage model

The Drage model has to describe the accumulation of drain water
in the drain canal system. It also takes into account the mixing
of drain water in this system origanating from different sources
and model units, on its way to the pumping stations. At these
points decisions will be taken whether the drain water will be used
again or not. For improvement also the blending with Nile water will
be considered, resulting in the quality of the irrigation water in
the next regional section. These data will be used as input data in
the other submodels.

2.5. The Evaluation model
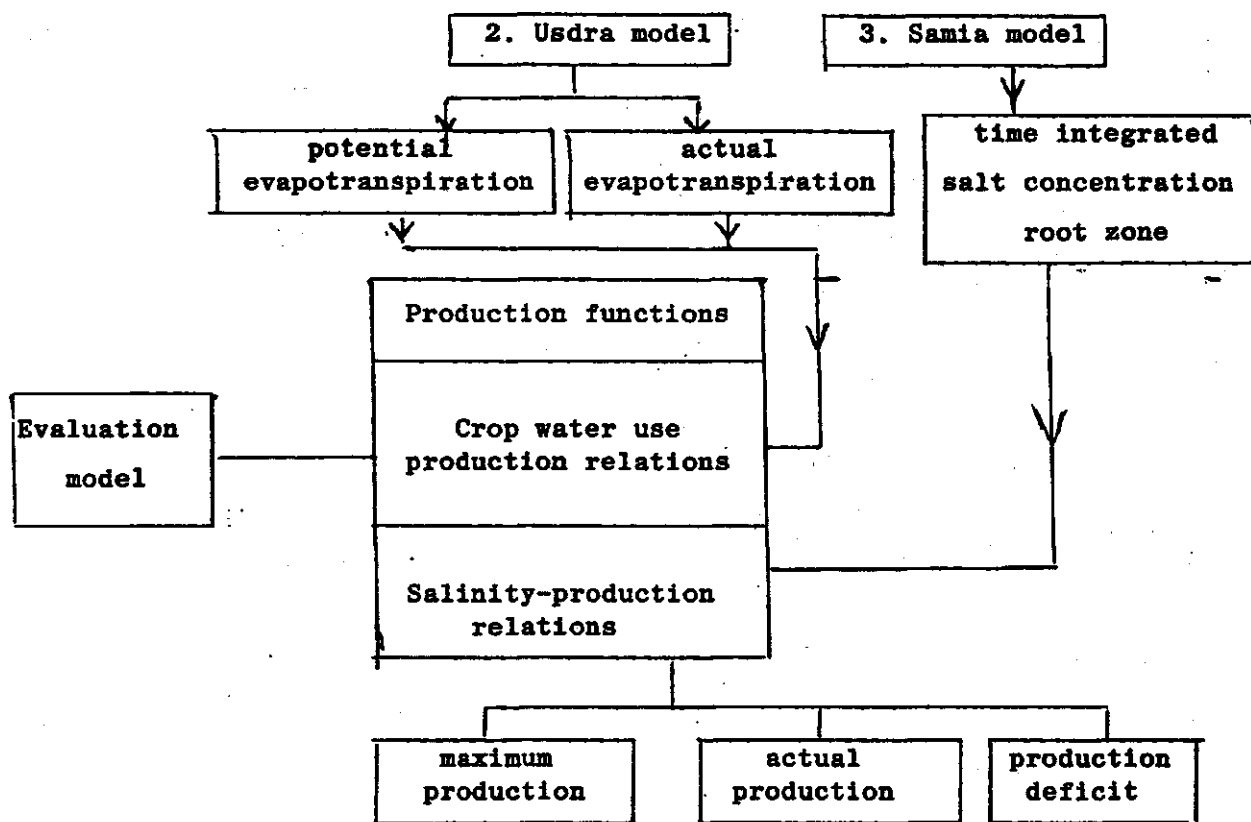
The Eva model is schematically given in fig. 9.

Fig. 9. Scheme of the evaluation model

The Eva model will mainly be based on crop water use-production
relations and salinity-production relations obtained from the relevant
literature.

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The input data of potential and actual crop water use are ob-
tained from the Uadra model and the time integrated salt concentration
in the root zone is obtained from the Samia model.
This model will give levels of maximum and actual production, as well
as the production deficit.

3. REQUIRED DATA COLLECTION

3.1. Data on the irrigation command areas

- Maps indicating the command inlet, the canal itself, the distri-
  butaries branching off, the areas served (watershed boundaries).
- Dimensions and capacity (in relation with distance from the
  command inlet) of these main canals.
- Number of distributaties served by the command inlet and total
  area served by the main canal (as well total gross-area as net
  cropped area).
- Data on the way in which the continuous inflow through the command
  inlet is rotated among the different distributaries (left/right
  rotation or upstreams/downstreams rotation?).
- Data on actual quantities supplied to the 50 canal command areas
  on monthly or decade basis for a period of at least one year.

3.2. Data on the distributary system (per irrigation command area)

- Dimensions and capacity of the distributaries (in relation with
  distance from the gate inlet).
- Land levels along the distributaries (detailed contour map).
- Average supply level in the distributary just after the inlet gate.
- Length of the distributaries.
- Area served by the distributaties.
- Bottom slope of the distributaries.
- Design level of the tail escape.
- Capacity of the sakkia's(in l/sec/feddan)
- Occurrence of motor pumps in the command area.

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3.3. Data on irrigation practices

- Irrigation schedule per crop per period. Official figures on irrigation interval and quantity advocated by the Ministry of Irrigation/ Agriculture as well as intervals and quantities recommended by pertinent crop water consumption studies. Any differences of requirements due to salinity status of the soil and/or location in the Delta should be taken into account.

3.4. Data on crops

- Crop rotation per delta subarea.
- Cropping pattern per delta subarea (preferably on a map).

3.5. Data on soil characteristics

- General soil map indicating roughly the soil texture Required Scale 1 : 100,000 till 1 : 300,000.
- Permeability of the soil.
- Salinity of the soil.
- Groundwater depth.

3.6. Data on drainage conditions

- Map indicating areas subsurface drained (drain depth).
- Data on distance and depth of field surface drains in non-subsurface drained areas.

3.7. Data on the aquifer

- Piezometric heads of the aquifer.
- Any known deep soil profiles in the Nile Delta.
- Any data on measurements on seepage and leakage in the Nile Delta.

3.8. Data on irrigation practices

- See required data under 3.3..
- Data on farmers priorities when irrigating their crops.

3.9. Data on irrigation water quality

- Regional distribution (maps) or per canal command area data on salinity and sar with seasonal variation (if any).

3.10. Data on vertical salt distribution in the soil

- Data from as much locations scattered in the Delta as possible on the vertical salt distribution in the profile including CEC, dry volumetric weight and ESP values.
- Data on distribution of solid calcite and gypsum.

3.11 Data on the main drainage system

- Maps indicating the drainage command areas, the main branches and the area's served These maps should give an indication of water level in the drain with respect to land surface.
- Drainage water quality in this drainage system (prefarably in a map)

3.12. Data on the deep aquifer

- See required data under 3.7.
- Map indicating quality (salinity and sar) of the seepage water.

3.13. Data on conveyance losses

- Conveyance losses from main canals such as leakage, evaporation, tail losses, leakage losses through distributary inlets when closed, etc.
- Data on tail end losses in distributaries.
- Any data and estimates on non-authorized reuse of drainage water.

3.14. Data on the main drainage system

- See required data under 3.11.
- Data on the stretches of main drains where the water level, due to pumping (lift), allows easy non-authorized reuse of drainage water and data on which part of the irrigation command areas this drainage water is easily available.

3.15. Any water and salt balance studies performed in the Delta should be made available (preferably in English) to enable calibration of the model or parts there of.

Reference should also be made to annex 1.

4. FUTURE ACTIVITIES ON MODELLING RE-USE OF DRAINAGE WATER

The future activities for the development of the model can be divided into 2 programmes.

Short term programme. This programme can be considered as a kind of feasibility study. In this study a first examination and testing of available data takes place, in order to be sure that the required level of detailed information can be obtained.

It is recommended that for this activity one or two staff members of the Drainage Research Institute work during 2 months at the Institute for Land and Water Management Research in cooperation with a dutch team of experts. The required set of data will be made available by the Drainage Research Institute.

Long term programme. The objectives of the second phase of the study will be:

- to assess for the present situation the quantity and the quality of the water drained off and which is not re-used for irrigation at the moment; the available measured data of drainage water quantity and quality will be used for model calibration;
- to predict the time trend of both drain water quantity and quality,

which will be influenced by sub-surface drainage, increase in cropping intensity and improved water management;

- to evaluate the consequences of improved water management and re-use of drain water in terms of crop production.

The objectives can best be obtained when a study in four integrated stages should be carried out.

Stage 1.

An extensive data collection programma to obtain sufficient topographical, hydrological and soil chemical data. Data of the irrigation regime, agricultural practice and data on water quality must be collected. A sensitivity analysis will be performed for the required level of accuracy of estimates for missing data.

Stage 2.

A further mathematical formulation of the required model and necessary adaptations with respect to data availability.

Stage 3.

Building the mathematical computer programme for the drain water re-use model. The model should meet the following criteria:

- the waterbalance of the model over monthly and annual periods must correspond with the available observed data;
- the calculated drain water quality data must correspond with the measured data at the pumping stations;
- when the model is verified for present conditions, there should be a reasonable certainty, that it will produce acceptable data in forcasting procedures.

Stage 4.

Optimization of the water management in the Nile Delta by analyzing different operational strategies.

QUESTIONS DISCUSSED WITH THE EGYPTIAN CONSULTANTS

1. Is the capacity at the inlet point of the distributary dependent
   on: - the level in the main canal
       - water level in the distributary
   If yes, detailed information of this dependency is required.

2. What are the design norms of the distributary canals? Can the
   design norms of the distributary be used in this study? If not,
   quantitative data on reduction of capacity due to poor maintenance
   are required.

3. What is the operational system during the inlet period? Is the
   opening of the inlet gate constant during this period?
   If not, detailed information on the operational procedures is
   required.

4. What is the capacity of the inlet system in relation to the area
   served? Detailed information and possible zonal variation (per
   Governorate or per irrigation district) is required.

5. Give detailed information on the expected future operational
   procedures to improve the irrigation efficiency of the system
   from 50% to 65% or more.

6. What is the maximum allowed level in the distributary canal before
   the overflow starts to work. What type of overflow is present at
   the tail end of the distributary and what are its hydraulic
   characteristics.

7. What are normally the distances between secondary distributaries?
   500 m? 800 m? 1000 m? more?

8. What are the lengthes of the secondary distributaries? What are
   the area's served and at which level start the overflow (tail
   escape) to work?

9. What is the capacity of the secondary distributaries in relation
   to area's served? Should the design norms be reduced due to poor
   maintenance? Detailed information is required, with zonal distri-
   bution (per governorate, irrigation district).

10. What are capacities of sakkia's, magma's and diesel pumps in relation to area served? Detailed information on the occurrence of the different irrigation means is required with emphasis on their zonal distribution.

11. What are the water levels in the distributary or secondary distributary canals before sakkia's, magma's and motor pumps can start to operate?

12. What is the quality of the irrigation water? Detailed information on seasonal and zonal variations in water quality are required.

13. What are the actual quantities supplied to the distributaries? Detailed information on seasonal and zonal variation is required.

14. Soil maps scale 1 : 250.000 for standardization model soils.

15. Contour maps of the Delta area.

16. Depth of the clay cap and spational variation (maps).

17. Data on horizontal and vertical permeability of the top soil and spational variation (maps).

18. Data on horizontal and vertical permeability of the sub soil and spational variation (maps).

19. Data on infiltration into and seepage from the sand aquifer and zonal distribution (maps).

20. Piezometric heads of the shallow and deep groundwater (maps.)

21. Data on soil moisture characteristics and capillary conductivity for the main soil groups.

22. Distribution of soil salinity, as well spational (zonal) variation (maps).

23. Salinity of shallow and deep ground water and spational variation (maps).

24. Effects of leaching and drainage on soil properties. Detailed quantitative information is required.

25. What percentage of the gross area is in non-agricultural use (villages, roads, railroads, etc)? Detailed information on zonal distribution (per Governorate, per district) is required.

26. What is the cropping pattern in summer and winter season in the
    different agricultural zones (per Governorate, per district)?
    Data required per crop (per agricultural zone):
    - area occupancy (percent)
    - planting date
    - harvesting data
    - soil cover (percent) and crop height during growing period
    - flowering data (if applicable)
    - irrigation schedule (frequency and quantity)
    - potential evapotranspiration per crop during growing period.

27. Data on crop production in relation to water use and soil salinity.

28. What is the expected future cropping pattern and its zonal distri-
    bution?

29. What are the drain depth and drain distances of the sub-surface
    drains for the different soil types? What is the zonal distribu-
    tion of these characteristics (maps)?

30. Which areas have been provided already with tile drainage? When
    was the system constructed in which area? (maps). What is the
    future plan with respect to tile drainage (maps)?

31. What are the drain depths and drain distances of the open field
    drains in areas not yet provided with tile drainage? Detailed
    information on zonal variation (maps) is required.

32. What is the density of the main open drainage system? What is the
    zonal variation (to be used for estimation of unofficial reuse
    of drainage water) ?

33. What is the quality of the water in the main open drainage system
    with both zonal distribution and seasonal variations?

34. What are the quantities of drainage water in the main open drains
    with both zonal distribution and seasonal variations?

35. For the pilot areas all the afore mentioned questions have to be
    answered,be it with more detail.

36. Which are the pilot areas chosen for the study? Preferably areas
    with existing detailed information should be selected in order to
    obtain a speedy confirmation of the model.

37. What is the irrigation schedule of the major crops in the Nile Delta

    Delta: Cotton

                   Rice

                   Maize

                   Berseem (Long)

                   Berseem (Short)

                   Wheat

    Detailed information on frequency and quantity of water application
    per crop (including pre-planting irrigation) is required.

38. How are these crop water requirements (frequency and quantity)
    translated into actual quantities supplied to the main canals and
    how are the distributary inlets operated?

39. What are the farmers priorities when irrigating his crops?
    Suppose all summer crops (cotton, rice and maize) need water,
    which crop will be irrigated first, second, last?
    Suppose both wintercrops need water which crop will be irrigated first?
    Berseem or wheat?

40. How much is an adequate irrigation application? Which allowance
    should be made for leaching?
    How much is the normal field application of irrigation water when
    the farmer uses the sakkia for irrigation? 50 mm? 100 mm? 150 mm?
    more?

41. If farmers have enough irrigation water they tend to over irrigate
    How much will this overirrigation be? 25%, 50%, more?
    Which percentage of the area will be overirrigated? Which percentage
    underirrigated?

42. What are the leaching requirements in relation to water quality?

43. How should the 20% conveyance losses be interpret? Are these the los-
    ses occurring after release of the water from the Asswan dam untill
    the inlet of the main irrigation canals? Or are these the assumed
    operational losses in the main irrigation canal-distribution canal
    system including the spill of water at the tail escapes?
    If so, should one assume that of the 3 mm/day total drainage to the
    sea about 1,5 mm is irrigation water spilled directly to drain and
    about 1,5 mm is leachate?