RE-USE OF DRAINAGE WATER

MODEL ANALYSIS

P.E. Rijtema

Report of a mission to Egypt
January 11 - February 7 1981
ADVISORY PANEL FOR LAND DRAINAGE IN EGYPT
### CONTENTS

#### 1. INTRODUCTION
- page 1

#### 2. AN OUTLINE OF A RE-USE MODEL
- page 2
  - 2.1. The supply system model
  - 2.2. The use and drainage model
    - 2.2.1. Meteorological data
    - 2.2.2. Crop rotation
    - 2.2.3. Maximum evaporative demand
    - 2.2.4. Actual crop water use, a simplified approach
    - 2.2.5. Actual evapo-transpiration and seepage flux
    - 2.2.6. Irrigation schedule
    - 2.2.7. Precipitation
    - 2.2.8. Drainage water, quantity
  - 2.3. The salt mixing analysis model
    - 2.3.1. General approach
    - 2.3.2. Downward movement in the unsaturated zone during refilling (Refill)
    - 2.3.3. Leaching and drainage water quality
    - 2.3.4. Redistribution of salt in the unsaturated zone (Redis)
    - 2.3.5. Chemical processes in the soil (Catex)
  - 2.4. The drainwater generation model
  - 2.5. The evaluation model
- page 3

#### 3. REQUIRED DATA COLLECTION
- page 43
  - 3.1. Data on the irrigation command areas
  - 3.2. Data on the distributary system (per irrigation command area)
  - 3.3. Data on irrigation practices
  - 3.4. Data on crops
  - 3.5. Data on soil characteristics
  - 3.6. Data on drainage conditions
  - 3.7. Data on the aquifer
  - 3.8. Data on irrigation practices
  - 3.9. Data on irrigation water quality
3.10. Data on vertical salt distribution in the soil 45
3.11. Data on the main drainage system 45
3.12. Data on the deep aquifer 45
3.13. Data on conveyance losses 45
3.14. Data on the main drainage system 46
3.15. Water and salt balance 46

4. FUTURE ACTIVITIES ON MODELLING RE-USE OF DRAINAGE WATER 46

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 Ministry 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
giving this assignment. The author had the benefit of intensive discus­sions with Dr. Mostafa El Gabaly, Dr. Mohamed Fahim and Dr. Mamdvah 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 were 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 advises 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 or 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
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.

1. Supply System model (Susy)
2. Use and Drainage model (Usdra)
3. Salt Mixing Analysis model (Samia)
4. Drain water Generation model (Drage)
5. Evaluation model (Eva)

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.

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. The use and drainage model

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 Nile delta. All calculations will be based on mean meteorological conditions.

2.2.2. Crop rotation

The main crop rotation in the Nile delta 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

<table>
<thead>
<tr>
<th>Area</th>
<th>Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Delta</td>
<td>vegetables - berseem(long) - maize - berseem (short) - cotton - wheat</td>
</tr>
<tr>
<td>Middle Delta</td>
<td>rice - berseem(long) - maize - berseem(short) - cotton - wheat</td>
</tr>
<tr>
<td>Northern Delta</td>
<td>rice - berseem(long) - rice - berseem(short) - cotton - wheat</td>
</tr>
</tbody>
</table>

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 Nile delta, 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 evaporation 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>
<thead>
<tr>
<th>Southern Delta</th>
<th>Mean monthly maximum evaporative demand $E_{\text{MAX}}$ in mm day$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop height cm</td>
<td>J</td>
</tr>
<tr>
<td>0</td>
<td>1.1</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
</tr>
<tr>
<td>20</td>
<td>2.1</td>
</tr>
<tr>
<td>30</td>
<td>2.3</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
</tr>
<tr>
<td>50</td>
<td>2.6</td>
</tr>
<tr>
<td>60</td>
<td>2.6</td>
</tr>
<tr>
<td>70</td>
<td>2.8</td>
</tr>
<tr>
<td>80</td>
<td>3.0</td>
</tr>
<tr>
<td>90</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil cover %</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>Winter</td>
<td>.31</td>
<td>.39</td>
<td>.47</td>
<td>.54</td>
<td>.63</td>
<td>.71</td>
<td>.81</td>
<td>.90</td>
<td>.95</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>.35</td>
<td>.43</td>
<td>.51</td>
<td>.59</td>
<td>.66</td>
<td>.75</td>
<td>.84</td>
<td>.90</td>
<td>.96</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Middle Delta</th>
<th>Mean monthly maximum evaporative demand $E_{\text{MAX}}$ in mm day$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop height cm</td>
<td>J</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.8</td>
</tr>
<tr>
<td>20</td>
<td>2.2</td>
</tr>
<tr>
<td>30</td>
<td>2.4</td>
</tr>
<tr>
<td>40</td>
<td>2.6</td>
</tr>
<tr>
<td>50</td>
<td>2.7</td>
</tr>
<tr>
<td>60</td>
<td>2.9</td>
</tr>
<tr>
<td>70</td>
<td>3.0</td>
</tr>
<tr>
<td>80</td>
<td>3.1</td>
</tr>
<tr>
<td>90</td>
<td>3.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil cover %</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>Winter</td>
<td>.28</td>
<td>.35</td>
<td>.43</td>
<td>.50</td>
<td>.58</td>
<td>.66</td>
<td>.75</td>
<td>.84</td>
<td>.90</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>.28</td>
<td>.35</td>
<td>.43</td>
<td>.50</td>
<td>.58</td>
<td>.66</td>
<td>.75</td>
<td>.84</td>
<td>.90</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Northern Delta</th>
<th>Mean monthly maximum evaporative demand $E_{\text{MAX}}$ in mm day$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop height cm</td>
<td>J</td>
</tr>
<tr>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>20</td>
<td>3.2</td>
</tr>
<tr>
<td>30</td>
<td>3.5</td>
</tr>
<tr>
<td>40</td>
<td>3.8</td>
</tr>
<tr>
<td>50</td>
<td>4.0</td>
</tr>
<tr>
<td>60</td>
<td>4.2</td>
</tr>
<tr>
<td>70</td>
<td>4.4</td>
</tr>
<tr>
<td>80</td>
<td>4.5</td>
</tr>
<tr>
<td>90</td>
<td>4.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil cover %</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction factor</td>
<td>Winter</td>
<td>.27</td>
<td>.34</td>
<td>.41</td>
<td>.49</td>
<td>.57</td>
<td>.67</td>
<td>.78</td>
<td>.86</td>
<td>.94</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Summer</td>
<td>.32</td>
<td>.40</td>
<td>.47</td>
<td>.55</td>
<td>.63</td>
<td>.72</td>
<td>.82</td>
<td>.90</td>
<td>.95</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Table 3. Values of maximum evaporative demand ($E_{\text{max}}$) in mm.day$^{-1}$ for different crops in the Southern, Middle and Northern Delta

<table>
<thead>
<tr>
<th>Period</th>
<th>Rice S / M / N</th>
<th>Maize S / M / N</th>
<th>Cotton S / M / N</th>
<th>Vegetables S / M / N</th>
<th>Barren long S / M / N</th>
<th>Barren short S / M / N</th>
<th>Wheat S / M / N</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2.0/2.1/2.3</td>
<td>2.0/2.1/2.3</td>
<td>2.0/2.1/2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2</td>
<td>2.1/2.2/2.3</td>
<td>2.1/2.2/2.3</td>
<td>2.3/2.4/2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td>3.0/3.4/3.7</td>
<td>3.0/3.4/3.7</td>
<td>3.6/4.0/4.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>3.3/3.5/4.3</td>
<td>3.3/3.5/4.3</td>
<td>3.8/4.3/4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>4.8/4.2/4.8</td>
<td>4.8/4.2/4.8</td>
<td>6.4/5.5/6.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>3.9/4.7/5.3</td>
<td>3.9/4.7/5.3</td>
<td>6.9/5.9/6.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>3.5/3.4/3.1</td>
<td>3.5/3.4/3.1</td>
<td>6.1/6.3/7.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>5.0/5.0/4.6</td>
<td>5.0/5.0/4.6</td>
<td>8.7/8.8/7.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>10.2/2.3/7.7</td>
<td>10.2/2.3/7.7</td>
<td>11.0/10.0/10.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>10.0/9.7/9.0</td>
<td>10.0/9.7/9.0</td>
<td>12.0/11.0/9.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1</td>
<td>13.6/10.8/9.1</td>
<td>13.6/10.8/9.1</td>
<td>6.2/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2</td>
<td>13.6/10.8/9.1</td>
<td>13.6/10.8/9.1</td>
<td>6.2/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1</td>
<td>15.3/6.9/9.8</td>
<td>15.3/6.9/9.8</td>
<td>9.6/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J2</td>
<td>11.0/6.5/9.2</td>
<td>11.0/6.5/9.2</td>
<td>9.2/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>9.3/7.7/9.1</td>
<td>9.3/7.7/9.1</td>
<td>7.8/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>9.0/7.1/8.7</td>
<td>9.0/7.1/8.7</td>
<td>7.4/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>8.2/6.6/8.5</td>
<td>8.2/6.6/8.5</td>
<td>6.6/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>7.8/6.2/8.0</td>
<td>7.8/6.2/8.0</td>
<td>6.2/ - / -</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td>5.4/ - / -</td>
<td>5.4/ - / -</td>
<td>2.4/3.0/2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O2</td>
<td>4.9/ - / -</td>
<td>4.9/ - / -</td>
<td>3.6/3.1/3.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>0.9/0.8/1.0</td>
<td>0.9/0.8/1.0</td>
<td>2.6/3.5/3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>1.8/1.6/2.0</td>
<td>1.8/1.6/2.0</td>
<td>2.7/2.4/3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>1.8/1.6/2.0</td>
<td>1.8/1.6/2.0</td>
<td>1.0/0.0/1.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>1.8/1.6/2.0</td>
<td>1.8/1.6/2.0</td>
<td>1.3/1.4/1.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.4. Actual crop water use, a simplified approach

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:

\[
E = E_{\text{max}} = - \frac{dM}{dt}, \quad M_i = aM_o \quad (1)
\]

\[
E = \frac{E_{\text{max}}}{aM_o} \cdot E_{\text{max}} = - \frac{dM_{\text{t}}}{dt}, \quad M_t < aM_o \quad (2)
\]

where: 
- \( E_{\text{re}} \) = real evapotranspiration in cm day\(^{-1}\)
- \( E_{\text{max}} \) = 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

Integration of the first equation yields:

\[
\int_{t=0}^{t=t'} E_{\text{max}} dt = - \int_{M_o}^{M_{t'}} dM_t \quad (3)
\]

or:

\[
t' = \left( \frac{M_{t'}}{M_o} - a \right) M_o E_{\text{max}}^{-1} \quad (3a)
\]

provided that: \( M_{t'} \geq aM_o \)

\( M_{t'} \) is the amount of available moisture present in the soil after application of irrigation at time \( t = 0 \). If the irrigation interval \( t_i < t' \) than the soil moisture deficit at the end of the irrigation interval equals:

\[
M_d = M_o - (M_{t'} + E_{\text{max}} t_i) \quad (4)
\]

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 \( t_i > t \), the second equation must also be used.

Depending on the value of \( M_o \), two different solutions are obtained.

When \( M_o > aM_o \):

\[
\int_{t=t}^{t} \frac{E_{\text{max}} \, dt}{aM_o} = - \int_{t=0}^{t} \frac{dM_t}{M_t} \tag{5}
\]

or:

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

or:

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

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

\[
M_d = M_o \left( 1 - a \exp \left[ - \left\{ \frac{E_{\text{max}} \cdot t}{aM_o} - \frac{M_o'/M_o - a}{a} \right\} \right] \right) \tag{6}
\]

Under the conditions of \( M_o < aM_o \) the solution of the differential equation becomes:

\[
\int_{t=0}^{t} \frac{E_{\text{max}} \, dt}{aM_o} = - \int_{t'}^{t} \frac{dM_t}{M_t} \tag{7}
\]

or:

\[
M_t = M_o \exp \left[ - \frac{E_{\text{max}} \cdot t}{aM_o} \right] \tag{7a}
\]

The soil moisture deficit equals in that case:

\[
M_d = M_o - M_o \exp \left[ - \frac{E_{\text{max}} \cdot t}{aM_o} \right] \tag{8}
\]

The real evapotranspiration can be calculated as:

\[
E_{\text{re}} = \left\{ M_d - (M_o - M_o') \right\} t_i^{-1} \tag{9}
\]
The value of $M'_O$ for the next interval equals when under irrigation is applied:

$$M'_O(T) = M'_O - M_d(T - 1) + f \cdot I_T$$  \hspace{1cm} (10)

where:
- $M'_O(T)$ = the available soil moisture at the beginning of the $T$th 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 $T$th 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:

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

where:
- $\psi_{osm}$ = the osmotic potential in bars
- $c_o$ = the salt concentration in the rootzone immediately after irrigation in meq/liter at field capacity
- $\theta_o$ = the volumetric soil moisture content in the rootzone at field capacity
- $\theta_t$ = the volumetric soil moisture content in the rootzone at time $t$
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 ($E_{\text{max}}$) and the salt concentration in the rootzone at field capacity

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

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

For the quantification of $W_{o}$, 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

<table>
<thead>
<tr>
<th>Drainage conditions</th>
<th>Soil texture</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>open drains 0.9 m</td>
<td>fine</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>4.2</td>
</tr>
<tr>
<td>tile drains 1.25 m</td>
<td>fine</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>5.0</td>
</tr>
<tr>
<td>tile drains 1.50 m</td>
<td>fine</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>12.1</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>5.5</td>
</tr>
</tbody>
</table>

2.2.5. Actual evapotranspiration and seepage flux

Evapotranspiration will be affected in regions with an influx of seepage water into the root system. 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:
\[ E_{re} = E_{max} = - \frac{dM}{dt} + \left( 1 - \frac{M_t}{M_o} \right) f_c \quad M_t \geq aM_o \]  
(12)

and

\[ E_{re} = \frac{M_t}{aM_o} \cdot E_{max} = - \frac{dM}{dt} + \left( 1 - \frac{M_t}{M_o} \right) f_c \quad M_t < aM_o \]  
(13)

where:
- \( E_{re} \) = real evaporative transpiration 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:

\[
t = \int_{t=0}^{t'} \frac{-dM}{E_{max} - \left( 1 - \frac{M_t}{M_o} \right) f_c} = \int_{t=0}^{t'} \frac{-dM}{E_{max} - (1 - a f_c) f_c} 
\]

or:

\[
t = \frac{aM_o}{f_c} \ln \left\{ \frac{E_{max} - \left( 1 - \frac{M_t}{M_o} \right) f_c}{E_{max} - (1 - a f_c) f_c} \right\} 
\]

(14a)

The remaining soil moisture volume at the end of the irrigation interval \( t_i < t' \) equals:

\[
M_t = M_o \left[ 1 - \frac{E_{max}}{f_c} + \left\{ \frac{E_{max}}{f_c} - \left( 1 - \frac{M_o}{M_o} \right) \right\} \exp - \frac{f_c t_i}{M_o} \right] 
\]

(15)

For \( 0 < t_i < t' \) the integrated value of the seepage contribution to evapotranspiration equals:

\[
S_{E_1} = \int_0^t \left( 1 - \frac{M_t}{M_o} \right) f_c \, dt 
\]

(16)

or
The total evapotranspiration equals in that case \( E_{\text{max} \cdot t} \).

When \( t > t' \) the differential equation (13) must also be used.

Integration of this equation yields:

\[
M_t = \frac{a M_0}{E_{\text{max}} + a f_c} \left[ f_c + \left\{ E_{\text{max}} \cdot (1-a) f_c \right\} \exp\left\{ -\frac{E_{\text{max}} + af_c}{a M_0} (t-t') \right\} \right] \quad (17)
\]

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

\[
S_E = E_{\text{max} \cdot t} - M_0 \left\{ \frac{E_{\text{max}}}{f_c} \right\} \left\{ 1 - \exp\left( -\frac{f_t}{E_{\text{max}}} \right) \right\} +
\]

\[
+ \left( 1 - \frac{a f_c}{E_{\text{max}} + a f_c} \right) f_c (t-t') - \frac{a^2 M_0 f_c}{(E_{\text{max}} + af_c)^2} \left\{ E_{\text{max}} \cdot (1-a) f_c \right\}
\]

\[
\left\{ 1 - \exp\left[ -\frac{E_{\text{max}} + af_c}{a M_0} t \right] \right\} \quad (17a)
\]

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

The total evapotranspiration equals under these conditions:

\[
E_{\text{max} \cdot t} = (M_0' - M_t) + S_{E_2} \quad (18)
\]

For the conditions that \( M_0' < a M_0 \) for \( t = 0 \) integration of eq.(13) results in the following expression:

\[
M_t = \frac{a M_0}{E_{\text{max}} + a f_c} \left[ f_c + \left\{ \frac{M_0'}{a M_0} \left( E_{\text{max}} + af_c \right) f_c \right\} \exp\left\{ -\frac{E_{\text{max}} + af_c}{a M_0} \cdot t \right\} \right] \quad (19)
\]

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

\[
S_E = \left\{ 1 - \frac{a f_c}{E_{\text{max}} + a f_c} \right\} f_c - \frac{a^2 M_0 f_c}{(E_{\text{max}} + af_c)^2} \left\{ \frac{M_0'}{a M_0} \left( E_{\text{max}} + af_c \right) - f_c \right\}
\]

\[
\cdot \left\{ 1 - \exp\left( -\frac{E_{\text{max}} + af_c}{a M_0} \cdot t \right) \right\} \quad (20)
\]

15
The total evapotranspiration equals in that case:

\[ E_{t4} = (M_0 - M_t) + S_E \]  

(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 °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 of irrigations applied and the 'ideal' quantity per irrigation gift (mm) for different crops on fine textured soils

<table>
<thead>
<tr>
<th>Period</th>
<th>Rice</th>
<th>Maize</th>
<th>Cotton</th>
<th>Vegetables</th>
<th>Berseem long</th>
<th>Berseem short</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>1x100</td>
<td></td>
<td></td>
<td>1x 50</td>
<td>1x50</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>J2</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td></td>
</tr>
<tr>
<td>F1</td>
<td></td>
<td>1x100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td></td>
<td>1x150</td>
<td></td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>1x 50</td>
<td>1x100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>1x100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td></td>
<td>1x 75</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>4x 10</td>
<td>1x150</td>
<td>1x100</td>
<td>1x 50</td>
<td>1x100</td>
<td>1x100</td>
<td></td>
</tr>
<tr>
<td>J1</td>
<td>4x 5</td>
<td>1x100</td>
<td></td>
<td>1x100</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>J2</td>
<td>4x100</td>
<td>1x 65</td>
<td>1x125</td>
<td>2x 50</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>J1</td>
<td>4x 5</td>
<td>1x 75</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td>1x100</td>
<td></td>
</tr>
<tr>
<td>J2</td>
<td>2x100</td>
<td>1x 75</td>
<td>1x100</td>
<td>2x 50</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>2x100</td>
<td>1x 75</td>
<td>1x100</td>
<td>2x 50</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>2x100</td>
<td>1x100</td>
<td>1x100</td>
<td>2x 50</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>2x100</td>
<td>1x100</td>
<td></td>
<td>2x 50</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>S2</td>
<td>2x100</td>
<td></td>
<td></td>
<td>2x 50</td>
<td>2x 50</td>
<td>2x 50</td>
<td></td>
</tr>
<tr>
<td>O1</td>
<td></td>
<td>1x 50</td>
<td>1x150</td>
<td>1x 50</td>
<td>1x150</td>
<td>1x50</td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td></td>
<td>1x 50</td>
<td></td>
<td></td>
<td></td>
<td>1x100</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td></td>
<td></td>
<td></td>
<td>1x 50</td>
<td>1x50</td>
<td>1x150</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td></td>
<td>1x 50</td>
<td>1x 50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td></td>
<td>1x 50</td>
<td>1x 50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>1560</td>
<td>640</td>
<td>1000</td>
<td>1100</td>
<td>950</td>
<td>560</td>
<td>550</td>
</tr>
</tbody>
</table>
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 Table 7.

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

<table>
<thead>
<tr>
<th>Period</th>
<th>Rice</th>
<th>Maize</th>
<th>Cotton</th>
<th>Vegetables</th>
<th>Berseem long</th>
<th>Berseem short</th>
<th>Wheat</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>J2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>F1</td>
<td>3.4</td>
<td>3.4</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>F2</td>
<td>2.5</td>
<td>2.5</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>M1</td>
<td>4.2</td>
<td>1.0</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>M2</td>
<td>1.3</td>
<td>4.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
</tr>
<tr>
<td>A1</td>
<td>3.4</td>
<td>5.9</td>
<td>6.8</td>
<td>6.8</td>
<td>6.8</td>
<td>6.8</td>
<td>6.8</td>
</tr>
<tr>
<td>A2</td>
<td>4.6</td>
<td>6.2</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>M1</td>
<td>6.2</td>
<td>6.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>M2</td>
<td>0.6</td>
<td>6.4</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>J1</td>
<td>0.9</td>
<td>3.0</td>
<td>6.4</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>J2</td>
<td>9.0</td>
<td>4.4</td>
<td>7.2</td>
<td>7.8</td>
<td>7.8</td>
<td>7.8</td>
<td>7.8</td>
</tr>
<tr>
<td>J1</td>
<td>8.0</td>
<td>6.4</td>
<td>6.1</td>
<td>7.3</td>
<td>7.3</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>J2</td>
<td>8.0</td>
<td>5.4</td>
<td>6.1</td>
<td>7.2</td>
<td>7.2</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>A1</td>
<td>7.5</td>
<td>4.9</td>
<td>6.0</td>
<td>6.6</td>
<td>6.6</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td>A2</td>
<td>7.1</td>
<td>5.6</td>
<td>6.1</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
</tr>
<tr>
<td>S1</td>
<td>6.5</td>
<td>5.8</td>
<td>1.8</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>S2</td>
<td>6.1</td>
<td>1.9</td>
<td>0.5</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>O1</td>
<td>5.6</td>
<td>4.4</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>O2</td>
<td>2.8</td>
<td>3.9</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>M1</td>
<td>1.5</td>
<td>0.8</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>M2</td>
<td>1.5</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>D1</td>
<td>1.9</td>
<td>1.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>D2</td>
<td>1.8</td>
<td>1.8</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Region</th>
<th>J</th>
<th>F</th>
<th>M</th>
<th>A</th>
<th>M</th>
<th>J</th>
<th>J</th>
<th>S</th>
<th>O</th>
<th>N</th>
<th>D</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>7.5</td>
<td>4.2</td>
<td>2.7</td>
<td>0.8</td>
<td>1.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.5</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>Middle</td>
<td>10.8</td>
<td>8.8</td>
<td>5.3</td>
<td>2.2</td>
<td>3.4</td>
<td>0.3</td>
<td>0.8</td>
<td>0.1</td>
<td>3.9</td>
<td>6.7</td>
<td>14.0</td>
<td>56.3</td>
</tr>
<tr>
<td>North</td>
<td>37.5</td>
<td>20.6</td>
<td>12.0</td>
<td>2.1</td>
<td>2.1</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>1.0</td>
<td>11.2</td>
<td>20.6</td>
<td>46.1</td>
</tr>
</tbody>
</table>

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:

\[ D_T = \left( f_s t_i - S_E \right)_T + \left( 1 - f \right)_T I_T \]

\[ f_s t_i \geq S_E \] (22a)

and

\[ D_T = \left( f_s t_i - S_E \right)_T + I_T - \left( M_o - M_{t(T-1)} \right) f_s t_i \geq S_E \] (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 \( T-1 \)
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

$$f_s t_1 + (1-\alpha) I_t < 0 \quad \text{or} \quad f_s t_1 + I_T - (M_0 - M_{t(T-1)}) < 0$$

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.

The Samia model has a very complex character, as it deals with non-steady downwards and upwards transport of water and salts. Moreover, 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. This 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 drainwater 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 negligible, 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 accumulation 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 irrigations 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 takes 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:

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

where:
- \( L_n \) = thickness of the \( n \)th layer in cm
- \( \theta_n \) = 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:

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

This equation can be solved under the boundary condition:

\( c_n(t) = c_n(t_o) \) for \( t = 0 \)

Introduction of a constant moisture volume per layer \( (L_n \theta_n = \text{constant}) \) gives:

\( A_0 = A_1 = A_2 = \ldots = A_n \).

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

\[
c_n(t) = c_1 + \sum_{k=0}^{n} \left[ c_k(t_o) - c_1 \right] \left[ A f_d t \right]^{n-k} \exp \left[ -A f_d t \right]^{1/(n-k)} \quad (24)
\]

where:
- \( c_1 \) = 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 \( L \Delta \theta \) cm of irrigation water is required to refill this layer. The time required for this moisture supply at mean infiltration flux \( f_d \) equals:

\[
t_o' = \frac{(L \Delta \theta)}{f_d}
\]  

(25)

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

\[
c_o(t_o') = \frac{L \theta \cdot c_o(t_o) + L \Delta \theta \cdot c_1}{L \theta (\theta_o + \Delta \theta_o)}
\]

(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:

\[
t_1' - t_0' = \frac{L \Delta \theta_1}{f_d}
\]

(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:

\[
c_o(t) = c_1 + \left[ c_o(t_0') - c_1 \right] \exp \left[ -A f_d (t - t_0') \right]
\]

(28)

where: \( A = \frac{L \theta}{\theta_o + \Delta \theta_o} \)

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:

\[
\bar{c}_o = c_1 + \left\{ A f_d (t_1' - t_0') \right\}^{-1} \left[ c_o(t_0') - c_1 \right] \left[ 1 - \exp \left[ -A f_d (t_1' - t_0') \right] \right]
\]

(28a)

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

\[
c_1(t_1') = \frac{L_1 \eta_1 c_1(o) + L_1 \Delta \theta_1 \bar{c}_o}{L_1 (\theta_1 + \Delta \theta_1)}
\]

(29)
The refilling of the moisture deficit of the $n^{\text{th}}$ layer requires a time step $t_n - t_{n-1}$, which equals $L_n \Delta \theta \cdot f^{-1}$. The mean salt concentration of the water entering this layer at $n$ is given by the general equation:

$$\tilde{c}_{n-1} = c_{n-1} + \frac{1}{t_n - t_{n-1}} \int_{t_{n-1}}^{t_n} \sum_{k=1}^{\infty} \left[ c_k(t_{n-1}') - c_k \right] \left[ \Delta \theta_d(t - t_{n-1}') \right]^{(n-1)-k} \cdot \exp \left[ -\Delta \theta_d (t-t_{n-1}') \right] \frac{1}{(n-1-k)!} \ dt$$

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:

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

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

$$c_n(t_n') = \frac{L_n \Delta \theta \cdot c_n(0) + L_n \Delta \theta \cdot \tilde{c}_{n-1}}{L_n (\Delta \theta_n + \Delta \theta_n')}$$

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 overirrigation 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 factor $b_n$ 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

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Number of unsaturated layers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>.333</td>
</tr>
<tr>
<td>2</td>
<td>.125</td>
</tr>
<tr>
<td>3</td>
<td>.067</td>
</tr>
<tr>
<td>4</td>
<td>.042</td>
</tr>
</tbody>
</table>

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 in 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 $f_d t$, so the equation can be rewritten as:

$$c_n(t) = c_1 + \sum_{k=0}^{n} \left[ c_k(t_n') - c_1 \right] [A(1-f)I_n]^k \exp \left[-A(I-M_d)\right] \left[1/(n-k)!\right] \tag{33a}$$

or:

$$c_n(t) = c_1 + \sum_{k=0}^{n} \left[ c_k(t_n') - c_1 \right] [A(1-f)I_n]^k \exp \left[-A(I-M_d)\right] \left[1/(n-k)!\right] \tag{33b}$$

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

<table>
<thead>
<tr>
<th>Layer n</th>
<th>After filling</th>
<th>Concentration layer n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$c_0(t') = \left(1 - b_2 M_d \right) c_0(0) + b_2 R_{10}$</td>
<td>$c_0(t') = \left(1 - Ab_2 M_d \right) c_0(0) + Ab_2 R_{10}$</td>
</tr>
<tr>
<td>1</td>
<td>$c_1(t') = c_1 + \sum_{k=0}^{n} \left[ c_0(t') - c_1 \right] \left[ -AR(h_1) \right]^{n-k} \exp \left[ -AR(h_1) \right]^{1/(n-k)}$</td>
<td>$c_1(t') = (1 - Ab_2 M_d) c_1(0) + Ab_2 R_{10}$</td>
</tr>
<tr>
<td>2</td>
<td>$c_2(t') = c_2 + \sum_{k=0}^{n} \left[ c_1(t') - c_2 \right] \left[ -AR(h_2) \right]^{n-k} \exp \left[ -AR(h_2) \right]^{1/(n-k)}$</td>
<td>$c_2(t') = (1 - Ab_2 M_d) c_2(0) + Ab_2 R_{10}$</td>
</tr>
<tr>
<td>3</td>
<td>$c_3(t') = c_3 + \sum_{k=0}^{n} \left[ c_2(t') - c_3 \right] \left[ -AR(h_3) \right]^{n-k} \exp \left[ -AR(h_3) \right]^{1/(n-k)}$</td>
<td>$c_3(t') = (1 - Ab_2 M_d) c_3(0) + Ab_2 R_{10}$</td>
</tr>
<tr>
<td>4</td>
<td>$c_4(t') = c_4 + \sum_{k=0}^{n} \left[ c_3(t') - c_4 \right] \left[ -AR(h_4) \right]^{n-k} \exp \left[ -AR(h_4) \right]^{1/(n-k)}$</td>
<td>$c_4(t') = (1 - Ab_2 M_d) c_4(0) + Ab_2 R_{10}$</td>
</tr>
</tbody>
</table>

Seepage from the aquifer

$R = L t + S_{G}$ if $C_{G} > 0$ if $R = L$

$R = M_d + S_{G}$ if $L = 1$ (see 2.2.2.2.)

Concentration of inflow water of layer $n$

$\tau_n = c_n + \frac{1}{AR} t_c \left[ c_0(t') + c_1(t') \right]$
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 $f_g$, expressed in cm.day$^{-1}$.

### 2.3.3.1. No effect of the groundwater aquifer

The flow to the drain can be considered schematically as a combination of horizontal and vertical fluxes. The scheme for the proposed model is given in fig. 5.

![Diagram](image)

**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 drain spacing ($\frac{1}{2}L$) in $n$ 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 filling

<table>
<thead>
<tr>
<th>Layer n</th>
<th>Concentration layer n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[ c_0(t'<em>0) = \left(1 - A b</em>{M_d}\right) c_o(o) + A b_{R E_1} - \left(1 - A b_{M_d}\right) c_o(o) + A b_{R E_1} ]</td>
</tr>
<tr>
<td>1</td>
<td>[ c_1(t'<em>1) = c_1 + \sum</em>{k=0}^{\infty} \left[ c_1(t'_0) - c_1 \right] \left[ A R(b_1) \right]^{n-k} \exp \left[-A R(b_1)\right] \left[1/(n-k)\right] ]</td>
</tr>
<tr>
<td>2</td>
<td>[ c_0(t'<em>2) = c_1 + \sum</em>{k=0}^{\infty} \left[ c_2(t'_1) - c_1 \right] \left[ A R(b_2) \right]^{n-k} \exp \left[-A R(b_2)\right] \left[1/(n-k)\right] ]</td>
</tr>
<tr>
<td>3</td>
<td>[ c_0(t'<em>3) = c_1 + \sum</em>{k=0}^{\infty} \left[ c_3(t'_2) - c_2 \right] \left[ A R(b_3) \right]^{n-k} \exp \left[-A R(b_3)\right] \left[1/(n-k)\right] ]</td>
</tr>
<tr>
<td>4</td>
<td>[ c_0(t'<em>4) = c_1 + \sum</em>{k=0}^{\infty} \left[ c_4(t'_3) - c_3 \right] \left[ A R(b_4) \right]^{n-k} \exp \left[-A R(b_4)\right] \left[1/(n-k)\right] ]</td>
</tr>
</tbody>
</table>

Seepage from the aquifer
\[ R = L + S_e \] if \( S_e \geq 1 \) \( R = 1 \)
\[ R + M_d + S_e \leq 1 \] (see 2.2.2.1.)

Concentration of inflow water of layer n during filling
\[ c_1 \]
\[ F_0 = c_1 + \frac{1}{A R b_1} \left[ c_0(t'_0) - c_1 \right] \left[1 - \exp \left[-A R b_1\right]\right] \]
\[ \bar{c}_1 = \frac{1}{4} \left[ c_1(t'_1) + c_1(t'_2) \right] \]
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 \( n = A(d_d \theta_d) \) and \( n = A(d_d \theta_d + 2d_b \theta_b) \).

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.

![Diagram](image)

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: \( \frac{1}{2} \cdot (1 - \alpha) \cdot L \), where \( \alpha \) is the greatest value of the two expressions:

28
$L_v$ = the length of the vertical pathway
$d_d$ = depth of drainage
$d_b$ = depth of drainage flux barrier (maximum = $\frac{1}{4}L$)
$k$ varies from 0 at a distance $\frac{1}{4}L$ to $m$ for a pathway above the drain.

The horizontal length of each pathway becomes:

$$L_h = \frac{1}{4} (1 - k/m) \cdot L$$  \hspace{1cm} (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:

$$f_h = \frac{L}{2d_b} \cdot f_v$$ \hspace{1cm} (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:

$$A_h = \frac{2d_b}{L} \cdot A_v$$ \hspace{1cm} (35a)

or:

$$L_{\theta_n} = \frac{L}{2d_b} \cdot (L_{\theta_n})_v$$ \hspace{1cm} (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:

$$n = d_d \frac{\theta_d}{L_n} + \frac{(1 - k/m)d_b \theta_b}{L_n} + \frac{1}{4} (1 - k/m) \frac{L \theta_b}{2d_b} + \frac{L}{(d_d + (1 - k/m)d_b \theta_b)} \cdot (L_{\theta_n})$$ \hspace{1cm} (36a)

or:

$$n = A \left\{ d_d \theta_d + 2 (1 - k/m) d_b \theta_b \right\} \cdot d_b \leq \frac{1}{4} L$$ \hspace{1cm} (36b)

where:

$d_d$ = drain depth in cm
$\theta_d$ = volumetric soil moisture fraction above drain depth
$d_b$ = depth of drainage barrier in cm below drain depth
$\theta_b$ = 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 \( \alpha \), where \( \alpha \) is given by:

\[ \alpha = \frac{D_I}{D_I + f \cdot t_s \cdot i} \]
\[ \alpha = \frac{-F + 1}{(1-f) I} \quad \text{or} \quad \alpha = \frac{-F + 1}{1 - \frac{1}{M_d}} \]

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: \( L_h = \frac{d}{2} (1 - \alpha)(1 - k^*/m^*)d \)

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

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

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

When \( \alpha \) 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:

\[ n = A_n \left( d_d \theta_d \right) \quad \text{and} \quad n = A_n \left\{ d_d \theta_d + 2 (1 - \alpha) d_b \right\} \]

The number of layers into account varies with the value of \( \alpha \).

2.3.3. 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 \( n_{\text{max}} \) and \( n \). The value of \( n_{\text{max}} \) is given by:

\[
n_{\text{max}} - n = 2A.(1 - \beta ).d \theta_b \quad \text{with} \quad \beta = D_s f_s t_i
\]

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 \( n_{\text{max}} - n = 2A.d \theta_b \).

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 actual 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:

\[
\left\{ \frac{1}{A} \left( f_o - f_i \right) \right\} \frac{dc_n(t)}{dt} = f_i c_{n+1} - f_o c_n(t) \quad (40)
\]

where: \( A = (L \theta_n)^{-1} \)

\( f_o = \) 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:

\[
f_i = f_{n+1,n} = \left( 1 - \sum_{0}^{n} b_n \right) \cdot (E_{re} - \bar{\gamma}_c) + \bar{\gamma}_c
\]

\[
f_o = f_{n,n-1} = \left( 1 - \sum_{0}^{n-1} b_n \right) \cdot (E_{re} - \bar{\gamma}_c) + \bar{\gamma}_c
\]
The seepage flux has its influence to the depth of drainage when $\alpha < 0$. 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: $L_h = \frac{1}{l} (1 - k/m) \cdot \ell$

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

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

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

$$c_n(t) = c_i + \sum_{k=0}^{n} \left[ c_k(t_n) - c_i \right] \left[ AD_I \right]^{n-k} \text{exp} \left[ - AD_I \left[1/(n-k)\right]\right]$$

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

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 $n_{\text{max}} = A \left( d_d \theta_d + 2 d_b \theta_b \right)$.

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

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

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

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

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 $n_{\text{max}}$ and $n_{\text{max}} - n$. 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 ratio is given the name Sodium Adsorption Ratio (sar) and is given by the expression:

\[
\text{sar} = \frac{[\text{Na}^+]}{\sqrt{\frac{1}{2} [\text{Ca}^{2+}] + [\text{Mg}^{2+}]}} = \frac{[\text{c}^+]}{\sqrt{\frac{1}{2} \text{c}^{2+}}}
\]

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:

\[
\text{ES} = \frac{0.015 \text{sar}}{1 + 0.015 \text{sar}}
\]

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

\[
c_n^+(t) = \frac{\text{sar}^2}{4} \left\{ -1 + \sqrt{1 + \frac{4}{\text{sar}^2}} \cdot c_n(t) \right\}
\]

and

\[
c_n^{2+}(t) = \frac{1}{2} c_n(t) + \frac{\text{sar}^2}{4} \left\{ 1 - \sqrt{1 + \frac{4}{\text{sar}^2}} \cdot c_n(t) \right\}
\]

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
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:

$$\frac{dc_n}{f_1 c_{n+1} - f_0 c_n(t)} = \frac{dt}{t} \quad (40a)$$

Integration yields:

$$c_n(t) = \frac{f_0}{f_1} c_{n+1} + \left\{ c_n(t_o) - \frac{f_1}{f_0} c_{n+1} \right\} \left\{ 1 - A(f_o - f_1)t \right\}^{f_o-f_1}$$

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:

$$\bar{c}_n(t) = \frac{2f_0 - f_1}{A(2f_o - f_1)} c_{n+1} + \frac{1}{A(2f_o - f_1)} \left\{ c_n(t_o) - \frac{f_1}{f_0} c_{n+1} \right\} \left\{ 1 - A(f_o - f_1)t \right\}^{f_o-f_1}$$

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

The top layer 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:

$$\frac{dc_0(t)}{f_1 c_1} = \frac{dt}{\left\{ \frac{1}{A} - (f_o - f_1) t \right\}} \quad (43)$$

Rearranging gives:

$$\frac{dc_0(t)}{f_1 c_1} = \frac{dt}{\left\{ \frac{1}{A} - (f_o - f_1) t \right\}} \quad (44)$$

Integration of this equation results in:

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

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$_2$CO$_3$ gives the reaction equation:

$$\text{CO}_2(g) + H_2O \leftrightarrow H_2\text{CO}_3 \quad \log k^O = -1.46 \quad (52)$$

The activity of CO$_2$-gas is here expressed in terms of the gas pressure P in bar.
In general terms one finds:

$$-\log [H_2\text{CO}_3] = 1.46 - \log P_{\text{CO}_2} \quad (52a)$$

The carbonic acid molecules entertain protolysis reactions according to:

$$H_2\text{CO}_3 \leftrightarrow H\text{CO}_3^- + H^+ \quad \log k^O = -6.35 \quad (53)$$
$$H\text{CO}_3^- \leftrightarrow CO_3^{2-} + H^+ \quad \log k^O = -10.38 \quad (54)$$

Combining these equations results in:

$$-\log [H\text{CO}_3^-] = 7.81 - \log P_{\text{CO}_2} - \text{pH} \quad (53a)$$

and

$$-\log [CO_3^{2-}] = 18.14 - \log P_{\text{CO}_2} - 2\text{ pH} \quad (54a)$$

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:

$$\text{CaCO}_3(s) \leftrightarrow Ca^{2+} + CO_3^{2-} \quad \log k^O = -8.35 \quad (55)$$

or

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

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 $ES(t) \approx ES(t_0)$, which results in $sar(t) \approx sar(t_0)$. 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 $sar(t_0)$.

The mass balance equations of the n'th layer can in that case be given as:

$$\frac{\partial}{\partial t} f_{n-1} c_{n-1}^{+} f_{t} - c_{n}^{+} f_{t} = c_{n}^{+}(t) \left[ L_{n}^{\theta} \right] t - c_{n}^{+}(t_0) \left[ L_{n}^{\theta} \right] t_0 +$$

$$+ \left\{ ES(t) - ES(t_0) \right\} \left\{ \frac{CEC}{100} \right\} \left[ L_{n}^{\rho} \right] L_{n}^{p} (50)$$

and

$$\frac{\partial}{\partial t} f_{n-1} c_{n-1}^{2+} f_{t} - c_{n}^{2+} f_{t} = c_{n}^{2+}(t) \left[ L_{n}^{\theta} \right] t - c_{n}^{2+}(t_0) \left[ L_{n}^{\theta} \right] t_0 +$$

$$+ \left\{ ES(t) - ES(t_0) \right\} \left\{ \frac{CEC}{100} \right\} \left[ L_{n}^{\rho} \right] L_{n}^{p} + \Delta [CaCO_3] (51)$$

where:

$c^+$ = \frac{1}{t} \left\{ c^+(t_0) + c^+(t) \right\}$ in meq.1$^{-1}$

$c^{2+}$ = \frac{1}{t} \left\{ c^{2+}(t_0) + c^{2+}(t) \right\}$ in meq.1$^{-1}$

$f_{i}$ = incoming flux in cm.day$^{-1}$

$f_{o}$ = outgoing flux in cm.day$^{-1}$

$L_{n}^{\theta}$ = moisture volume of layer n in cm

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

$CEC \frac{L_{n}^{\rho}}{100}$ = cation exchange capacity of layer n in meq.

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

$c^+$ and $c^{2+}$, as well as $c_n^+(t)$ and $c_n^{2+}(t)$ are as a first approach calculated with the assumption $sar(t) = sar(t_0)$, leaving $ES(t)$ as the only unknown factor, which can be calculated from the equations. When $ES(t)$ differs too much from $ES(t_0)$ 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
\[
\log \left[ \text{CaCO}_3^- \right] = 3.24 - \text{pH} \quad (61)
\]

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:

\[
[\text{Ca}^{2+}] + \left[ \text{CaCO}_3^- \right] + \left[ \text{CaHCO}_3^- \right] = \frac{10^{-8.35} + 10^{1.98} - \text{pH}}{[\text{CO}_3^{2-}] + [\text{HCO}_3^-]} + 10^{-5.15} + 10^{3.24} - \text{pH} \quad (62)
\]

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:

\[\text{CaSO}_4 \cdot 2 \text{H}_2\text{O} \rightleftharpoons \text{Ca}^{2+} + \text{SO}_4^{2-} + 2 \text{H}_2\text{O} \quad \log k_S^0 = -4.61 \quad (63)\]

or

\[\left[ \text{Ca}^{2+} \right] = \frac{10^{-4.61}}{[\text{SO}_4^{2-}]} \quad (63a)\]

As with the carbonates the soluble complex is involved. The formation reaction of the uncharged ion-pair \(\text{CaSO}_4^0\) reads:

\[\text{Ca}^{2+} + \text{SO}_4^{2-} \rightleftharpoons \text{CaSO}_4^0 \quad \log k^0 = 2.31 \quad (64)\]

In a system where also solid gypsum is present the concentration of \(\text{CaSO}_4^0\) 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:

\[\left[ \text{Ca}^{2+} \right] + \left[ \text{CaSO}_4^0 \right] = \frac{10^{-4.61} + 10^{-2.29}}{[\text{SO}_4^{2-}]} \quad (65)\]

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] = \text{pH} - 1.98 + \log \left[ HCO_3^- \right] \quad (56)

or

\left[ Ca^{2+} \right] \left[ CO_3^{2-} \right] = 10^{-8.35} \quad (55b)

and

\left[ Ca^{2+} \right] \left[ HCO_3^- \right] = 10^{-1.98} - \text{pH} \quad (56a)

Adding together gives

\left[ Ca^{2+} \right] \left[ CO_3^{2-} \right] + \left[ HCO_3^- \right] = 10^{-8.35} + 10^{1.98} - \text{pH} \quad (57)

or

\left[ Ca^{2+} \right] = \frac{10^{-8.35} + 10^{1.98} - \text{pH}}{\left[ CO_3^{2-} \right] + \left[ HCO_3^- \right]} \quad (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 \( CaCO_3^0 \) 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:

\( Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3^0 \quad \log k^o = 3.20 \quad (58) \)

and

\( Ca^{2+} + HCO_3^- \leftrightarrow CaHCO_3^+ \quad \log k^o = 1.26 \quad (59) \)

or

- \log \left[ Ca^{2+} \right] - \log \left[ CO_3^{2-} \right] + \log \left[ CaCO_3^0 \right] = 3.20 \quad (58a)

and

- \log \left[ Ca^{2+} \right] - \log \left[ HCO_3^- \right] + \log \left[ CaHCO_3^+ \right] = 1.26 \quad (59a)

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

\[ \log \left[ CaCO_3^0 \right] = -5.15 \quad (60) \]

As long as solid calcite is present in the soil the concentration of \( CaCO_3^0 \) 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 $\text{HCO}_3^-$, the $\text{CO}_3^{2-}$ and the $\text{SO}_4^{2-}$ 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:

\[
(x - \Delta x)(y_1 - \Delta y_1) = C_1
\]
and
\[
(x - \Delta x)(y_2 - (\Delta x - \Delta y_1)) = C_2
\]

Both equations give as result:

\[
\Delta y_1 = y_1 - \frac{C_1}{x - \Delta x}
\]

and

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

where:

- $x =$ the $\text{Ca}^{2+}$-concentration in meq.1$^{-1}$
- $y_1 =$ the $\text{SO}_4^{2-}$-concentration in meq.1$^{-1}$
- $y_2 =$ the $\text{HCO}_3^- + \text{CO}_3^{2-}$-concentration in meq.1$^{-1}$
- $C_1 = 6.14 \times 10^{-2}$
- $C_2 = (0.0011 + 10^{7.38-pH}) \times 10^{-2}$

$\Delta x$ and $\Delta y_1$ are positive unless case of precipitation.

When under saturation exists, without the presence of solid gypsum equation (69) does not hold and $\Delta y_1$ equals zero. When no solid calcite is present equation (70) does not hold and $\Delta y_1$ equals in that case $\Delta x$. The equations (69) and (70) have no meaning when both solid phases are not present.

For soils with solid $\text{CaCO}_3$, the pH can be calculated by the equation:

\[
pH = (p k_2 - p k_1) + p[H(Ca + Mg)] + p \text{Alk}
\]

where $p [H(Ca+Mg)]$ and $p \text{Alk}$ are the negative logarithms of the equivalent concentrations of Ca + Mg and of the equivalent concentration of titrable base ($\text{CO}_3^{2-}$ and $\text{HCO}_3^-$), respectively. $pk_2$ and $pk_{SO}$ are the negative logarithms of the second dissociation constant of $\text{H}_2\text{CO}_3$ and the solubility constant of $\text{CaCO}_3$ 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:

\[ a_i = f_i c_i \]  \hspace{1cm} (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:

\[ -\log f_i = A z_i^2 \left( \frac{\sqrt{I}}{1 + \sqrt{I}} - 0.3 I \right) \]  \hspace{1cm} (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:

\[ I = \frac{1}{2} \sum c_i z_i^2 \]  \hspace{1cm} (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\(_3^0\) and CaSO\(_4^0\) equal unity.

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

\[ c_{\text{Ca}^{2+}} = \frac{10^6}{2f_2} \left\{ \frac{10^{-8.35} + 10^{1.98} - \text{pH}}{2f_2 c_{\text{CO}_3}^{-2} + f_5 c_{\text{HCO}_3}^--} \right\} \]  \hspace{1cm} (57b)

and

\[ c_{\text{Ca}^{2+}} = \frac{10^6}{4 f_2^2} \left\{ \frac{10^{-4.61}}{c_{\text{SO}_4}^--} \right\} \]  \hspace{1cm} (63b)

The equations (57b) and (63b) give the maximum value of \( c_{\text{Ca}^{2+}} \) 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 originating 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.

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

Fig. 9. Scheme of the evaluation model
The input data of potential and actual crop water use are obtained from the Usdra 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 distributaries branching off, the areas served (watershed boundaries).
- Dimensions and capacity (in relation with distance from the command inlet) of these main canals.
- Number of distributaries 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 distributaries.
- 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.
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 (preferably 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 programme 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 forecasting procedures.

Stage 4.

Optimization of the water management in the Nile Delta by analyzing different operational strategies.
ANNEX 1

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 lengths 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 distribution (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 date
- 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 distribution?

29. What are the drain depth and drain distances of the sub-surface drains for the different soil types? What is the zonal distribution 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?

- 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 winter crops 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 overirrigate. 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 interpreted? Are these the losses occurring after release of the water from the Asswan dam until 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?