SALTMOD

Description of Principles, User Manual,
and Examples of Application

On website www.waterlog.info/saltmod.htm

A computer program for the prediction of the salinity of soil moisture, ground water and drainage water, the depth of the water table, and the drain discharge in irrigated agricultural lands, using different (geo)hydrologic conditions, varying water management options, including the use of ground water for irrigation, and several cropping rotation schedules.

Windows version

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The manual for the SaltMod user interface is to be found on:
https://www.waterlog.info/pdf/SaltMod menu.pdf

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(For the Dos verson, the user menu was extensively described, the Windows version is supposed to be self-eplanatory, so no description is given)

1. INTRODUCTION

1.1. General

Saltmod is computer program for the prediction of the salinity of soil moisture, ground water and drainage water, the depth of the water table, and the drain discharge in irrigated agricultural lands, using different (geo)hydrologic conditions, varying water management options, including the use of ground water for irrigation, and several cropping rotation schedules.

The water management options include irrigation, drainage, and the use of subsurface drainage water from pipe drains, ditches or wells for irrigation.

The computer program was originally made in Fortran by R.J. Oosterbaan and Isabel Pedroso de Lima at ILRI. A user shell in Turbopascal was developed by H. Ramnandanlal, and improved by R.A.L. Kselik of ILRI, to facilitate the management of input and output data.

Now, a Windows version is available, written in Delphi by Oosterbaan.

The program was designed keeping in mind a relative simplicity of operation to promote its use by field technicians and project planners. It aims at using input data that are generally available, or that can be estimated with reasonable accuracy, or that can be measured with relative ease. Saltmod has been used and tested extensively. A selection of reports and publications on the use of Saltmod is given in the references.

A combination of SaltMod with a polygonal groundwater model (SahysMod) is also available, see https://www.waterlog.info/sahysmod.htm

The SaltMod menu can be seen at https://www.waterlog.info/pdf/SaltMod menu.pdf

1.2. Rationale

Most of the computer models available for water and solute transport in the soil (e.g. Swatre, Drainmod) are based on Richard's differential equation for the movement of water in unsaturated soil in combination with a differential salinitity dispersion equation. The models require input of soil characteristics like the relation between unsaturated soil moisture content, water tension, hydraulic conductivity and dispersivity. These relations vary to a great extent from place to place and are not easy to measure. The models use short time steps and need at least a daily data base of hydrologic phenomena. Altogether this makes model application to a fairly large project the job of a team of specialists with ample facilities.

There is a need for a computer program that is easier to operate and that requires a simpler data structure. Therefore, the Saltmod program was designed keeping in mind a relative simplicity of operation to promote its use by field technicians, engineers and project planners. It aims at using input data that are generally available, or that can be estimated with reasonable accuracy, or that can be measured with relative ease. Although the calculations are done numerically and have to be repeated many times, the final results can be checked by hand using the formulas in this manual.

Saltmod aims at predicting the long-term hydro-salinity in terms of general trends, not in exact predictions of how, for example, the situation would be on the first of April in ten years from now.

Further, Saltmod gives the option of the re-use of drainage and well water and it can account for farmers' responses to water logging, soil salinity, water scarcity and overpumping from the aquifer. Also it offers the possibility to introduce subsurface drainage systems at varying depts and with varying capacities so that they can be optimized.

Other features of Saltmod are found in the next section.

2. PRINCIPLES

2.1. Seasonal approach

The computation method Saltmod is based on seasonal water balances of agricultural lands. Four seasons in one year can be distinguished, e.g. dry, wet, cold, hot, irrigation or fallow seasons. The number of seasons (N_s) can be chosen between a minimum of one and a maximum of four. The larger the number of seasons becomes, the larger is the number of input data required. The duration of each season (T_s) is given in number of months ($0 < T_s < 12$). Day to day water balances are not considered for several reasons:

- daily inputs would require much information, which may not be readily available;
- the method is especially developed to predict long term, not day-to-day, trends and predictions for the future are more reliably made on a seasonal (long term) than on a daily (short term) basis, due to the high variability of short term data;
- even though the precision of the predictions for the future may still not be very high, a lot is gained when the trend is sufficiently clear; for example, it need not be a major constraint to design appropriate salinity control measures when a certain salinity level, predicted by Saltmod to occur after 20 years, will in reality occur after 15 or 25 years.

2.2. Hydrological data

The method uses seasonal water balance components as input data. These are related to the surface hydrology (like rainfall, evaporation, irrigation, use of drain and well water for irrigation, runoff), and the aquifer hydrology (like upward seepage, natural drainage, pumping from wells). The other water balance components (like downward percolation, upward capillary rise, subsurface drainage) are given as output. The quantity of drainage water, as an output, is determined by two drainage intensity factors for drainage above and below drain level respectively (to be given with the input data), a drainage reduction factor (to simulate a limited operation of the drainage system), and the height of the water table, resulting from the computed water balance. Variation of the drainage intensity factors and the drainage reduction factor gives the opportunity to simulate the impact of different drainage options.

2.3. Agricultural data

The input data on irrigation, evaporation, and surface runoff are to be specified per season for three kinds of agricultural practices, which can be chosen at the discretion of the user:

- A: irrigated land with crops of group A
- B: irrigated land with crops of group B
- U: non-irrigated land with rainfed crops or fallow land

The groups, expressed in fractions of the total area, may consist of combinations of crops or just of a single kind of crop. For example, as the A type crops one may specify the lightly irrigated cultures, and as the B type the more heavily irrigated ones, such as sugarcane and rice. But one can also take A as rice and B as sugarcane, or perhaps trees and orchards. The A, B and/or U crops can be taken differently in different seasons, e.g. A=wheat+barley in winter and A=maize in summer while B=vegetables in winter and B=cotton in summer.

Un-irrigated land can be specified in two ways: (1) as U=1-A-B and (2) as A and/or B with zero irrigation. A combination can also be made.

Further, a specification must be given of the seasonal rotation of the different land uses over the total area, e.g. full rotation, no rotation at all, or incomplete rotation. This occurs with a rotation index. The rotations are taken over the seasons within the year. To obtain rotations over the years it is advisable to introduce annual input changes as explained in sect. 2.9.

When a fraction A1, B1 and/or U1 in the first season differs from fractions are A2, B2 and/or U2 in the second season, because the irrigation regimes in the seasons differ, the program will detect that a certain rotation occurs. If one wishes to avoid this, one may specify the same fractions in all seasons (A2=A1, B2=B1, U2=U1), but the crops and irrigation quantities may have to be adjusted in proportion.

Cropping rotation schedules vary widely in different parts of the world. Creative combinations of area fractions, rotation indices, irrigation quantities and annual input changes can accommodate many types of agricultural practices.

Variation of the area fractions and/or the rotational schedule gives the opportunity to simulate the impact of different agricultural practices on the water and salt balance.

2.4. Soil strata

Saltmod accepts four different reservoirs, three of which are in the soil profile:

1. a surface reservoir
2. an upper (shallow) soil reservoir or root zone
3. an intermediate soil reservoir or transition zone
4. a deep reservoir or aquifer.

The upper soil reservoir is defined by the soil depth from which water can evaporate or be taken up by plant roots. It can be equalled to the root zone. It can be saturated, unsaturated, or partly saturated, depending on the water balance. All water movements in this zone are vertical, either upward or downward, depending on the water balance. (In a future version of Saltmod, the upper soil reservoir may be divided into two equal parts to detect the trend in the vertical salinity distribution.)

The transition zone can also be saturated, unsaturated or partly saturated. All flows in this zone are vertical, except the flow to subsurface drains.

If a horizontal subsurface drainage system is present, this must be placed in the transition zone, which is then divided into two parts: an upper transition zone (above drain level) and a lower transition zone (below drain level).

If one wishes to distinguish an upper and lower part of the transition zone in the absence of a subsurface drainage system, one may specify in the input data a drainage system with zero intensity.

The aquifer has mainly horizontal flow. Pumped wells, if present, receive their water from the aquifer only. In the combined SAHYSMOD model, the flow in the aquifer is determined depending on area variations of depths and levels of the water table.

2.5. Water balances

The water balances are calculated for each reservoir separately. The excess water leaving one reservoir is converted into incoming water for the next reservoir. The three soil reservoirs can be assigned a different thickness and storage coefficients, to be given as input data. In a particular situation, the transition zone or the aquifer need not be present. Then, it must be given a minimum thickness of 0.1 m.

The depth of the water table, calculated from the water balances, is assumed to be the same for the whole area. If this assumption is not acceptable, the area must be divided into separate units.

Under certain conditions, the height of the water table influences the water balance components. For example a rise of the water table towards the soil surface may lead to an increase of evaporation, surface runoff, and subsurface drainage, or a decrease of percolation losses from canals. This, in turn, leads to a change of the water balance, which again influences the height of the water table, etc. This chain of reactions is one of the reasons why Saltmod has been developed into a computer program. It takes a number of repeated calculations to find the correct equilibrium of the water balance, which would be a tedious job if done by hand. Other reasons are that a computer program facilitates the computations for different water management options over long periods of time (with the aim to simulate their long-term impacts) and for trial runs with varying parameters.

2.6. Drains, wells, and re-use

The sub-surface drainage can be accomplished through drains or pumped wells.

The subsurface drains are characterised by drain depth and drainage capacity. The drains are located in the transition zone. The subsurface drainage facility can be applied to natural or artificial drainage systems. The functioning of an artificial drainage system can be regulated through a drainage control factor.

When no drainage system is present, installing drains with zero capacity offers the opportunity to obtain separate water and salt balances for an upper and lower part of the transition zone.

The pumped wells are located in the aquifer. Their functioning is characterised by the well discharge.

The drain and well water can be used for irrigation through a re-use factor. This may have an impact on the salt balance and the irrigation efficiency or sufficiency.

2.7. Salt balances

The salt balances are calculated for each reservoir separately. They are based on their water balances, using the salt concentrations of the incoming and outgoing water. Some concentrations must be given as input data, like the initial salt concentrations of the water in the different soil reservoirs, of the irrigation water and of the incoming ground water in the aquifer. The concentrations are expressed in terms of electric conductivity (EC in dS/m). When the concentrations are known in terms of g salt/l water, the rule of thumb: 1 g/l -> 1.7 dS/m can be used. Usually, salt concentrations of the soil are expressed in ECe, the electric conductivity of an extract of a saturated soil paste. In Saltmod, the salt concentration is expressed as the EC of the soil moisture when saturated under field conditions. As a rule, one can use the conversion rate EC : ECe = 2 : 1.

Salt concentrations of outgoing water (either from one reservoir into the other or by subsurface drainage) are computed on the basis of salt balances, using different leaching or salt mixing efficiencies to be given with the input data. The effects of different leaching efficiencies can be simulated by varying their input value.

If drain or well water is used for irrigation, the method computes the salt concentration of the mixed irrigation water in the course of the time and the subsequent impact on the soil and ground water salinities, which again influences the salt concentration of the drain and well water. By varying the fraction of used drain or well water (to be given in the input data), the long term impact of different fractions can be simulated.

The dissolution of solid soil minerals or the chemical precipitation of poorly soluble salts is not included in the computation method, but to some extent it can be accounted for through the input data, e.g. by increasing or decreasing the salt concentration of the irrigation water or of the incoming water in the aquifer.

2.8. Farmers' responses

If required, farmers' responses to water logging and salinity can be automatically accounted for. The method can gradually decrease:

1. the amount of irrigation water applied when the water table becomes shallower;
2. the fraction of irrigated land when the available irrgation water is scarce;
3. the fraction of irrigated land when the soil salinity increases; for this purpose, the salinity is given a stochastic interpretation.

The responses influence the water and salt balances, which, in their turn, slow down the process of water logging and salinization. Ultimately an equilibrium situation will be brought about.

The user can also introduce farmers' responses by manually changing the relevant input data. Perhaps it will be useful first to study the automatic farmers' responses and their effect and thereafter decide what the farmers' responses will be in the view of the user.

Response 1. is different for ponded rice and "dry foot" crops.

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2.9. Annual input changes

The program may run with fixed input data for the number of years determined by the user. This option can be used to predict future developments based on long-term average input values, e.g. rainfall, as it will be difficult to assess the future values of the input data year by year.

The program also offers the possibility to follow historic records with annually changing input values (e.g. rainfall, irrigation, agricultural practices), the calculations must be made year by year. If this possibility is chosen, the program creates transfer files by which the final conditions of the previous year (e.g. water table and salinity) are automatically used as the initial conditions for the subsequent period. This facility renders it possible to use various generated rainfall sequences drawn randomly from a known rainfall probability distribution and obtain a stochastic prediction of the resulting output parameters.

If the computations are made with annual changes, not all input parameters can be changed, notably the thickness of the soil reservoirs and their total porosities as these would cause illogical shifts in the water and salt balances.

2.10 Output data

The output of Saltmod is given for each season of any year during any number of years, as specified with the input data. The output data comprise hydrological and salinity aspects. The data are filed in the form of tables that can be inspected directly or further analyzed with spreadsheet programs. The interpretation of the output is left entirely to the judgement of the user. The program offers the possibility to develop a multitude of relations between varied input data, resulting outputs and time. Different users may wish to establish different cause-effect or correlational relationships. The program offers only a limited number of standard graphics, as it is not possible to foresee all different uses that may be made.

Although the computations need many iterations, all the end results can be checked by hand using the equations presented in the following sections.

2.11 Other users' suggestions

In the previous paragraphs some users' suggestions were given. Some other suggestions are given below.

Some of the input data are interdependent. These data can, therefore, not be indiscriminately varied. In very obvious illogical combinations of data, the program will give a warning. The correctness of the input remains the responsibility of the user.

The selection of the area to be analysed by Saltmod should be governed by the uniformity of the distribution of the cropping, irrigation and drainage characteristics over the area. If these characteristics are randomly varied in space, it is advisable to use a larger area and the area average values of the input parameters. If, on the other hand, more uniform sub-areas can be identified, it is advisable to use the sub-areas separately for the analysis. It is also possible to use first the larger area approach and to use some of the outputs as inputs in the restricted area approach. For example, an area may have non-irrigated, fallow, land next to irrigated land. The resulting capillary rise in the fallow land can be obtained as output from the larger area approach, and used as ground water input in a separate analysis for the fallow or irrigated land.

If the user wishes to determine the effect of variations of a certain parameter on the value of other parameters, the program must be run repeatedly according to a user-designed schedule.

This procedure can be used for the calibration of the model or for the simulation runs.

The program is designed to make use of spreadsheet programs for the detailed output analysis, in which the relations between various input and output variables can be established according to the scenario developed by the user.

3. WATER BALANCE EQUATIONS

3.1. The reservoir concept

The principles of the water balances in Saltmod are illustrated in fig. 1, where the four reservoirs are shown on which the model is built: (1) surface reservoir, (2) root zone (3) transition zone and (4) aquifer. For each reservoir a water balance can be made with the hydrologic components. All quantities of the components are expressed as seasonal volumes per unit surface area, giving a seasonal depth of water with dimension [L].

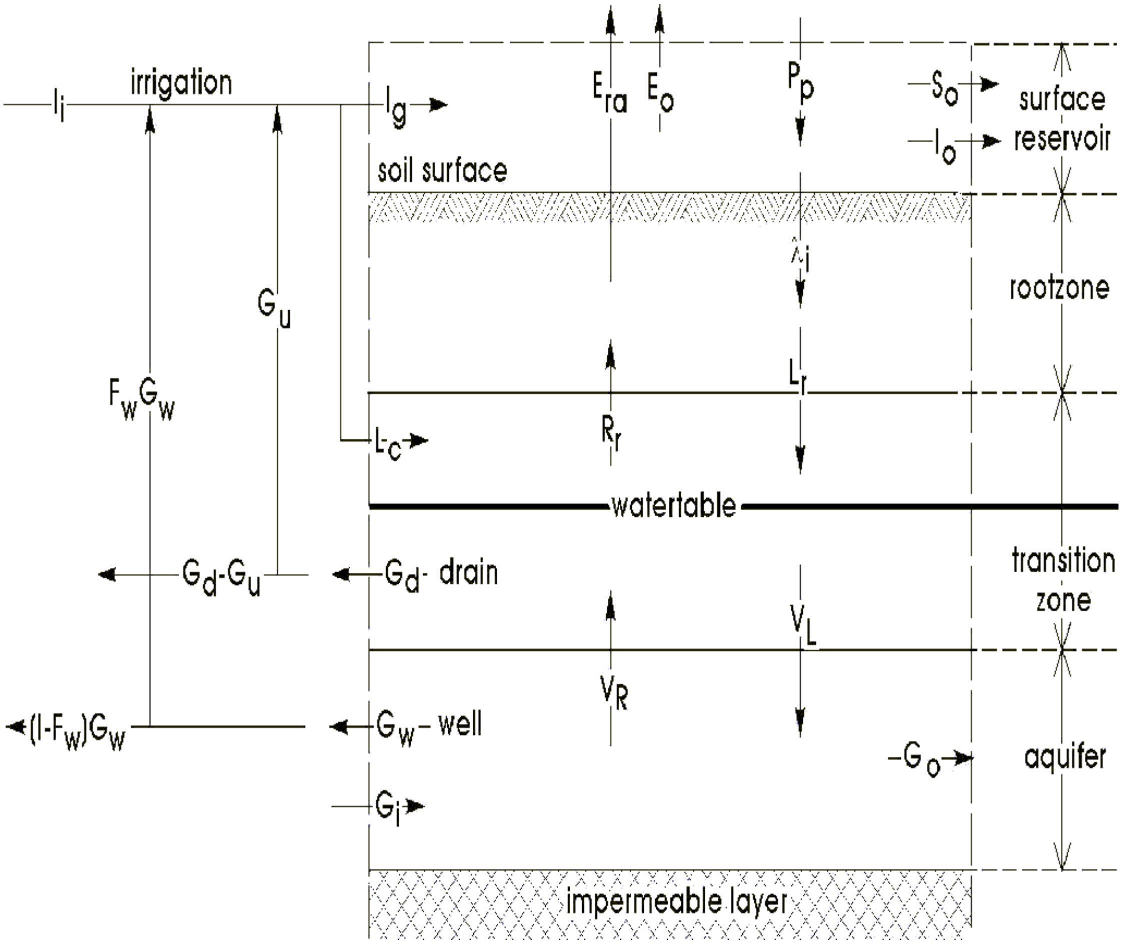

Figure 1. The concept of 4 reservoirs with hydrological inflow and outflow components

A water balance is based on the principle of the conservation of mass for boundaries defined in space and time and can be written as:

$$\text{Inflow} = \text{Outflow} + \text{Storage} \quad (1)$$

When the storage is positive the water content increases and, when negative (i.e. there is depletion instead of storage), it decreases.

In fig.1 it is assumed that all balance factors are uniformly distributed over the area and that the water table remains within the transition zone. They represent a particular case of Saltmod. In later sections, adjustments to other conditions are made.

3.1.1. The surface reservoir

The surface reservoir is located on top of the soil. The water balance of the surface reservoir for a certain period reads:

$$P_p + I_g + \lambda_o = E_o + \lambda_i + I_o + S_o + \Delta W_s \quad (2)$$

where: P_p is the amount of water vertically reaching the soil surface, such as precipitation and sprinkler irrigation, I_g is the gross irrigation inflow including the natural surface inflow, the drain and well water used for irrigation, but excluding the percolation losses from the canal system, E_o is the amount of evaporation from open water, λ_o is the amount of water seeping upward through the soil surface from the root zone into the surface reservoir, λ_i is the amount of water infiltrated through the soil surface into the root zone, I_o is the amount of irrigation water leaving the area through the canal system (bypass), S_o is the amount of surface runoff or surface drainage leaving the area, and ΔW_s is the change in amount of water stored in the surface reservoir.

3.1.2. The root zone

The root zone corresponds to the depth of soil from which evapo-transpiration takes place. Its water balance reads:

$$\lambda_i + R_r = \lambda_o + E_{ra} + L_r + \Delta W_f + \Delta W_r \quad (3)$$

where: R_r is the amount of capillary rise into the root zone, E_{ra} is the amount of actual evapo-transpiration from the root zone, L_r is the amount of percolation loss from the root zone, ΔW_f is the storage of moisture in the root zone between field capacity and wilting point, and ΔW_r is the storage of water in the root zone between field capacity and full saturation.

The factor R_r is the opposite of L_r and these components cannot occur simultaneously, i.e. when $R_r > 0$ then $L_r = 0$ and vice versa.

When water balances are made for fairly long periods of time, for instance a season or a year, the storage ΔW_f is often negligibly small compared to the other hydrological components. In Saltmod, therefore, this storage is set equal to zero and the water balance changes to:

$$\lambda_i + R_r = \lambda_o + E_{ra} + L_r + \Delta W_r \quad (4)$$

3.1.3. The transition zone

The transition zone is the zone between root zone and aquifer. Its lower limit can be fixed in different ways according to local conditions: (a) at the interface between a clay layer on top of a sandy layer, (b) at the annually greatest depth to water table, (c) at the greatest depth to which the influence of a subsurface drainage system extends, (d) at the depth where horizontal ground-water flow is converted into vertical flow of ground water or vice versa. The water balance of the transition zone reads:

$$L_r + L_c + V_r = R_r + V_L + G_d + \Delta W_x \qquad (5)$$

where: L_c is the percolation loss from the irrigation canal system, V_R is the amount of vertical upward seepage from the aquifer into the transition zone, V_L is the amount of vertical downward drainage from the saturated transition zone to the aquifer, G_d is the total amount of natural or artificial drainage of ground water to ditches or pipe drains, and ΔW_x is the water storage in the transition zone between field capacity and wilting point.

The component V_R is the opposite of V_L and these cannot occur simultaneously, i.e. when $V_R > 0$ then $V_L = 0$ and vice versa.

3.1.4. The aquifer

The water balance of the aquifer can be written as:

$$G_i + V_L = G_o + V_R + G_w + \Delta\Delta W_q \qquad (6)$$

where: G_i is the amount horizontal ground water inflow through the aquifer, G_o is the amount of horizontal ground water outflow through the aquifer, G_w is the amount ground water pumped from the aquifer through wells, and ΔW_q is the ground water storage in the aquifer.

3.1.5. Top soil water balance

When the water table is in the transition zone, the balances of the surface reservoir and the root zone may be combined into the top soil water balance, by adding eqn. 2 and 4:

$$P_p + I_g + R_r = E_a + I_o + S_o + L_r + \Delta W_r + \Delta W_x \qquad (7)$$

with:

$$E_a = E_o + E_{ra} \qquad (8)$$

where E_a is the total actual evapo-transpiration.

In the top soil water balance, the infiltration component λ_i is not present. The same holds for the components R_r and L_r. All these components represent vertical flows linking the two reservoirs.

Using:

$$I_f = I_g - I_o \tag{9}$$

$$V_s = P_p + I_f - S_o \tag{10}$$

where V_s represents the total surface-water resource and I_f is the net field irrigation, eqn. 7 can be reduced to:

$$V_s + L_c = E_a + \Delta W_r + \Delta W_x \tag{11}$$

3.1.6. Sub-soil water balance

When the water table is in the root zone, the capillary rise R_r and percolation L_r do not exist, because the transition zone is saturated. Also, the values of ΔW_x and ΔW_q are zero. Thus it is preferable to combine the water balances of root zone, transition zone and aquifer, giving the sub-soil water balance:

$$\lambda_i + L_c + G_i = \lambda_o + E_{ra} + G_o + G_d + G_w + \Delta W_r \tag{12}$$

3.1.7. Agronomic water balance

When the water table is in the aquifer, the root zone and transition zone are unsaturated and the components V_R and V_L have to be replaced by R_r and L_r. Thus, it is preferable to combine the water balances of the surface reservoir, root zone and transition zone, giving the agronomic water balance:

$$P_p + I_g + L_c = I_o + S_o + E_a + G_d + \Delta W_s + \Delta W_r + \Delta W_x \tag{13}$$

3.1.8. Geo-hydrologic water balance

With a water table in the transition zone, the balances of the transition zone and aquifer can be combined into the geo-hydrologic water balance, in which the storage ΔW_q may be considered zero as the aquifer is fully saturated:

$$L_r + L_c + G_i = R_r + G_o + G_d + G_w + \Delta W_x \tag{14}$$

Here, the linkage components V_R and V_L have vanished.

3.1.9. Overall water balance

When the water table remains above the soil surface, the values of ΔW_r, ΔW_x and ΔW_q are zero, as the soil is fully saturated. Thus, it is preferable to combine the water balances of all the reservoirs:

$$P_p + I_g + L_c + G_i = E_a + I_o + S_o + G_o + G_d + G_w + \Delta W_s \qquad (15)$$

In this overall water balance, all linkage components have disappeared.

3.2. Model calculations water balance top soil

Saltmod accepts a maximum of four seasons, the durations of which are expressed in months. The total duration of the seasons is 12 months. During the year, the agricultural land use may change from season to season and the distribution of the water resources depends on the agricultural land use. To accommodate the rotational land use, Saltmod distinguishes 3 types of land use (fig. 2):

A: irrigated land under group A crops
B: irrigated land under group B crops
U: non-irrigated land (U)

The distinction between group A and B crops is made to introduce the possibility of having lightly and heavily irrigated crops. Examples of the second kind are submerged rice and sugarcane. The latter crop may cover more than one season. The distinction also gives the possibility to introduce permanent instead of arable crops like orchards. The non-irrigated land may consist of rainfed crops and temporary or permanently fallow land.

Each land use type is determined by an area fraction A, B, and U respectively. The sum of the fractions equals unity:

$$A + B + U = 1 \qquad (16)$$

The water balance components discussed before now need adjustment as follows.

The total field irrigation I_f (expressed in m^3/season per m^2 total area) of eqn. 9 can now be written as:

$$I_f = I_{aA}A + I_{aB}B \qquad (17)$$

where (fig.3): I_{aA} and I_{aB} are the field irrigation applications to the areas under group A and B crops respectively (m^3/season per m^2 area under A and B crops respectively).

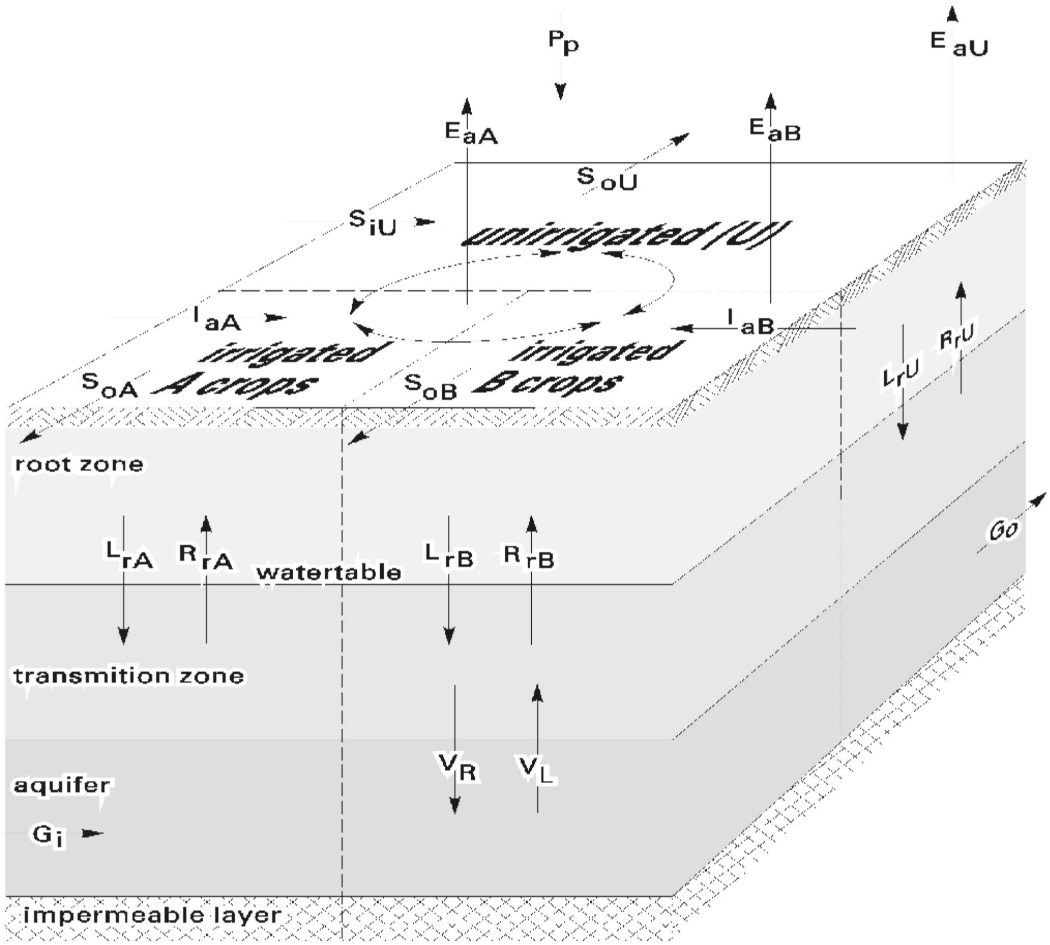

Figure 2. Three types of rotated agricultural land use (A, B, and U) with the different hydrological factors involved.

The quantity of irrigation water or surface flow entering the area I_i (m^3/season per m^2 total area) is found from:

$$I_i = I_f + I_o + L_c - F_wG_w - G_u \tag{18}$$

where: F_w is the fraction of the pumped well water G_w used for irrigation and G_u is the quantity of subsurface drainage water used for irrigation.

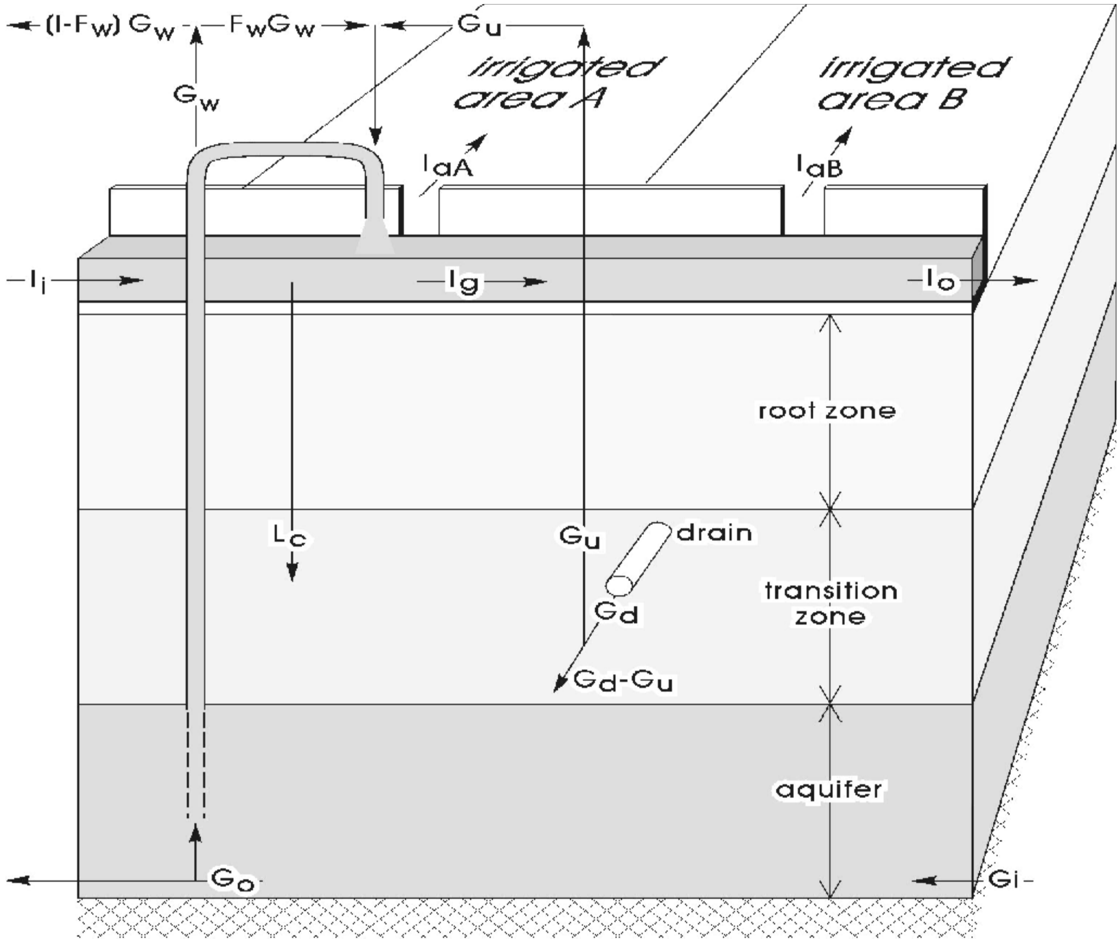

Figure 3. Water balance factors of the canal, drain and well systems.

The total percolation from the root zone L_{rT} (m^3/season per m^2 total area) is calculated from:

$$L_{rT} = L_{rA}A + L_{rB}B + L_{rU}U \tag{19}$$

where: L_{rA}, L_{rB}, and L_{rU} are the amounts of percolation from the root zone of the A, B and U land respectively (m^3/season per m^2 area of A and B and U land respectively), and:

$$L_{rA} = V_A - E_{aA} \tag{19a}$$

$$L_{rB} = V_B - E_{aB} \tag{19b}$$

$$L_{rU} = V_U - E_{aU} \tag{19c}$$

where: V_A, V_B, V_U are the amounts of surface water resources of the A, B, and U land respectively, E_{aA}, E_{aB}, and E_{aU} are the amounts of actual evapotranspiration of the A, B and U land respectively. All units are in m^3/season per m^2 area of A and B and U land respectively.

The total surface water resources V_s (m^3/season per m^2 total area) in eqn. 10 can also be calculated from:

$$V_s = V_A A + V_B B + V_U U \qquad (20)$$

where:

$$V_A = P_p + I_{iA} - S_{oA} \qquad (20a)$$

$$V_B = P_p + I_{iB} - S_{oB} \qquad (20b)$$

$$V_U = P_p + S_{iU} - S_{oU} \qquad (20c)$$

where: V_A, V_B, V_U are the site specific surface water resources of the A, B, and U land respectively (m^3/season per m^2 area of A and B and U land respectively), and S_{oA}, S_{oB}, S_{oU} are the amounts of surface runoff or surface drainage from the A, B, and U land respectively (m^3/season per m^2 area of A and B and U land).

The capillary rise R_r in 12 depends on atmospheric demand, characterised by the potential evapo-transpiration E_p, available water V_s, and depth of water table D_w. The processes and calculations involved are described in section 3.3. With the results obtained, the capillary rise R_{rT} (m^3/season per m^2 total area) can be determined as:

$$R_{rT} = R_{rA} A + R_{rB} B + R_{rU} U \qquad (21)$$

where: R_{rA}, R_{rB}, and R_{rU} are the amounts of capillary rise into the root zone of the A, B, and U land respectively (m^3/season per m^2 area of A and B and U land respectively).

The actual evapo-transpiration E_a of eqn. 12 depends on atmospheric demand, characterised by the potential evapo-transpiration E_p, available water V_s, and capillary rise R_r delivered to the root zone. The processes and calculations involved are also described in section 3.3. With the results obtained, the actual evapo-transpiration E_a (m^3/season per m^2 total area) can be determined as:

$$E_a = E_{aA} A + E_{aB} B + E_{aU} U \qquad (22)$$

3.3. Capillary rise and actual evapo-transpiration

The amount of capillary rise depends on the depth of the water table (D_w, m), the potential evapo-transpiration (E_p, m/season), the surface water resources (V_s, m/season) and the moisture deficit (M_d, m/season), representing the dryness of the top soil. In Saltmod, the seasonal average depth D_w determines a capillary rise factor (F_c).

3.3.1. Depth of the water table and capillary rise factor

When the water table is below a critical depth (D_c, m), there is no potential capillary rise. When the water table is shallower than halfway the root zone ($2D_r$, m), the potential velocity of capillary rise is maximum as determined by the moisture deficit but not more than E_p. The influence of the depth of the water table between $2D_r$ and D_c is expressed in Saltmod by a capillary rise factor (F_c) which ranges from 1, when $D_w < ½2D_r$, to 0, when $D_w >= D_c$. Within the range there is a linear relation. Hence:

$$F_c = 1 \qquad [D_w < ½D_r] \qquad (23a)$$

$$F_c = 0 \qquad [D_w > D_c] \qquad (23b)$$

$$F_c = 1 - (D_w - ½D_r)/(D_c - ½D_r) \qquad [½D_r < D_w < D_c] \qquad (23c)$$

The above equations represent an approximation of the usually reported S-curves (e.g. Kabat and Beekma 1994) by 3 straight lines (fig. 4).

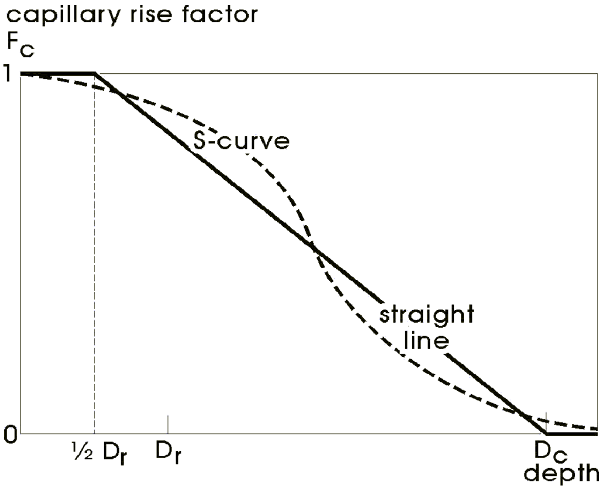

Figure 4. The S-curve of the capillary rise factor approximated by straight line segments.

3.3.2. Potential evapo-transpiration and moisture deficit

The moisture deficit (M_d, m/season) is defined as:

$$M_d = E_p - F_s V_s \text{ with the condition } M_d > 0. \qquad (24)$$

where: E_p is the potential evapo-transpiration (m/season), F_s is the storage fraction (-) of the surface water resources, representing the moisture holding capacity, and V_s is the surface water resources (m/season, eqn.20).

The storage efficiency F_s can also be described as the maximium attainable irrigation efficiency, with a perfect irrigation system, given the prevailing water holding properties of the soil.

When no capillary rise occurs, the product F_sV_s represents the effective surface water resources, i.e. the part of the resources that is available for the evapo-transpiration, whereas the quantity $(1-F_s)V_s$ represents the part lost by percolation. When capillary rise does occur, Saltmod adjusts the effective and lost quantities of the resources V_s.

When the term $E_p-F_sV_s$ is negative, the effective quantity of resources V_s is more than the evapo-transpiration E_p, and there is no moisture deficit. Then, M_d is taken equal to zero.

3.3.3. Apparent capillary rise and actual evapo-transpiration

In Saltmod, the apparent quantity of capillary rise (R_a, m per season) is found from:

$$R_a = F_cM_d \qquad (25)$$

i.e. the product of the capillary rise factor and the moisture deficit. When any of these two factors is zero, there is no capillary rise. The actual evapo-transpiration (E_a, m/season) is found from:

$$E_a = F_sV_s + R_a \qquad (26a)$$

With the above equations it is ensured that the evapo-transpiration E_a is never greater than the evapo-transpiration E_p.

The principles described for the calculation of the site specific surface water resources V_s of the areas under group A crops, group B crops and the non-irrigated (U) land, can also be applied to calculate the site specific values of E_a. For this we use the site specific values F_{sA}, F_{sB}, F_{sU} given with the input and the site specific apparent capillary rise R_{aA}, R_{aB}, R_{aU} to be derived from eqn. 25 as well as the site specific moisture deficit M_{dA}, M_{dB} and M_{dU} to be derived from eqn. 24, one gets the site specific values of E_a as:

$$E_{aA} = F_{sA}V_{sA} + R_{aA} \qquad (26b)$$

$$E_{aB} = F_{sB}V_{sB} + R_{aB} \qquad (26c)$$

$$E_{aU} = F_{sU}V_{sU} + R_{aU} \qquad (26d)$$

3.3.4. Capillary rise

In Saltmod, the amount of capillary rise (R_r) is defined as the contribution of the ground water to the evapo-transpiration. A part of the apparent evapo-transpiration R_a represents the return of percolation losses of the surface water resources from the transition zone into the root zone, whence it evaporates or transpires. This part can be considered as recovered after having been temporarily lost during the season. It does not represent a contribution from the ground water. Therefore the capillary rise proper is calculated as:

$$R_r = E_a - V_s \tag{27}$$

Hence, the part considered temporarily lost but recovered is:

$$I_c = R_a - R_r = (1-F_s)V_s \tag{28}$$

The principles described for the calculation of the site specific surface water resources V_s of the areas under group A crops, group B crops and the non-irrigated (U) land, can also be applied to calculate the site specific values of R_r:

$$R_{rA} = E_{aA} - V_{sA} \tag{29a}$$

$$R_{rB} = E_{aB} - V_{sB} \tag{29b}$$

$$R_{rU} = E_{aU} - V_{sU} \tag{29c}$$

The depth of the water table D_w influences the values of the factor F_c, the evaporation E_a and the capillary rise R_r, which in their turn will influence the depth D_w. Therefore, Saltmod uses a numerical method, by trial and error, until the correct balance is reached.

3.4. The subsurface drainage

In Saltmod, the presence of a subsurface drainage system is indicated by the key K_d, which can attain the values 0 or 1.$K_d = 0$ indicates that no subsurface drainage system is present and the subsurface drain discharge $G_d = 0$. When K_d =1, a subsurface drainage system is present (fig. 5) and the drain discharge is calculated on the basis of Hooghoudt's drainage equation (Ritzema 1994):

$$G_{dt} = \frac{8K_bD_e(D_d-D_w)}{Y^2} + \frac{4K_a(D_d-D_w)^2}{Y^2} \tag{30}$$

where: G_{dt} is the total drain discharge (m/day), D_d is the drain depth (m), D_w is the depth of the water table (m), K_b is the hydraulic conductivity below drain level (m/day), D_e is the equivalent depth of the impermeable layer (m), K_a is the hydraulic conductivity above drain level (m/day), and Y is the drain spacing (m).

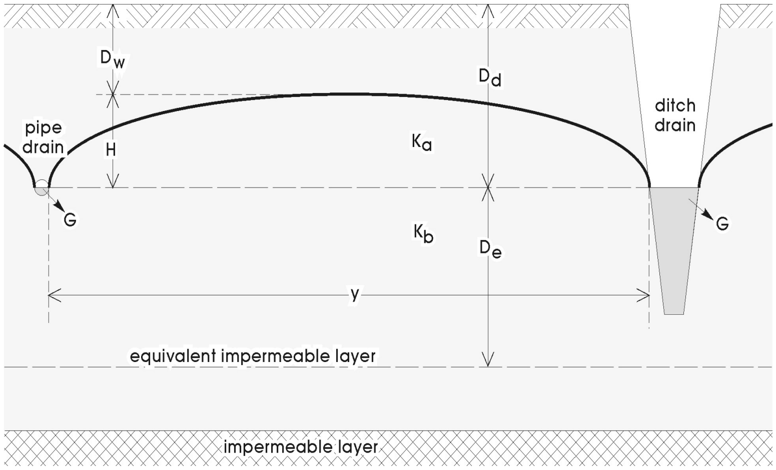

Figure 5. Some factors in Hooghoudt's drainage equation

The first term on the right-hand side of eqn. 30 represents the discharge (G_{db}) from below the drain level and the second term the discharge (G_{da}) from above drain level.

Writing:

$$H = D_d - D_w \qquad (31)$$

where H is the hydraulic head (m), one obtains:

$$G_{dt} = G_{db} + G_{da} \qquad (32a)$$

where:

$$G_{da} = 4K_aH^2/Y^2 \qquad (32b)$$

$$G_{db} = 8K_bD_eH/Y^2 \qquad (32c)$$

Here, the condition has been set that $H >= 0$. When $H < 0$, the values of G_{da} and G_{db} (m/day) are set equal to zero.

In Saltmod, the drains are assumed to be situated in the transition zone so that the drain depth D_d must be in the range $D_r < D_d < D_r+D_x$, where D_r is the thickness of the root zone (m) and D_x is the thickness of the transition zone (m).

Defining:

$$G_{da}/H^2 = 4K_a/Y^2 = Q_{H2} \text{ (Ratio of } G_a \text{ to } H^2) \qquad (33a)$$

$$G_{db}/H = 8K_bD_e/Y^2 = Q_{H1} \text{ (Ratio of } G_b \text{ to } H) \qquad (33b)$$

it can be seen that the ratio's Q_{H1} and Q_{H2} represent the hydraulic conductivity and depth of the soil and the drain spacing. Now, one can write:

$$G_{dt} = Q_{H1}H + Q_{H2}H^2 \qquad (34)$$

Saltmod provides the opportunity to introduce a checked drainage system through the introduction of a drainage control (drainage reduction) factor F_{rd}, having values between zero and 1. When the factor is 1, the drainage is fully checked and, when zero, it is totally unchecked. The factor F_{rd} can also be used for partial drainage of the area. Thus, eqn. 34 changes into:

$$G_c = (1-F_{rd})(Q_{H1}H+Q_{H2}H^2) \qquad (35a)$$

where G_c stands for the controlled drain discharge. Similarly the two discharge components change into:

$$G_{ca} = (1-F_{rd})G_a \qquad (35b)$$

$$G_{cb} = (1-F_{rd})G_b \qquad (35c)$$

To change the discharge from m/day to m/season, the following conversions are made:

$$G_d = 30G_cT_s \qquad (36a)$$

$$G_a = 30G_{ca}T_s \qquad (36b)$$

$$G_b = 30G_{cb}T_s \qquad (36c)$$

where T_s is the duration of the season (months).

When $D_w < 0$, there is a ponded water case (the water table is above the soil surface), and the drain discharge is higher than the case is according to the Hooghoudt equation. Saltmod then simply assumes a double value of the discharge:

$$G_{pd} = 2G_d \qquad [D_w < 0] \qquad (37a)$$

$$G_{pa} = 30G_aT_s \qquad [D_w < 0] \qquad (37b)$$

$$G_{pb} = 30G_bT_s \qquad [D_w < 0] \qquad (37c)$$

The depth of the water table influences the values of the head H and the discharges G_a, G_b and G_d, which again will influence the depth D_w. Therefore, Saltmod uses a numerical method of integration of the drain discharge over the season, using a trial and error procedure, until the correct balance is obtained. The procedure must also incorporate the trial and error procedure developed for the relation between capillary rise, actual evapo-transpiration and depth of water table.

3.5. Model calculations water balance transition zone

Eqn. 6 can be rewritten in two ways:

$$V_L = G_o - G_i + G_w + \Delta W_q \qquad [V_R = 0, \quad V_L > 0] \qquad (38a)$$

$$V_R = G_i - G_o - G_w - \Delta W_q \qquad [V_L = 0, \quad V_R > 0] \qquad (38b)$$

where the components G_i, G_o, and G_w are supposed to be known, so that V_L and V_R can be calculated.

Further, Eqn. 5 can be rewritten as:

$$G_d = L_{rT} + L_c + V_R - R_r - V_L - \Delta W_x \qquad (39)$$

and the subsurface drainage G_d needs to meet this condition. However, the subsurface drainage is also found from eqn. 35c or 36, depending on the depth of the water table D_w. The reconciliation of the values is discussed in section 3.4.

3.6. Model calculations depth of the water table

The percolation from the irrigation canal system L_c (assumed to be a known quantity), total percolation from the root zone L_{rT} (eqn. 19), the total capillary rise R_r (eqn. 21), the total subsurface drainage (G_d), and the incoming and outgoing ground water flow in the aquifer (G_i and G_o) make up the geo-hydrologic water balance (eqn. 12). Setting the total seasonal storage equal to:

$$\Delta W = \Delta W_s + \Delta W_r + \Delta W_s + \Delta W_q \qquad (40a)$$

and combining the water balances of all four reservoirs (eqn 13), we find:

$$\Delta W = P_p + I_g + L_{rT} + G_i - E_a - I_o - S_o - G_d - G_o - G_w \qquad (40b)$$

To find the change in the depth of the water table due to the storage, the total storage ΔW is first assigned to the reservoir in which the initial average water table is found:

$$D_w = D_{wi} - \Delta W / P_{ei} \qquad (41)$$

where: D_w seasonal average depth of the water table (m), D_{wi} is the initial depth of the water table (m), i.e. the seasonal average depth of the previous season, P_{ei} is the drainable or refillable pore space of the reservoir in which the initial water table is found, equal to P_{eq} when the initial water table is in the aquifer, P_{ex} when in the transition zone, P_{er} when in the root zone, and $P_{es} = 1$ when in the surface reservoir. The pore spaces are supposed to be known.

When it appears that initial and new water table are found in different reservoirs, the maximum possible storage ΔW_M in the initial reservoir is subtracted from the total storage ΔW, the initial water table is moved to the boundary between the initial and next reservoir, the initial depth of the water table is set equal to the boundary depth with the next reservoir (D_{Bn}), and the remaining storage ΔW_D is assigned to the next reservoir. Thus, eqn. 41a changes to:

$$D_w = D_{Bn} - \Delta W_D/P_{ei} \qquad (42)$$

with:

$$\Delta W_D = \Delta W - \Delta W_M \qquad (43)$$

and:

$$\Delta W_{Mi} = P_{ei}(D_{Bn} - D_{wi}) \qquad (44)$$

When the storage ΔW is positive, the water table rises and the depth of the water table decreases. The next reservoir is the one encountered just above the initial reservoir. When the storage ΔW is negative, the water table drops and the depth of the water table increases. The next reservoir is the one to be found just below the initial reservoir.

When the water table passes through more than one interface, the procedure is repeated as many times as required.

The depth of the boundary between the surface and root zone reservoir D_1, the root zone and transition zone D_2, the transition zone and aquifer, D_3, and the bottom depth of the aquifer, D_4, are found from:

$$D_1 = 0 \qquad (45a)$$

$$D_2 = D_r \qquad (45b)$$

$$D_3 = D_r + D_x \qquad (45c)$$

$$D_4 = D_r + D_x + D_q \qquad (45d)$$

where: D_r is the thickness of the root zone (m), D_x is the thickness of the transition zone (m), and D_q is the thickness of the aquifer (m). These values determine the boundary depth D_{Bn} of the next reservoir.

As the depth D_w determines the water balance while the water balance determines the depth D_w, a numerical calculation procedure by trial and error is required to strike the correct balance.

3.7. Irrigation efficiencies and sufficiencies

The field irrigation efficiency F_f is defined as the ratio of the amount of irrigation water evaporated to the amount of irrigation water applied to the field. For the group A crop(s) we find:

$$F_{fA} = (E_{aA}-R_{rA})/(I_{aA}+P_p) \qquad (46a)$$

The irrigation efficiency of the group B crop(s) is similarly given by:

$$F_{fB} = (E_{aB}-R_{rB})/(I_{aB}+P_p) \qquad (46b)$$

The total irrigation efficiency, disregarding the bypass, is:

$$F_{ft} = [A(E_{aA}-R_{rA})+B(E_{aB}-R_{rB})]/[I_t+P_p] \qquad (47)$$

where:

$$I_t = I_f + L_c \qquad (48)$$

The field irrigation sufficiency J_s is defined is defined by the ratio of the amount of actual over potential evapo-transpiration. For the group A crop(s) it is found from:

$$J_{sA} = E_{aA}/E_{pA} \qquad (49a)$$

The field irrigation sufficiency of the group B crop(s) is similarly calculated as:

$$J_{sB} = E_{aB}/E_{pB} \qquad (49b)$$

The total irrigation sufficiency becomes:

$$J_{st} = (J_{sA}A+J_{sB}B)/(A+B) \qquad (49c)$$

Irrigation can be:

1 efficient and sufficient
2 inefficient but sufficient
3 efficient but insufficient
4 inefficient and insufficient

The product of efficiency and sufficiency is a measure for irrigation effectiveness.

The effectiveness of field irrigation for the land under group A crops is:

$$J_{eA} = F_{fA}J_{sA}$$

The effectiveness of field irrigation for the land under group B crops is:

$$J_{eB} = F_{fB}J_{sB}$$

and the toal field irrigation effectiveness becomes:

$$J_{et} = (AJ_{eA}+BJ_{eB})/(A+B)$$

The irrigation sufficiencies, efficiencies and effectiveness are a tool to judge variations in agricultural and water management practices on irrigation performance.

4. SALT BALANCE EQUATIONS

4.1. Change in salt content

The salt balances are, like eqn. 1, based on:

incoming salt = outgoing salt + storage of salt

In addition we have:

- incoming salt = inflow x salt concentration of the inflow
- outgoing salt = outflow x salt concentration of the outflow
- salt concentration of the outflow = leaching efficiency x time averaged salt concentration of the water in the reservoir of outflow
- change in salt concentration of the soil = salt storage divided by amount of water in the soil

Hence, the salt balances are based on the water balances.

In Saltmod, the salt balances are calculated separately for the different reservoirs and, in addition, for different types of cropping rotation, indicated by the key K_r that can reach the values 0, 1, 2, 3, and 4. $K_r = 0$ indicates that there is no annual cropping rotation and all land use types are fixed to the same areas each year. $K_r = 4$ indicates that there is full annual cropping rotation and that the land use types are continually moved over the area. The other values of K_r indicate intermediate situations that are explained elsewhere.

The time averaged salt concentration of the percolating water is calculated according to the theory of leaching.

In the following, all salt concentrations are expressed as electric conductivity (EC) in dS/m. Salt concentrations of soil moisture are given on the basis of saturated soil. Quantities of salt, being the product of an amount of water in m/season and a concentration in dS/m, are expressed in dS/season.

4.2. Salt leaching

When the soil is being desalinised by percolation (leaching) one usually obtains an exponentially decreasing salinity in the course of time (e.g. van Hoorn and van Alphen, 1994). The graphic presentation of this phenomenon is called leaching curve or salinity depletion curve (fig. 6).

The salt concentration (C_l dS/m) of the water percolating from a reservoir can be taken proportional to the salt concentration in the reservoir (C_r, dS/m):

$$C_l = F_l C_r \qquad (50)$$

where the factor F_l is called leaching efficiency.

The change of salt concentration C_r can be described by the differential equation:

$$P_tD \frac{dC_r}{dt} = - C_1L \tag{51}$$

where: P_t is the total porosity fraction (-) of the reservoir, D is the thickness (m) of the reservoir, L is the percolation velocity (m per unit of time), and t is the time (any unit).

Using eqn. 49 and writing $\alpha=F_1L/P_tD$, the above equation can be changed into:

$$\frac{dC_r}{dt} = - \alpha C_r \tag{52a}$$

or:

$$\frac{dC_r}{C_r} = - \alpha\ dt \tag{52b}$$

or:

$$d\ln C_r = - \alpha.dt \tag{52c}$$

The general solution of eqn. 52c is:

$$\ln C_r = - \alpha t + \beta_c \tag{53a}$$

where: β_c is the integration constant.

Using $C_r=C_1$, $C_r=C_2$, and $C_r=C_m$ when $t=t_1$, $t=t_2$, and $t_m=2(t_1+t_2)$ (i.e. the mid time) respectively, one finds from eqn. 53a:

$$\ln C_1= - \alpha t_1 + \beta_c \quad \text{or:} \quad t_1 = (\beta_c-\ln C_1)/\alpha \tag{53b}$$

$$\ln C_2= - \alpha t_2 + \beta_c \quad \text{or:} \quad t_2 = (\beta_c-\ln C_2)/\alpha \tag{53c}$$

$$\ln C_m= - \alpha t_m + \beta_c \quad \text{or:} \quad t_m = (\beta_c-\ln C_m)/\alpha \tag{53d}$$

Using again $t_m=(t_1+t_2)/2$ one gets from eqn. 53b and c:

$$t_m = \frac{\beta_c-\ln C_1+\beta_c-\ln C_2}{2\alpha} = \frac{\beta_c - ½\ln(C_1C_2)}{\alpha} \tag{54}$$

Comparing eqn. 54 with eqn. 53d one can see that:

$$\ln C_m = ½\ln(C_1C_2) \tag{55a}$$

or:

$$C_m = (C_1C_2)^{0.5} = \sqrt{C_1C_2} \tag{55b}$$

Eqn. 55b shows that the time averaged salinity C_m can be taken as the logarithmic (or geometric) mean of the initial (C_1) and final (C_2) salinity (fig. 6).

Saltmod uses the geometric mean to calculate the leaching. Since the amount of salt removed depends on C_m, which depends on C_1 and C_2, and since C_2 again depends on the amount of salt removed, a trial and error procedure is required to find the correct balance.

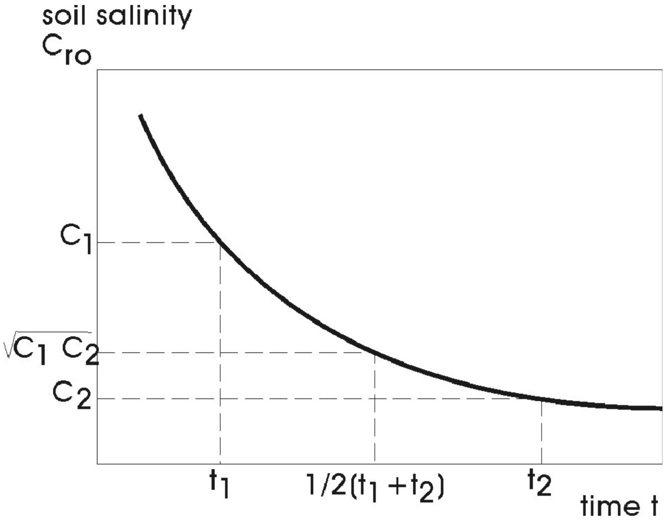

Figure 6. The leaching curve and the geometric mean of soil salinity in a time interval

4.3. Salt balances under full cropping rotation

In the salt balances under full cropping rotation (K_r=4), all hydrological and salinity values of the different land use types are pooled (fig. 7).

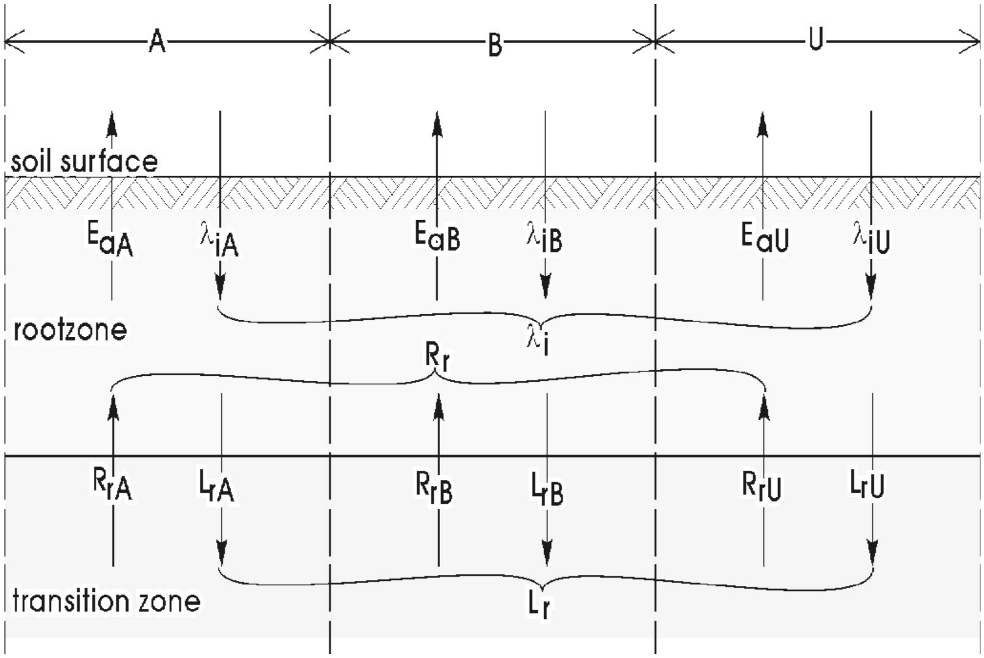

Figure 7. Pooled hydrological factors in areas under full cropping rotation ($K_r = 4$)

4.3.1. Above the soil surface

The salt balance above the soil surface is calculated only when the water table is above the soil surface using the overall water balance (eqn. 15). The infiltration is calulated from:

$$\lambda_i = G_o + G_w + G_d + G_i \qquad [\lambda_i > 0] \qquad (56a)$$

and the upward seepage λ_o from:

$$\lambda_o = G_i - G_w - G_d - G_o \qquad [\lambda_o > 0] \qquad (56b)$$

The amount of salt brought into the surface reservoir by irrigation, rainfall and upward flow of ground water is:

$$Z_{se} = C_i(I_{aA}A + I_{aB}B + S_{iU}U) + C_pP_p + C_{r4i}\lambda_o \qquad (57a)$$

where C_i is the salt concentation of the irrigation water including the re-use of drain and well water (eqn. 60, dS/m), and C_{r4i} is the salt concentration of the soil moisture in the root zone at the start of the season when saturated, equal to the salt concentration of the same at the end of the previous season (dS/m).

The amount of salt flowing out by surface drainage is:

$$Z_{so} = C_{si}(I_o + S_{oA}A + S_{oB}B + S_{oU}U + \lambda_i) \qquad (57b)$$

where C_{si} is the initial salt concentration of the water above the soil surface, i.e. at the start of the season.

The final amount of salt stored above the soil surface, i.e. at the end of the season, now becomes:

$$Z_{sf} = Z_{si} + Z_{se} + Z_{so} \tag{57c}$$

where Z_{si} is the initial salt storage above the soil surface, i.e. at the start of the season.

Amounts of salt Z_s are expressed in m water height x EC in dS/m, i.e. m.dS/m, which can be interpreted as the salinity of the water if it stands 1 m above the soil surface. When the water height is more, the salinity is proportionally less and vice versa.

The concentration C_p can usually be taken equal to zero, but in coastal areas it may reach a positive value that is assumed to be known.

4.3.2. Root zone

The salt balance of the root zone depends on three situations:

1 - the water table is below the soil surface in the present and the previous season, or it is above the soil surface while it was below in the previous season

2 - the water table is above the soil surface in the present and previous season

3 - the water table is below the soil surface in the present season while it was previously above it

Water table situation 1

The salt balance of the root zone is made on the basis of the top soil water balance (eqn. 7):

$$\Delta Z_{r4} = P_pC_p + (I_g-I_o)C_i - S_o(0.2C_{r4i}+C_i) + R_{rT}C_{xki} - L_{rT}C_{L4} \tag{58a}$$

where: ΔZ_{r4} is salt storage in the root zone when K_r=4 (dS/season), C_p is the salt concentration of the rain water (dS/m), C_i is the salt concentration of the surface irrigation water including the use of drain or well water for irrigation (dS/m), C_{xki} is the salt concentration of the capillary rise based on soil salinity in the transition zone, when saturated, at the end of the previous season and depending on the presence or absence of a subsurface drainage system as defined in eqn. 59a,b (dS/m), and C_{L4} (eqn. 62) is the seasonal average salt concentration of the percolation water (dS/m).

In the above equations it can be seen that the salt concentration of the surface drainage S_o is assumed to be equal to the concentration C_i of the irrigation water plus 20% of the salt concentration of the root zone C_r. Hence, the leaching efficiency of the surface drainage water is tentatively set at a low value 0.2. In a future version of Saltmod, this value may be made variable

Water table situation 2

Eqn. 58a changes into:

$$\Delta Z_{r4} = \lambda_i(C_{st}-C_{L4}) - \lambda_o(C_{L4}-C_{xki}) \quad (58b)$$

Water table situation 3

Eqn. 58a is used, but the amount of salt stored above the soil surface Z_{si} is added to the root zone:

$$\Delta Z_{r4} = P_pC_p + (I_g-I_o)C_i - S_o(0.2C_{r4i}+C_i) + R_{rT}C_{xki} - L_{rT}C_{L4} + Z_{si} \quad (58c)$$

Subsequently the value of Z_{si} is made equal to zero.

The initial salt concentation of the transition zone C_{xki} depends on the presence of a subsurface drainage system. If present then:

$$C_{xki} = C_{xai} \quad (59a)$$

otherwise:

$$C_{xki} = C_{xi} \quad (59b)$$

where: C_{xi} is the salt concentration of the water in the transition zone, when saturated, at the end of the previous season (EC in dS/m), C_{xai} is the salt concentration of the water in the part of the transition zone which is above drain level, when saturated (EC in dS/m).

4.3.2.1 Salt concentration of the irrigation water

The salt concentration C_i of the irrigation water depends on the use of ground water for irrigation:

$$C_i = (I_iC_{ic}+D_dC_{di}+F_wG_wC_{qi})/(I_i+D_d+F_wG_w) \quad (60)$$

where: C_{ic} is the known seasonal average salt concentration of the inflowing canal water (dS/m), C_{di} is the salt concentration of the drainage water at the end of the previous season (dS/m), C_{qi} is the salt concentration of the water in the aquifer, when saturated, at the end of the previous season (dS/m).

4.3.2.2 Initial salt concentration of the drainage water

The calculation of the salt concentration C_{di} is based on eqn. 32 and found from:

$$C_{di} = F_{lx}(G_{db}C_{xbi}+G_{da}C_{xai})/G_{dt} \quad (61)$$

where: F_{lx} is the leaching efficiency of the transition zone (-), C_{xbi} is the salt concentration of the soil moisture in the part of the transition zone below drain level, when saturated, at the end of the previous season (dS/m), C_{xai} is the salt concentration of the soil moisture in the part of the transition zone above drain level, when saturated, at the end of the previous season (dS/m).

4.3.2.3. Salt concentration of the percolation water

The seasonal average salt concentration C_{L4} of the percolation water is found from:

$$C_{L4} = F_{lr}C_{r4v} \tag{62}$$

where: C_{r4v} is the seasonal average salt concentration of the soil moisture in the root zone when saturated (dS/m), and F_{lr} is the leaching efficiency of the root zone (-). The average C_{r4v} is calculated from:

$$C_{r4v} = (C_{r4i}C_{r4f})^{1/2} \qquad [C_{r4f} < C_{r4i}] \tag{63a}$$

$$C_{r4v} = (C_{r4i}+C_{r4f})/2 \qquad [C_{r4f} > C_{r4i}] \tag{63b}$$

where: C_{r4f} is the final salt concentration of the soil moisture in the root zone when saturated (dS/m), at the end of the present season (dS/m).

4.3.2.4. Final salt concentration in the root zone

The final salt concentration of the soil moisture in the root zone, when saturated, is calculated as:

$$C_{r4f} = C_{r4i}+\Delta Z_{r4}/P_{tr}D_r \tag{64}$$

Since the salt storage, or change in salt content, ΔZ_{r4} depends on the salt concentration of the percolation water C_{L4}, which again depends on the final salt concentration C_{r4}f, a trial and error calculation procedure is required to strike the correct balance for the calculation of C_{r4f} in eqn. 64.

4.3.3. Transition zone

The salt balance of the transition zone depends on the absence or presence of a subsurface drainage system.

4.3.3.1. Absence of a subsurface drainage system

In the absence of a subsurface drainage system, the salt balance of the transition zone is based on the water balance of the same (eqn. 5):

$$L_{rT}C_{L4} + L_cC_{ic} + V_RC_{qi} = R_{rT}C_{xv} + F_{lx}V_LC_{xv} + \Delta Z_x \tag{65}$$

where: C_{qi} is the salt concentration of the water in the aquifer, when saturated, of the previous season (EC in dS/m), C_{xv} (eqn. 69a,b) is the seasonal average salt concentration of the water in the transition zone, when saturated (EC in dS/m), and ΔZ_x is the storage of salt in the transition zone.

When the water table is above the soil surface we find that $L_{rT}=\lambda_i$ and $R_{rT}=\lambda_o$.

4.3.3.2. Presence of a subsurface drainage system

When a subsurface drainage system is present, the steady state water balance of the transition zone (eqn. 5) is split into a balance of the upper part, above drain level, and a lower part, below drain level. For the upper part we have:

$$L_{rT} + L_c + V_R - V_L - G_b = R_{rT} + G_a \qquad (66a)$$

and for the lower part:

$$L_{rT} + L_c - R_{rT} - G_a + V_R = V_L + G_b \qquad (66b)$$

As in the root zone, we have $L_{rT}=\lambda_i$ and $R_{rT}=\lambda_o$ when the water table is above the soil surface.

Hence, the salt balance of the upper part becomes:

$$\Delta Z_{xa} = L_{rT}C_{L4} + L_cC_{ic} + (V_R-V_L-G_b)F_{lx}C_{xbi} - R_{rT}C_{xa} - F_{lx}G_aC_{xa} \qquad (67)$$

where: ΔZ_{xa} is the salt storage in the part of the transition zone above drain level (dS/season), C_{xav} is the seasonal average salt concentration of the water in the part of the transition zone, when saturated, above the drain level (EC in dS/m), and C_{xbi} is the salt concentration of the water in the part of the transition zone below drain level, when saturated, at the end of the previous season (EC in dS/m).

The salt balance of the lower part becomes:

$$\Delta Z_{xb} = F_{lx}(L_{rT}+L_c-R_{rT}-G_a)C_{xav} + V_RC_{qi} - F_{lx}(V_L + G_b)C_{xbv} \qquad (68)$$

where: ΔZ_{xb} is the salt storage in the part of the transition zone above drain level (dS/season), C_{xbv} is the seasonal average salt concentration of the water in the part of the transition zone, below the drain level (EC in dS/m).

4.3.3.3. Average concentration of the water in the transition zone

In the absence of a subsurface drainage system, the seasonal average salt concentration C_{xv} of the transition zone, when saturated, is found from:

$$C_{xv} = (C_{xi}C_{xf})^{1/2} \qquad [C_{xf} < C_{xi}] \qquad (69a)$$

$$C_{xv} = (C_{xi}+C_{xf})/2 \qquad [C_{xf} > C_{xi}] \qquad (69b)$$

where: C_{xi} is the salt concentration of the soil moisture in the transition zone, when saturated, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{xf} is the final salt concentration of the soil moisture in the transition zone, when saturated, at the end of the season (dS/m).

In the presence of a subsurface drainage system, the seasonal average salt concentration C_{xav} of the upper part of the transition zone, when saturated, above the level of the water table, is found from:

$$C_{xav} = (C_{xai}C_{xaf})^{1/2} \qquad [C_{xaf} < C_{xai}] \qquad (70a)$$

$$C_{xav} = (C_{xai}+C_{xaf})/2 \qquad [C_{xaf} > C_{xai}] \qquad (70b)$$

where: C_{xai} is the salt concentration of the soil moisture in the transition zone, when saturated, above drain level at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{xaf} is the salt concentration of the same at the end of the season (dS/m).

In the presence of a subsurface drainage system, the seasonal average salt concentration C_{xbv} of the lower part of the transition zone, when saturated, below the level of the water table, is found from:

$$C_{xbv} = (C_{xbi}C_{xbf})^{1/2} \qquad [C_{xbf} > C_{xbi}] \qquad (71a)$$

$$C_{xbv} = (C_{xbi}+C_{xbf})/2 \qquad [C_{xbf} > C_{xbi}] \qquad (71b)$$

where: C_{xbi} is the salt concentration of the soil moisture in the transition zone, when saturated, below drain level at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{xbf} is the salt concentration of the same at the end of the season (dS/m).

4.3.3.4. Final salt concentration in the transition zone

In the absence of a subsurface drainage system, the final salt concentration of the soil moisture in the transition zone, when saturated, is calculated as:

$$C_{xf} = C_{xi} + \Delta Z_x/P_{tx}D_x \qquad (72)$$

Since the salt storage, or change in salt content, ΔZ_x, depends on the salt concentration of the water draining vertically downward to the aquifer, which again depends on the final salt concentration C_{xf}, a trial and error calculation procedure is required to strike the correct balance.

In the presence a subsurface drainage system, the final salt concentration of the soil moisture in the upper part of the transition zone, when saturated, above drain level, is calculated as:

$$C_{xaf} = C_{xai} + \Delta Z_{xa}/\{P_{tx}(D_d-D_r)\} \qquad (73a)$$

Since the salt storage, or change in salt content, ΔZ_{xa}, depends on the salt concentration of the drainage water, which again depends on the final salt concentration C_{xaf}, a trial and error calculation procedure is required to strike the correct balance.

In the presence a subsurface drainage system, the final salt concentration of the soil moisture in the lower part of the transition zone, when saturated, below drain level, is calculated as:

$$C_{xbf} = C_{xbi} + \Delta Z_{xb}/\{P_{tx}(D_r+D_x-D_d)\} \qquad (73b)$$

Since the salt storage, or change in salt content, ΔZ_{xb}, depends on the salt concentration of the drainage water, which again depends on the final salt concentration C_{xbf}, a trial and error calculation procedure is required to strike the correct balance.

4.3.4. Aquifer

The salt balance of the aquifer zone is based on the water balance of the same (eqn. 6):

$$\Delta Z_q = G_i C_h + V_L C_{xx} - (G_o + V_R + G_w) C_{ov} \qquad (74)$$

where: C_h is the salt concentration of the horizontally inflowing ground water (dS/m), C_{ov} is the seasonal average salt concentration of the horizontally outflowing ground water (dS/m), and C_{xx} is the salt concentration of the water in the transition zone, depending on the absence or presence of a subsurface drainage system (dS/m):

$$C_{xx} = C_{xv} \qquad [K_d = 0] \qquad (75a)$$

$$C_{xx} = C_{xbv} \qquad [K_d = 1] \qquad (75b)$$

The final salt concentration of the soil moisture in the aquifer, when saturated, is calculated as:

$$C_{qf} = C_{qi} + \Delta Z_q / P_{tq} D_q \qquad (76)$$

Since the salt storage, or change in salt content, ΔZ_q, depends on the seasonal average salt concentration of the water draining horizontally out of the aquifer C_{ov}, which again depends on the final salt concentration C_{qf}, a trial and error calculation procedure is required to strike the correct balance.

4.3.5. Salt concentration of drain and well water

The seasonal average salt concentration C_d (EC in dS/m) of the subsurface drainage water is calculated on the basis of eqn. 32 as a weighted average of the seasonal average salt concentrations of the flows entering the drain from above and below drain level:

$$C_d = F_{lx} (G_{da} C_{xav} + G_{db} C_{xbv}) / G_{dt} \qquad (77)$$

The seasonal average salt concentration C_w of the pumped well water is found from:

$$C_w = F_{lx} C_{qv} \qquad (78)$$

4.4. Salt balances under zero cropping rotation

In the salt balances under zero cropping rotation (K_r=0), all hydrological and salinity values for the root zones of the different land use types are separated, but in the transition zone they are pooled (fig. 8).

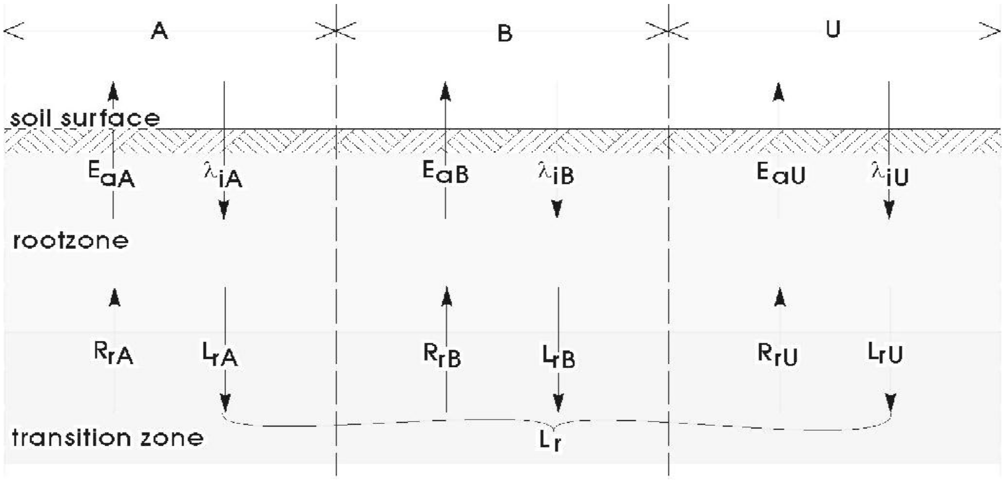

Figure 8. Separated hydrological factors in the root zone under zero cropping rotation ($K_r = 0$), pooling of factors in the transition zone

4.4.1. Above the soil surface

The principles of the salt balance described in sect. 4.3.1 apply equally here.

The amount of salt entering the water body above the soil surface is calculated slightly differently as:

$$Z_{se} = C_i(I_{aA}A+I_{aB}B+S_{iU}U) + C_pP_p + (C_{r0Ai}+C_{r0Bi}+C_{r0Ui})\lambda_o \qquad (79)$$

where: C_{r0Ai} is the salt concentration of the soil moisture in the root zone, when saturated, of the group A crop(s), at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{r0Bi} is the salt concentration of the soil moisture in the root zone, when saturated, of the group B crop(s), at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{r0Ui} is the salt concentration of the soil moisture in the root zone, when saturated, of the non-irrigated land at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m).

The calculations of Z_{so} and Z_{sf} remain unchanged.

4.4.2. Root zone

The water table situations are as described in sect. 4.3.1.

Water table situation 1
The salt balance of the root zone (eqn. 56) is split into 3 parts:

$$\Delta Z_{r0A} = P_pC_p + I_{aA}C_i + R_{rA}C_{xki} - S_{oA}(0.2C_{r0Ai}+C_i) - L_{rA}C_{L0A} \qquad (80a)$$

$$\Delta Z_{r0B} = P_pC_p + I_{aB}C_i + R_{rB}C_{xki} - S_{oB}(0.2C_{r0Bi}+C_i) - L_{rB}C_{L0B} \tag{80b}$$

$$\Delta Z_{r0U} = P_pC_p + S_{iU}C_i + R_{rU}C_{xki} - S_{oU}(0.2C_{r0Ui}+C_i) - L_{rU}C_{L0U} \tag{80c}$$

where: ΔZ_{r0A} is the salt storage in the root zone of the irrigated group A crop(s) when $K_r=0$ (dS/season), ΔZ_{r0B} is the salt storage in the root zone of the irrigated group B crop(s) when $K_r=0$ (dS per season), ΔZ_{r0U} is the salt storage in the root zone of the non-irrigated land when $K_r=0$ (dS/season), C_{L0A} is the seasonal average salt concentration of the percolation water from the irrigated group A crop(s) (dS/m), C_{L0B} is the seasonal average salt concentration of the percolation water from the irrigated group B crop(s) (dS/m), and C_{L0U} is the seasonal average salt concentration of the percolation water from the non-irrigated land (dS/m).

Water table situation 2

Eqns. 80a,b,c are changed into:

$$\Delta Z_{r0A} = \lambda_i(C_{si}-C_{L0A}) - \lambda_o(C_{L0A}-C_{xki}) \tag{80d}$$

$$\Delta Z_{r0B} = \lambda_i(C_{si}-C_{L0B}) - \lambda_o(C_{L0B}-C_{xki}) \tag{80e}$$

$$\Delta Z_{r0U} = \lambda_i(C_{si}-C_{L0U}) - \lambda_o(C_{L0U}-C_{xki}) \tag{80f}$$

Water table situation 3

Eqns. 80a,b,c are used with the value of Z_{si} added to each like in eqn. 58c. Subsequently the value of Z_{si} is made equal to zero.

The seasonal average salt concentrations C_{L0A}, C_{L0B}, and C_{L0U} of the percolation water in the above equations are found from:

$$C_{L0A} = F_{lr}C_{r0Av} \tag{81a}$$

$$C_{L0B} = F_{lr}C_{r0Bv} \tag{81b}$$

$$C_{L0U} = F_{lr}C_{r0Uv} \tag{81c}$$

where: C_{r0Av} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the group A crop(s) when $K_r=0$ (dS/m), C_{r0Bv} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the group B crop(s) when $K_r=0$ (dS/m), and C_{r0Uv} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the non-irrigated land when $K_r=0$ (dS/m). They are calculated from the following six equations depending on whether the salinity is decreasing or increasing:

$$C_{r0Av} = (C_{r0Ai}C_{r0Af})^{1/2} \qquad [C_{r0Af} < C_{r0Ai}] \tag{82a}$$

$$C_{r0Av} = (C_{r0Ai}+C_{r0Af})/2 \qquad [C_{r0Af} > C_{r0Ai}] \tag{82b}$$

$$C_{r0Av} = (C_{r0Ai}C_{r0Af})^{1/2} \qquad [C_{r0Af} < C_{r0Ai}] \tag{82c}$$

$$C_{r0Av} = (C_{r0Ai}+C_{r0Af})/2 \qquad [C_{r0Af} > C_{r0Ai}] \tag{82d}$$

$$C_{r0Av} = (C_{r0Ai}C_{r0Af})^{1/2} \qquad [C_{r0Af} < C_{r0Ai}] \tag{82e}$$

$$C_{r0Av} = (C_{r0Ai} + C_{r0Af})/2 \qquad [C_{r0Af} > C_{r0Ai}] \qquad (82f)$$

where: C_{r0Af} is the final salt concentration of the soil moisture in the root zone, when saturated, of the group A crop(s) at the end of the present season (dS/m), C_{r0Bf} is the final salt concentration of the soil moisture in the root zone, when saturated, of the non-irrigated land at the end of the present season (dS/m), C_{r0Uf} is the final salt concentration of the soil moisture in the root zone, when saturated, of the non-irrigated land at the end of the present season (dS/m).

The final salt concentrations of the soil moisture in the root zone are calculated as:

$$C_{r0Af} = C_{r0Ai} + \Delta Z_{r0A}/P_{tr}D_r \qquad (83a)$$

$$C_{r0Bf} = C_{r0Bi} + \Delta Z_{r0B}/P_{tr}D_r \qquad (83b)$$

$$C_{r0Uf} = C_{r0Ui} + \Delta Z_{r0U}/P_{tr}D_r \qquad (83c)$$

Since the salt storage, or change in salt content depends on the salt concentration of the percolation water, which again depends on the final salt concentration, a trial and error calculation procedure is required to strike the correct balance for the calculation of the final salt concentrations in eqns. 83a, b and c.

4.4.3. Transition zone

The seasonal average salt concentration C_{L0} of the percolation water into the transition zone is calculated as the weighted average of the salt concentrations of the percolation water from the A, B, and U areas:

$$C_{L0} = (L_{rA}C_{r0Av}A+L_{rB}C_{r0Bv}B+L_{rU}C_{r0Uv}U)/(L_{rA}A+L_{rB}B+L_{rU}U) \qquad (84)$$

The other salt balances of the transition zone are calculated with the equations of section 4.3.2, C_{L0} replacing C_{L4}.

When the water table is above the soil surface we find that $L_{rA}=L_{rB}=L_{rU}=\lambda_i$ and $R_{rA}=R_{rB}=R_{rU}=\lambda_o$.

4.5. Salt balances under intermediate cropping rotations

4.5.1. Types of cropping rotation

Saltmod offers the following three intermediate cropping rotation types:

1. A part or all of the non-irrigated land is permanently used unchanged throughout the seasons (e.g. permanently uncultivated land, non-irrigated grazing land, non-irrigated (agro-forestry, abandoned land). The rotation key K_r is set equal to 1.

2. A part or all of the land under group A crop(s) is permanently used unchanged throughout the seasons (e.g. the land under irrigated sugarcane, double irrigated rice cropping). The rotation key K_r is set equal to 2.
3. A part or all of the land under group B crop(s) is permanently used unchanged throughout the seasons (e.g. the land under irrigated orchards). The rotation key K_r is set equal to 3.

It is immaterial whether one assigns a permanent land use type either to the A or B group of crop(s). Also, a group of crops may consist of only one type of crop. It would be a good practice to reserve one group for the intensively irrigated crops and the other for the more lightly irrigated crops.

The Saltmod program calculates the minimum seasonal area fraction of the land use fractions A, B and U. These minima are called A_c, B_c and U_c respectively. Depending on the value of K_r, we have the following situations:

1. $K_r = 1$. The fraction U_c is used as the permanently non-irrigated land, throughout the seasons, and the fraction $1-U_c$ is the land with fully rotational land use of irrigated A and/or B type crops and/or non-irrigated land
2. $K_r = 2$. The fraction A_c is used as the permanently irrigated land under group A crop(s), throughout the seasons, and the fraction $1-A_c$ is the land with fully rotational land use of irrigated A and/or B type crops and/or non-irrigated land
3. $K_r = 3$. The fraction B_c is used as the permanently irrigated land under group B crop(s), throughout the seasons, and the fraction $1-B_c$ is the land with fully rotational land use of irrigated A and/or B type crops and/or non-irrigated land

4.5.2. Part of the area permanently non-irrigated, K_r=1

When K_r=1, the salt balance of the root zone (eqn. 56) is split into 2 parts, one separate part for the permanently non-irrigated area U_c and one pooled part for the remaining area $1 - U_c$ with full cropping rotation. The balances read as follows.

4.5.2.1 Above soil surface

The principles of the salt balance described in sect. 4.3.1 apply equally here.

The amount of salt entering the water body above the soil surface is calculated slightly differently as:

$$Z_{se} = C_i(I_{aA}A+I_{aB}B+S_{iU}U) + C_pP_p + (C_{r1Ui}+C_{r1*i})\lambda_o \qquad (85)$$

where: C_{r1Ui} is the salt concentration of the soil moisture in the root zone, when saturated, in the permanently non-irrigated land, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{r1*i} is the salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently non-irrigated area, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m).

The calculations of Z_{so} and Z_{sf} remain unchanged.

4.5.2.2 Root zone

Water table situation 1

The salt balance of the root zone (eqn. 56) is split into 2 parts, one separate part for the permanently non-irrigated area U_c and one pooled part for the remaining area $1-U_c=U^*$ with full cropping rotation (fig. 9). The balance reads:

$$\Delta Z_{r1U} = P_pC_p + S_{iU}C_i + R_{rU}C_{xki} - S_{oU}(0.2C_{r1Ui}+C_i) - L_{rU}C_{L1U} \qquad (86a)$$

$$\Delta Z_{r1*} = P_pC_p + (\Omega_{1A}I_{aA}+\Omega_{1B}I_{aB}+\Omega_{1U}S_{iU})C_i + (\Omega_{1A}R_{rA}+\Omega_{1B}R_{rB}+\Omega_{1U}R_{rU})C_{xki}$$

$$- (\Omega_{1A}S_{oA}+\Omega_{1B}S_{oB}+\Omega_{1U}S_{oU})(0.2C_{r1*i}+C_i) - (\Omega_{1A}L_{rA}+\Omega_{1B}L_{rB}+\Omega_{1U}L_{rU})C_{L1*} \qquad (86b)$$

where: ΔZ_{r1U} is the salt storage in the root zone of the permanently non-irrigated land, throughout the seasons, when $K_r=1$ (dS/season), ΔZ_{r1*} is the salt storage in the root zone of the land outside the permanently non-irrigated area, when $K_r=1$ (dS/ season), C_{L1U} is the seasonal average salt concentration of the percolation water from the permanently non-irrigated land (dS/m), C_{L1*} is the seasonal average salt concentration of the percolation water from the land outside the permanently non-irrigated area (dS/m). Ω_{1U}, Ω_{1A} and Ω_{1B} are area weight factors (eqns. 87a,b,c).

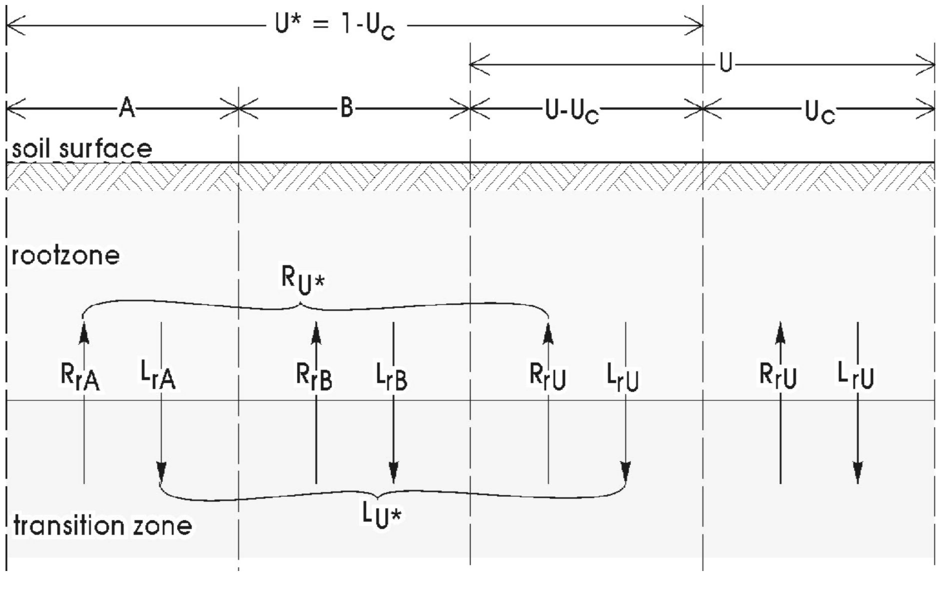

Figure 9. Separate hydrological factors in the root zone of the permanently non-irrigated land (U_c) and pooled factors in the remaining rotational land (U^*)

Water table situation 2
When the water table is above the soil surface, eqns. 86a,b are changed into:

$$\Delta Z_{r1U} = \lambda_i(C_{si}-C_{L1U}) - \lambda_o(C_{L1U}-C_{xki}) \qquad (86c)$$

$$\Delta Z_{r1*} = \lambda_i(C_{si}-C_{L1*}) - \lambda_o(C_{L1*}-C_{xki}) \qquad (86d)$$

Water table situation 3
Eqns. 86a,b,c are used with the value of Z_{si} added to each like in eqn. 58c. Subsequently the value of Z_{si} is made equal to zero.

The weight factors in eqns. 86a, b are defined as:

$$\Omega_{1U} = (U-U_c)/(1-U_c) \qquad (87a)$$

$$\Omega_{1A} = A/(1-U_c) \qquad (87b)$$

$$\Omega_{1B} = B/(1-U_c) \qquad (87c)$$

The seasonal average salt concentrations C_{L1U} and C_{L1*} of the percolation water in the equations 86a,b,c,d are found from:

$$C_{L1U} = F_{lr}C_{r1Uv} \qquad (88a)$$

$$C_{L1*} = F_{lr}C_{r1*v} \qquad (88b)$$

where: C_{r1Uv} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the permanently non-irrigated land, when K_r=1 (dS/m), C_{r1*v} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently non-irrigated area, when K_r=1 (dS/m). They are calculated from the following four equations depending on whether the salinity is decreasing or increasing:

$$C_{r1Uv} = (C_{r1Ui}C_{r1Uf})^{1/2} \qquad [C_{r1Uf} < C_{r1Ui}] \qquad (89a)$$

$$C_{r1Uv} = (C_{r1Ui}+C_{r1Uf})/2 \qquad [C_{r1Uf} > C_{r1Ui}] \qquad (89b)$$

$$C_{r1*v} = (C_{r1*i}C_{r1*f})^{1/2} \qquad [C_{r1*f} > C_{r1*i}] \qquad (89c)$$

$$C_{r1*v} = (C_{r1*i} + C_{r1*f})/2 \qquad [C_{r1*f} > C_{r1*i}] \qquad (89d)$$

where: C_{r1Uf} is the final salt concentration of the same at the end of the present season (dS/m), C_{r1*f} is the final salt concentration of the same at the end of the present season (dS/m).

The final salt concentrations of the soil moisture in the root zone are calculated as:

$$C_{r1Uf} = C_{r1Ui} + \Delta Z_{r1U}/P_{tr}D_r \qquad (90a)$$

$$C_{r1*f} = C_{r1*i} + \Delta Z_{r1*}/P_{tr}D_r \qquad (90b)$$

As explained in sect. 4.5.2.2, a trial and error calculation procedure is required to strike the correct balance for the calculation of the final salt concentrations in eqn. 90a and b.

4.5.2.3 Transition zone

The seasonal average salt concentration C_{L1} of the percolation water L_r from the root zone into the transition zone is calculated as the weighted average of the salt concentrations of the percolation water from the U_c and $U^*=1-U_c$ areas.

The percolation L_{rU*} in the U* area, i.e. outside the permanently non-irrigated land, expressed in m^3/season per m^2 outside area, is found from:

$$L_{rU*} = \Omega_{1U}L_{rU} + \Omega_{1A}L_{rA} + \Omega_{1B}L_{rB} \qquad (91)$$

and the salt concentration C_{L1} from:

$$C_{L1}=[L_{rU}C_{r1Av}U_c+L_{rU*}C_{r1*v}(1-U_c)]/L_r \qquad (92)$$

When the water table is above the soil surface we replace the percolation L_r and capillary rise R_r in eqn. 91, 92 and other by $L_{rA}=L_{rB}=L_{rU}=\lambda_i$ and $R_{rA}=R_{rB}=R_{rU}=\lambda_o$. The weight factors Ω then play no role.

The other salt balances of the transition zone are calculated using the equations of section 4.3.2, C_{L1} replacing C_{L4}.

4.5.3. Part of the irrigated area permanently under group A crop(s), $K_r=2$

When $K_r=2$, the salt balance of the root zone (eqn. 56) is split into 2 parts in a similar way as described in section 4.5.2 (fig. 9) for $K_r=1$. One part represents the permanently irrigated area A_c under group A crop(s), and one part the remaining area $1-A_c=A^*$ with full cropping rotation.

4.5.3.1 Above soil surface

The principles of the salt balance described in sect. 4.3.1 apply equally here.

The amount of salt entering the water body above the soil surface is calculated slightly differently as:

$$Z_{se} = C_i(I_{aA}A+I_{aB}B+S_{iU}U) + C_pP_p + (C_{r2Ai}+C_{r2*i})\lambda_o \qquad (93)$$

where: C_{r2Ai} is the salt concentration of the soil moisture in the root zone, when saturated, in the permanently irrigated land under group A crop(s), at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{r2*i} is the salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently irrigated land under group A crop(s) at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m).

The calculations of Z_{so} and Z_{sf} remain unchanged.

4.5.3.2 Root zone

Water table situation 1

The salt balance of the root zone (eqn. 56) is split into 2 parts, one separate part for the permanently irrigated area A_c and one pooled part for the remaining area $1-A_c=A^*$ with full cropping rotation. The two salt balances of the root zone thus read:

$$\Delta Z_{r2A} = P_pC_p + I_{aA}C_i + R_{rA}C_{xki} - S_{oA}(0.2C_{r2Ai}+C_i) - L_{rA}C_{L2A} \qquad (94a)$$

$$\Delta Z_{r2*} = P_pC_p + (\Omega_{2A}I_{aA}+\Omega_{2B}I_{aB}+\Omega_{2U}S_{iU})C_i + (\Omega_{2A}R_{rA}+\Omega_{2B}R_{rB}+\Omega_{2U}R_{rU})C_{xki}$$

$$- (\Omega_{2A}S_{oA}+\Omega_{2B}S_{oB}+\Omega_{2U}S_{oU})(0.2C_{r2*i}+C_i) - (\Omega_{2A}L_{rA}+\Omega_{2B}L_{rB}+\Omega_{2U}L_{rU})C_{L2*} \qquad (94b)$$

where: ΔZ_{r2A} is the salt storage in the root zone of the permanently irrigated land under group A crop(s), throughout the seasons, when $K_r=2$ (dS/season), ΔZ_{r2*} is the salt storage in the root zone of the land outside the permanently irrigated area under group A crop(s), when $K_r=2$ (dS/season), C_{L2A} is the seasonal average salt concentration of the percolation water from the permanently irrigated land under group A crop(s), throughout the seasons (dS/m), C_{L2*} is the seasonal average salt concentration of the percolation water from the land outside the permanently irrigated area under group A crops (dS/m). Ω_{2U}, Ω_{2A} and Ω_{2B} are area weight factors (eqns. 95a,b,c).

Water table situation 2

When the water table is above the soil surface, eqns. 94a,b are changed into:

$$\Delta Z_{r2A} = \lambda_i(C_{si}-C_{L2A}) - \lambda_o(C_{L2A}-C_{xki}) \qquad (94c)$$

$$\Delta Z_{r2*} = \lambda_i(C_{si}-C_{L2*}) - \lambda_o(C_{L2*}-C_{xki}) \qquad (94d)$$

Water table situation 3

Eqns. 94a,b,c are used with the value of Z_{si} added to each like in eqn. 58c. Subsequently the value of Z_{si} is made equal to zero.

The weight factors in eqns. 94a,b are defined as:

$$\Omega_{2A} = (A-A_c)/(1-A_c) \qquad (95a)$$

$$\Omega_{2B} = B/(1-A_c) \qquad (95b)$$

$$\Omega_{2U} = U/(1-A_c) \qquad (95c)$$

The seasonal average salt concentrations C_{L2A} and C_{L2*} of the percolation water are found from:

$$C_{L2A} = F_{lr}C_{r2Av} \qquad (96a)$$

$$C_{L2*} = F_{lr}C_{r2*v} \qquad (96b)$$

where: C_{r2Av} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the permanently irrigated land under group A crop(s), when $K_r=2$ (dS/m), C_{r2*v} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently irrigated land under group A crop(s), when $K_r=2$ (dS/m). They are calculated from:

$$C_{r2Av} = (C_{r2Ai}C_{r2Af})^{1/2} \qquad [C_{r2Af} < C_{r2Ai}] \qquad (97a)$$

$$C_{r2Av} = (C_{r2Ai}+C_{r2Af})/2 \qquad [C_{r2Af} > C_{r2Ai}] \qquad (97b)$$

$$C_{r2*v} = (C_{r2*i}C_{r2*f})^{1/2} \qquad [C_{r2*f} < C_{r2*i}] \qquad (97c)$$

$$C_{r2*v} = (C_{r2*i} + C_{r2*f})/2 \qquad [C_{r2*f} > C_{r2*i}] \qquad (97d)$$

where: C_{r2Af} is the final salt concentration of the same at the end of the present season (dS/m), C_{r2*f} is the final salt concentration of the same at the end of the present season (dS/m).

The final salt concentrations of the soil moisture in the root zone are calculated as:

$$C_{r2Af} = C_{r2Ai} + \Delta Z_{r2A}/P_{tr}D_r \qquad (98a)$$

$$C_{r2*f} = C_{r2*i} + \Delta Z_{r2*}/P_{tr}D_r \qquad (98b)$$

Since the salt storage, or change in salt content depends on the salt concentration of the percolation water, which again depends on the final salt concentration, a trial and error calculation procedure is required to strike the correct balance for the calculation of the final salt concentrations in eqns. 98a and b.

4.5.3.2 Transition zone

The seasonal average salt concentration C_{L2} of the percolation water L_r from the root zone into the transition zone is calculated as the weighted average of the salt concentrations of the percolation water from the Ac and A*=1-Ac areas.

The percolation L_{rA*} in the A* area, i.e. outside the permanently irrigated land under group A crop(s), expressed in m^3/season per m^2 outside area, is found from:

$$L_{rA*} = \Omega_{2A}L_{rA} + \Omega_{2B}L_{rB} + \Omega_{2U}L_{rU} \qquad (99)$$

and the salt concentration C_{L2} from:

$$C_{L2}=[L_{rA}C_{r2Av}A_c+L_{rA*}C_{rA*v}(1-A_c)]/L_r \qquad (100)$$

The other salt balances of the transition zone are calculated using the equations of section 4.3.2 with C_{L4} replaced by C_{L2}.

When the water table is above the soil surface we replace the percolation L_r and capillary rise R_r in eqn. 99, 100 and other by $L_{rA}=L_{rB}=L_{rU}=\lambda_i$ and $R_{rA}=R_{rB}=R_{rU}=\lambda_o$. The weight factors Ω then play no role.

4.5.4. Part of the irrigated area permanently under group B crop(s), K_r=3

When K_r=3, the salt balance of the root zone (eqn. 56) is split into 2 parts in a similar way as described in section 4.5.2 (fig. 9) for K_r=1. One part represents the permanently irrigated area B_c under group A crop(s), and one part the remaining area $1-B_c=B^*$ with full cropping rotation.

4.5.4.1 Above soil surface

The principles of the salt balance described in sect. 4.3.1 apply equally here.

The amount of salt entering the water body above the soil surface is calculated slightly differently as:

$$Z_{se} = C_i(I_{aA}A+I_{aB}B+S_{iU}U) + C_pP_p + (C_{r03Bi}+C_{r3i})\lambda_o \qquad (101)$$

where: C_{r3Bi} is the salt concentration of the soil moisture in the root zone, when saturated, in the permanently irrigated land under group A crop(s), at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m), C_{r3i} is the salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently irrigated land under group A crop(s) at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m).

The calculations of Z_{so} and Z_{sf} remain unchanged.

4.5.4.2 Root zone

Water table situation 1

The salt balance of the root zone (eqn. 56) is split into 2 parts, one separate part for the permanently irrigated area B_c and one pooled part for the remaining area $1-B_c=B^*$ with full cropping rotation. The two salt balances of the root zone thus read:

$$\Delta Z_{r3B} = P_pC_p + I_{aB}C_i + R_{rB}C_{xki} - S_{oB}(0.2C_{r3Bi}+C_i) - L_{rB}C_{L2B} \qquad (102a)$$

$$\Delta Z_{r3*} = P_pC_p + (\Omega_{3A}I_{aB}+\Omega_{3B}I_{aB}+\Omega_{3U}S_{iU})C_i + (\Omega_{3A}R_{rA}+\Omega_{3B}R_{rB}+\Omega_{3U}R_{rU})C_{xki}$$

$$- (\Omega_{3A}S_{oA}+\Omega_{3B}S_{oB}+\Omega_{3U}S_{oU})(0.2C_{r3*i}+C_i) - (\Omega_{3A}L_{rA}+\Omega_{3B}L_{rB}+\Omega_{3U}L_{rU})C_{L3*} \qquad (102b)$$

where: ΔZ_{r3A} is the salt storage in the root zone of the permanently irrigated land under group B crop(s), throughout the seasons, when K_r=3 (dS/season), ΔZ_{r3*} is the salt storage in the root zone of the land outside the permanently irrigated area under group B crop(s), when K_r=3 (dS/season), C_{L3B} is the seasonal average salt concentration of the percolation water from the permanently irrigated land under group B crop(s), throughout the seasons (dS/m), C_{L3*} is the seasonal average salt concentration of the percolation water from the land outside the permanently irrigated area under group A crops (dS/m). Ω_{3U}, Ω_{3A} and Ω_{3B} are area weight factors (eqns. 103a,b,c).

Water table situation 2

When the water table is above the soil surface, eqns. 101a,b are changed into:

$$\Delta Z_{r3A} = \lambda_i(C_{si}-C_{L3A}) - \lambda_o(C_{L3A}-C_{xki}) \qquad (102c)$$

$$\Delta Z_{r3*} = \lambda_i(C_{si}-C_{L3*}) - \lambda_o(C_{L3*}-C_{xki}) \qquad (102d)$$

Water table situation 3

Eqns. 101a,b,c are used with the value of Z_{si} added to each like in eqn. 58c. Subsequently the value of Z_{si} is made equal to zero.

The weight factors in eqns. 101a,b are defined as:

$$\Omega_{3A} = (B-B_c)/(1-B_c) \qquad (103a)$$

$$\Omega_{3B} = A/(1-B_c) \qquad (103b)$$

$$\Omega_{3U} = U/(1-B_c) \qquad (103c)$$

The seasonal average salt concentrations C_{L3A} and C_{L3*} of the percolation water are found from:

$$C_{L3A} = F_{lr}C_{r3Bv} \qquad (104a)$$

$$C_{L3*} = F_{lr}C_{r3*v} \qquad (104b)$$

where: C_{r3Bv} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the permanently irrigated land under group B crop(s), when K_r=3 (dS/m), C_{r3*v} is the seasonal average salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently irrigated land under group Bcrop(s), when K_r=3 (dS/m). They are calculated from:

$$C_{r3Bv} = (C_{r3Bi}C_{r3Bf})^{1/2} \qquad [C_{r3Bf} < C_{r3Bi}] \qquad (105a)$$

$$C_{r3Bv} = (C_{r3Bi}+C_{r3Bf})/2 \qquad [C_{r3Bf} > C_{r3Bi}] \qquad (105b)$$

$$C_{r3*v} = (C_{r3*i}C_{r3*f})^{1/2} \qquad [C_{r3*f} < C_{r3*i}] \qquad (105c)$$

$$C_{r3*v} = (C_{r3*i} + C_{r3*f})/2 \qquad [C_{r3*f} > C_{r3*i}] \qquad (105d)$$

where: C_{r3Bf} is the final salt concentration of the same at the end of the present season (dS/m), C_{r3*f} is the final salt concentration of the same at the end of the present season (dS/m).

The final salt concentrations of the soil moisture in the root zone are calculated as:

$$C_{r3Bf} = C_{r3Bi} + \Delta Z_{r3B}/P_{tr}D_r \qquad (106a)$$

$$C_{r3*f} = C_{r3*i} + \Delta Z_{r3*}/P_{tr}D_r \qquad (106b)$$

Since the salt storage, or change in salt content depends on the salt concentration of the percolation water, which again depends on the final salt concentration, a trial and error calculation procedure is required to strike the correct balance for the calculation of the final salt concentrations in eqns. 106a and b.

4.5.4.3 Transition zone

The seasonal average salt concentration C_{L3} of the percolation water L_r from the root zone into the transition zone is calculated as the weighted average of the salt concentrations of the percolation water from the Ac and A*=1-Ac areas.

The percolation L_{rB*} in the B* area, i.e. outside the permanently irrigated land under group B crop(s), expressed in m^3/season per m^2 outside area, is found from:

$$L_{rB*} = \Omega_{3A}L_{rA} + \Omega_{3B}L_{rB} + \Omega_{3U}L_{rU} \tag{107}$$

and the salt concentration C_{L3} from:

$$C_{L3}=[L_{rA}C_{r3Bv}A_c+L_{rB*}C_{rB*v}(1-B_c)]/L_r \tag{108}$$

The other salt balances of the transition zone are calculated using the equations of section 4.3.2 with C_{L4} replaced by C_{L3}.

When the water table is above the soil surface we replace the percolation L_r and capillary rise R_r in eqn. 107, 108 and other by $L_{rA}=L_{rB}=L_{rU}=\lambda_i$ and $R_{rA}=R_{rB}=R_{rU}=\lambda_o$. The weight factors Ω then play no role.

5. AREA FREQUENCY DISTRIBUTION OF SOIL SALINITY

The spatial variation in soil salinity under irrigated conditions is very high and the variation itself is very dynamic depending upon the agricultural, irrigation and drainage practices. The Gumbel distribution is assumed to fit the cumulative probability distribution of the root zone salinity: it is appropriately skew to the right, and it permits an easy introduction of a standard variation proportional to the mean.

The root zone salinities that are likely to occur at 20%, 40%, 60% and 80% of cumulative frequencies are computed by taking the predicted root zone salinity as the mean.

The cumulative Gumbel distribution, applied to salt concentration C, can be written as:

$$C_\varphi = \mu - c/\alpha - \{\ln(-\ln\varphi)\}/\alpha \qquad (109)$$

where: C_φ is the value of C at cumulative frequency φ (dS/m), μ is the mean of C values (dS/m), c is Euler's constant, equal to 0.577, α equals $\pi/\sigma\sqrt{6}$, and σ is the standard deviation of the C values (dS/m). By assuming the relationship:

$$\sigma = \varepsilon.\mu \qquad (110)$$

where ε is a constant proportional to the size of the area, eqn. 103 is converted to:

$$C_\varphi = \mu\ [\ 1 - 0.45\varepsilon - 0.78\varepsilon\ \{\ln(-\ln\varphi)\}\ ] \qquad (111)$$

In table 1 different values are given to ε, depending on the size of the area. The relation is empirical and derived from various cases based on traditional soil sampling with an auger up to 30cm depth. Combined or larger size samples would give smaller ε values.

Table1. Values of the proportion $\varepsilon=\sigma/\mu$ in relation to size of the area (ha)

Area lower limit	Area upper limit	ε
0	100	0.35
100	1000	0.41
1000	10000	0.53
10000	100000	0.67

The Gumbel relations used in Saltmod are arbitrary and need to be verified for a larger number of situations. However, the procedure used at least gives a reasonable indication of the possible area variations.

Fig. 10 shows an example of a Gumbel frequency distribution of soil salinity with a plot of the field data and the line used in Saltmod. The data are obtained in the traditional way from the Gohana region, Haryana, India, and refer to an area of 2000 ha. In total 400 samples were taken in groups of 4. Per group, the average value is used. The figure is therefore based on 100 data. Their mean value is μ=5.1 and the standard deviation is σ=3.5.

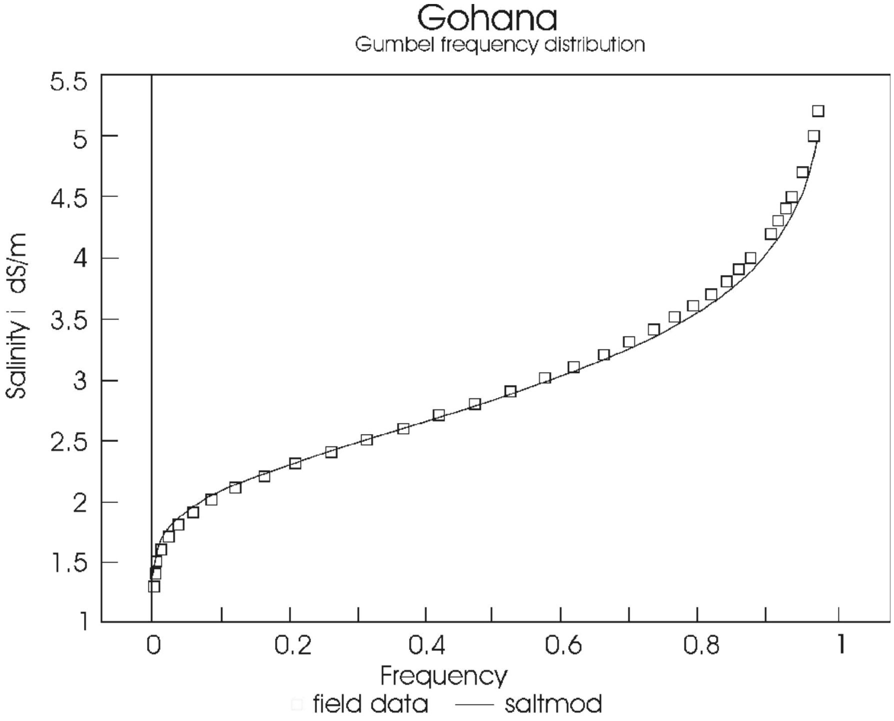

Figure 10 Cumulative Gumbel frequency distribution of soil salinity observations in the Gohana area, Haryana, India, and the Saltmod prediction (data from D.P.Sharma, CSSRI, Karnal, India)

In the example of fig. 10 the concurrence of the field data and the Saltmod estimates is fairly high.

6. FARMERS' RESPONSES

To simulate farmers' responses, the irrigated areas (A and B) can be gradually reduced if the water table becomes shallow, or if the salinity of the root zone becomes high. This is done by defining the farmers' response key K_f=1 in the input data file. The responses are the following:

- a reduction of the irrigated area when the land becomes saline; this leads to an increase in the permanent fallow land, abandoned for agriculture
- a reduction of the irrigated area when irrigation water is scarce and the irrigation sufficiency low; this leads to an increase in the rotational fallow land
- a decrease of the field application of irrigation water when the water table becomes shallow; this leads to a more efficient field irrigation, reduced percolation, a greater depth of the water table, and higher soil salinity

When Saltmod is used with intermediate changes in the input data during the whole period of calculation, the response key is automatically set equal to zero, because it is supposed that the adjustments to simulate farmers' responses will be done by the user.

6.1. Reduction of irrigated area when salinization or irrigation deficiency occurs

When the final root zone salinity of the irrigated area under A or B type crops is more than the initial salinity (C_{A0}, C_{B0}, as given with the input) and more than 5 dS/m, or when the irrigation sufficiency (T_A, T_B, as calculated by the program) is less than 0.8, the irrigated fractional areas A and B are reduced as follows:

$$A_n = \beta_1 A_p \tag{112}$$

$$B_n = \beta_1 B_p \tag{113}$$

where: A_n, A_p, B_n and B_p are the A and B values of the next and the present year respectively, and the β_1 values are given in table 2.

Table 2. Relation between reduction factor β_1, soil salinity (dS/m) and irrigation sufficiency (-)

Salinity	Sufficiency	β_1
> 12	< 0.7	0.90.
8 – 12	0.7 - 0.8	0.95
< 8	> 0.8	1.00

When judging the salinity limits used one may take into account that they are area averages, so that there are patches of land with a higher salinity, and that the salinity at field saturation used here is about half the salinity of the commonly used saturation extract. The increased value of the non-irrigated area fraction U is:

$$U_n=1-A_n-B_n \tag{114}$$

When the soil salinity is greater than 5 dS/m and the value of the rotation key K_r is not equal to 1 (i.e. there is no permanently fallow land), its value is changed into 1, so that the presence of permanently fallow, abandoned, land is assured.

When the sufficiency Js_A and/or Js_B of field irrigation equals unity, then the bypass (I_{on}) of irrigation water in the canal system is increased accordingly:

$$I_{on} = I_{op} + \tau_A(A_p-A_n)I_{aA} + \tau_B(B_p-B_n)I_{aB} \tag{115}$$

where: I_{on} and I_{op} are values of I_o in the next and present year respectively, and τ_A=1 when Fs_A=1, τ_B=1 when Fs_B=1, otherwise τ_A and τ_B are zero.

At the same time, when the sufficiency is less than one, then the amounts of field irrigation in the reduced areas are increased:

$$I_{An} = I_{Ap}/\beta_1 \tag{115a}$$

$$I_{Bn} = I_{Bp}/\beta_1 \tag{115b}$$

where: I_{An} , I_{Ap} , I_{Bn} , and I_{Bp} are the amounts of field irrigation I_{aA} and I_{aB} in the A and B areas of the next and present year respectively.

Now, the adjustment of the soil salinity values of the permanently non-irrigated area U_c (if K_r=1), the permanently irrigated A_c (if K_r=2) and B_c (if K_r=3) areas is required respectively as follows:

$$C_{1Ufn} = \frac{U_n(1-\beta_1)C_{r1*f} + U_cC_{r1Uf}}{U_n(1-\beta_1) + U_c} \tag{116a}$$

$$C_{2Afn} = \frac{A_n(1-\beta_1)C_{r2*f} + A_cC_{r2Af}}{A_n(1-\beta_1) + A_c} \qquad (116b)$$

$$C_{3Bfn} = \frac{B_n(1-\beta_1)C_{r3*f} + B_cC_{r3Bf}}{B_n(1-\beta_1) + B_c} \qquad (116c)$$

where: C_{r2An} is the adjusted final salt concentration of the soil moisture, when at field saturation, in the root zone of the permanently irrigated land under group A crop(s), used for the start of the next year, K_r=2 (EC in dS/m), C_{r3Bn} is the adjusted final salt concentration of the soil moisture, when at field saturation, in the root zone of the permanently irrigated land under group B crop(s), used for the start of the next year, K_r=3 (EC in dS/m), and C_{r1Un} is the adjusted final salt concentration of the soil moisture, when at field saturation, in the root zone of the permanently non-irrigated land, used for the start of the next year, K_r=1 (EC in dS/m)

As a result of the area reductions and irrigation increases, it may happen that the salinity in the irrigated areas is reduced again. If this brings the soil salinity below the initial levels, as given in the input, then the above processes are reversed (i.e. multiplication with β becomes division and vice versa), but the irrigated areas will not become larger, and the amounts of field irrigation not smaller, than their initial values as given with the input.

6.2. Reduction of irrigation when water logging occurs

If the seasonal average depth of water table D_w is less than 0.6 m, or less than -0.1 m for ponded rice crops, the bypass is increased and the irrigation is reduced as follows:

$$I'_{on} = I_{on} + \beta_2(I_{A0}A_p + I_{B0}B_p) \qquad (117)$$

$$I'_{An} = I_{An} - \beta_2 I_{A0} \qquad (118a)$$

$$I'_{Bn} = I_{Bn} - \beta_2 I_{B0} \qquad (118b)$$

where: I'_{An}, I'_{Bn} and I'_{ocn} are the adjusted values of the field irrigation in the A and B areas and the adjusted value of the bypass for the next year respectively, I_{An}, I_{Bn} and I_{ocn} are the previously (section 5.1) adjusted values of the field irrigation in the A and B areas and the previously adjusted value of the bypass respectively, I_{A0} and I_{B0} are the initial values of the field irrigation in the A and B areas as given with the input respectively, and A_n and B_n are the adjusted values of the A and B areas as discussed in the previous section, and the reduction factor β_2 is given in table 3.

Table 3. Relation between average depth of water table D_w (m) and reduction factor β_2

D_w range		
rice crop	non-rice	β_2
-0.10 to -0.20	0.5 - 0.6	0.05
-0.20 to -0.25	0.4 - 0.5	0.10
-0.25 to -0.30	0.3 - 0.4	0.15
-0.30 to -0.35	0.2 - 0.3	0.20
-0.35 to -0.40	0.1 - 0.2	0.25
< -0.40	< 0.1	0.30

The reductions of the field irrigation due to the presence of a shallow water table may reinforce or reduce the irrigation adjustments discussed in the previous section. When, due to the area reductions discussed in the previous section, the water table drops again to greater depths, then above processes are reversed, (addition instead of subtraction and vice versa) but the irrigation will not become greater than the initial irrigation given with the input.

7. ALPHABETICAL LIST OF ALL SYMBOLS USED

A	Fraction of total area occupied by irrigated group A crops (-)
A_c	Fraction of total area permanently occupied by irrigated group A crops throughout the seasons (-)
A_n	Adjusted fraction of total area occupied by irrigated group A crops for the next year (-)
A_p	Fraction of total area occupied by irrigated group A crops in the present year (-)
α	Factor inversely proportional to the standard deviation of salt concentration expressed in EC (m/dS)
B	Fraction of total area occupied by irrigated group B crops (-)
B_c	Fraction of total area permanently occupied by irrigated group B crops throughout the seasons (-)
B_n	Adjusted fraction of total area occupied by irrigated group B crops for the next year (-)
B_p	Fraction of total area occupied by irrigated group B crops in the present year (-)
$\beta\beta_1$	Reduction factor for irrigated area fractions (-)
β_2	Reduction factor of irrigation applications (-)
β_c	Integration constant
c	Euler constant (-)
C	Salt concentration (dS/m)
C_1	Salt concentration at time t_1 (dS/m)
C_2	Salt concentration at time t_2 (dS/m)
C_{A0}	Initial salt concentration of the soil moisture, when at field saturation, in the root zone of the irrigated land under group A crop(s) (EC in dS/m)
C_d	Seasonal average salt concentration of the drainage water (EC in dS/m)
C_{di}	Salt concentration of the subsurface drainage water of the previous season (EC in dS/m)
C_φ	Salt concentration at cumulative frequency φ (EC in dS/m)
C_{gp}	Salt concentration of the capillary rise depending on the presence or absence of a subsurface drainage system (EC in dS/m)
C_{gi}	Salt concentration of the capillary rise at the end of the previous season (EC in dS/m)
C_h	Salt concentration of the horizontally flowing water into the aquifer, when saturated (dS/m)
C_i	Salt concentration of the surface irrigation water including the use of drain or well water for irrigation (dS/m)
C_{ic}	Seasonal average salt concentration of the inflowing canal water (EC in dS/m)
C_L	Salt concentration of percolation water (EC in dS/m)
C_{L0}	Seasonal average salt concentration of the percolation water to the transition zone when K_r=0 (EC in dS/m)
C_{L0A}	Seasonal average salt concentration of the percolation water from the irrigated group A crop(s) when K_r=0 (EC in dS/m)
C_{L0B}	Seasonal average salt concentration of the percolation water from the irrigated group B crop(s) when K_r=0 (EC in dS/m)
C_{L0U}	Seasonal average salt concentration of the percolation water from the non-irrigated land when K_r=0 (EC in dS/m)

C_{L1U}	Seasonal average salt concentration of the percolation water from the permanently non-irrigated land when K_r=1 (EC in dS/m)
C_{L1*}	Seasonal average salt concentration of the percolation water from the land outside the permanently non-irrigated area when K_r=1 (EC in dS/m)
C_{L2A}	Seasonal average salt concentration of the percolation water from the permanently irrigated land under group A crop(s) when K_r=2 (EC in dS/m)
C_{L2*}	Seasonal average salt concentration of the percolation water from the land outside the permanently irrigated area under group A crop(s) when K_r=2 (EC in dS/m)
C_{L3B}	Seasonal average salt concentration of the percolation water from the permanently irrigated land under group B crop(s) when K_r=3 (EC in dS/m)
C_{L3*}	Seasonal average salt concentration of the percolation water from the land outside the permanently irrigated area under group B crop(s) when K_r=3 (EC in dS/m)
C_{L4}	Seasonal average salt concentration of percolation water when K_r=4 (EC in dS/m)
C_m	Salt concentration at time t_m (dS/m)
C_{of}	Salt concentration of the horizontally outflowing water from the aquifer, when saturated, at the end of the present season (EC in dS/m)
C_{oi}	Salt concentration of the horizontally outflowing water from the aquifer, when saturated, at the end of the previous season (EC in dS/m)
C_{ov}	Seasonal average salt concentration of the horizontally outflowing water from the aquifer, when saturated (EC in dS/m)
C_p	Salt concentration of the rain water (EC in dS/m)
C_{qf}	Salt concentration of the soil moisture in the aquifer, when saturated, at the end of the present season (EC in dS/m)
C_{qi}	Salt concentration of the soil moisture in the aquifer, when saturated, at the end of the previous season (EC in dS/m)
C_{qv}	Seasonal average salt concentration of the water in the aquifer, when saturated (EC in dS/m)
C_{q0}	Initial salt concentration of the ground water in the aquifer (EC in dS/m)
C_r	Salt concentration of the water in root zone when at field capacity (EC in dS/m)
C_{r0Af}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the group A crop(s), when K_r=0, at the end of the present season (EC in dS/m)
C_{r0Ai}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the group A crop(s), when K_r=0, at the start of the season, equal to the salt concentration of the same at the end of the previous season (EC in dS/m)
C_{r0Bf}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the group B crop(s), when K_r=0, at the end of the present season (EC in dS/m)
C_{r0Bi}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the group B crop(s), when K_r=0, at the start of the season when saturated, equal to the salt concentration of the same at the end of the previous season (EC in dS/m)

C_{r0Uf}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the non-irrigated land, when $K_r=0$, at the end of the present season (EC in dS/m)
C_{r0Ui}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the non-irrigated land, when $K_r=0$ at the start of the season, equal to the salt concentration of the same at the end of the previous season (EC, dS/m)
C_{r1Uf}	Salt concentration of the soil moisture in the root zone, when at field capacity, in the permanently non-irrigated land, when $K_r=1$, at the end of the present season (dS/m)
C_{r1Ui}	Salt concentration of the soil moisture in the root zone, when at field capacity, in the permanently non-irrigated land, when $K_r=1$, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m)
C_{r1Un}	Adjusted final salt concentration of the soil moisture, when at at field capacity, in the root zone of the permanently non-irrigated land, used for the start of the next year, $K_r=1$ (EC in dS/m)
C_{r1Uv}	Seasonal average salt concentration of the soil moisture in the root zone, when at field capacity, of the permanently non-irrigated land, when $K_r=1$ (dS/m)
C_{r1*f}	Salt concentration of soil moisture in the root zone, when at field capacity, of the land outside the permanently non-irrigated area, when $K_r=1$, at the end of the present season (dS/m).
C_{r1*i}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently non-irrigated area, when $K_r=1$, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m)
C_{r1*v}	Seasonal average salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently non-irrigated area, when $K_r=1$ (dS/m)
C_{r2Af}	Salt concentration of the soil moisture in the root zone, when saturated, in the permanently irrigated land under group A crop(s), when $K_r=2$, at the end of the present season (dS/m)
C_{r2Ai}	Salt concentration of the soil moisture in the root zone, when at field capacity, in the permanently irrigated land under group A crop(s), when $K_r=2$, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m)
C_{r2An}	Adjusted final salt concentration of the soil moisture, when at at field capacity, in the root zone of the permanently irrigated land under group A crop(s), used for the start of the next year, $K_r=2$ (EC in dS/m)
C_{r2Av}	Seasonal average salt concentration of the soil moisture in the root zone, when at field capacity, of the permanently irrigated land under group A crop(s), when $K_r=2$ (dS/m)
C_{r2*f}	Salt concentration of the soil moisture, when at field capacity, of the land outside the permanently irrigated land under group a crop(s), when $K_r=2$, at the end of the present season (dS/m)
C_{r2*i}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently irrigated land under group a crop(s), when $K_r=2$, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m)

C_{r2*v}	Seasonal average salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently irrigated land under group A crop(s), when K_r=2 (dS/m)
C_{r3Bf}	Salt concentration of the soil moisture in the root zone, when saturated, in the permanently irrigated land under group B crop(s), when K_r=3, at the end of the present season (dS/m)
C_{r3Bi}	Salt concentration of the soil moisture in the root zone, when at field capacity, in the permanently irrigated land under group B crop(s), when K_r=3, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m)
C_{r3Bn}	Adjusted final salt concentration of the soil moisture, when at at field capacity, in the root zone of the permanently irrigated land under group B crop(s), used for the start of the next year, K_r=3 (EC in dS/m)
C_{r3Bv}	Seasonal average salt concentration of the soil moisture in the root zone, when at field capacity, of the permanently irrigated land under group B crop(s), when K_r=3 (dS/m)
C_{r3*f}	Salt concentration of the soil moisture in the root zone, when saturated, of the land outside the permanently irrigated land under group a crop(s), when K_r=3, at the end of the present season (dS/m)
C_{r3*i}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently irrigated land under group a crop(s), when K_r=3, at the start of the season, equal to the salt concentration of the same at the end of the previous season (dS/m)
C_{r3*v}	Seasonal average salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently irrigated land under group A crop(s), when K_r=3 (dS/m)
C_{r4f}	Salt concentration of the soil moisture in the root zone at the end of the season, when at field capacity and K_r=4 (EC in dS/m)
C_{r4i}	Salt concentration of the soil moisture in the root zone, at end of the previous season when at field capacity and K_r=4 (EC in dS/m)
C_{r4v}	Seasonal average salt concentration of the soil moisture in the root zone when at field capacity and when K_r=4 (EC in dS/m)
C_{xaf}	Salt concentration of the water in the part of the transition zone above drain level, when saturated, at the end of the season (EC in dS/m)
C_{xai}	Salt concentration of the water in the part of the transition zone above drain level, when saturated, at the end of the previous season (EC in dS/m)
C_{xav}	Seasonal average salt concentration of the water in the transition zone, above drain level, when saturated (EC in dS/m)
C_{xa0}	Initial salt concentration of the ground water in the upper part of the transition zone, i.e. above drain level (EC in dS/m)
C_{xbf}	Salt concentration of the water in the transition zone below drain level, when saturated, at the end of the season (EC in dS/m)
C_{xbi}	Salt concentration of the water in the transition zone below drain level, when saturated, at the end of the previous season (EC in dS/m)
C_{xbv}	Seasonal average salt concentration of the water in the transition zone below drain level, when saturated (EC in dS/m)
C_{xb0}	Initial salt concentration of the ground water in the transition zone below drain level, when saturated (EC in dS/m)
C_{xf}	Salt concentration of the water in the transition zone, when saturated, at the end of the season (EC in dS/m)

C_{xi}	Salt concentration of the water in the transition zone, when saturated, at the end of the previous season (EC in dS/m)
C_{xki}	Salt concentration of the capillary rise at the end of the previous season and depending on the presence or absence of a subsurface drainage system (dS/m)
C_{xv}	Seasonal average salt concentration of the water in the transition zone, when saturated (EC in dS/m)
C_{x0}	Initial salt concentration of the soil moisture in the transition zone (EC in dS/m)
C_{U0}	Initial salt concentration of the soil moisture, when at field saturation, in the root zone of the non-irrigated land (EC in dS/m)
C_{U1f}	Salt concentration of the soil moisture, when at field saturation, in the root zone of the permanently non-irrigated land at the end of the season, $K_r=1$ (EC in dS/m)
C_{U1*f}	Salt concentration of the soil moisture, when at field saturation, in the root zone of the land outside the permanently non-irrigated land at the end of the season, $K_r=1$ (EC in dS/m)
C_{U1n}	Adjusted final salt concentration of the soil moisture, when at field saturation, in the root zone of the permanently non-irrigated land, used for the start of the next year, $K_r=1$ (EC in dS/m)
C_w	Seasonal average salt concentration of the pumped well water (EC in dS/m)
D	Thickness of a reservoir (m)
D_{Bn}	Boundary depth of adjacent reservoir (m)
D_c	Critical depth of the water table for capillary rise (m), $D_c > D_r$
D_d	Depth of subsurface drains (m), $D_r < D_d < D_r + D_t$
D_e	Hooghoudt's equivalent depth of the impermeable layer (m)
D_q	Thickness of the aquifer (m)
D_r	Thickness of the root zone (m), $D_r > 0.1 > D_{cr}$
D_x	Thickness of the transition zone between root zone and aquifer (m)
D_w	Seasonal average depth of the water table below the soil surface (m)
D_{wi}	Initial depth of the water table (m), equal to D_w of the previous season
D_{w0}	Initial depth of the water table in the first year (m)
D_1	Depth of the boundary between surface and root zone reservoir (m)
D_2	Depth of the boundary between root zone and transition zone (m)
D_3	Depth of the boundary between transition zone and aquifer (m)
D_4	Depth of the bottom of the aquifer (m)
ΔW_D	Change in storage remaining after a reservoir has been filled (m^3/season per m_2 total area)
ΔW_M	Maximum possible storage in a reservoir (m^3/season per m_2 total area)
ΔW_q	Change in storage of water in the aquifer (m^3/season per m_2 total area)
ΔW_r	Storage of water in the root zone reservoir (m^3/season per m_2 total area)
ΔW_s	Storage of water in the surface reservoir (m^3/season per m_2 total area)
ΔW_x	Storage of water in the transition zone (m^3/season per m_2 total area)
ΔW	Total storage of water (m^3/season per m_2 total area)
ΔZ_{r0A}	Salt storage in the root zone of the irrigated group A crop(s) when $K_r=0$ (dS/season)
ΔZ_{r0B}	Salt storage in the root zone of the irrigated group B crop(s) when $K_r=0$ (dS/season)

ΔZ_{r0U}	Salt storage in the root zone of the non-irrigated land when $K_r=0$ (dS/season)
ΔZ_{r1U}	Salt storage in the root zone of the permanently non-irrigated land, throughout the seasons, when $K_r=1$ (dS/season)
ΔZ_{r1*}	Salt storage in the root zone of the land outside the permanently non-irrigated area, when $K_r=1$ (dS/season)
ΔZ_{r2A}	Salt storage in the root zone of the permanently irrigated land under group A crop(s), throughout the seasons, when $K_r=1$ (dS/season)
ΔZ_{r2*}	Salt storage in the root zone of the land outside the permanently irrigated land under group A crop(s), when $K_r=1$ (dS/season)
ΔZ_{r3B}	Salt storage in the root zone of the permanently irrigated land under group B crop(s), throughout the seasons, when $K_r=3$ (dS/season)
ΔZ_{r3*}	Salt storage in the root zone of the land outside the permanently irrigated land under group B crop(s), when $K_r=3$ (dS/season)
ΔZ_{r4}	Salt storage in the root zone when $K_r=4$ (dS/season)
ΔZ_x	Salt storage in the transition zone (dS/season)
ΔZ_{xa}	Salt storage in the part of the transition zone above drain level (dS/season)
ΔZ_{xb}	Salt storage in the part of the transition zone below drain level (dS/season)
ΔZ_q	Salt storage in the aquifer (dS/season)
E_a	Total actual evapo-transpiration (m^3/season per m^2 total area)
E_{aA}	Actual evapo-transpiration (m^3/season per m^2 irrigated area under group A crop(s)
E_{aB}	Actual evapo-transpiration (m^3/season per m^2 irrigated area under group B crop(s)
E_{aU}	Actual evapo-transpiration (m^3/season per m^2 non-irrigated area)
E_{ra}	Actual evapo-transpiration from the root zone (m^3/season per m^2 non-irrigated area)
E_{pA}	Potential evapo-transpiration of irrigated group A crop(s) (m^3/season per m^2 irrigated area under group A crops)
E_{pB}	Potential evapo-transpiration of the irrigated group B crop(s) (m^3/season per m^2 irrigated area under group B crops)
E_{pU}	Potential evapo-transpiration of the non-irrigated area (m^3/season per m^2 non-irrigated area)
ε	Proportionality factor (-)
F_c	Capillary rise factor (-)
F_{fA}	Field irrigation efficiency of group A crop(s) (-)
F_{fB}	Field irrigation efficiency of group B crop(s) (-)
F_{ft}	Total field irrigation efficiency (-)
F_l	Leaching efficiency (-)
F_{lq}	Leaching efficiency of the aquifer (-)
F_{lr}	Leaching efficiency of the root zone (-)
F_{lx}	Leaching efficiency of the transition zone (-)
F_{rd}	Reduction factor of the drainage function for water table control or for partial drainage of the area (-)
F_{sA}	Seasonal storage efficiency of irrigation and rain water in irrigated land under group A crop(s): fraction of irrigation and rainwater stored in the root zone of A crop(s) as an average for all irrigations and rain-storms (-)
F_{sB}	Seasonal storage efficiency of irrigation and rain water in irrigated land under group B crop(s): fraction of irrigation and rain water

	stored in the root zone of B crop(s) as an average for all irrigations and rain-storms (-)
F_{sU}	Seasonal storage efficiency of rain water in non-irrigated land: fraction of rainwater stored in the root zone of non-irrigated lands as an average for all rain-storms (-)
F_w	Fraction of pumped well water used for irrigation (-), $0 < F_w < 1$
φ	Cumulative frequency (-)
G_d	Total amount of subsurface drainage water (m^3/season per m^2 total area)
G_a	Subsurface drainage water originating from ground water flow above drain level (m^3/season per m^2 total area)
G_b	Subsurface drainage water originating from ground water flow below drain level (m^3/season per m^2 total area)
G_c	Total amount of controlled subsurface drainage water (m^3/day per m^2 total area)
G_{ca}	Subsurface drainage water originating from ground water flow above drain level (m^3/day per m^2 total area)
G_{cb}	Subsurface drainage water originating from ground water flow below drain level (m^3/day per m^2 total area)
G_u	Part of the subsurface drainage water used for irrigation (m^3/season per m^2 total area)
G_i	Horizontally incoming ground water flow through the aquifer (m^3/season per m^2 total area)
G_o	Horizontally outgoing ground water flow through the aquifer (m^3/season per m^2 total area)
G_w	Ground water pumped from wells in the aquifer (m^3/season per m^2 total area)
H	Hydraulic head (m)
I_{aA}	Irrigation water applied to the irrigated fields under group A crop(s) (m^3/season per m^2 area under group A crops)
I_{aB}	Irrigation water applied to the irrigated fields under group B crop(s) (m^3/season per m^2 area under group B crops)
I_{An}	Irrigation water applied to the irrigated fields under group A crop(s) in the next year (m^3/season per m^2 area under group A crops)
I_{Ap}	Irrigation water applied to the irrigated fields under group A crop(s) in the present year (m^3/season per m^2 area under group A crops)
I_{Bn}	Irrigation water applied to the irrigated fields under group B crop(s) in the next year (m^3/season per m^2 area under group B crops)
I_{Bp}	Irrigation water applied to the irrigated fields under group A crop(s) in the present year (m^3/season per m^2 area under group A crops)
I_c	Part of the irrigation application recovered after percolation by capillary rise (m/season)
I_f	Amount of irrigation water applied to the fields (m^3/season per m^2 total area)
I_g	Gross amount of field irrigation water (m^3/season per m^2 total area)
I_i	Irrigation water supplied by the canal system (m^3/season per m^2 total area)
I_o	Water leaving the area through the irrigation canal system (m^3/season per m^2 total area)

I_t	Total amount of irrigation water applied, including the percolation losses from the canals, the use of drainage and/or well water, and the bypass (m^3/season per m^2 total area)
J_{eA}	Field irrigation effectiveness of group A crops (-)
J_{eB}	Field irrigation effectiveness of group B crops (-)
J_{et}	Total field irrigation effectiveness (-)
J_{sA}	Field irrigation sufficiency of group A crops (-)
J_{sB}	Field irrigation sufficiency of group B crops (-)
J_{st}	Total field irrigation sufficiency (-)
K_a	Hydraulic conductivity of the soil above drainage level (m/day)
K_b	Hydraulic conductivity of the soil below drainage level (m/day)
K_d	Key for the presence of a subsurface drainage system: yes -> K_d=1, no -> K_d = 0
K_f	Key for farmers' responses to water logging, salinization or irrigation scarcity: yes -> K_f=1, no -> K_f=0
K_r	Key for rotational type of agricultural land use (-): K_r = 0, 1, 2, 3 or 4. Possible landuse types are: irrigated land under group A crops, irrigated land under crops group B crops, and non-irrigated land (U); K_r=0no rotation K_r=4full rotation K_r=1part or all of the U-type land remains permanently unchanged, the remaining land is under full rotation K_r=2part or all of the A-type land remains permanently unchanged, the remaining land is under full rotation K_r=3part or all of the B-type land remains permanently unchanged, the remaining land is under full rotation
K_y	Key for yearly changes of input data (-), 0 -> no, 1 -> yes
L	Velocity of percolation (m/time unit)
L_{rA}	Percolation from the root zone (m^3/season per m^2 irrigated area under group A crops)
L_{rB}	Percolation from the root zone (m^3/season per m^2 irrigated area under group B crops)
L_c	Percolation from the irrigation canal system (m^3/season per m^2 total area)
L_r	Total percolation from the root zone (m^3/season per m^2 total area)
L_{rU}	Percolation from the root zone in the non-irrigated area (m^3/season per m^2 non-irrigated area)
8_i	Infiltration through the soil surface into the root zone (m^3/season per m^2 non-irrigated area)
8_o	Upward seepage through the soil surface from the root zone (m^3/season per m^2 non-irrigated area)
M_{Di}	Moisture deficit in a reservoir (m/season)
μ	Mean value of soil salinity used in the Gumbel frequency distribution (EC in dS/m)
N_s	Number of seasons per year, min. 1, max. 4
N_y	Number of years for model running (-), max. 99
Σ_{1A}	Weight factor for the irrigated land under group A crop(s) in the presence of permanently non-irrigated land, K_r=1 (-)
Σ_{1B}	Weight factor for the irrigated land under group B crop(s) in the presence of permanently non-irrigated land, K_r=1 (-)
Σ_{2A}	Weight factor for the irrigated land under group A crop(s) outside the permanently irrigated land under group A crop(s), K_r=2 (-)

Σ_{2B}	Weight factor for the part of the irrigated land under group B crop(s) outside the permanently irrigated land under group A crop(s), $K_r=2$ (-)
Σ_{2U}	Weight factor for the part of the non-irrigated area in the presence of permanently irrigated land under group A crop(s), $K_r=2$ (-)
Σ_{3A}	Weight factor for the irrigated land under group A crop(s) in the presence of permanently irrigated land under group B crop(s), $K_r=3$(-)
Σ_{3B}	Weight factor for the part of the irrigated land under group B crop(s) outside the permanently irrigated land under group B crop(s), $K_r=3$ (-)
Σ_{3U}	Weight factor for the part of the non-irrigated area in the presence of permanently irrigated land under group B crop(s), $K_r=3$ (-)
P_{ei}	Drainable or refillable pore space in the reservoir where the water table is located at the start of the season (-)
P_{er}	Effective porosity (drainable or refillable pore space) of the root zone (m/m)
P_{eq}	Effective porosity (drainable or refillable pore space) of the aquifer (m/m)
P_{ex}	Effective porosity (drainable or refillable pore space) of the transition zone (m/m)
P_p	Rainfall/precipitation (m^3/season per m^2 total area)
P_{tq}	Total pores pace of the aquifer (m/m)
P_{tr}	Total pore space of the root zone (m/m)
P_{tx}	Total pore space of the transition zone (m/m)
Q_{H1}	Ratio of drain discharge and height of the water table above drain level (m/day per m)
Q_{H2}	Ratio of drain discharge and squared height of the water table above drain level (m/day per m^2)
R_{rA}	Capillary rise into the root zone (m^3/season per m^2 irrigated area under group A crops)
R_{rB}	Capillary rise into the root zone (m^3/season per m^2 irrigated area under group B crops)
R_a	Apparent amount of capillary rise into the root zone (m/season)
R_r	Total capillary rise into the root zone (m^3/season per m^2 total area)
R_{rU}	Capillary rise into the root zone of the non-irrigated land (m^3/season per m^2 non-irrigated area)
S_{iU}	Surface inflow of water from surroundings into the non-irrigated area (m^3/season per m^2 non-irrigated area)
S_{oA}	Outgoing surface runoff or surface drain water from irrigated land under group A crop(s) (m^3/season per m^2 irrigated area under group A crops)
S_{oB}	Outgoing surface runoff or surface drain water from irrigated land under group B crop(s) (m^3/season per m^2 irrigated area under group B crops)
S_{oU}	Outgoing surface runoff water from the non-irrigated area (m^3/season per m^2 non-irrigated area)
σ	Standard deviation of soil salinity used in the Gumbel frequency distribution (dS/m)
t	Time (T)
t_1	Moment 1 of time (T)
t_2	Moment 2 of time (T)
t_m	Middle time (T)
T_s	Duration of the season (months)

τ	Dummy variable (-)
U	Non-irrigated fraction of total area (-)
U_c	Permanently non-irrigated fraction of total area throughout the seasons (-)
U_n	Adjusted non-irrigated fraction of total area for the next year (-)
V_A	Surface water resources in the irrigated area under group A crop(s) (m^3/season per m^2 irrigated area under group A crops)
V_B	Surface water resources in the irrigated area under group B crop(s) (m^3/season per m^2 irrigated area under group B crops)
V_L	Vertical downward drainage into the aquifer (m^3/season per m^2 total area)
V_R	Vertical upward seepage from the aquifer (m^3/season per m^2 total area)
V_s	Total surface water resources (m^3/season per m^2 total area)
V_U	Surface water resources in the non-irrigated area (m^3/season per m^2 non-irrigated area)
Y	Spacing of parallel subsurface drains (m)
Ze	Amount of salt entering the surface reservoir (m.dS/m)
Zf	**Final amount of salt stored above the soil surface, i.e. at the en of the season (m.dS/m)**
Zi	Initial amount of salt stored above the soil surface, i.e. at the start of the season (m.dS/m)
Zo	Amount of salt leaving the surface reservoir (m.dS/m)

8. USER MENU

For the DOS versions, the user menu was extensively described. The Windows version is supposed to be self-explanatory, so the description is not anymore given.

9. LIST OF SYMBOLS OF INPUT DATA

The symbols of input data used in the computer program are slightly different from those used in the description of the theory due to the difference in possibilities between a programming language and a word processor.

In some of the following symbols of input variables the sign # is used to indicate the season number: # = 1, 2, 3, or 4

A#	Fraction of total area occupied by irrigated group A crops in season # (-), 0 <A# <
B#	Fraction of total area occupied by irrigated group B crops in season # (-), 0 <B# <
C_{ic}	Salt concentration of the incoming canal water (EC in dS/m)
C_{A0}	Initial salt concentration of the soil moisture, at field capacity, in the root zone of the irrigated land under group A crop(s) (EC in dS/m)
C_{B0}	Initial salt concentration of the soil moisture, at field saturation, in the root zone of the irrigated land under group B crop(s) (EC in dS/m)
C_h	Salt concentration of the incoming ground water (EC in dS/m)
C_p	Salt concentration of the rain water (EC in dS/m)
C_{q0}	Initial salt concentration of the ground water in the aquifer (EC in dS/m)
C_{x0}	Initial salt concentration of the soil moisture in the transition zone (EC in dS/m)
C_{xa0}	Initial salt concentration of the ground water in the upper part of the transition zone, i.e. above drain level (EC in dS/m)
C_{xb0}	Initial salt concentration of the ground water in the lower part of the transition zone, i.e. below drain level (EC in dS/m)
C_{U0}	Initial salt concentration of the soil moisture, when at field saturation, in the root zone of the non-irrigated land (EC in dS/m)
D_c	Critical depth of the water table for capillary rise (m), $D_{cr} > D_r$
D_d	Depth of subsurface drains (m), $D_d > D_r$
D_q	Thickness of the aquifer (m)
D_r	Thickness of the root zone (m), $D_r > 0.1 > D_{cr}$
D_x	Thickness of the transition zone between root zone and aquifer (m)
D_{w0}	Initial depth of the water table (m)
E_{pA}#	Potential evapo-transpiration of irrigated group A crop(s) in season # (m^3/season per m^2 irrigated area under group A crops)
E_{pB}#	Potential evapo-transpiration of irrigated group B crop(s) in season # (m^3/season per m^2 irrigated area under group B crops)

E_{pU}#	Potential evapo-transpiration of non-irrigated area in season # (m^3/season per m^2 non-irrigated area)
F_{la}	Leaching efficiency of the aquifer (-), $F_{la} > 0$
F_{lr}	Leaching efficiency of the root zone (-), $F_{lr} > 0$
F_{lt}	Leaching efficiency of the transition zone (-), $F_{lt} > 0$
F_{rd}	Reduction factor of the drainage function for water table control or for partial drainage of the area (-)
F_{sA}#	Storage efficiency of irrigation and rain water in irrigated land under group A crop(s): fraction of irrigation and rainwater stored in the root zone of A crop(s), average of all irrigations and rain storms (-), $0 < F_{sA} < 1$
F_{sB}#	Storage efficiency of irrigation and rain water in irrigated land under group B crop(s): fraction of irrigation and rain water stored in the root zone of B crop(s), average for all irrigations and rain storms (-), $0 < F_{sB} < 1$
F_{sU}#	Efficiency of rain water in non-irrigated land: fraction of rainwater stored in the root zone of non-irrigated lands as an average for all rain storms (-), $0 < F_{sU} < 1$
F_w#	Fraction of pumped well water used for irrigation (-), $0 < F_w < 1$
G_u#	Subsurface drainage water used for irrigation in season # (m^3/season per m^2 total area), $G_u\# < G_d$
G_i#	Horizontally incoming ground water flow through the aquifer in season # (m^3/season per m^2 total area)
G_o#	Horizontally outgoing ground water flow through the aquifer in season # (m^3/season per m^2 total area)
G_w#	Ground water pumped from wells in the aquifer in season # (m^3/season per m^2 total area)
I_{aA}#	Irrigation water applied to the irrigated fields under group A crop(s) in season # (m^3/season per m^2 area under group A crops)
I_{aB}#	Irrigation water applied to the irrigated fields under group B crop(s) in season # (m^3/season per m^2 area under group B crops)
$_o$#	Water leaving the area through the irrigation canal system in season # (bypass, m^3/season per m^2 total area)
K_d	Key for the presence of a subsurface drainage system: yes -> $K_d = 1$, no -> $K_d = 0$
K_f	Key for farmers' responses to water logging, salinization or irrigation scarcity: yes -> $K_f = 1$, no -> $K_f = 0$
K_r	Key for rotational type of agricultural land use (-): K_r = 0, 1, 2, 3 or 4. Possible landuse types are: irrigated land under group A crops, irrigated land under group B crops, and non-irrigated land (U); K_r=0no rotation K_r=4full rotation K_r=1part or all of the non-irrigated land remains permanently unchanged, the remaining land is under full rotation K_r=2part or all of the irrigated land under group A crop(s) remains permanently unchanged, the remaining land is under full rotation K_r=3part or all of the irrigated land under group B crop(s) remains permanently unchanged, the remaining land is under full rotation
K_y	Key for yearly changes of input data (-)
L_c#	Percolation from the irrigation canal system in season # (m^3/season per m^2 total area)

N_s	Number of seasons per year, $N_s = 1, 2, 3$, or 4
N_y	Number of years for model running (-), $1 < N_y < 99$
P_{eq}	Effective porosity (drainable or refillable pore space) of the aquifer (m/m), $0 < P_{eq} < P_{tq}$
P_{er}	Effective porosity (drainable or refillable pore space) of the root zone (m/m), $0 < P_{er} < P_{tr}$
P_{ex}	Effective porosity (drainable or refillable pore space) of the transition zone (m/m), $0 < P_{ex} < P_{tx}$
P_p#	Rainfall in season # (m^3/season per m^2 total area)
P_{tq}	Total pore space of the aquifer (m/m), $P_{eq} < P_{tq} < 1$
P_{tr}	Total pore space of the root zone (m/m), $P_{er} < P_{tr} < 1$
P_{tx}	Total pore space of transition zone (m/m), $P_{ex} < P_{tx} < 1$
Q_{H1}	Ratio of drain discharge and height of the water table above drain level (m/day per m)
Q_{H2}	Ratio of drain discharge and squared height of the water table above drain level (m/day per m^2)
RcA#	Wether group A crops in season # is paddy (1) or not (0)
RcA#	Wether group B crops in season # is paddy (1) or not (0)
S_{iU}#	Surface inflow from surroundings into the non-irrigated area in season # (m^3/season per m^2 non-irrigated area)
S_{oA}#	Outgoing surface runoff or surface drain water from irrigated land under group A crop(s) in season # (m^3/season per m^2 irrigated area under group A crops)
S_{oB}#	Outgoing surface runoff or surface drain water from irrigated land under group B crop(s) in season # (m^3/season per m^2 irrigated area under group B crops)
S_{oU}#	Outgoing surface runoff water from the non-irrigated area in season # (m^3/season per m^2 non-irrigated area)
T_s#	Duration of the season # (months)

10 LIST OF SYMBOLS OF OUTPUT DATA

A	Seasonal fraction of the area under irrigated group A crop(s) (-), equal to the input value A_1, A_2, A_3 or A_4, depending on the season, or determined by eqn. 106 when the key for farmers' responses K_f=1
A_c	Fraction of the area permanently under irrigated group A crop(s) throughout the seasons (-)
B	Seasonal fraction of the area under irrigated group B crop(s) (-), equal to the input value B_1, B_2, B_3 or B_4, depending on the season, or determined by eqn. 107 when the key for farmers' responses K_f=1
B_c	Fraction of the area permanently under irrigated group B crop(s) (-)
C_d	Seasonal average salt concentration of the drainage water, eqn 75 (EC in dS/m)
C_{qf}	Salt concentration of the soil moisture in the aquifer, when saturated, at the end of the season (EC in dS/m), eqn. 74
C_{rA}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the permanently irrigated land under group A crop(s) at the end of the present season (EC in dS/m), only used when the rotation key K_r=0 or K_r=2 and equal to C_{r0Af} in eqn. 80a or C_{r2Af} in eqn. 93a respectively
C_{rB}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the permanently irrigated land under group B crop(s) at the end of the present season (EC in dS/m), only used when the rotation key K_r=0 or K_r=3 and equal to C_{r0Bf} in eqn. 80b or C_{r3Bf} in eqn. 100a respectively
C_{rU}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the permanently non-irrigated (U) land at the end of the present season (EC in dS/m), only used when the rotation key K_r=0 or K_r=1 and equal to C_{r0Uf} in eqn. 80c or C_{r1Uf} in eqn. 86a respectively
C_{1*}	Salt concentration of soil moisture in the root zone, when at field capacity, of the land outside the permanently non-irrigated (U) area at the end of the present season (EC in dS/m), only used when the rotation key K_r=1 and equal to C_{r1*f} in eqn. 86b
C_{2*}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently irrigated land under group A crop(s) at the end of the present season (EC in dS/m), only used when the rotation key K_r=2 and equal to C_{r2*f} in eqn. 93b
C_{3*}	Salt concentration of the soil moisture in the root zone, when at field capacity, of the land outside the permanently irrigated land under group B crop(s) at the end of the present season (dS/m), only used when the rotation key K_r=3 and equal to C_{r3*f} in eqn. 100b
C_{r4}	Salt concentration of the soil moisture in the root zone, when at field capacity in the fully rotated land at the end of the season (EC in dS/m), only used when the rotation key K_r=4 and equal to C_{r4f} in eqn. 62
C_{xa}	Salt concentration of the soil moisture in the transition zone aquifer above drain level, when saturated, at the end of the season (EC in dS/m), only used when the drainage key K_d=1 and equal to C_{xaf} in eqn. 72a
C_{xb}	Salt concentration of the soil moisture in the transition zone below drain level, when saturated, at the end of the season (EC in dS/m), only used when the drainage key K_d=1 and equal to C_{xbf} in eqn. 72b

C_{xf}	Seasonal average salt concentration of the soil moisture in the transition zone, when saturated, at the end of the season (EC in dS/m), only used when the drainage key K_d=0, eqn. 70
C_w	Seasonal average salt concentration of the pumped well water (EC in dS/m), eqn. 76
D_w	Seasonal average depth of the water table below the soil surface (m), eqn. 41, 42
E_{aU}	Actual evapo-transpiration in the non-irrigated land (m^3/season per m^2 non-irrigated area), eqn. 27
F_{fA}	Field irrigation efficiency of group A crop(s) (-), eqn. 46a
F_{fB}	Field irrigation efficiency of group B crop(s) (-), eqn. 46b
F_{ft}	Total field irrigation efficiency (-), eqn. 47
G_d	Total amount of subsurface drainage water (m^3/season per m^2 total area), only used when the drainage key K_d=1, eqn. 36a and 38
G_a	Subsurface drainage water originating from ground water flow above drain level (m^3/season per m^2 total area), only used when the drainage key K_d=1, eqn. 36c
G_b	Subsurface drainage water originating from ground water flow below drain level (m^3/season per m^2 total area), only used when the drainage key K_d=1, eqn. 36b
I_{aA}	Amount of field irrigation (m^3/season per m^2 irrigated land under group A crop(s)), equal to the input value I_{aA1}, I_{aA2}, I_{aA3} or I_{aA4}, depending on the season, or determined by eqn. 110a and 113a when the key for farmers' responses K_f=1
I_{aB}	Amount of field irrigation (m^3/season per m^2 irrigated land under group B crop(s)), equal to the input value I_{aB1}, I_{aB2}, I_{aB3} or I_{aB4}, depending on the season, or determined by eqn. 110b and 113b when the key for farmers' responses K_f=1
I_o	Water leaving the area through the irrigation canal system (bypass, m^3/season per m^2 total area), equal to the input value I_{o1}, I_{o2}, I_{o3} or I_{o4}, depending on the season, or determined by eqn. 109 and 112 when the key for farmers' responses K_f=1
I_s	Net amount of irrigation water supplied by the canal system including the percolation losses from the canals, but excluding the use of drain and well water and the bypass (m^3/season per m^2 total area): I_s=I_i(eqn. 18)-I_o
I_t	Total amount of irrigation water applied, including the percolation losses from the canals and the use of drainage and/or well water, but excluding the bypass (m^3/season per m^2 total area), eqn. 48
J_{sA}	Irrigation sufficiency of group A crop(s) (-), eqn. 49a
J_{sB}	Irrigation sufficiency of group B crop(s) (-), eqn. 49b
K_r	Key for rotational type of agricultural land use (-): K_r = 0, 1, 2, 3 or 4. This value may be the same as the one given with the input or it may be changed by the program. Possible landuse types are: irrigated land under group A crops, irrigated land under crops group B crops, and non-irrigated land (U); K_r=0no rotation K_r=4full rotation K_r=1part or all of the non-irrigated land remains permanently unchanged, the remaining land is under full rotation K_r=2part or all of the irrigated land under group A crop(s) remains permanently unchanged, the remaining land is under full rotation

	$K_r=3$ part or all of the irrigated land under group B crop(s) remains permanently unchanged, the remaining land is under full rotation
L_{rA}	Percolation from the root zone (m^3/season per m^2 irrigated area under group A crops), eqn. 19a
L_{rB}	Percolation from the root zone (m^3/season per m^2 irrigated area under group B crops), eqn. 19b
L_{rT}	Total percolation from the root zone (m^3/season per m^2 total area), eqn. 19
L_{rU}	Percolation from the root zone in the non-irrigated area (m^3/season per m^2 non-irrigated area), eqn. 19c
R_{rA}	Capillary rise into the root zone (m^3/season per m^2 irrigated area under group A crop(s), eqn. 27a
R_{rB}	Capillary rise into the root zone (m^3/season per m^2 irrigated area under group B crop(s), eqn. 27b
R_{rT}	Total capillary rise into the root zone (m^3/season per m^2 total area), eqn. 21
R_{rU}	Capillary rise into the root zone of the non-irrigated land (m^3/season per m^2 non-irrigated area), eqn. 27c
U	Seasonal fraction of the non-irrigated area (-), equal to the input value U_1, U_2, U_3 or U_4, depending on the season, or determined by eqn. 108 when the key for farmers' responses $K_f=1$
U_c	Fraction of the permanently non-irrigated area throughout the seasons (-)

11 CASE STUDY EGYPT

The case study based on the article "Drainage and Salinity Predictions in the Nile Delta, using Saltmod" (Oosterbaan and Abu Senna, 1990).

11.1. Introduction

The Mashtul area in the Nile Delta, Egypt, suffered from water logging and salinity. For reclamation, a drainage pilot area was installed and many water and salt balance factors were measured. However, some factors could not be measured, notably the leaching efficiency of the root zone and the natural drainage of ground water through the aquifer (there was no upward seepage of ground water from the aquifer into the upper soil layers). Before applying Saltmod, these factors must be determined. This can be done by running trials with Saltmod, using different values of leaching efficiency and natural drainage, and choosing those values that produce soil salinities and depths to water table that correspond with the actually measured values. The procedure is called calibration.

Thereafter, as an example of application, the effects of different drain depths will be investigated and the optimum drain depth will be determined. Further the initial situation will be reconstructed using the farmers' responses to water logging and salinity.

In the Mashtul area, there are irrigated crops of group B (rice, 20%) and A (non-rice, 80%) in summer and only crops of group A in winter (100%).

The basic data of the pilot area are in the file MPBAS.DAT (table 1, section 8.2).

11.2. Calibrating the leaching efficiency

Leaching efficiencies of the root zone (F_{lr}) are given a range of arbitrary values and the corresponding salinity results of the program are compared with the values actually measured. The efficiency producing the best match is assumed to be the real efficiency. The arbitrary F_{lr} values are taken as 0.1, 0.2, 0.4, 0.6, 0.8 and 1.0. One can introduce these values in the input file through the input menu, by renaming the input file each time the value of F_{lr} has been changed, e.g. MP01.INP, MP02.INP, MP04.INP etc. By doing the calculations, the output files, in this example, will be named MP01.RES, MP02.RES, MP04.RES, etc. By inspecting the output files and transferring the values of the salinity results to a spreadsheet program, fig. 11 was prepared.

In fig. 11 the actually measured salinity values are also indicated. Since the soil salinity expressed in EC at field saturation is about double the soil salinity expressed in ECe of the saturation extract, and the actual measurements were done on ECe values, the necessary corrections have been made.

From the figure the following conclusions can be drawn:

1. The curve corresponding to F_{rl} = 0.8 is matching best to the observed values.

2. The match is not perfect due to random or systematic measuring errors and/or imperfection of the model. However, the fitting is close enough to warrant the conclusion that the real F_{lr} value is 0.8. From here on all subsequent calculations will be based on this F_{lr} value.
3. Changes of F_{lr} values in the range of 0.6 to 1.0 have relatively little influence on the salinity, whereas changes in the range of smaller F_{lr} values have a considerable influence.

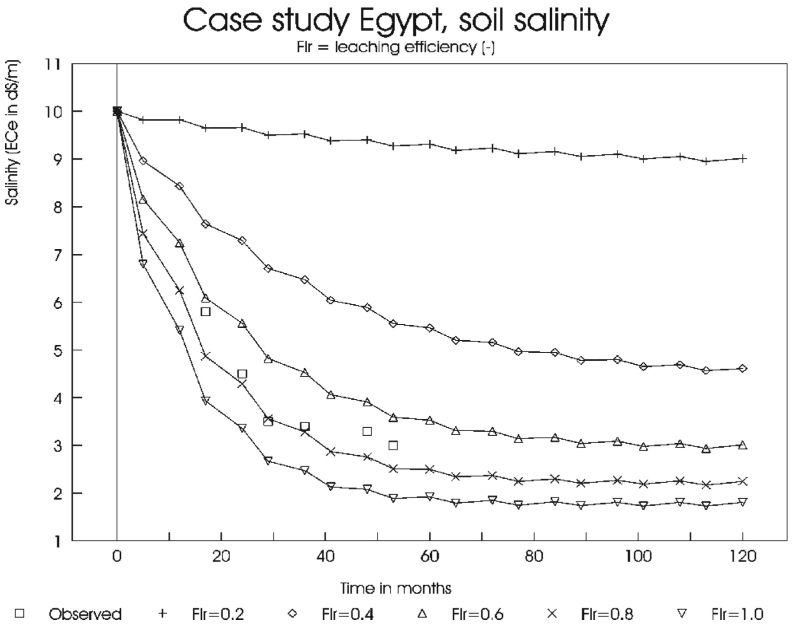

Figure 11. Calibration of leaching efficiency (F_{lr}) to observed soil salinity.

Vanegas (1993) carried out a similar study in the Tagus delta, Portugal, but he found a much lower probable value of F_{lr}: in the order of 0.15. This explained the difficulty of reclaiming these soils to a great extent. The Nile and Tagus deltas both have heavy alluvial clay soils but they must have quite different leaching properties.

In fig. 12, trends of the salinity (C_{xa}) of the upper part of the transition zone, above drain level, and the salt concentration (C_d) of the drainage water are shown. It can be seen that the salinity C_{xa} exhibits a slight increase during the first year as the leaching of the root zone brings the salts downward, but it decreases later on. The salinity C_d is not very variable as the drains receive their water from below drain level. Yet a slight curvature can be detected: during the first 5 years there is a slight increase and thereafter a decrease.

Due to the comparatively smaller vertical scale fig. 12 shows, more clearly than fig. 11, that in the course of the time there is a slight resalinization during the summer (second season), but it is taken care of during winter and the salt balance is well under control as the salinities establish themselves at a low enough level.

It can be concluded that the reaction of C_{xa} lags somewhat behind that of C_{r4}, but the reaction of C_d lags behind that of the upper part of C_{xaf}.

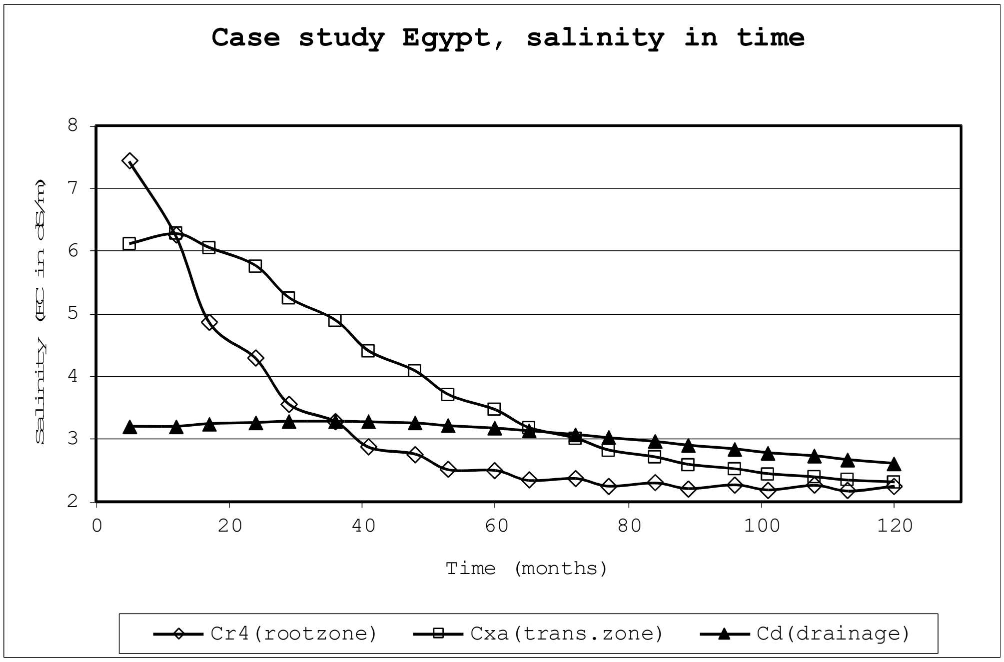

Figure 12. Salinity (EC in dS/m) of the root zone (C_{r4}), upper part of the transition zone (C_{xa}) and of the drainage water (C_d) at the end of the season versus time.

11.3. Determining the natural subsurface drainage

The natural subsurface drainage (G_n=G_o-G_i) is defined as excess of the horizontally outgoing over the horizontally incoming ground water in m/season. It can be determined by setting the G_i values at zero, varying arbitrarily the G_o values, and finding the corresponding values of the depth to water table (D_w) and the drain discharge (G_d). The most likely value of the natural drainage is the one giving D_w and G_d values that agree with the observed values. Taking into account that the 1st season (5 months) is shorter than the second season (7 months), the arbitrary G_{o1} and G_{o2} values, i.e. the G_o values for the 1st and 2nd season respectively, are in pairs: (0.00, 0.00), (0.03, 0.04), (0.06, 0.08), (0.09, 0.12), and (0.12, 0.16). As the inflow G_i is taken equal to zero, the G_o values of both seasons together give the annual G_n values as shown in table 7. For the 2nd year, the resulting D_w and G_d values are also shown in the table.

As rainfall in the Nile Delta is negligibly small, and the High Dam has an enormous capacity providing a constant irrigation over the years, it is not required to introduce annual changes in rainfall and irrigation, so that the drainage results for the years beyond year 5 are the same as in table 7.

Table 7 Values of annual natural drainage towards the underground (G_n, m/year), seasonal average depth of the water table (D_w, m) and quantity of drainage water (G_d, m/season) for the 5th year.

G_n Annual Value	1st season (summer)		2nd season (winter)	
	D_w	G_d	D_w	G_d
0.00	0.95	0.18	1.14	0.15
0.07	1.01	0.15	1.20	0.11
0.14	1.07	0.13	1.26	0.06
0.21	1.13	0.10	1.32	0.03
0.28	1.24	0.05	2.17	0.00

In the first years, due to transition from an un-drained to a drained situation, the D_w and G_d values are somewhat different, and therefore the more stable fifth year was chosen to present the results of the computations.

It was observed that the actual seasonal average depth of the water table varied between 1.0 and 1.1 m in summer (season 1) and between 1.2 and 1.3 m in winter (season 2), with corresponding drain discharges between 100 and 150 mm in summer and 50 and 100 mm in winter. Comparing the observed values with those of table 7 learns that the actual annual G_n value is probably in the range between 0.10 and 0.20 m. Although this result is not very accurate, there is proof that a modest amount of natural drainage is present. For further calculations it will be assumed that the correct value of the annual natural subsurface drainage amounts to G_n=0.14 m, from which follows G_{o1}=0.06 and G_{o2}=0.08 m/season for the 1st and 2nd season respectively, in proportionality to the duration of both seasons (5 and 7 months respectively).

11.4. Simulating effects of varying drain depths

As an example of the effects that can be calculated for different water management options, we will study the effects of varying drain spacing to see if there exists an optimum drain depth. We will also use the drain depth D_d=0.6 m as it existed before the installation of the pilot area as well as D_d=1.4 m, the drain depth adopted in the pilot area. The whole range of D_d values and the corresponding results of the calculations of some of the decisive parameters are shown in table 8. When D_d=0.6 m, the root zone depth D_r must be changed into 0.5 m, otherwise a warning will be given that the condition $D_d>D_r$ is not met.

Table 8 shows that an increase of the drain depth decreases the soil salinity (C_{r4}) and increases the drain discharge (G_d), but in this example the effects are not dramatic. The influence on depth to water table (D_w) is more pronounced. Safwat Abdel-Dayem and Ritzema (1990) have shown that the seasonal average drain depth in the Nile delta should not be less than 0.7 m to avoid decline in crop yield (fig. 13). Therefore, according to the table, a minimum drain depth of D_d = 1.0 is required to safeguard the crop production. A drain depth of D_d = 1.4 m appears to be excessive.

Table 8 Drain depth (D_d, m), soil salinity (C_{r4}, dS/m), field irrigation efficiency of the group A crops (FaA, -), field irrigation sufficiency of the group A crops (JsA, -), seasonal average depth of the water table (D_w, m), and quantity of drainage water (G_d, mm per season) for the 10th year.

Drain Depth D_d	C_{r4}	FaA	JsA	D_w	G_d
	1st season (summer)				
0.6	2.7	0.84	0.99	0.37	105
0.8	2.5	0.83	0.98	0.55	112
1.0	2.4	0.82	0.97	0.74	117
1.2	2.2	0.81	0.96	0.93	122
1.4	2.1	0.80	0.95	1.12	127
	2nd season (winter)				
0.6	2.8	0.86	0.97	0.55	31
0.8	2.7	0.84	0.95	0.74	37
1.0	2.5	0.82	0.93	0.94	45
1.2	2.3	0.81	0.92	1.12	54
1.4	2.2	0.80	0.91	1.31	57

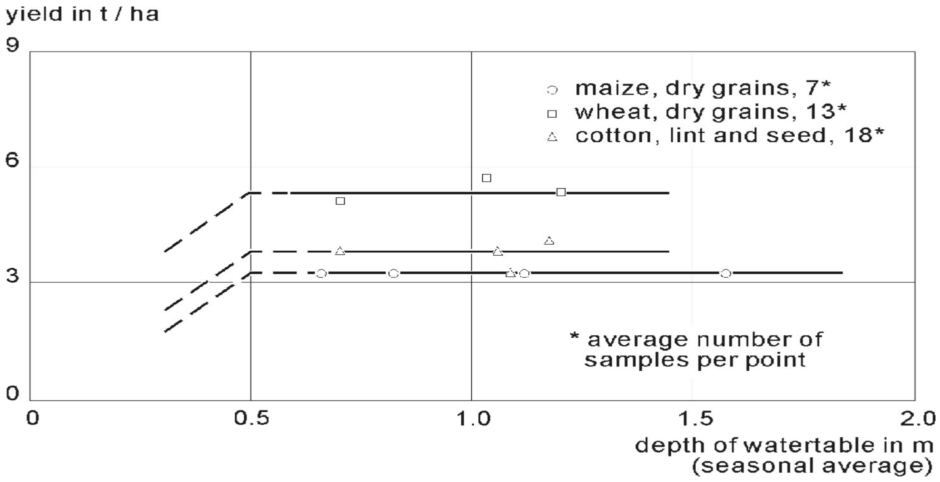

Figure 13. The average yield of some irrigated crops versus seasonal average depth of the water table. Data from the Mashtul pilot area in the Nile Delta, Egypt (Safwat Abdel-Dayem and Ritzema 1990)

It is unlikely that farmers will maintain the high irrigation applications when the water table becomes shallow, as is the case when the drain depth is 0.6 m. The farmers responses will be simulated in the next section.

11.5. Reconstructing the initial conditions

To reconstruct the initial conditions, before the installation of the drainage pilot area, the farmers responses have to be simulated. This can be done by changing manually the input values of the corresponding parameters each year. Saltmod also has a provision for automatic adjustments, which will be applied here. We use the same data as in the previous section, restrict ourselves to the case with D_d = 0.6 m, D_r=0.5 m, and Q_{H1} = 0.002 (i.e the original drainage system was shallower and less intensive than the later system), change the value of the farmers' response key K_f from 0 (= no response) to 1, and give the initial root zone salinities C_{A0}, C_{B0}, and C_{U0} the value 2 dS/m, approximately equal to the value attained 10 years after the installation of the pilot area. The results are shown in fig. 14, but only for the first season.

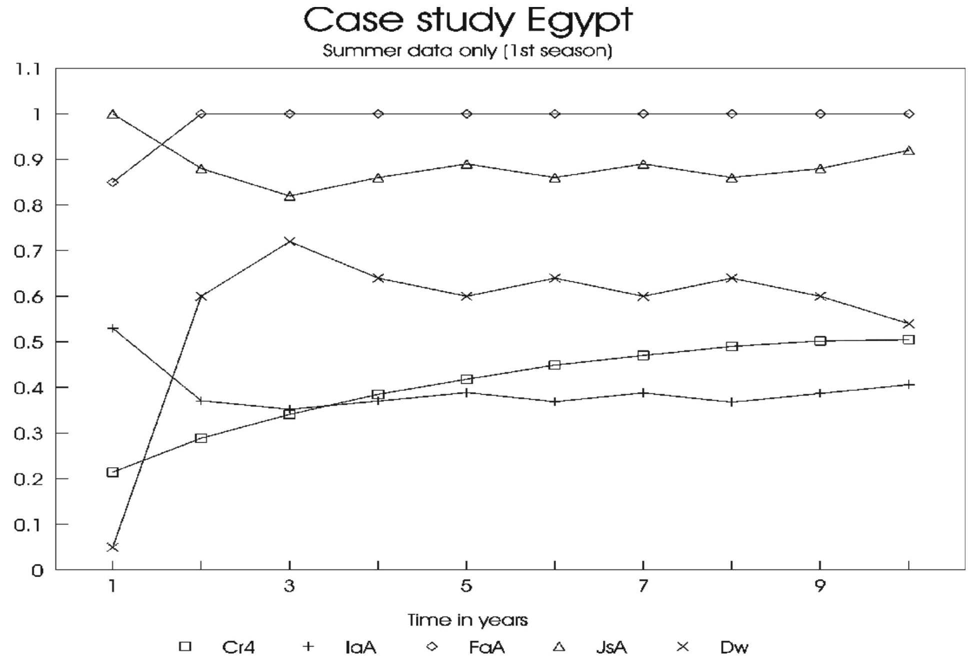

Figure 14. Soil salinity of the root zone (C_{r4}, S/m), seasonal quantity of field irrigation of group A crops (I_{aA}, m), the corresponding irrigation efficiency (F_{aA}, -) and sufficiency (J_{sA}, -), and depth of water table (D_w, m) for the first season (summer) against time.

Fig. 14 shows that after the first 5 months of the first season, the water table rises close to the soil surface (the depth D_w = 0.1 m). The farmers respond by cutting the irrigation supply (I_{aA}) from 530 mm to about 370 mm/season with oscillations of about 50 mm/season. The desired result is an increase in the depth of the water table (D_w) to about 0.6 m with oscillations of 0.05 m. The gains are: saving irrigation water and give a better agricultural performance. The field irrigation efficiency (F_{fA}) goes up from 85% to almost 100% The price is a decrease in field irrigation sufficiency (J_{sA}) from 100% to below 90%, indicating that the crop production may drop due some shortage of water. Worse, however is the gradually increasing soil salinity C_{r4} from 0.2 S/m (or 2 dS/m) to 0.5 S/m (or 5 dS/m), due to insufficient leaching.

12 CASE STUDY INTERACTIONS

12.1. Introduction

Saltmod can be used to analyze data from pilot areas, as done in the previous case study, where data are available for calibration, but also to demonstrate the interactions between irrigation, water table, salinity and agriculture.

A scenario is presented for an area with a water table at 10 m depth when irrigation starts. There are two seasons: an irrigation season, and a non-irrigation season when agriculture is rainfed. Initially, during the irrigation season, 100% of the area is under irrigation. There is no natural or artificial drainage and no use of ground water for irrigation. For this scenario, Saltmod is run in "automatic gear": the program runs for 25 years without changing the external boundary conditions (e.g. rainfall) but generating automatic internal responses to changing internal conditions, such as the farmers' responses, which are simulated through in built mechanisms. For example:

- reduction of irrigated area when irrigation water is scarce,
- reduction in irrigation supply per ha when the water table becomes shallow,
- abandoning land upon salinization.

In this scenario, the option to change conditions annually and manually ("manual gear") by interactive intervention is not used.

Table 9 shows the input file and the results of the computations with those input data are presented in the following figures prepared by a spread-sheet program in which the groups of output data, saved in .PRN files, were imported.

The trends revealed in the figures and the interactions between the various variable involved are discussed hereunder.

Table 9. Input data used in the case study "Interactions".

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Filename interact.inp
Simulation farm responses

1.      Area    Ns      Kd      Kf      Kr
        100.0   2       0       1       4
2.      Ny      Ky
        20      1
3.      Ts1     Ts2
        5.0     7.0
4.      A1      B1      A2      B2
        1.000   0.000   0.000   0.000
5.      RcA1    RcB1    RcA2    RcB2
         0       0       0       0
6.      Lc1     Io1     Lc2     Io2
        0.100   0.000   0.000   0.000
7.      IaA1    EpA1    IaA2    EpA2
        0.500   0.700   0.000   0.800
8.      IaB1    EpB1    IaB2    EpB2
        0.000   0.000   0.000   0.000
9.      Pp1     EpU1    Pp2     EpU2
        0.100   0.500   0.500   0.800
10.     FsA     FsB     FsU
        0.800   0.500   0.900
11.     Gi1     Go1     Gi2     Go2
        0.000   0.000   0.000   0.000
12.     SiU1    SoU1    SiU2    SoU2
        0.000   0.000   0.000   0.000
13.     SoA1    SoB1    SoA2    SoB2
        0.000   0.000   0.000   0.000
14.     Gw1     Fw1     Gw2     Fw2
        0.000   0.000   0.000   0.000
15.     Dr      Ptr     Dx      Ptx     Dq      Ptq
        0.600   0.500   4.000   0.500   6.000   0.500
16.     Per     Flr     Pex     Flx     Peq     Flq
        0.050   0.700   0.050   0.800   0.200   1.000
17.     Cx0     Cq0     Cic     Cg      Cp
        1.000   1.000   0.500   0.000   0.000
18.     CA0     CB0     CU0     Dw0     Dc
        2.000   2.000   2.000   10.00   1.500
```

12.2. Irrigation efficiency, sufficiency, depth to water table and irrigated area fraction

Fig. 15, giving only the data for the irrigation season, shows that the irrigated area decreases in the first 4 years from 100% to about 80%, and that in the years 8 to 12 it again increases to about 95% Thereafter a stong reduction sets in to below 70% The reductions/indreases have different causes.

The figure shows the reason for the first reduction, presenting the irrigation sufficiency, defined here as the ratio between actual evapo-transpiration and the potential evapo-transpiration of the irrigated crops. In the first 4 years the sufficiency increases from less than 70% to over 80% Apparently there is not enough irrigation water available to irrigate all crops with acceptable sufficiency and the farmers leave some of the land temporarily fallow so that more water can be applied to the remaining irrigated land. The fallow land is not permanently left fallow, but in rotation with the irrigated land.

The depth of the water table in fig. 15 decreases steadily during the first 5 years, i.e the water table is rising. Especially during the 4th year there is a sharp rise due to a smaller porosity of the soil. From the 5th year, the depth of the water table becomes less than 1 m, and deep percolation losses can no longer occur. Thus, more water comes available to the plants and the sufficiency rises to almost 100%

Fig. 15 also shows the irrigation efficiency, defined here as the ratio between the amounts of irrigation water used by the crop and the amount of irrigation water applied. The difference between these two amounts may be called deep percolation losses. Due to the rise of the water table, field irrigation losses by deep percolation reduce and, therefore, both efficiency and sufficiency increase

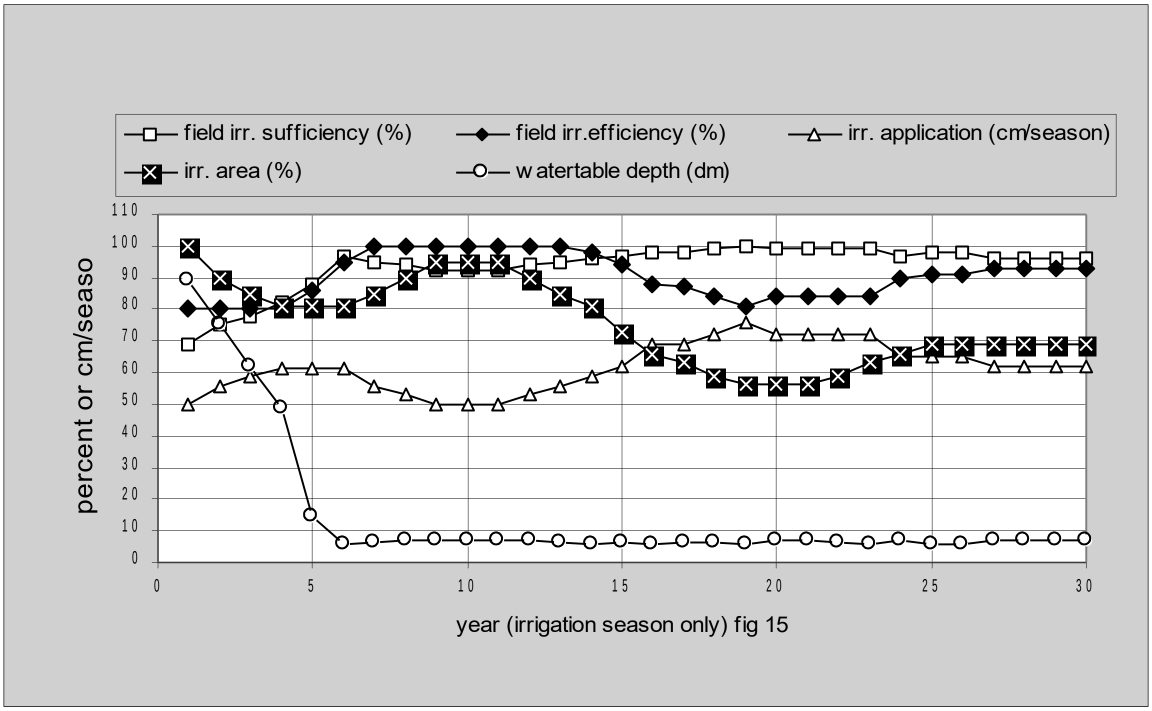

Figure 15. Relations between irrigated area (A, %), amount of field irrigation water (I_{aA}, cm/season), total irrigation efficiency (F_{ft}, %), field irrigation sufficiency (J_{sA}, %) and depth to water table (D_w, dm).

Initially, although the irrigation application per ha increases, the efficiency does not decrease much due to the existing lack of sufficiency: there is no over-irrigation and only unavoidable losses occur. After 4 years the efficiency increases sharply as the water table becomes shallow and the percolation losses can no longer occur. Any water percolating down to the water table is recovered by capillary rise.

However, after year 13 the efficiency comes down again, which is related to the simultaneous reduction of irrigated area. Apparently, for some reason, the farmers have decided to increase the deep percolation and leaching. The explanation is offered by the trend of soil salinity in fig. 16.

12.3. Irrigation and soil salinity

Fig. 16 shows that the soil salinity C_{r4} hardly increases during the first 4 years, as leaching through deep percolation checks it. Only seasonal fluctuations occur: in the irrigation season a slight build-up of salinity occurs as the irrigation efficiency is high, but in the non-irrigated rainy season the salts are washed out.

When towards year 6 the water table comes close to the soil surface, deep percolation is restricted. Thus, leaching is less and the input of salts brought by the irrigation water causes a rising salinity level. The salinity reaches a maximum in the 14th and 15th year thereafter it decreases. The reduction is the result of the increasing supply of irrigation water per ha as demonstrated in Fig. 15.

One may wonder how it would be possible to increase the irrigation supply per ha, increasing the deep percolation, while the water table remains shallow. Fig. 16, depicting the non-irrigated land may shed some light on this phenomenon. It demonstrates that the non-irrigated area (rotational fallow) increase from 0 to about 20% during the first 5 years. As discussed before, this is related to the sufficiency problem. Thereafter, from year 6 to 10, the non-irrigated area reduces again because more irrigation water becomes available as the water table rises and the losses are reduced. However, from year 11, the fallow land increases rapidly to more than 30 % and close to 40%.

Salinity usually develops patch-wise and the area frequency distribution of the salinity (not shown here, but to be found by scrolling through the output file) will show that, in year 10, 20% of the land has salinity higher than 97 cS/m (9.7 dS/m). In the salty patches, crop production becomes so low that agriculture is not feasible, and the patches are abandoned for irrigated cultivation.

The abandoned land becomes dry and capillary rise of water from the water table to the soil surface occurs. Upon evaporation of the water, the salts remain behind in the soil and the soil salinity increases further (see C_{rU} in fig. 16). At the same time, the abandoned land serves as a drainage area for the surrounding irrigated land, so that here percolation and salt leaching can continue. Hence, the salts are transported from the irrigated to the non-irrigated land, thereby safeguarding the irrigated from salinization (this is sometimes called "sacrificial drainage"). Therefore, from year 15 to year 23, the salinity C_{1*} of the irrigated land, next the abandoned land, is reduced from 120 cS/m to 55 cS/m. In the years 11 to 19 there is a transition phase, as the land is not abandoned abruptly but gradually.

Farmers' responses to adversely changing conditions are slow, but in the end the may "overshoot". When the salinity has reached a safe level, they try to restore the older situation, and return to a more daring, risky, operation, overshooting again, until they re-discover the unfavourable effects. In the long run an equilibrium situation will be reached. In this example after some 25 to 30 years, but the equilibrium will be dynamic (cyclic).

The above land and water management measures are combined in fig. 17 illustrating an increase of application of irrigation water per ha during the years 12 to 19. This is made possible by leaving more land non-irrigated (U_c land) and at the same time the leaching of the irrigated land is increased. Fig. 18 depicts the subsequent processes of percolation and capillary rise.

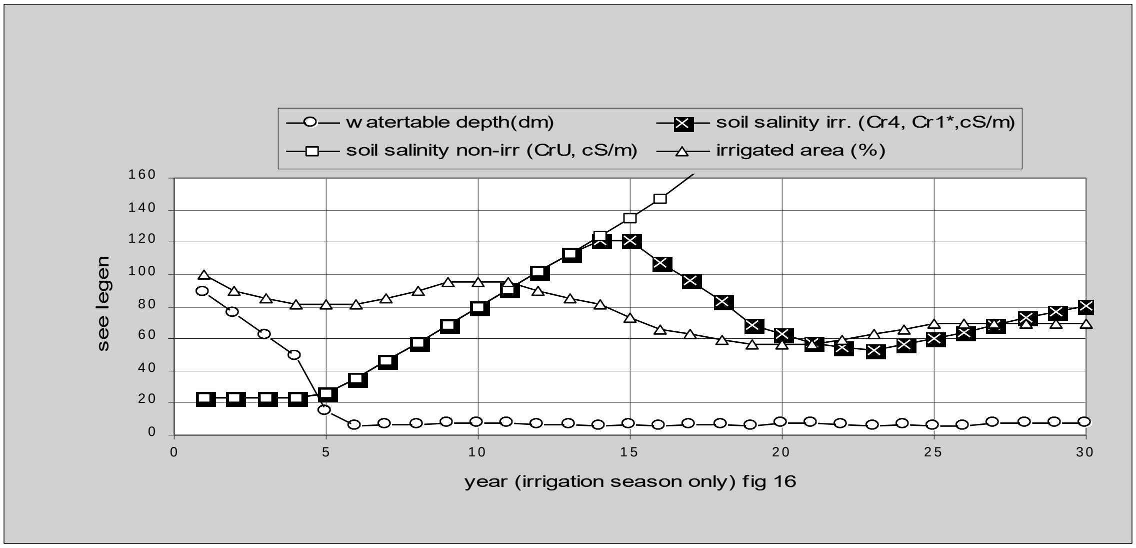

Figure 16. Relations between depth of water table (D_w, dm), soil salinity of the root zone of the area under rotated land use (C_{r4}, EC in cS/m), soil salinity of the root zone in the permanently fallow and abandoned land (C_{rU}, EC in cS/m) and soil salinity of the root zone in the un-abandoned land (C_{1*}, EC in cS/m).

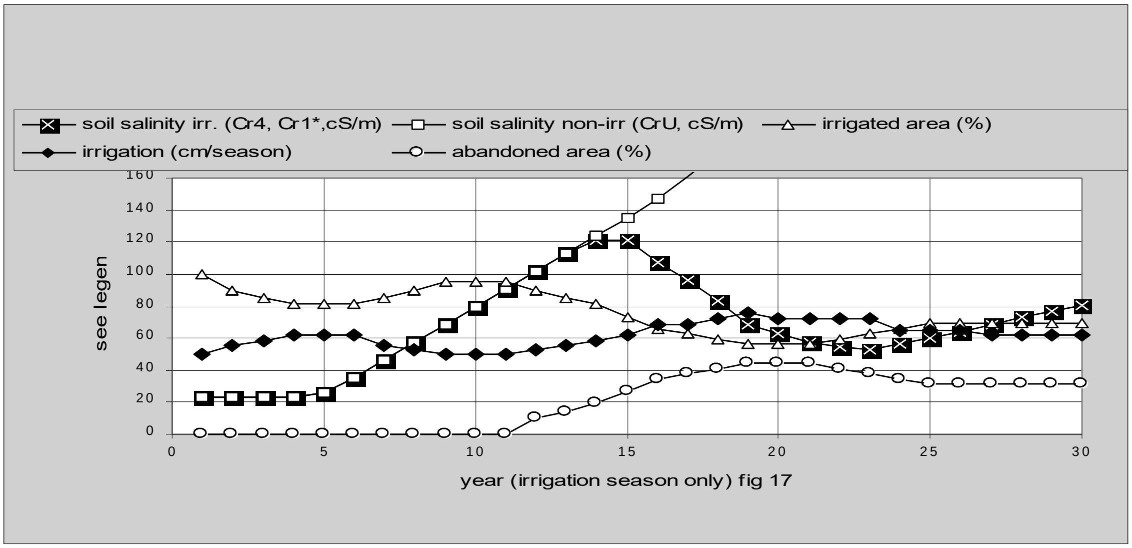

Figure 17. Combined relations between parameters shown and explained in fig.15 and 16.

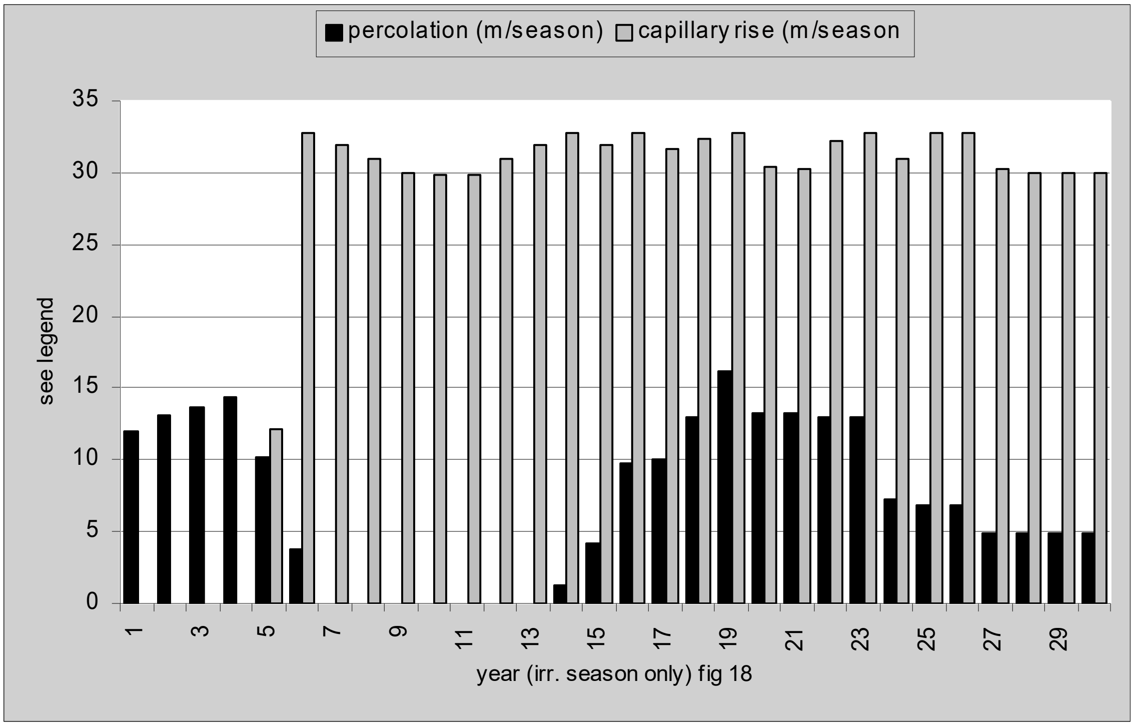

Figure 18. Average percolation as if resulting from the total area (L_{rT}) and average capillary rise (R_{rT}).

12.4. Conclusion

From the previous examples the following conclusions are drawn.

1. Irrigation and agricultural practices both determine the water and salt balance, which in turn determine these practices. There is a boomerang effect. All contributing factors are interwoven into a coherently knitted tissue.
2. Isolated drainage measures to combat problems of water logging and salinity run the risk of failure.
3. Hydro-agro-salinity models such as Saltmod are a useful tool to understand the intricate interrelations.

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