# The role of farmers' responses in the Agro-Hydro-Salinity model SaltMod regarding water management, cropping patterns, or crop rotations, in the case of inadequate irrigation, drainage (water logging) problems, and/or excess soil salinity

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**Abstract**
The SaltMod model deals with agricultural, hydrological and soil situations. It aims at assessing practical situations in farm lands, It works with such phenomena as rainfall, irrigation, potential and actual evaporation, cropping patterns and crop rotations, soil conditions, salt balances, surface and subsurface drainage, natural drainage to the underground or upward seepage of groundwater. When the water table becomes too shallow, the soil salinity too high, or the irrigation sufficiency too low, the model can give the user the option to activate the farmers' responses adapting the on-farm irrigation or cropping practices. In this article examples will be given of logical farmers' responses to water management and cropping practices that are inadequate to maintain in the long run.

**Contents**

# 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. [**Ref.** 1]. The complete SaltMod manual has been published [**Ref. 2**].

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

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 [**Ref. 3**]

A combination of SaltMod with a polygonal groundwater model (SahysMod) is also available [**Ref. 4, Ref 5**].

## 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 salinity 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 over-pumping from the aquifer. Also it offers the possibility to introduce subsurface drainage systems at varying depths 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, cropping sequences

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 rain-fed 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 equal 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 characterized 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 characterized 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 irrigation 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.

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.

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## 3. SALTMODM'S INPUT USER MENU AND EXAMPLES

The previous SaltMod model had a user interface for the input file that was susceptible to improvement to make the operations by the user more streamlined. For this purpose, the SaltModM (the last M stands for Modernized) was developed applied in this article

After clicking the "Open input file" button (under right in *Figure 1*), the input file (red square) "Interact.inp" appears (see Title1).

At the left a column can be seen with selection options for different groups of input data from which the "General data" has been selected (blue arrow).

In Figure 1 it can be seen that the number of seasons per year has been set at 2 (yellow square) from maximum 4, that the Kd selection box (presence of a subsurface drainage system) is set to "no" (orange square), that the Kp selection box (pumping from wells) is also set to "no" (pink

square), that the Kr selection box (rotation type) is set to "4" (brown square), meaning that all crops in all seasons are fully rotated throughout the years, and that the Kf selection box (farmers responses) is set to "yes" (purple square). Clicking on the "Save group" button (green square) leads to get the general data recorded, including the changes made.
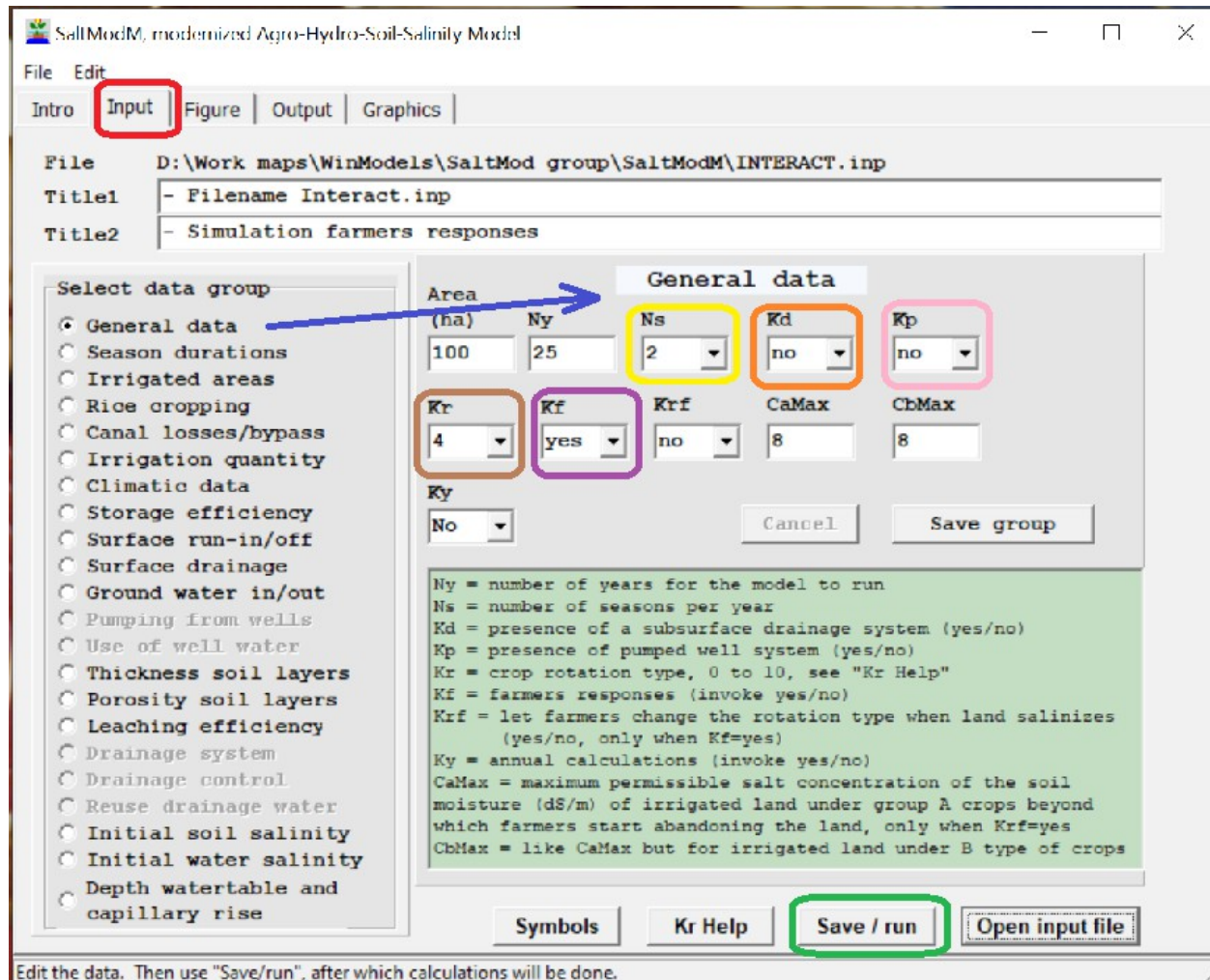


*Figure 1. The input user face of SaltModM with "General data" exposed. The green area explains the symbols used, while these and other symbols employed can be consulted clicking on the "Symbols" button. Clicking on the "Kr help" button reveals an explanation of all the Kr numbers used as crop rotational indices. The "Save / run" button (green square) makes the SaltModM program to save the input data and do the computations.*

It is the absence of a drainage system (red square, Kd being the index for the presence of a drainage system, but the box gives "no") or the absence of a pumped well system (pink square, Kp being the index for the presence of such a system, but the box gives "no) that will give the farmers problems, as will be explained in continuation. .
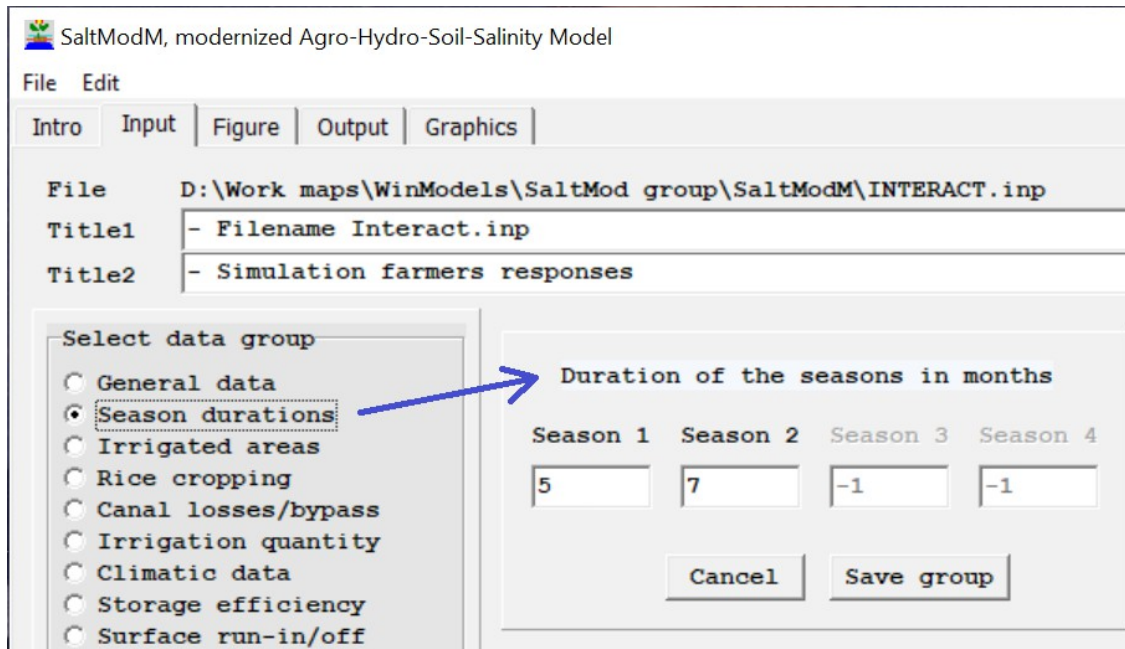
*Figure 2. Part of the input tab sheet in which the season durations are to be specified in months.*

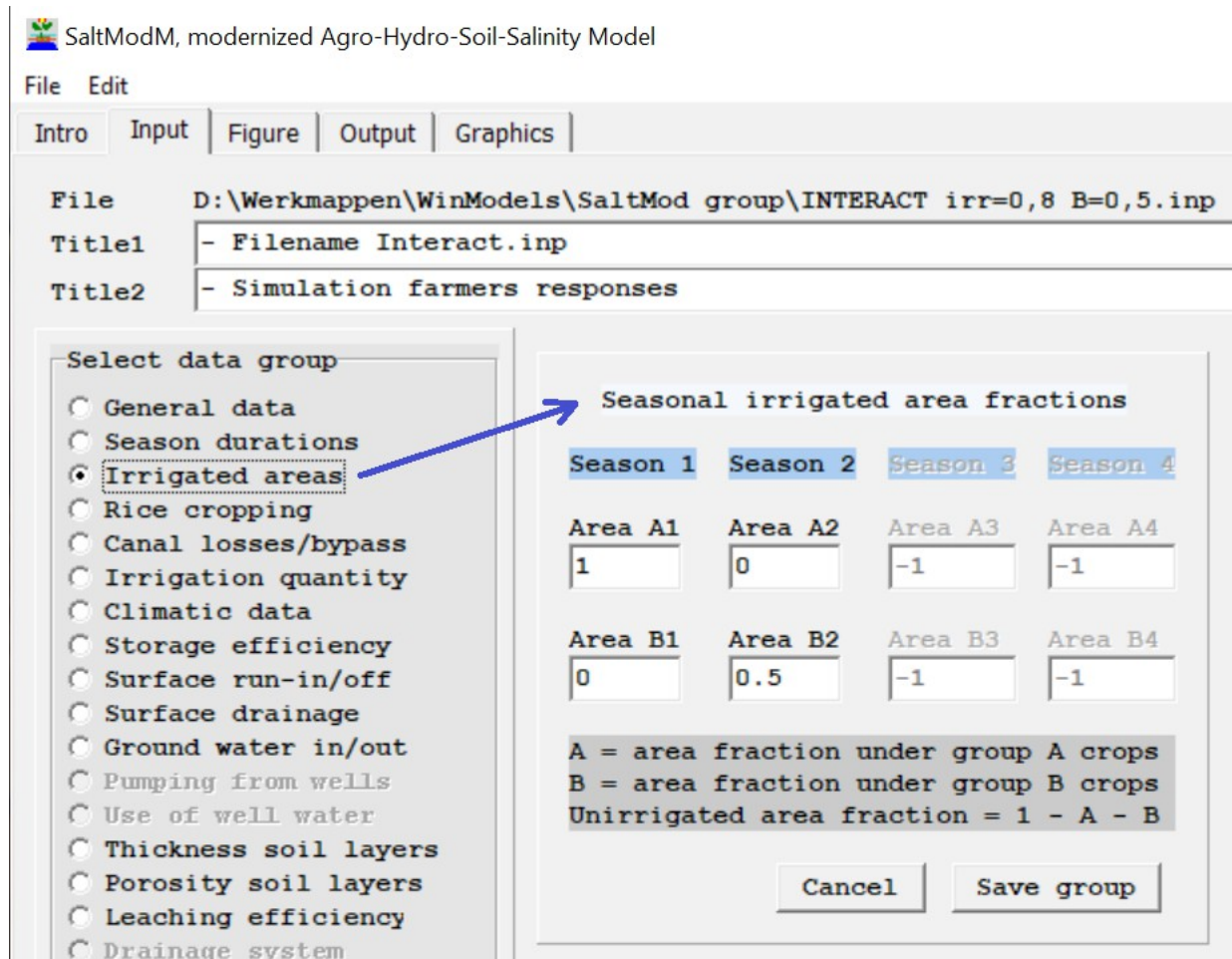In *Figure 3* the fractions of the irrigated areas have been defined.

**Figure 3**. *Definition of the fractions of the irrigated lands. In season 1, 100% of the area is irrigated and under A type of crops (area A1). In season 2, 50% of the area is irrigated and under B type crops (area B2). As there is no pumping from wells (Figure 1, pink square) the selection options "Pumping from wells" and "Use of well water" have been disabled.*

In *Figure 4* the fractions of the application of irrigation water in m$^3$ per season per m$^2$ A1 area (area under A type of crops) and per m$^2$ B2 area (area under B type of crops). The A1 and B2 areas have previously been specified, see *Figure 3*.
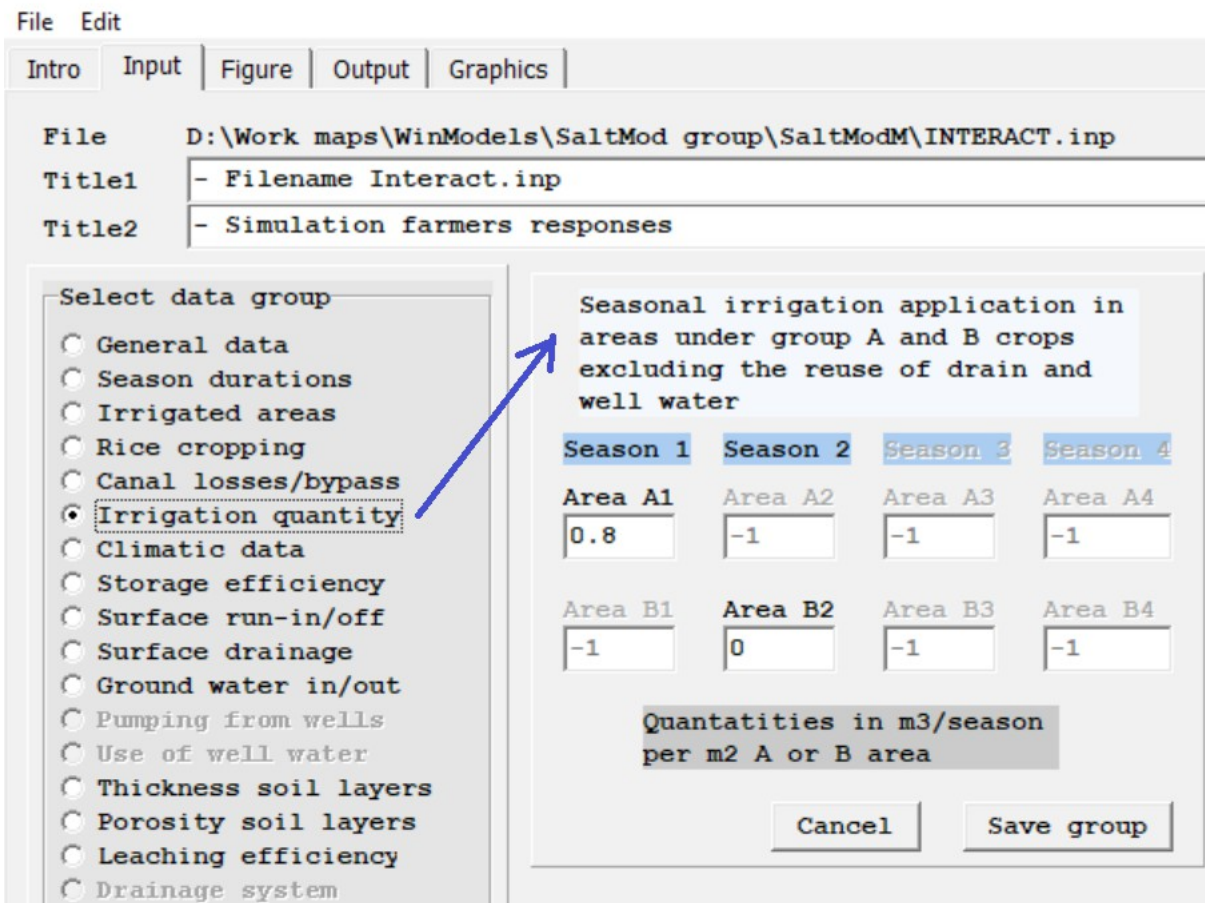
*Figure 4*. *Definition of the irrigation application. In season 1, The A1 area receives m³ per m²*
*of irrigation water and the B2 area receives no irrigation gifts while the B type of crops depend*
*in the rainfall, see* Figure 5 *hereunder. As the areas B1 and A2 are zero (see* Figure 3*), they*
*cannot receive irrigation turns and their data boxes are disabled*

Finally, *in Figure 5*, the climatic data rainfall and potential evapo-transpiration are presented,
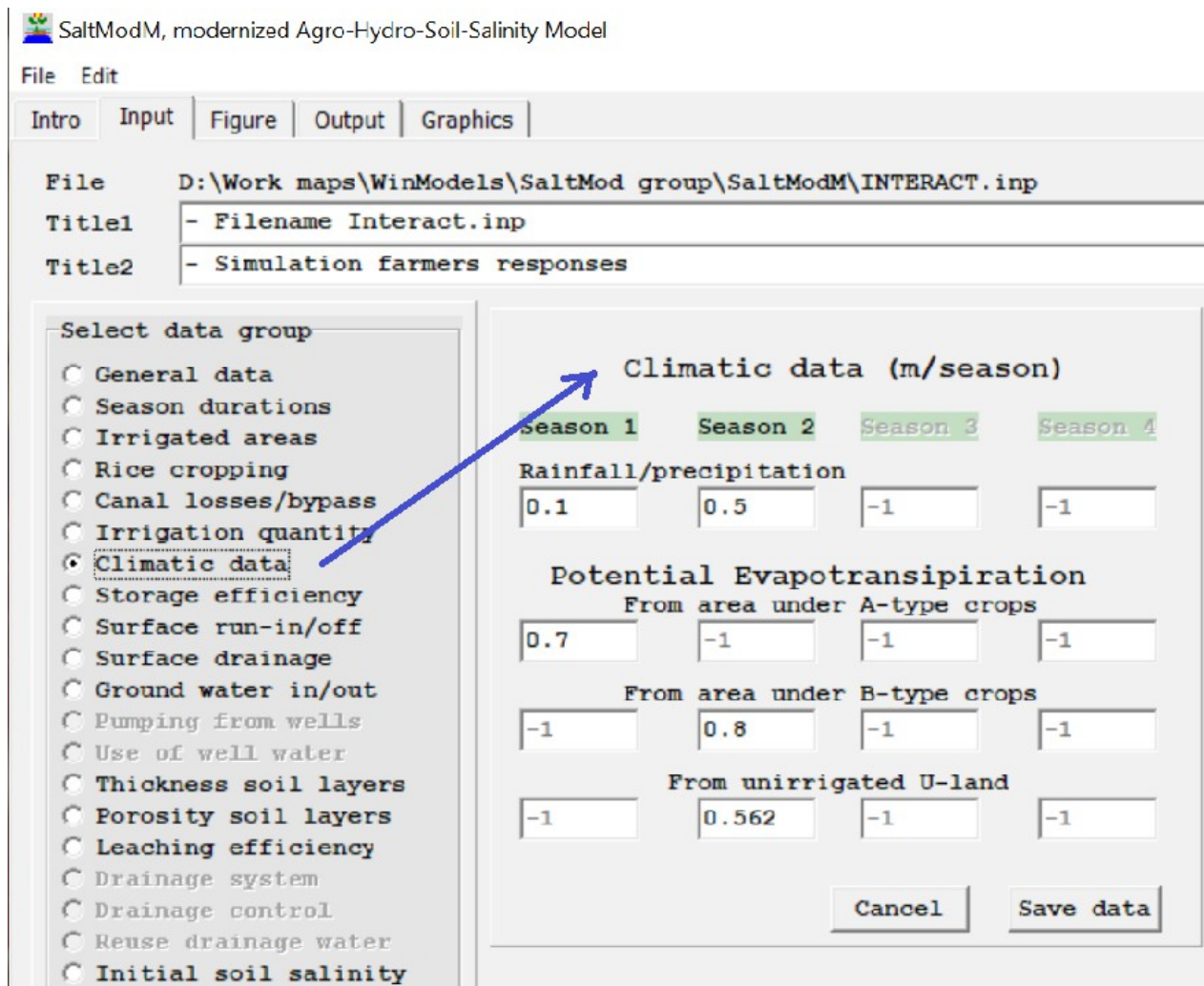
**Figure 5**. *Climatic data. The rainfall in season 1 is only 0.1 m (100 mm) and in season 2 it is more (0.5 m or 500 mm). In season 1, the area under A-type crops has a potential evaporation of 0.7 m (700 mm) while the irrigation is 800 mm (Figure 4). In season 2, the area under B type crops (50%, Figure 3) has a potential evaporation of 0.8 m while the irrigation is zero (Figure 4), but the rainfall is 0.5 m (or 500 mm). Hence the water supply is scarce. For the un-irrigated land U in season 2 (50% = 100% minus 0% A land – 50% B land) the potential evaporation is 0.0.562 m.*

It is not considered necessary to continue demonstrating all the remaining selection options (see Figure 1) as they follow similar procedures and speak for themselves.

## 4. SALTMODM'S OUTPUT USER MENU AND EXAMPLES

After clicking on the "Save / run" button in the input menu (figure 1) and defining the file name for saving the input data and creation of an output file, a print of the output file will appear as depicted in *figure 6*. Before that, if relevant, a warning may be given as illustrated in *figure 7*.
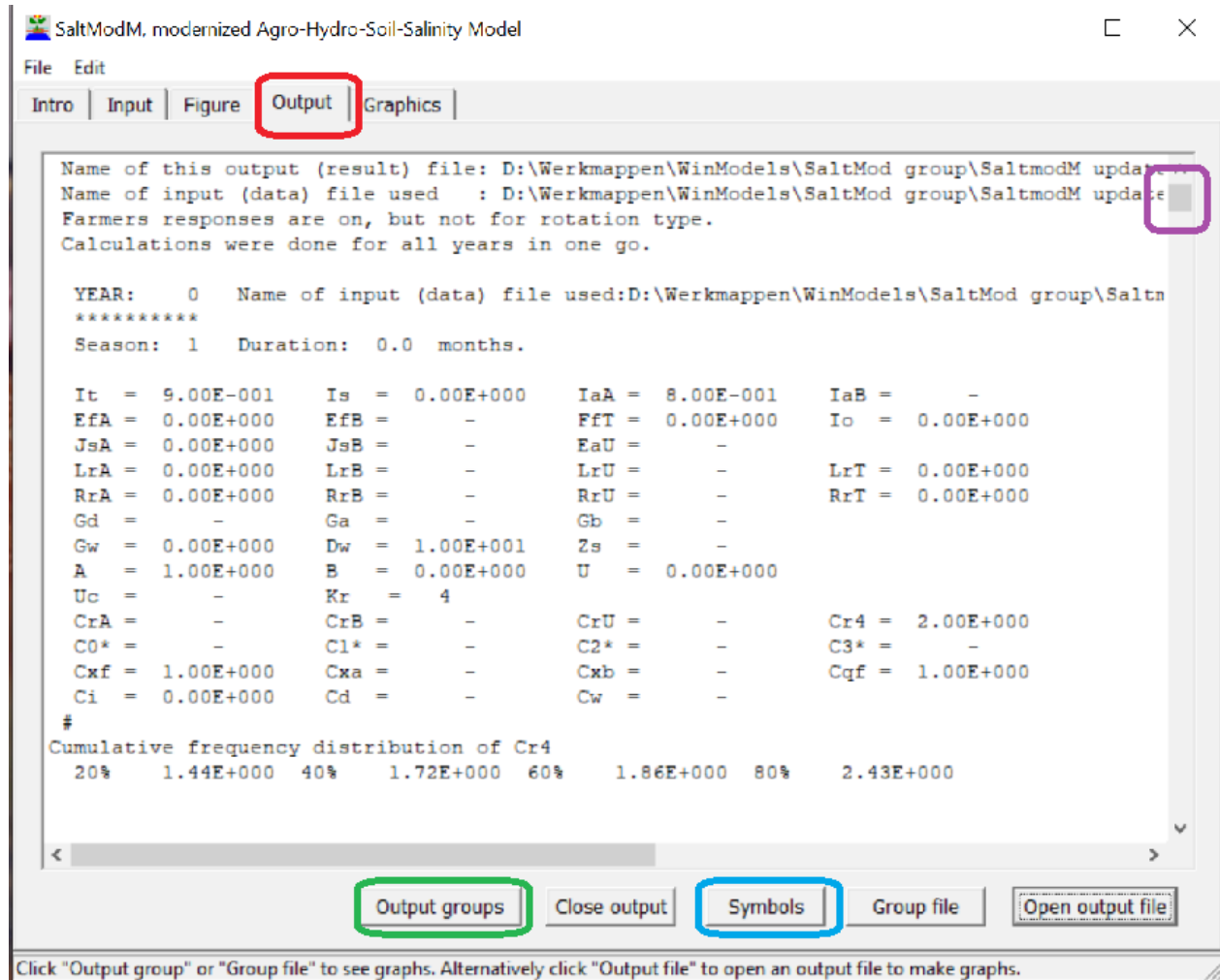


**Figure 6**. *Picture of the output file. There is a massive number of output results that can be all inspected with the scroll bar (purple square). The "Symbols" button (blue square) may help to get a definition of the output symbols. However, it will be difficult to form an interpretation with this system, and therefore the button "Output groups" has been installed. It will produce a list of data groups that will work in a way to get a clearer table of the group selected (*figure 8*) and further in the process to see the graphics.*
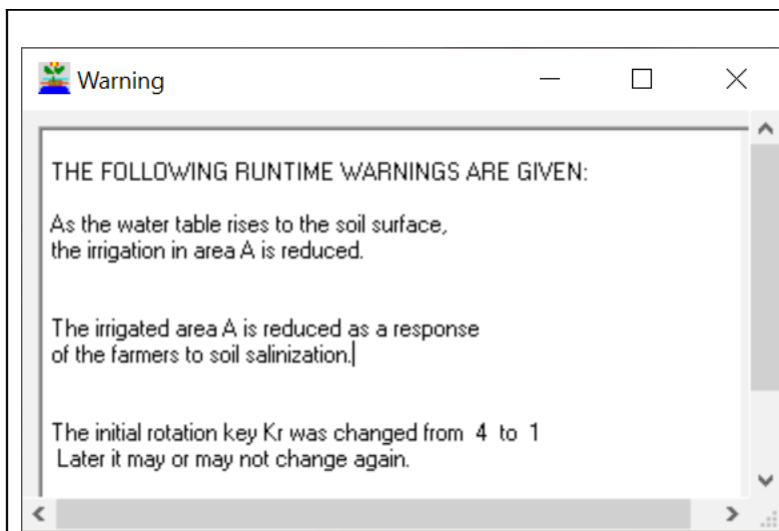
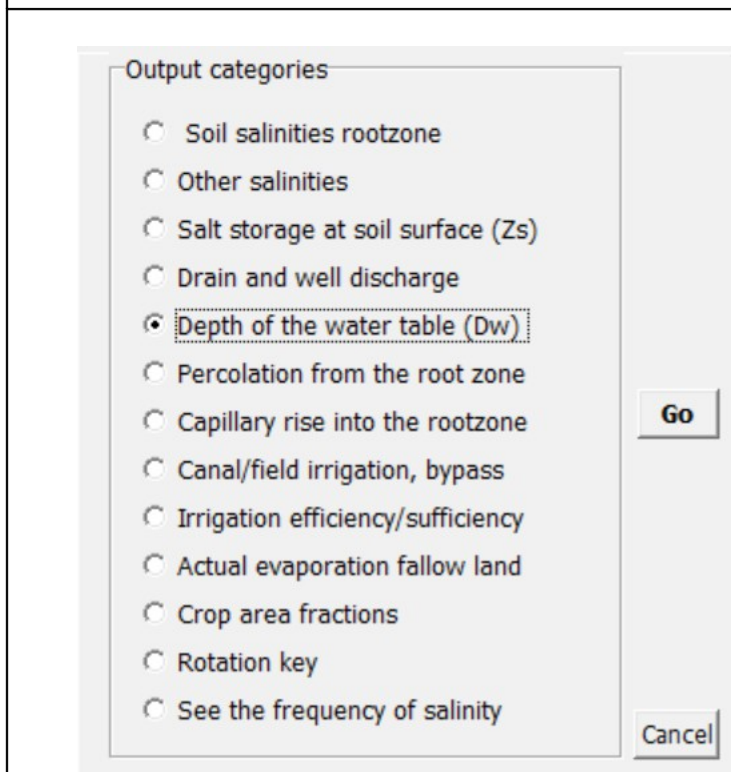| | |
|---|---|
| <br><br>**Warning**<br><br>THE FOLLOWING RUNTIME WARNINGS ARE GIVEN:<br><br>As the water table rises to the soil surface,<br>the irrigation in area A is reduced.<br><br>The irrigated area A is reduced as a response<br>of the farmers to soil salinization.<br><br>The initial rotation key Kr was changed from 4 to 1<br>Later it may or may not change again. | ***Figure 7.***<br><br>*In the particular case dealt with in this article a warning was together with the appearance of the output menu.*<br>*Farmers' responses are a diminishing of the irrigation gifts to offset the problem of water logging as well a reduction of the area under irrigation abandoning salinized land.*<br>*The crop rotation key Kr=4 (meaning a complete rotation of the crops over the area throughout the years) was changed into Kr=1 (meaning that there is fixed fraction of un-irrigated, abandoned, land).* |
| <br><br>Output categories<br><br>○ Soil salinities rootzone<br>○ Other salinities<br>○ Salt storage at soil surface (Zs)<br>○ Drain and well discharge<br>◉ Depth of the water table (Dw)<br>○ Percolation from the root zone<br>○ Capillary rise into the rootzone    **Go**<br>○ Canal/field irrigation, bypass<br>○ Irrigation efficiency/sufficiency<br>○ Actual evaporation fallow land<br>○ Crop area fractions<br>○ Rotation key<br>○ See the frequency of salinity    Cancel | ***Figure 8.***<br><br>*When clicking on the "Output groups" button in figure 6, a list of items appears as shown here.*<br><br>*In the figure the "Depth of the water table" is chosen.*<br><br>*Clicking on the "Go" button will produce a clear table of the item requested (see* figure 9*).* |
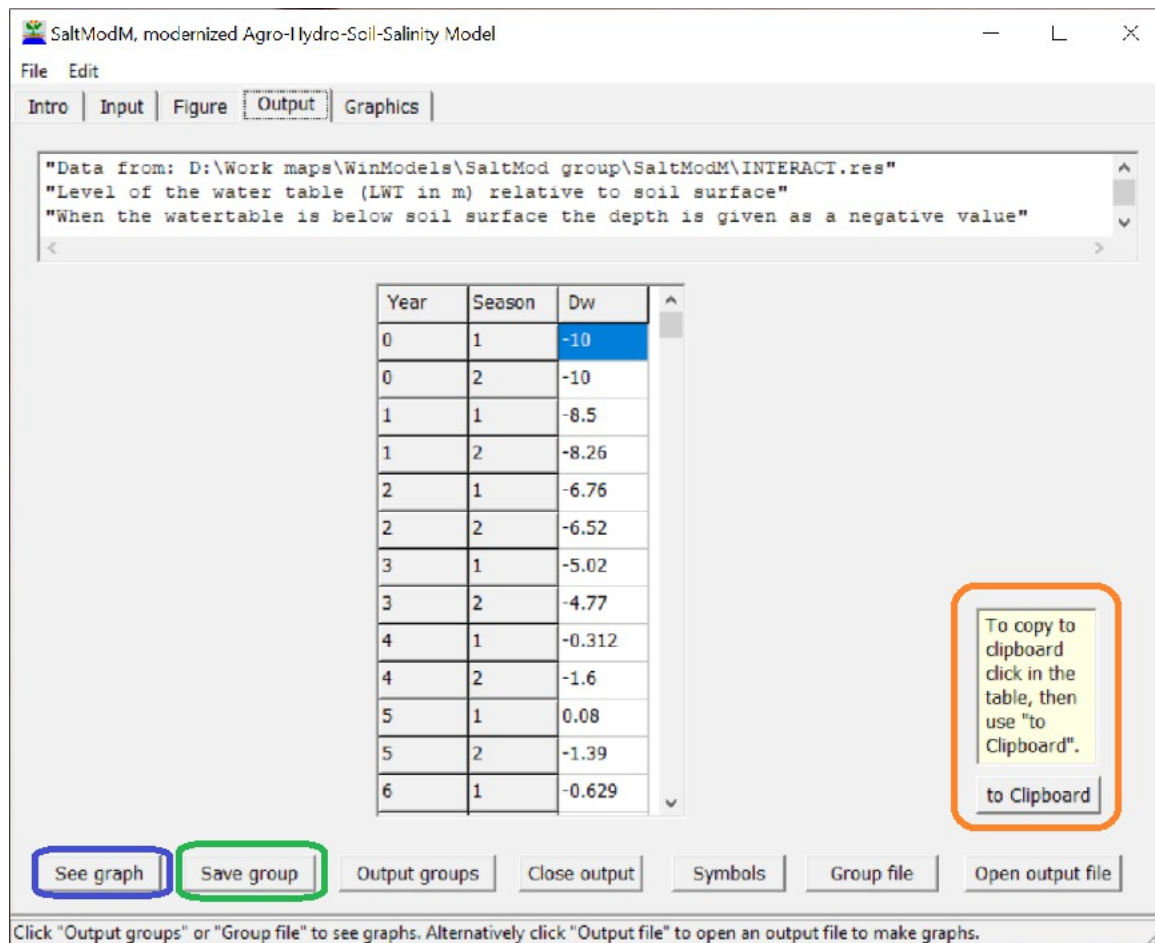
*Figure 9*. *Table of Dw (depth water table) values for each season of each year. The table maybe copied to the clipboard (red square) and can thus be pasted for example in an Excel spreadsheet. Clicking on the "See graph" button will result in the presentation of the relevant graph. Various examples of graphics thus obtained are given in the following figures. Further the data group can be saved in a \*.prn file (with text file format) for further use if required.*

The first warning in figure 7 concerns a reduction of the irrigated area A due to a water table too shallow for successful crop production. The SaltModM graph of the depth of the water table is pictured in figure 10.
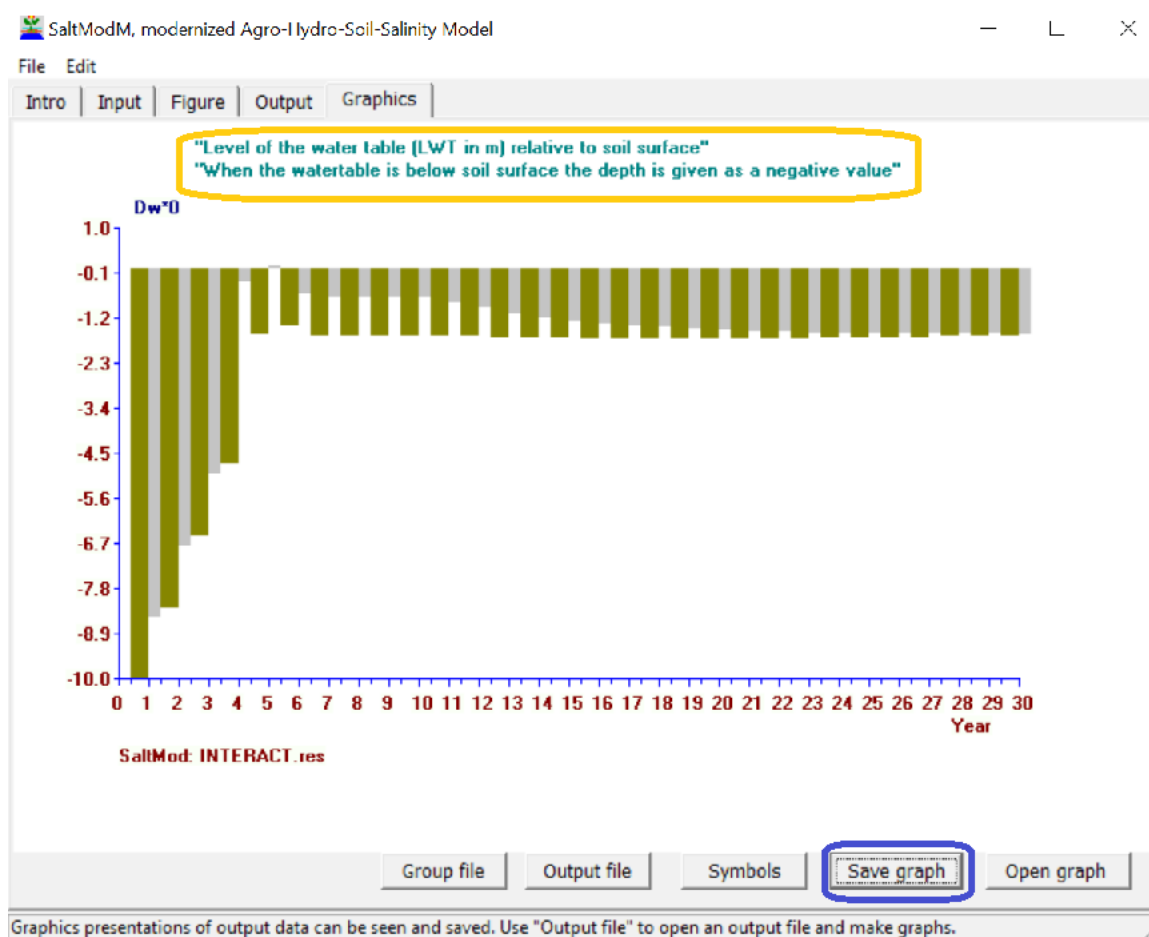
*Figure 10*. *Initially the depth of the water table was 10 m below the soil surface, but the depth decreases rapidly in the years 1 to 5 owing to downward percolation of the unused part of the irrigation water. Owing to the reduction of the irrigated gift (see* figure 7*), which reduces the percolation losses, the water table establishes itself at a greater depth reaching an equilibrium of about 1.5 m depth in later years, which is good enough for the plants* [**Ref. 6**].

Please note that in this graph the depth has a grayish-green color for season 1 and a dark green color for season 2.

The question remains: how much reduction of the quantity of irrigation water has occurred under the farmers' responses? The answer can be found in the next *figure 11*.
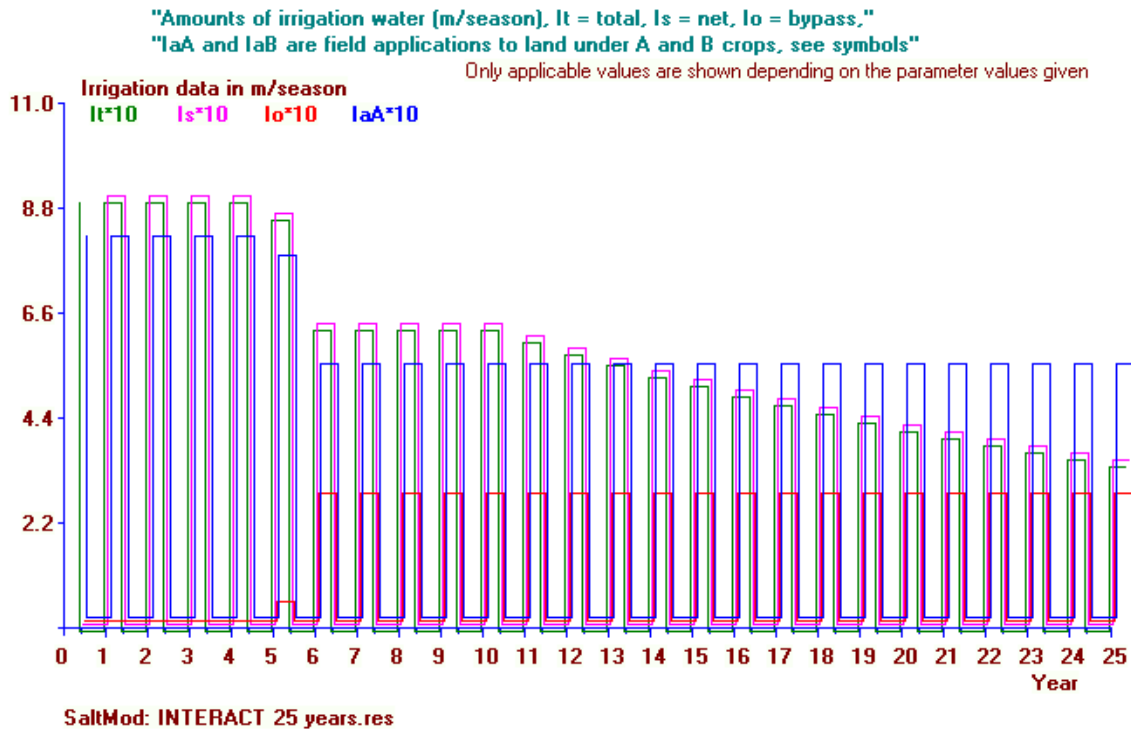
**Figure 11**. *From year 5 and following the quantity of irrigation water IaA(blue lines) given to the A type crops on the A land in season 1, which initially had a value of 0,8 m/season (in the graph this amount is multiplied with 10 for simpler scaling), according to the farmers' responses, is reduced to about 0.54 m/season. The reduction happens after year 5 corresponding to the year when depth of the water table has become too shallow (see* figure10 *and* **Ref. 7** *).*

Please note that the first warning given in figure 7 refers to this phenomenon in combination with the water table problem depicted in figure 10.

The warning message also contains the phrase "The irrigated area is reduced as a response of the farmers to soil salinization". The soil salinity in the course of the time is shown in the next figure 12.
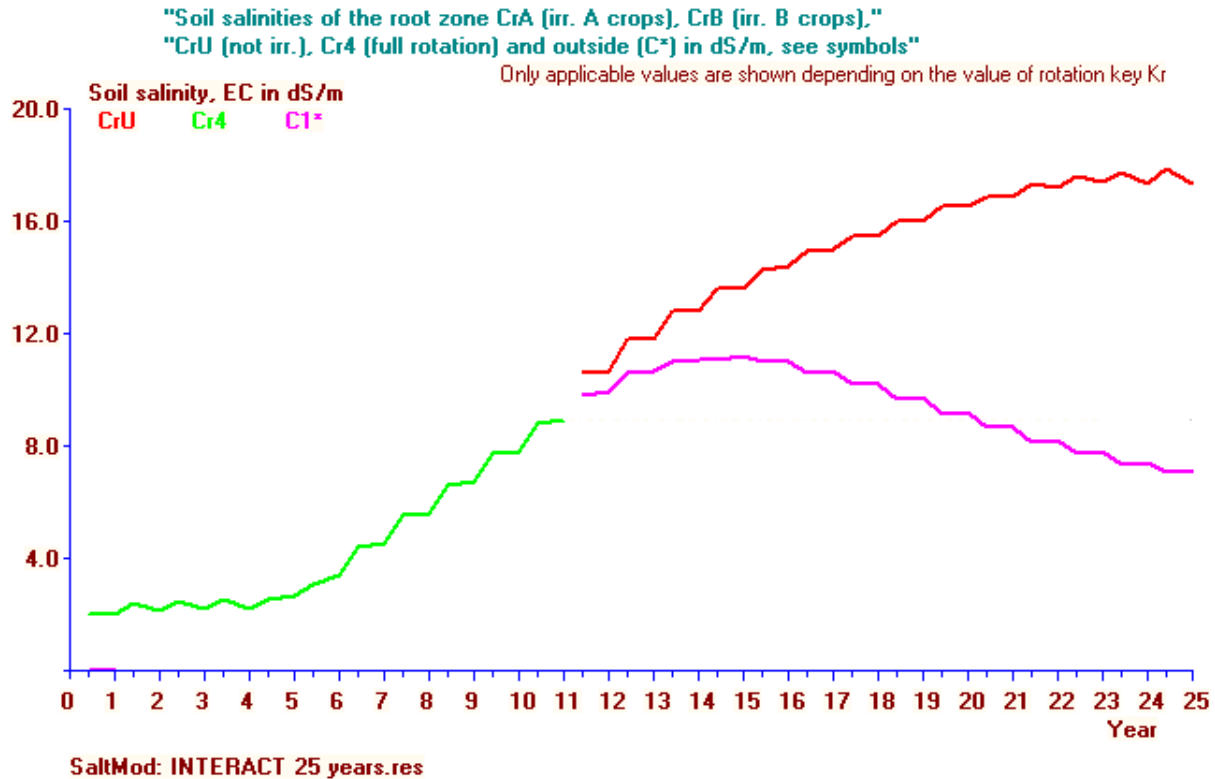
*Figure 12*. Soil salinity in the course of the time. Initially, during the years 1 to 5, the soil salinity does not increase. Thereafter, when the water table comes close to the soil surface (see figure 10*), the salinity starts to increase, until year 10 when a influential change occurs. The green curve represents the salinity Cr4, meaning the salt concentration in the soil refers to the situation of full crop rotation when the rotation index Kr=4 (see figure 1*). The warning message tells that this index has been changed to Kr=1, meaning that a fraction of the land is left permanently fallow. In this case the reason is that the soil salinity in the year 11 has reached a value of Cr4 = 10 dS/m. This salinity is too high for profitable crop growth [**Ref. 8, Ref 9**]. Hence, part of the land is abandoned. In the abandoned land, the salinity continues to rice (CrU, salt concentration in the un-rrigated, abandoned, land, red line), while in the remaining land, where irrigation keeps to be practiced, the soil salinity goes down (C1\*, salt concentration in the land outside the abandoned area, purple line). The land that remains irrigated becomes more productive.

The reason for the improvement in the C1\* salinity is that in the abandoned land the water table is relatively deeper so that it attracts water from the irrigated land. This water moves up by capillary rise and is evaporated, leaving the dissolved salts behind. Hence, the abandoned land serves as a drainage area for the irrigated land while the salts dissolved in the groundwater are carried with the drainage flow from the irrigated land to the abandoned land, reason why the soil salinity in the irrigated land reduces while it keeps increasing in the abandoned U area,

The phrase "The irrigated area is reduced as a response of the farmers to soil salinization" in the warning (*figure 7*) makes it necessary to have a look at the area irrigated in the course of the time. This is done in the next *figure 13*.
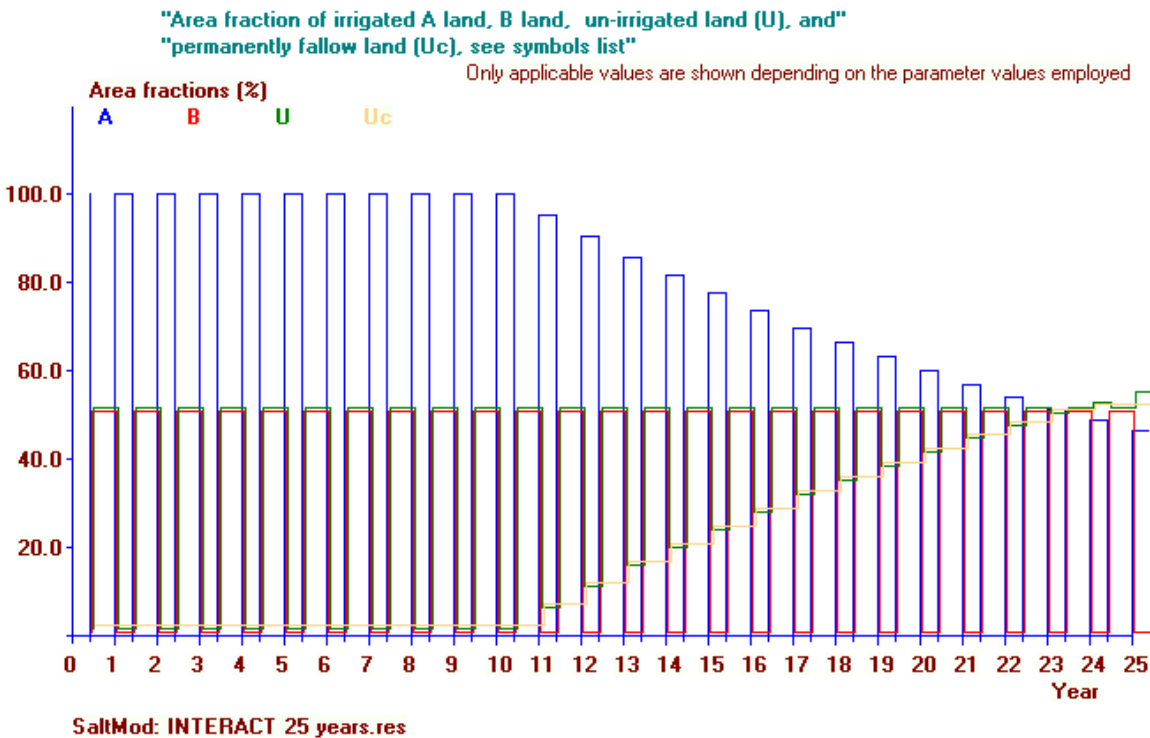


*Figure 13*. *Initially, the irrigated A land with A type crops (blue lines) in season 1 is 100% of the total area. However, in year 11 when the soil salinity Cr4 reaches a critically high value (see* figure 1) *, the fraction of irrigated land deceases until reaching a value of about 50%, while in the mean time the abandoned land (Uc) rises from 0% to 50% (yellow line). These phenomena stand in relation to the development of soil salinity (*figure 12) *and with the change of the crop rotation index Kr=4 Kr=1 (see* figure 7 *and the subscript under* figure 12).

Normally, the salinization of agricultural land affects a considerable area of irrigation projects, in the order of 20 to 30% [**Ref. 9** ]. When the agriculture in such a fraction of the land is abandoned, a new salt and water balance is attained, a new equilibrium is reached, and the situation becomes finally stable.

In this example, the salinity affects more than 20 to 30% of the land, owing to the fact that here it concerns a relatively small area (100 ha, see figure 1), whereas in larger irrigation projects not everywhere the conditions are as limiting as in this example.

In the last figure of this article some of the data of the Interact output file used are combines in one graph (*figure 14*).
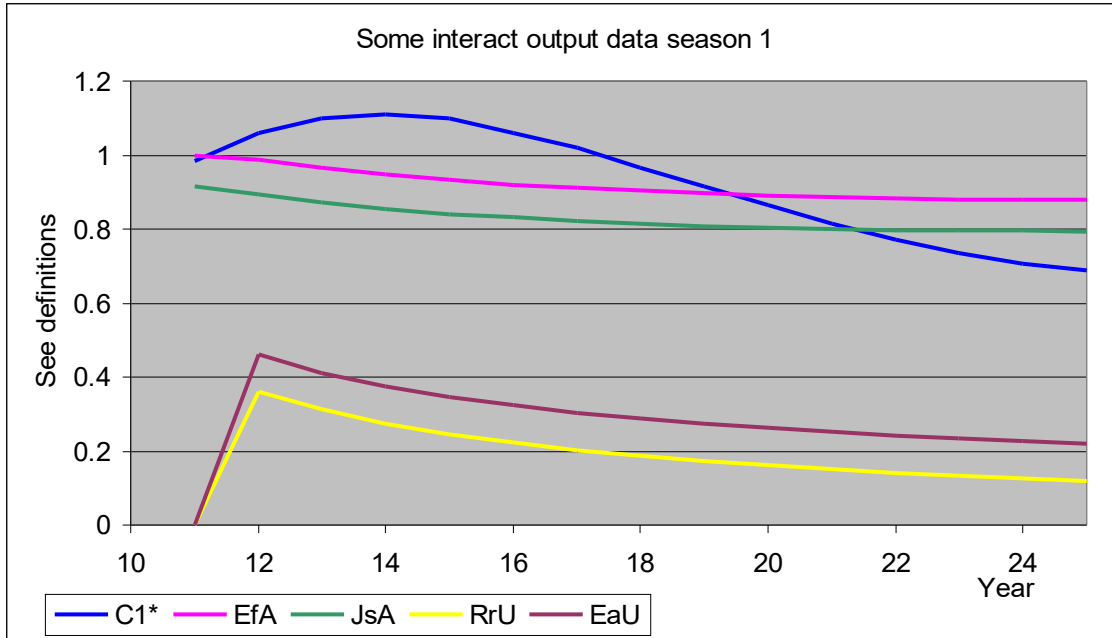
**Figure 14**. *Picture of some of the output data combines in one graph. Defini7tions: C1\* (blue line) is the soil salinity of the irrigated area outside the abandoned land in S/m instead of the usual dS/m, EfA (pink line) is the irrigation efficiency in the irrigated A land under A type of crops as a fraction of total amount of irrigation water used by the crop, JsA (green line) is the irrigation sufficiency indicating the water consumption by the crop as a fraction of the potential evapotranspiration, RrU (yellow line) is the capillary rise of the groundwater into the upper unsaturated zone of the un-irrigated, abandoned, U land in m/season, and EaU (purple line) is the actual evaporation from the upper unsaturated zone of the un-irrigated, abandoned, land in m/season.*

Comments on <u>figure 14</u>:

1 –The unfavorably high soil salinity in the irrigated land (C1\*, blue line) in year 11 slowly reduces owing to the reduction of the irrigated area as discussed in figure 7 and figure 13.

2 – The irrigation efficiency EfA descends from 1 (100%) in year 11 when the water table was shallow to about 90% in year 25. Hence, in year 25 part of the irrigation water (10%) is considered lost, but in fact it flows to the un-irrigated land where the water table is deeper, and removes salts from the root zone in the irrigated land helping to lower the excessively high soil salinity in the irrigated land (C1\*, blue line).

3 – Owing to the relatively to the losses of irrigation water, the amount of irrigation gets less than the potential evapotranspiration and the irrigation sufficiency (JsA, green line) descends from initially 1 (100%) in year 11 to 0.8 (80%) in year 25, which is not favorable for optimal crop production.

4 – The capillary rise RrU in the un-irrigated (abandoned) land (yellow line) and the subsequent actual evaporation (purple line) cause an increase of the soil salinity in the un-irrigated U land (*figure 12*), but helps here to lower the groundwater level and to attract groundwater from the irrigated land, so that the excessive soil salinity in the irrigated land (blue line) diminishes as explained in comment 2.

## 5. CONCLUSION

The relations between the agro-hydro-salinity factors in irrigated lands are complicated, interactive, and mutually influential. A software model like SaltMod (or the modernized SaltModM) can therefore be helpful to assess the interrelations between rainfall, irrigation, evaporation, subsurface drainage, groundwater in- and outflow, level of the groundwater table, soil and aquifer salinity, cropping pattern and crop rotations. One might say: "SaltMod is a tool for interweaving all these elements into a well designed pattern".

Of course, the situation described in this paper will completely change when a drainage system is installed or pumping from wells is introduced, However, farmers usually need assstance for that.

## 6. REFERENCES

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