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Using SALTMOD to Predict Drainage and Salinity in the Nile Delta

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Abstract

SALTMOD is a computation method which makes it possible to predict soil and water salinities and watertable depth in agricultural land Linder different (geo-) hydrological conditions and varying water-management scenarios. In this article, the method is applied to data from the Mashtul Pilot Area in Egypt°s Nile Delta.
The Pilot Area was established for drainage and salinity control in 1980 near Zaga-zig. It has yielded much information on water and salt balances and related factors such as irrigation and crop production. Some important factors, however, like the leaching efficiency of the soil and the natural drainage to the underlying aquifer, could not be determined. Nor were any intensive observations made of the depth of the watertable or of the amount of irrigation water applied before the the Pilot Area was established.
In this article, SALTMOD is used, after its calibration, to estimate the values of the unknown variables in Mashtul. Further, seasonally applied volumes of irrigation water and corresponding depths of the watertable are simulated for the situation that existed before the Pilot Area was established. The method is also used to simulate the impact of alternative water-management options (e.g. different drain depths) on irrigation, soil and groundwater salinity, and depth of watertable.

Keywords

Land drainage, hydrological conditions, salinity prediction, SALTMOD, water management.

Introduction

When the natural underground drainage of irrigated land in (semi-) arid regions is insufficient to leach the salts that are brought in with the irrigation water, the land can be affected by the twin problems of a shallow watertable and a high soil salinity. The problems can be aggravated when groundwater moves upward into the rootzone. This groundwater can originate from canal water that infiltrates into the soil elsewhere, or from excess irrigation water that percolates downward, either in fields nearby or

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in higher-lying lands farther away (Figure l). As the water thus lost moves through the underground, it picks up salt and brings it to the already affected yields.

Insufficient natural underground drainage can be corrected by artificial drainage systems consisting of ditches, subsurface channels (mole drains), and subsurface pipe drains, laid more or less parallel to the soil surface at some depth (0.5 to l.5 m and sometimes more), These systems are called horizontal drainage systems; they can work entirely by gravity but. if there is no free outfall through which to evacuate the water, pumps can be used. Insufficient natural drainage can also be corrected by a vertical drainage system, which consists of pumped wells.

Not long ago, it was estimated that, world-wide, 52 million ha of irrigated land needed improved drainage systems (United Nations l977). In Egypt"s Nile Delta, almost l.4 million ha have so far been equipped with pipe drainage systems. This covers roughly two-thirds of the total cultivable area of Egypt (Abdel-Dayem 1988). Many new drainage projects are envisaged, and monitoring programs are being considered to evaluate the effectiveness and efficiency of the older drainage projects and to find out whether agricultural or technical drainage criteria need to be refined. New pilot areas are being planned for the further development of criteria.

With such investments at stake. salt-and-water-balance models can be instrumental in the planning, design, monitoring, and evaluation of the projects. SALTMOD is such a model. It was developed to make long-term predictions of the impact of water-management programs (including drainage) on the height of the watertable, and on the salt contents of the soil, the groundwater, and the drainage effluent. It can also assess the impact of re-used drainage water. Although, so far, SALTMOD has been tested only on a few, small, drainage experimental fields (in Portugal, India, and Egypt), its aim is to make the predictions valid for larger areas, So, it includes areal frequency distributions of the predicted factors, and it accommodates different kinds of agricultural practices such as rain-fed and irrigated agriculture, distinguishing in the latter between ‘dry-foot’ crops and submerged paddy fields. It can also simulate farmers’ agricultural and water-management responses to changes in watertable depth and soil salinity e responses which can influence the salt and water balances.

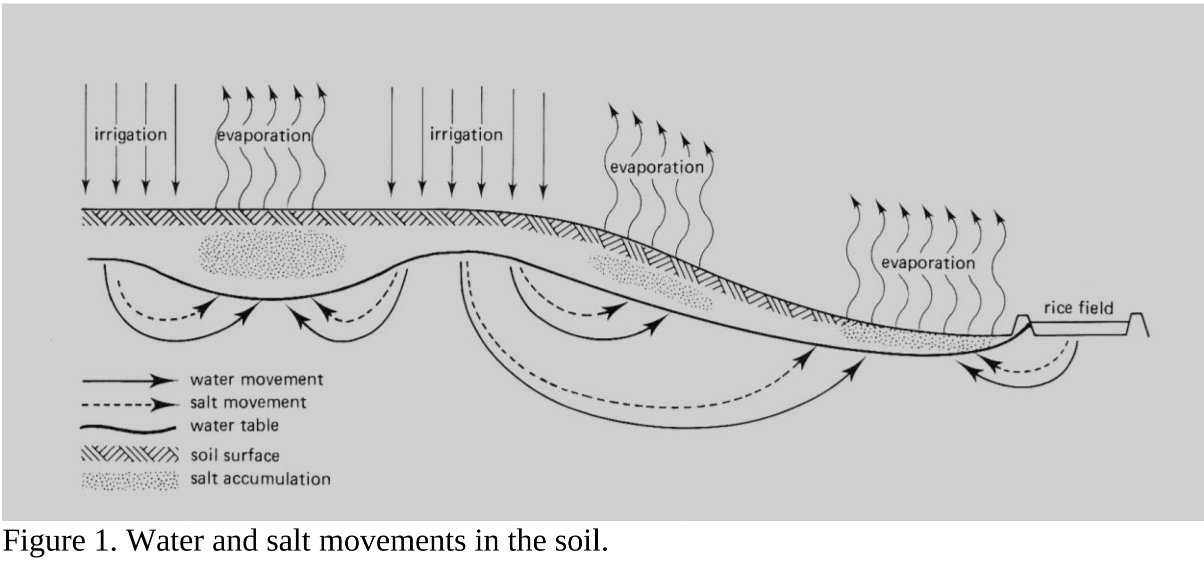

Figure 1. Water and salt movements in the soil.

In the following, the principles of SALTMOD will be explained. The method will be tested with data from the Mashtul Pilot Area and will be applied to estimate the values of some of the unknown variables (e.g. the natural drainage to the underground and the leaching efficiency). The unknown depth of the watertable and the volumes of irrigation water applied before the establishment of the Pilot Area will be simulated. The method will also be used to simulate the impact of alternative water-management options (e.g. different drain depths) on irrigation, soil and water salinity, and depth of the watertable.

The Principles of SALTMOD

The computation method SALTMOD is based on seasonal water balances of agricultural lands. Two seasons in one year are distinguished (e.g. a dry and a wet season, or a summer and a winter season). Day-to-day water balances are not considered for three reasons:

- Daily inputs would require a great deal of information, which may not be readily available;
- The method has been especially developed to predict long-term trends;
- Future predictions made on a seasonal (long-term) basis are more reliable than those made on a daily (short-term) basis, because of the much higher variability of short-term hydrological phenomena.

As input data, the method uses water-balance components. These are related to the surface hydrology (e.g rainfall, evaporation, irrigation, re-use of drainage water, runoff) and to the aquifer hydrology (e.g. upward seepage, natural drainage. pumping from wells). The other water-balance components (e.g. downward percolation, capillary rise, gravity drainage) are obtained as outputs. The quantity of drainage water is determined by two drainage intensity factors (i.e. for drainage above and below drain level) f to be given with the input data f and by the height of the watertable, resulting from the computed water balance. By varying the drainage intensity factors, one can simulate the impact of different drainage systems.

The input data of irrigation, evaporation, and surface runoff are to be specified for three kinds of agricultural practices: rain-fed agriculture or fallow land, irrigation of ‘dry-foot` crops, and irrigation of submerged rice fields (paddy land), for which areal fractions have to be given with the input data. By varying these fractions. one can simulate the impact of different agricultural practices on the water and salt balance.

Under certain conditions, the height of the watertable influences the water-balance components. For example, if the watertable comes close to the soil surface. it may lead to an increase in capillary rise, evaporation, surface runoff, and subsurface drainage, or to a decrease in irrigation and in less percolation losses from irrigated fields and irrigation canals. This, in turn, leads to a change in the water balance, which again influences the height of the watertable.

The above chain of reactions is one of the reasons why SALTMOD was developed into a computer program. It takes a great many iterative calculations to find the final 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 of simulating their long-term impacts ~ and for trial runs with varying parameters.

SALTMOD accepts four different reservoirs in the soil profile: a surface reservoir, an upper (shallow) soil reservoir, an intermediate soil reservoir or transition zone, and a deep reservoir or aquifer. If a horizontal subsurface drainage system is present, the transition zone is divided into two parts: an upper transition zone above drain level and a lower transition zone below it. 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 different thicknesses and storage coefficients, to be given as input data. In a particular situation, the transition zone or the aquifer need not be present. They must then be given a minimum thickness.

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 saturated, unsaturated. or partly saturated, depending on the water balance. All water movements in this Zone are vertical, either upward or downward, also depending on the water balance. The transition zone, too, can be saturated, unsaturated, or partly saturated. All flows in this zone are vertical, except the flow to subsurface drains, if present. The aquifer has horizontal and vertical flow. Pumped wells, if present, receive their water from the aquifer only.

The salt balances are calculated for each reservoir separately. They are based on water balances and on the salt concentrations of the incoming and outgoing water. Some concentrations (e.g. the initial salt concentrations of the water in the different soil reservoirs, in the irrigation water, and in the incoming groundwater in the aquifer) must be given as input data, The concentrations can be expressed in any consistent units (e.g. mmho,/cm or mg/l).

Salt concentrations of outgoing water e either from one reservoir into the other or by drainage f are computed on the basis of the salt balance, with different leaching or salt-mixing efficiencies to be given with the input data. The amount of salt removed during a season is based on the weighted average salt concentration during the season. The weight factor is introduced to take into account an exponential leaching function with time. Since the average concentration depends on initial and final salt concentrations, and since the final salt concentration depends on the leaching, which, again, depends on the average concentration, a trial-and-error procedure has to be applied to calculate the correct salt balance.

The effects of different leaching efficiencies can be simulated by varying their input value. If drain or well water is re-used for irrigation, the method computes the salt concentration of the mixed irrigation water in the course of time and the subsequent impact on the soil and groundwater salinities. which again influences the salt concentration of the re-used drainage water. By varying the fraction of re-used drain or well water (to be given in the input data), one can simulate the long-term impact of different re-use policies.

The dissolution of solid soil minerals or the chemical precipitation of poorly soluble salts is not included in the method, but can be taken into account to some extent 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).

The output of SALTMOD is given for each season of any year for any number of years, as specified with the input data. The output consists of the seasonal volumes of drainage water and capillary rise, the seasonal average depth of the watertable, the salt concentration of the different soil reservoirs at the end of the season, and the seasonal average salt concentration of the drainage water and the mixed irrigation water, as well as some indicators of irrigation efficiency and sufficiency. lf required, farmers’ responses to waterlogging and salinity can be taken into account. When the watertable becomes shallower, for example, the method can gradually increase the fraction of paddy land; or, with a shallow watertable or increasing soil salinity, it can gradually reduce the fraction of cultivated land and the amount of irrigation water applied. These adjustments influence the water and salt balances, which e in turn a slow down the process of waterlogging and salinization. Ultimately, an equilibrium situation will arise.

Some of the input data are inter-dependent, notably the irrigation data. These data cannot, therefore, be indiscriminately varied. ln very obvious illogical combinations of data, the program will give a warning, but no more than that. The correctness of the input data remains the responsibility of the user.

The selection of the area to be analyzed 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, it is advisable to use a larger area. If, on the other hand, the spatial distribution can lead to the designation of more uniform sub-areas, it is advisable to analyze the sub-areas separately. It is also possible to use first the larger-area approach and then use some of the outputs as inputs in the sub-area approach. For example, an area may have fallow unirrigated land next to irrigated land. The resulting capillary rise in the fallow land can be obtained as output from the larger-area approach. This can then be used either as a groundwater input in a separate approach for the fallow land or as a groundwater output in a separate approach for the irrigated land.

The output data are filed in the form of tables. Their interpretation is left entirely to the user. The program offers the possibility of developing 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, therefore, offers no standard graphics.

If the user wishes to determine the effect of variations in a certain parameter on the value of other parameters, he must run the program repeatedly according to a user-designed schedule. SALTMOD is a highly interactive program.

Calibration of SALTMOD

The SALTMOD computation method was calibrated for the zone of Collector I of the Mashtul Pilot Area against four factors: the soil salinity in the rootzone, the salt concentration ofthe drainage water, the depth of the watertable, and the drain discharge. Figure 2 shows the computed values of these factors and compares them with their measured values as reported by the Pilot Areas and Drainage Technology Project (1987).

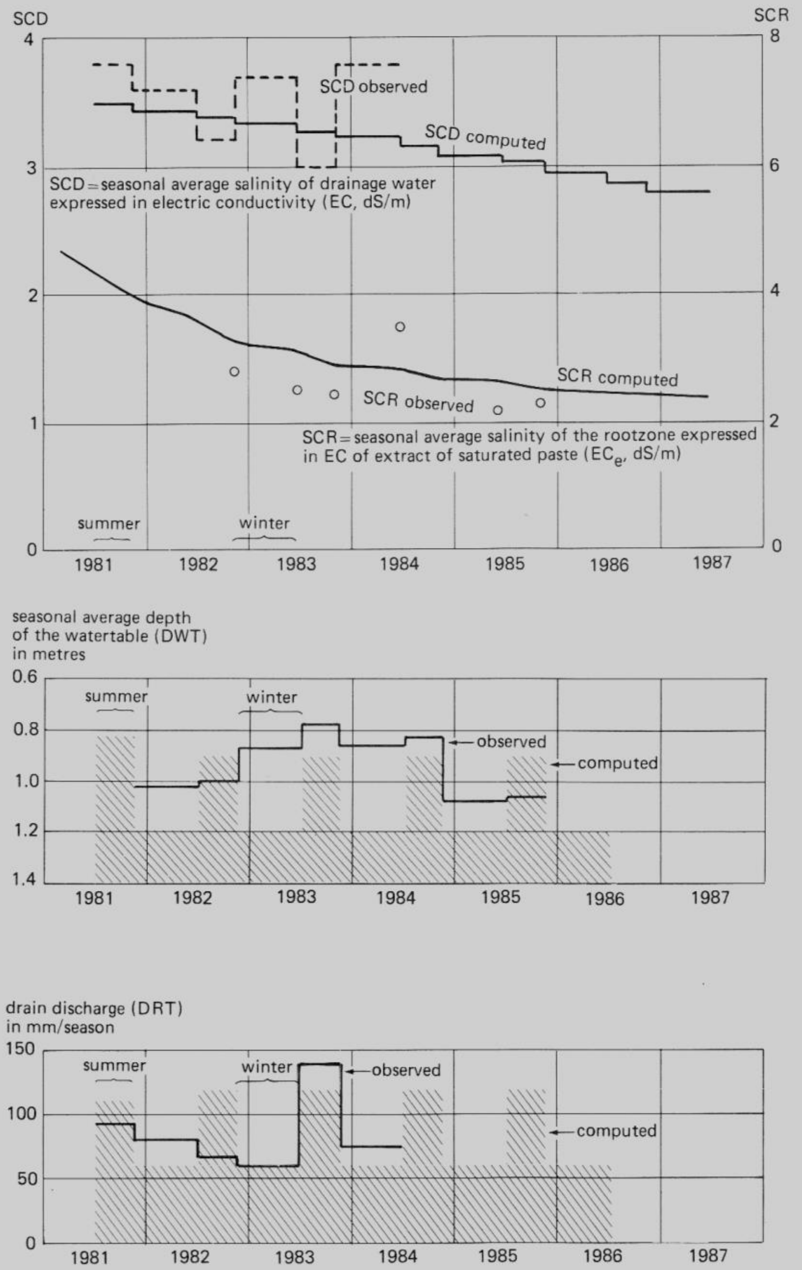

Figure 2. Computed and observed values of four factors of the Mashtul Pilot Area in which a drainage system was installed in 1980/81

The match of the data is obtained by varying the leaching efficiency of the rootzone and the natural drainage to the aquifer until the best possible agreement is found. The effects of different leaching efficiencies and natural drainage values (neither factor could be measured) are shown in Figure 3 and Table 1. Other input data of SALTMOD (e.g. irrigation, evaporation, and drainage intensity) could not be varied for the calibration process because they were measured.

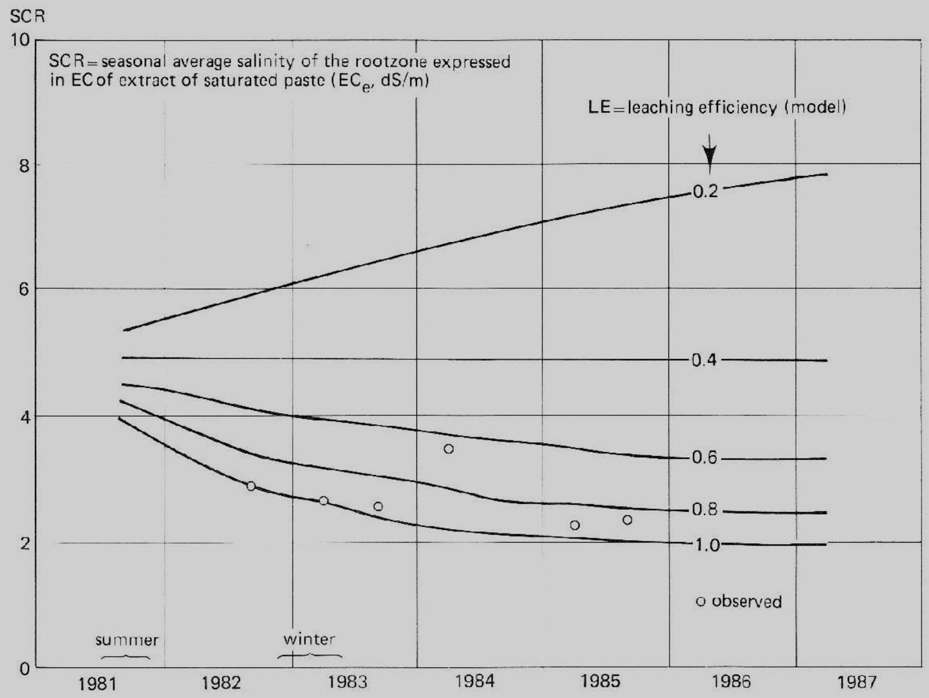

Figure 3 The simulated effects of different leaching efficiencies (LE) of the rootzone on soil salinity obtained with SALTMOD.

Anyone interpreting the data of Figures 2 and 3 should note that SALTMOD calculates the soil salinity as the salt concentration of the soil moisture at field saturation, whereas in the laboratory it was determined from an extract of a saturated soil paste, which contains roughly twice as much water. Therefore a factor 0.5 is used to convert the electric conductivities (EC) in the model to that of the extract (ECC).

Table 1 The simulated effects of different values of NDR (the natural drainage to the aquifer) on DWT (the seasonal average depth of the watertable) and DRT (the drain discharge), obtained with SALTMOD.

NDR mm/year	DWT (m)		DRT (mm/season)	
	Summer	Winter	Summer	Winter
0	0.64	0.97	162	123
70	0.77	1.07	133	91
140	0.81	1.20	120	60
210	1.01	1.29	79	22
280	1.17	2.10	43	0
Range of observed values*)	0.8-1.1	0.9-1.2	70-140	60-95

*) This range is also shown in Figure 2

Figure 2 shows that the match between computed and observed values is not perfect, but, in terms of percentage, the deviations are small. One can reduce the deviations, in principle, by performing the computations season by season, giving each season a separate input. We do not do so in this article, however, because:

-- The seasonal amounts of irrigation water are not accurately known because of the use of mobile irrigation pumps whose discharges were not measured;
- The objective of SALTMOD is to give long-term predictions so that preference is given to using long-term average inputs rather than trying to explain yearly variations.

The seasonal inputs of irrigation and evaporation used for the calibration were therefore taken as a seasonal average over the period 1981 to 1986. This explains why the values of DWT (depth to watertable) and DRT (amount of drainage water) in Figure 2 have seasonal but not yearly variations.

Another reason why the match of the data in Figure 2 is not perfect can be found in the unreliability of some of the field measurements. In winter l983, for example, it was observed that the drain discharge was exceptionally low whereas the watertable was relatively high. This does not seem logical. Such inconsistencies give an extra reason for considering long-term trends rather than trying to explain short-term variations.

An interesting conclusion to be drawn from Figure 2 is that the salt concentration of the drainage water (SCD) is relatively independent of the salt concentration of the soil moisture in the rootzone (SCR) because the SCD curve is slightly convex whereas the SCR curve is concave. The main reason for this is that the water percolating from the rootzone does not go directly to the drains, but first passes through the transition zone below drain level before reaching the drains, and this transition zone has a large buffering effect.

Such predictions of the salinity of drainage water are of importance if one is considering the re-use of drainage water for irrigation (Oosterhaan l988). Figure 3 shows that a leaching efficiency (which is defined as the ratio of the salt concentration of the water reaching the transition zone and the average salt concentration of the soil moisture in the rootzone when at field saturation) of between 0,6 and l.0 gives computed salt concentrations of the rootzone that correspond to the observed values. Figure 3 also shows that, in this range, the calculated salt concentration is not very sensitive to differences in leaching efficiency. A value of 0.8 is taken to represent the true value.

Table l, which was prepared to analyze the effects of the natural drainage to the aquifer, shows the following tendencies:

- The observed values of DWT (depth to watertable) in summer are best explained by values of NDR (natural drainage) in the range of l40 to 250 mm/year;
- The observed values of DWT in winter are best explained by values of NDR in the range of 0 to l40 mm/year;
- The observed values DRT (the drain discharge) in summer are best explained by values of NDR in the range of 70 to 210 mm/year;
- The observed values of DRT in winter are best explained by values of NDR in the range of 70 to 140 mm/year.

The conclusion is that there is definitely a positive natural drainage in the Mashtul

Pilot Area: of the order of 100 mm/year or more. Part of the unexplainable variations are due to inconsistencies in the observed values as explained earlier. In the following, an NDR value of 140 mm is taken to represent its true value.

The presence of natural drainage to the underground was confirmed by observations in deep and shallow piezometers placed in the Mashtul Pilot Area. These reveal that the groundwater at shallow depth has a higher piezometric pressure than at greater depth, the difference being about 1 m (Pilot Areas and Drainage Technology Project 1987). Also, the water-balance studies conducted by the Groundwater Research Institute (IWACO/RIGW 1988) show that there is natural drainage of about 0.5 mm/day.

To confirm the presence of natural drainage still further, SALT1\/[OD was used to estimate the equilibrium salt and water balances under the drainage conditions pertaining before the new drainage system was installed in 1980/81. Varying degrees of natural drainage (NDR) were used. The results are shown in Table 2. They demonstrate that, with values of NDR of 70 mm/year or less, one obtains soil salinity (SCRSQ) values greater than 7 mmhos/cm, which are higher than those found just before the installation of the new system. The actual value of SCR was about 5 mmhos/cm (Figure 2). For a value of NDR = 210 mm/year, the reverse is true: SCRW < 3 mmhos/' cm. These results confirm the hypothesis that NDR is in the range of 100 to 200 mm/ year.

Table 2 The simulated effects of different values of NDR (the natural drainage to the aquifer in mm/year) on several water and salt balance factors, obtained with SALTMOD under the drainage conditions pertaining in the Mashtul Pilot Area prior to the installation of the new drainage system in 1980/81

NDR	SCR_{eq}	IR	E_f	S_f	DWT	DRT	CAP
				Summer season			
0	9.3	250	100	76	0.49	40	86
70	7.8	280	100	75	0.51	23	54
140	4.5	310	100	74	0.52	20	20
210	3.1	480	92	97	0.50	25	0
280	2.4	530	85	100	0.53	18	0
				Winter season			
0	9.7	330	99	75	0.51	32	32
70	7.8	450	94	97	0.56	16	0
140	4.4	500	88	100	0.57	13	0
210	3.1	500	85	96	0.95	0	0
280	2.4	500	80	91	1.46	0	0

SCReq = Equilibrium salt concentration of the soil moisture at field saturattion expressed in electric conductivity (dS/m)
Note; SCRcq = 2 ECe
IR = Amount of irrigation water applied to the crops other than rice in mm season
Ef = Field irrigation efficiency for crops other than rice in %
Sf = Field irrigation sufficiency for crops other than rice in %
DWT = Average depth of the watertable in m
DRT = Amount of subsurface drainage water in mm/season
CAP = Amount of capillary rise in mm/season

Table 2 further shows that, at small values of NDR, the irrigation sufficiency (defined as the ratio of actual over potential evapotranspiration) is less than l00%. This is explained by the presence of a shallow watertable, which forces the farmers to apply less irrigation water than required for full (potential) crop evapotranspiration. Even the occurrence of capillary rise, which stems in this case from the deep percolation losses from the irrigation canals, is not sufficient to cover the full evaporative demand of the crops. In other words, despite the presence of a high watertable, the crops suffer from drought.

It can also be seen from Table 2 that, in winter, the maximum irrigation sufficiency (l00%) is reached at an NDR value of l40 mm/year, but at the same time the Held irrigation efficiency drops to less than 90%. In other words, the higher the NDR value, the more irrigation water can be applied without causing excessively high watertables, but at the same time more irrigation water is lost to the underground. This, however, has a favourable effect on the salt balance.

At still higher values of NDR (up to 280 mm/year), Table 2 shows that the depth of the watertable in winter becomes so deep that the field irrigation efficiency drops to 80%, and that, because of excessive deep percolation losses, the irrigation sufficiency also drops (to 90%). In summer, the effects of different NDR values show a similar trend as in winter, but this trend occurs at higher levels of NDR. For example, the maximum sufficiency (l00%) is obtained in summer at an NDR of 280 mm/year instead of 140 mm/year in winter. This is explained by the fact that more irrigation water is required in summer than in winter and that the presence of submerged rice fields in summer, with considerable percolation losses, accounts for the maintenance of a higher watertable than in winter.

Application of SALTMOD with Varying Drain Depths

Once the model has been calibrated, it can be used to predict the effects of changing water-management conditions (scenarios). A question that may be asked, for example, is: ‘To what extent can the drain depth in the Mashtul Pilot Area (which is currently l .35 m on the average) be reduced without causing serious waterlogging and salinity? To answer this question, SALTMOD was used to make predictions for drain depths of 1.35, l.2, l.0, 0.8 and 0.6 m, while maintaining the other water-management conditions as used before (e.g. as in Figure 2). The results of the predictions are presented in Table 3.

Anyone interpreting Table 3 should note that the SCRQQ values represent an areal average and that f`rom place to place both higher and lower values occur.
Table 3 shows that drain depths (DD) of l.0 m are quite acceptable. They do not lead to excessively high values of SCR, whereas they increase field irrigation efficiencies (Et) above those obtained with the present drain depth of 1.35 m. This is partly due to a reduction of the deep percolation losses from the irrigated fields. as a consequence of the somewhat shallower watertables (DWT).

Further, it can be seen that, with the increased field irrigation efficiencies obtained with shallower drain depths, the drain discharge (DRT) is reduced. It is also reduced by a decrease in the percolation losses from the field irrigation canals. (The latter effect is not shown in Table 3, but is reproduceable by SALTMOD.)

Table 3 Simulation of the effects of various drain depths (DD in m) on several salt-and-water-balance factors in the Mashtul Pilot Area obtained with SALTMOD after its calibration against natural drainage and leaching efliciency. (For an explanation of symbols, see Table 2.)

DD	SCR_{eq} dS/m	IR mm	E_f %	S_f %	DWT m	DRT mm	CAP mm
	Summer season						
1.35*)	2.4	530	85	100	0.90	103	0
1.2	2.9	530	85	100	0.77	99	0
1.0	3.6	480	93	99	0.67	77	0
0.8	3.8	310	99	70	0.61	45	0
0.6**)	4.5	310	100	74	0.52	20	20
	Winter season						
1.35*)	2.4	500	80	91	1.17	60	0
1.2	3.1	500	88	100	1.14	22	0
1.0	3.7	500	88	100	0.95	19	0
0.8	3.9	500	88	100	0.76	16	0
0.6**)	4.5	500	88	100	0.57	13	0

*) As in present Pilot Area. (Compare data with those of Figure 2.)
**) As in Pilot Area before installation of the new drainage system in 1980. (Compare data with those of Table 2 with NDR 1 140.)

It can also be seen from Table 3 that, at drain depths shallower than 0.8 m, the irrigation sufficiency (Sf) is severely reduced in summer, but not in winter. The reduced sufficiency is- explained by the relatively high summer level of the watertable, so that the amount of irrigation water (IR) has to be decreased to avoid problems of waterlogging. In summer, therefore, the plants suffer from some degree of drought despite the presence of a relatively shallow watertable. Also, with shallower drain depths, there is an increase in capillary rise (CAP), but only when the drain depth is very shallow (0.6 m or less). This accounts for the increase in soil salinity.

A conclusion from this particular application of SALTMOD is that the drain depth in the Mashtul Pilot Area could have been reduced from 1.35 to 1.2 m, and perhaps to 1.0 m, while maintaining the same drain spacings, without harming the agricultural production. The positive effects of the reduced drain depth would have been (1) an easier (and less costly) job of drain installation, (2) a saving of irrigation water, (3) a reduced drain discharge, and hence (4) the possibility of reducing drain diameters (which is cost saving) or of increasing drain length (which would increase the spacings of the collector drains and reduce their cost per ha).

In Conclusion

ln this article, we have presented an example of the application of SALTMOD, using various drain depths. The model offers many more possibilities of application for situations as found in the Mashtul Pilot Area (e.g. one could estimate the effects of the re-use of drainage water or of pumping from the aquifer), but also for entirely different situations (Oosterbaan 1988).

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