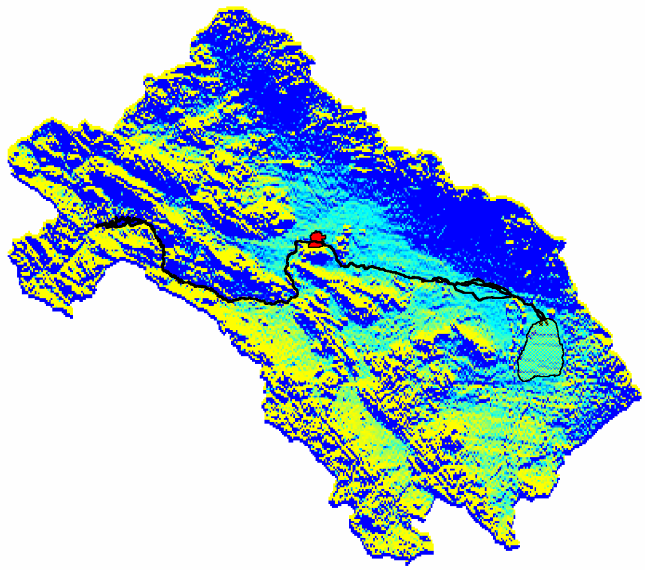
Sustainable Irrigation and Water Management in the Zayandeh Rud Basin, Iran

Exploring Field Scale Salinity Using Simulation Modeling, Example for Rudasht Area, Esfahan Province, Iran

P. Droogers, M. Akbari, M. Torabi, E. Pazira



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The IAERI-EARC-IWMI collaborative project is a multi-year program of research, training and information dissemination fully funded by the Government of the Islamic Republic of Iran that commenced in 1998. The main purpose of the project is to foster integrated approaches to managing water resources at basin, irrigation system and farm levels, and thereby contribute to promoting and sustaining agriculture in the country. The project is currently using the Zayendeh Rud basin in Esfahan province as a pilot study site. This research report series is intended as a means of sharing the results and findings of the project with a view to obtaining critical feedback and suggestions that will lead to strengthening the project outputs. Comments should be addressed to:

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Exploring field scale salinity using simulation modeling, example for Rudasht area, Esfahan Province, Iran

P. Droogers, M. Akbari, M. Torabi, E. Pazira.

Abstract

One-third of the irrigated land in the major irrigation countries is affected by salinity or is expected to become so in the near future. A rapid assessment to evaluate the effect of changes in irrigation water quality and quantity is applied for the Rudasht irrigation project in Iran. This was performed by using a physically based, well-tested simulation model for crop growth, water and salt transport at field scale. Results indicate that the current practice of 900 mm annual irrigation application rates for cotton, given the current salinity level of 4 dS m^{-1}, is close to the optimal one. Graphs are presented to evaluate the effect of different combinations of application rates and salinity levels on yields, and the water and salt balance. It was concluded that the methodology presented here is versatile, rapid, and transferable to other conditions. Moreover, the method produces output at a high spatial and temporal resolution over a long time frame.

Introduction

Salinity is one of the major problems in irrigated agriculture all over the world. Many areas are facing reduced production as a result of salinity and, even worse, areas have been abandoned for any agricultural activity due to severe salinity levels. It is estimated that roughly one-third of the irrigated land in the major irrigation countries is already badly affected by salinity or is expected to become so in the near future (Kijne et al., 1998). Some estimates for major irrigation countries are: Pakistan 14 percent, China 15 percent, India from 27 to 60 percent, Egypt 30 percent, and Iraq 50 percent (Ghassemi et al., 1995). Two major salinity problems are likely to occur in irrigated areas if no careful irrigation management is applied. First of all, salts will accumulate in the soil as irrigation water always contains some salts, while water transpired by plants or evaporated by the soil will not remove any salts. In an attempt to reduce this salt accumulation, a surplus of irrigation water is supplied to leach these salts from the root zone. This leads in many cases to a second problem, water logging due to rising groundwater. Often, this groundwater is also very saline and will increase the salinity level of the root zone substantially. So, irrigation applications must be large enough to minimize salt accumulation in the root zone and low enough to limit the hazard of water logging. Obviously, problems related to water logging can also be diminished by an adequate drainage system.

Field trials can be useful to analyze and test different scenarios related to salinity. However, several important limitations of these field experiments have become more and more apparent. First of all, their validity is limited to the area and the physical conditions the experiments have been conducted. Secondly, field trials are often conducted over a short period of a couple of years, ignoring a very important topic in salinity related problems: the long-term effects. These long-term effects can be a gradual, but constant, salt accumulation in the root zone and the groundwater, as well as in rising or falling water tables. Finally, the number of scenarios that can be studied by field experiments is necessary limited, given practical considerations as labor input, available fields, and noticeable expenses. Simulation models can be applied as an extension of field tests to overcome these restrictions of field experiments. Nowadays, well-tested and validated simulation models are available and are ready to be applied to answer questions related to salinity.

For the Rudasht irrigation project in the Zayandeh Rud basin in Iran a rapid assessment procedure was tested based on the SWAP model; a physically based, well-tested simulation model for crop growth, water and salt transport at field scale. No measurement campaign was conducted but data from an existing data set was used. Emphasis will be put on the output from the model in terms of long term effects, spatial and temporal resolution, expected crop yields, and water and salt balances.

In summary the objectives of this paper are to demonstrate the possibility of making combined use of data and a simulation model for a rapid assessment of salinity problems. This approach was tested by analyzing the water and salt balance and yields in relation to the quantity and quality of water applied for irrigation.

Materials and methods

Study area

The Rudasht irrigation project (52° lon., 32.5° lat) is located east of Esfahan in the central part of Iran and has an altitude of approximately 1500 m (Fig. 1). The climate is arid with temperatures ranging from 30°C in summer down to 3°C in winter. Average annual precipitation is 150 mm. Soils in the area are alluvial deposits and are fine textured. The old irrigation system will be expanded, which will result in a total command area of approximately 47,000 ha. Main crops are winter wheat and barley, sugar beet, cotton and melons.

Simulation model

The Soil-Water-Atmosphere-Plant (SWAP) model was applied to simulate all the terms of the water and salt balance and to estimate relative yields (actual over potential yield). SWAP is an integrated physically based simulation model for water, solute and heat transport in the saturated-unsaturated zone in relation to crop growth. For this study the water and salt transport and crop growth modules were used. The first version of the SWAP model was already written in 1978 (Feddes et al., 1978) and from then on a continuous development of the program started. The version used for this study is SWAP2.0 and is described by Van Dam et al. (1997).

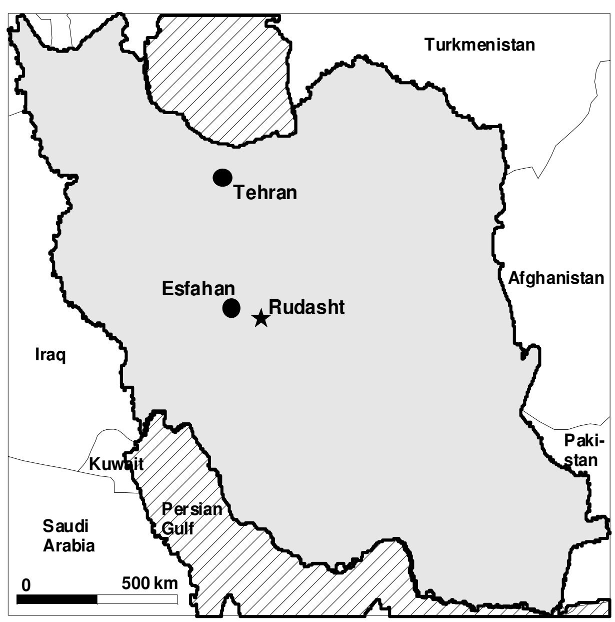

Figure 1. Location of the Roodhast area in the Esfahan region, Iran.

The core part of the program is the vertical flow of water in the unsaturated-saturated zone, which can be described by the well-known Richards' equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}+1\right)-S(h)\right] \tag{1}$$

where θ denotes the soil water content ($cm^3\ cm^{-3}$), t is time (d), h (cm) the soil matric head, z (cm) the vertical coordinate, taken positive upwards, K the hydraulic conductivity as a function of water content ($cm\ d^{-1}$). S (d^{-1}) represents the water uptake by plant roots (Feddes et al., 1978), defined in case of an uniform root distribution as:

$$S(h) = \alpha(h)\frac{T_{pot}}{|z_r|} \tag{2}$$

with T_{pot} is potential transpiration ($cm\ d^{-1}$), z_r is rooting depth (cm), and α (-) is a reduction factor as function of h and accounts for water deficit and oxygen deficit. Except for the very wet conditions, unlimited water uptake by plants was at h > -1000 cm Between these points and permanent wilting point, h = -5000 cm, a linear reduction was assumed. Below h = -5000 cm water uptake was assumed to be zero. Total actual transpiration, T_{act}, was calculated as the depth integral of the water uptake function S.

Actual soil evaporation can be estimated by the Richards' equation using the potential evaporation as the upper boundary condition. However, this requires information about the soil hydraulic properties of the first few centimeters of the soil, which are hardly measurable and are highly variable in time as a consequence of rain, crust and crack formation, and cultivation (Van Dam et al, 1997). All these processes reduce the real actual evaporation in comparison with the values obtained by applying Richards' equation. Therefore the additional soil reduction function option from SWAP was implied, whereby the actual evaporation is a function of the potential evaporation, the soil moisture content of the top soil, an empirical soil specific parameter, and the time since the last significant rainfall. Details of this procedure are given by Boesten en Stroosnijder (1986).

Crop yields can be computed using a simple crop growth algorithm based on Doorenbos and Kassam (1979) or by using a detailed crop growth simulation module that partitions the carbohydrates produced between the different parts of the plant, as a function of the different phenological stages of the plant (Van Diepen et al. 1989). For this specific case the first method was used as detailed crop parameters were lacking. Potential evapotranspiration is partitioned into potential soil evaporation and crop transpiration using the leaf area index. Actual crop transpiration and soil evaporation are obtained as a function of the available soil water in the top layer or the root zone for, respectively, evaporation and transpiration. Finally irrigation can be prescribed at fixed times, scheduled according to different criteria, or by using a combination of both.

SWAP can deal with solute transport processes in general. For salinity studies it can be assumed that salt can be described as a conservative solute, no adsorption or decomposition, and diffusion rate is very small, so it can be ignored. This implies that salt transport is only governed by the convection-dispersion process. The effect of salinity on crop yields is taken into account and is defined by a critical ECe level below which no salt stress occurs and the decline of rootwater uptake above this ECe maximum level in percentage crop yield reduction per $dS\ m^{-1}$. For the cotton crop used here the ECe maximum is defined as 7.7 dS m^{-1} and the decline as 5% per dS m^{-1} (Doorenbos and Kassam, 1979).

The SWAP model has been applied and tested already for many different conditions and locations and has been proven to produce reliable and accurate results. A more detailed description of the model and all its components is beyond the scope of this paper, but can be found in Van Dam et al. (1997).

Input data

Soils

In order simulate the flow of water the soil hydraulic functions, water retention and hydraulic conductivity curves, are required. These soil hydraulic functions are often not available and, moreover, require specific equipment to determine these properties. Pedo-transfer functions can be used to derive these difficult-to-measure soil hydraulic functions from easily obtainable data such as texture and soil bulk density (e.g. Tietje and Tapkenhinrichs 1993). Recently, Wösten et al. (1998) developed a set of pedo-transfer functions using a soil database including data of 4030 horizons. These pedo-transfer functions were used to obtain the soil hydraulic properties required as described according the Mualem-Van Genuchten equations (Van Genuchten, 1980). Variation in soil properties was limited in the area and therefore only one soil type was considered. Table 1 shows the measured soil properties and the derived soil hydraulic characteristics.

The soil hydraulic characteristics for the top three layers are depicted in Figure 2. The water holding capacity of the top soil is substantially higher than the ones from the deeper soil layers. Assuming values for field capacity as pF 2.0 and for wilting point as pF 4.0, the water holding capacity is 0.21, 0.21 and 0.13 $cm^3\ cm^{-3}$ for respectively 0-30, 30-55 and 55-75 cm depths. Also hydraulic conductivity is higher for the top layers than for the deeper layers.

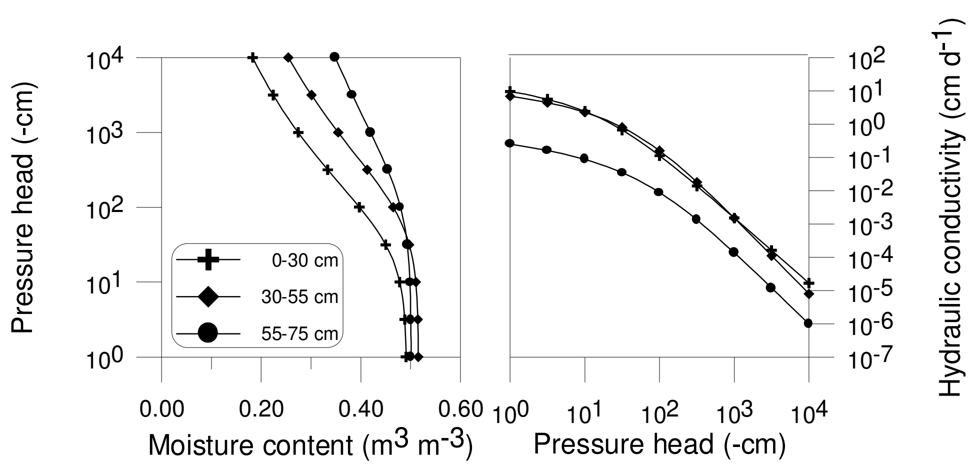

Figure 2. Soil hydraulic functions for the top soil layers.

Table 1. Soil properties and derived soil hydraulic functions, as described according to the Van Genuchten parameter set.

depth	clay	sand	silt	OM	θ_{res}	θ_{sat}	α	n	K_{sat}	L
cm	%	%	%	%	$m^3\ m^{-3}$	$m^3\ m^{-3}$	cm^{-1}	-	$cm\ d^{-1}$	-
0-30	35	21	44	0.5	0.000	0.492	0.0264	1.178	42.0	-2.196
30-55	64	10	26	0.4	0.000	0.516	0.0122	1.147	30.2	0.046
55-75	68	4	28	0.3	0.000	0.501	0.0078	1.083	2.3	0.251
75-115	48	2	50	0.2	0.000	0.431	0.0138	1.082	4.3	-2.743
> 115	32	8	60	0.2	0.000	0.424	0.0167	1.131	9.8	-1.982

OM is soil organic matter, θ_{res} is residual soil moisture content, θ_{sat} is saturated soil moisture content, K_{sat} is saturated hydraulic conductivity, α, n, and L are fitting parameters.

Climate data

Monthly meteorological data was available for a station in the vicinity of the Rudasht area over a period of 11 years. SWAP requires daily input data so it was assumed that the daily data was similar as the monthly average ones. In addition, for rainfall the monthly maximum and the day this maximum occurred, was available, and was used in SWAP. This ensured us that the most variable meteorological factor was correctly taken into account in the simulations.

As we are interested in the long term effects of different scenarios we used one reference year and applied this over a period of 10 years in order to get the equilibrium stage. The selection of one reference year was done by considering the total annual precipitation as well as the distribution of this precipitation during the year. Table 2 shows the characteristics of the entire data set from which was decided to select 1991 as the reference year.

Table 2. Climate data from Esfahan station in the vicinity of the Rudasht irrigation scheme.

year	precipitation (mm)			temperature (^{o}C)		
	mean	summer	winter	mean	summer	winter
1986	165	12	153	15.9	34.7	8.1
1987	61	30	31	17.2	35.2	10.0
1988	71	1	70	17.4	35.5	9.5
1989	139	7	132	16.5	36.5	8.1
1990	78	6	72	17.4	36.4	9.1
1991	122	10	113	16.9	35.7	9.2
1992	123	36	86	15.5	34.6	7.5
1993	199	10	188	16.3	35.8	8.6
1994	125	23	102	17.0	36.0	9.2
1995	123	38	85	15.8	35.9	8.1
1996	148	21	127	15.6	35.5	7.7
average	123	18	105	16.5	35.6	8.6

Crops

Main crops in the area are winter wheat and barley, sugarbeet, and cotton. For this study we selected to analyze the effect of different irrigation management scenarios on cotton. Cotton is seeded at the beginning of April and yield is harvested at the beginning of

October. Potential yields for cotton in this area is around 5000 kg ha^{-1}, but actual yields are frequently reported to be only halve of this due to salinity problems.

Bottom boundary condition

Groundwater levels are reported to be around 200 cm below surface, but may increase substantially during the irrigation season. A bottom flux groundwater relationship was used here, as this is appropriate to evaluate changes in water table depths. No detailed data was available for this, so a general exponential relationship was used:

$$q_{bot} = ae^{b|h|} \quad (3)$$

where a and b are empirical coefficients, here defined as –0.3 cm d^{-1} and –0.01 cm^{-1}, respectively. These values result in a water table behavior comparable to the reported qualitative field observations: a water table depth of around 200 cm and some water logging after substantial irrigation applications.

Irrigation

Irrigation applications according to normal farmer practices are very high in an attempt to compensate for the poor water quality. For cotton a total application will reach between 800 and 1000 mm, given in quantities of about 100 mm. As no detailed information was available on the exact date of irrigation applications, it was assumed that farmers irrigated the crop at the most appropriate time. This was performed by using a timing criterion in the SWAP model, based on the ratio of actual over potential crop transpiration (T_{crit}). By changing this criterion in the range from 0.3 to 0.95, different amount of irrigation will be simulated. Each application was assumed to be constant at 100 mm which was in accordance with local farm practice.

Water quality was very poor with reported salinity levels between 2 and 6 dS m^{-1}. As no trend was apparent in these levels during the year, we assumed here a constant level of 4 dS m^{-1}.

Scenarios

In order to explore the effect of different water management decisions, scenarios were defined. The first scenario is the baseline scenario, which describes the current situation, and will function as a reference for the other scenarios. The other scenarios are based on changes in water quantity and quality and their effect on the water and salt balance and crop yields.

Baseline

The baseline is used as a reference and can be considered as the ‘business as usual’ case. The cotton crop was considered, as this is an important industrial crop in the area, also in the perspective of the renewal and expansion of the system. Irrigation inputs were used as applied by the average farmer and includes a total of 900 mm as defined before. The salinity of the irrigation water was considered to be constant during the year of 4 dS m^{-1}. No drainage was considered and the groundwater depth was simulated using the flux-groundwater relationship as described before.

In order to focus on long term effects and analyze an equilibrium state, a period of 10 years was considered for which all the input data was kept constant. Also weather data was kept similar for these 10 years, in order to avoid disturbance from extreme weather conditions. Obviously, extreme weather conditions exist in reality and can be studied in detail using a historic range of climate data to explore the probability of occurrence of certain conditions. This is beyond the scope of this paper, as we want to explore long term effects only, but can be found elsewhere (e.g. Droogers et al., 1999).

Water quantity

The baseline irrigation applications were defined by 9 times an application of 100 mm. As a result of changes in upstream management, inter-basin flows, or irrigation development, more or less water could become available for the scheme, or, moreover, a change in the cropped area in the scheme itself can change the water availability for irrigation at field level. In order to distribute the water of the different scenarios as optimally as possible an irrigation scheduling criterion from SWAP was used based on the ratio actual over potential crop transpiration. Different ratios, ranging from 0.3 to 0.95, were used, resulting in total irrigation application between 300 and 1500 mm. Results of these simulations were compared with the baseline scenario of a total of 900 mm water applied.

Water quality

As a consequence of changes in upstream water utilization and management, salinity levels in the river can change. To explore the effect of these changes, simulations were performed with decreased salinity levels (1 and 2 dS m^{-1}), which occurs as a result of the development of inter-basin flows. The development of more irrigation upstream of the Rudasht area, could lead to a further deterioration of water quality and therefore a scenario was analyzed using an increased salinity level of 6 dS m^{-1}. All the other input parameters were assumed to be unchanged.

Table 3. Annual water for the baseline scenario at equilibrium stage, 900 mm irrigation with a salinity level of 4 dS m^{-1}.

	Potential mm	Inflow mm	Outflow mm
Transpiration	922		640
Evaporation	1145		246
Precipitation		118	
Irrigation		900	
Bottom flux			130
Surface runoff			0
Mass balance error			2
Total	2067	1018	1018

Results

Baseline

All the terms of the water balance, as simulated by SWAP for the baseline scenario in equilibrium stage, are shown in Table 3. This equilibrium stage was reached by applying the model for a period of 10 years while keeping all the input data constant. It appears that this equilibrium stage was reached already after 5 years for the water balance and the topsoil salinity levels. However, groundwater salinity levels were just reaching an almost equilibrium stage after these 10 years, at a level of about 27 dS m^{-1}. From table 3 is appears that the irrigation application was almost equal to the potential transpiration. However, part of this irrigated water could not be used directly by the crop, as a consequence of percolation to the groundwater and losses by soil evaporation.

Figure 3 shows the daily trend in the water balance. Irrigation inputs were 900 mm, according to normal field practices. As the exact dates of the irrigation applications were unknown, we allowed the model to distribute this 900 mm as optimally as possible.

This was accomplished by setting the T_{crit} (the ratio of actual over potential crop transpiration) to the value that simulated this 900 mm. After some trials a value of 0.63 appeared to be appropriate. Clearly the rise in groundwater due to irrigation with the associated negative aspects of water logging can be seen. Interesting is that during the peak growing season, June-August, water is not the limiting factor as can be seen from the high water table, but the crop is being stressed due to salinity and some aeration problems related to the high water table.

Table 4. Effect of the changes in irrigation water quantity on yields and salt and water balance.

Precipitation	Irrigation	Percolation	Surface Runoff	T_{pot}	T_{act}	E_{pot}	E_{act}	Relative Yield	Salinity[1]	Groundwater[2]
------------------------------				mm y^{-1}	------------------------------			%	dS m^{-1}	cm
118	300	-6	0	922	212	1145	196	29	34.5	-515
118	400	-27	0	922	266	1145	206	33	33.4	-364
118	500	-58	0	922	341	1145	216	38	29.7	-301
118	600	-77	0	922	418	1145	224	44	26.8	-275
118	700	-93	0	922	496	1145	233	51	24.4	-261
118	800	-109	0	922	568	1145	241	58	22.1	-244
118	900	-130	0	922	640	1145	246	66	19.7	-244
118	1000	-159	14	922	688	1145	253	71	17.3	-227
118	1100	-191	92	922	680	1145	258	70	16.4	-232
118	1200	-222	172	922	656	1145	264	66	15.9	-221
118	1300	-252	285	922	604	1145	272	61	16.1	-221
118	1400	-284	371	922	583	1145	279	59	15.7	-214
118	1500	-306	479	922	543	1145	288	56	16.0	-215

[1]Salinity is the average salinity of the topsoil (0-100 cm) during the growing season.
[2]Groundwater depth reflects the situation at the end of the growing season.

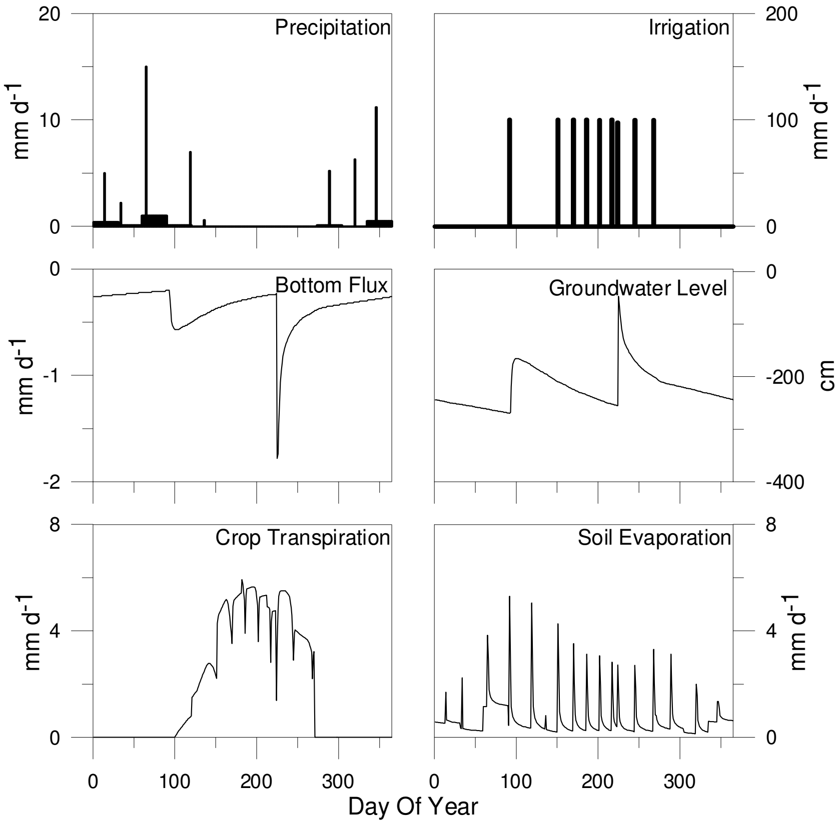

Figure 3. Annual water balance for the baseline scenario.

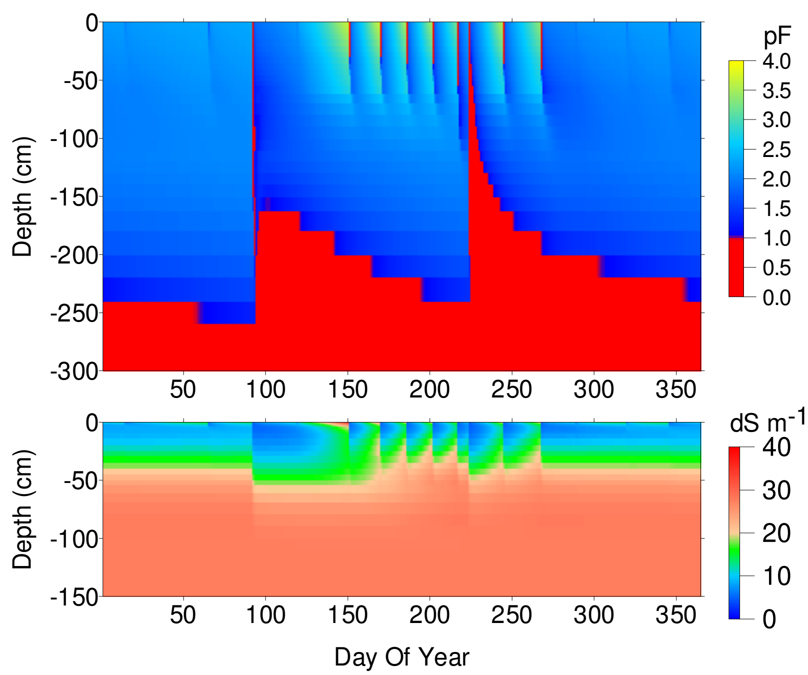

Figure 4. Water and salinity profiles for the baseline scenario at equilibrium stage for one year for the top soil as simulated using SWAP.

The SWAP model offers the opportunity to evaluate processes in unlimited spatial and temporal resolution. As an example, Figure 4 shows the soil moisture status and the solute concentrations for one year for the top soil. Water contents higher than pF 1.0, h = -10 cm, are considered to be negative for the plant as water uptake is restricted due to aeration problems. From pF 3.0 crops stress started and no water uptake by roots take place if the soil is dryer than pF 4.0. From Figure 4 it is clear that the irrigation input is just low enough to prevent the soil of severe drying out and not too high to cause water logging problems. The salinity levels (Fig. 4 bottom) are constant for the lower soil profile, but major variations can be observed in top soil salinity levels. Interesting is that a substantial salt accumulation has been developed in the lower soil layers, with values around 25 dS m^{-1}, while irrigation water had a salinity level of 4 dS m^{-1}. Note that salinity levels presented here reflect the actual levels for the current soil water, while field measurement are normally based on a soil sample brought to saturation.

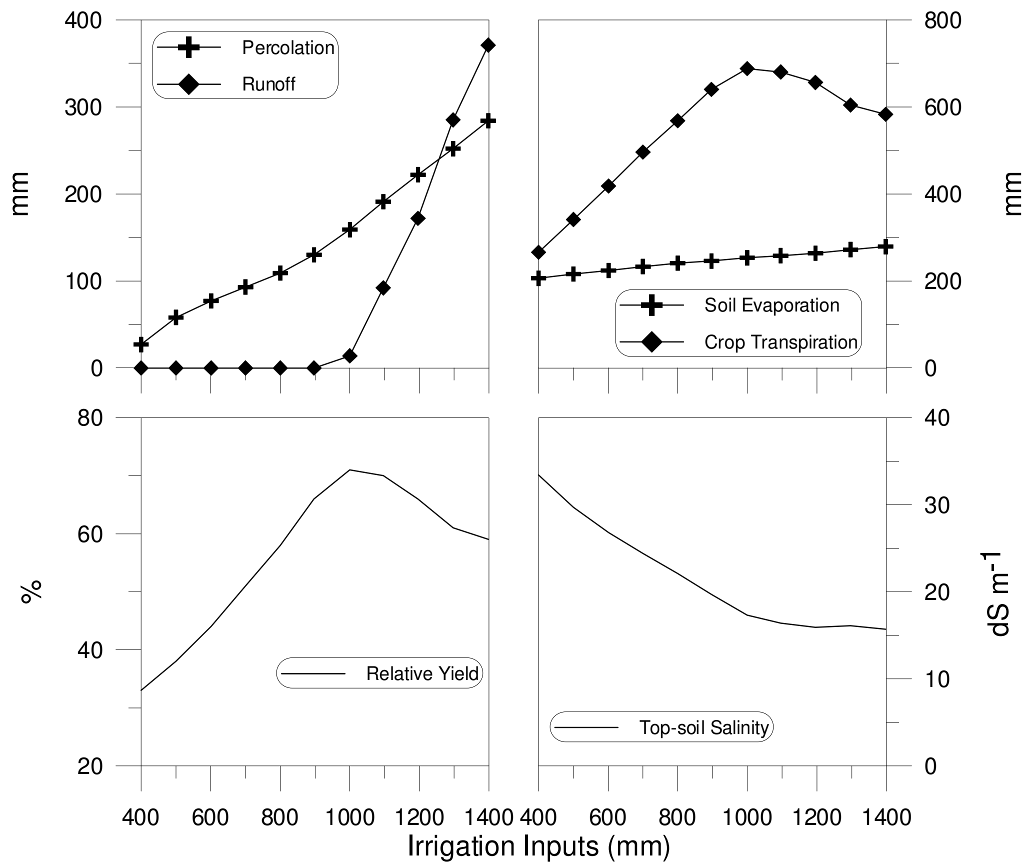

Figure 5. The effect of changes in water quantities applied by irrigation on the soil water balance, crop yields and soil salinity levels.

Changes in water quantity

The effect of a change in irrigation supplies in terms of total amount applied water, was analyzed using the result of the SWAP model (Table 4). In Figure 5 the relationship between water applied and the annual terms of the water balance, expected crop yields and soil salinity are displayed. Runoff is zero as long as annual irrigation applications are lower than 900 mm. Higher irrigation applications will increase this runoff noticeably. An almost linear relationship exists between the amount of water applied by irrigation and the amount of percolation, with a slope of 25%. Soil evaporation is also linear related to the irrigation supply. Crop transpiration and relative yields reach their top at an irrigation input of about 1000 mm. A higher supply will reduce the soil salinity levels slightly, but will cause water logging with all the negative aspects associated with this.

In general it appears that the current practice of applying 900 mm of irrigation is close to the optimal amount. However, with increasing competition of water less water might become available for irrigation in the near future. Results displayed in Table 4, can be used to estimate the expected crop yields given a certain amount of water available for irrigation. With the current water management crop yields are about 65% of potential, while this can drop to 50 and 40 % for respectively 700 and 500 mm of irrigation.

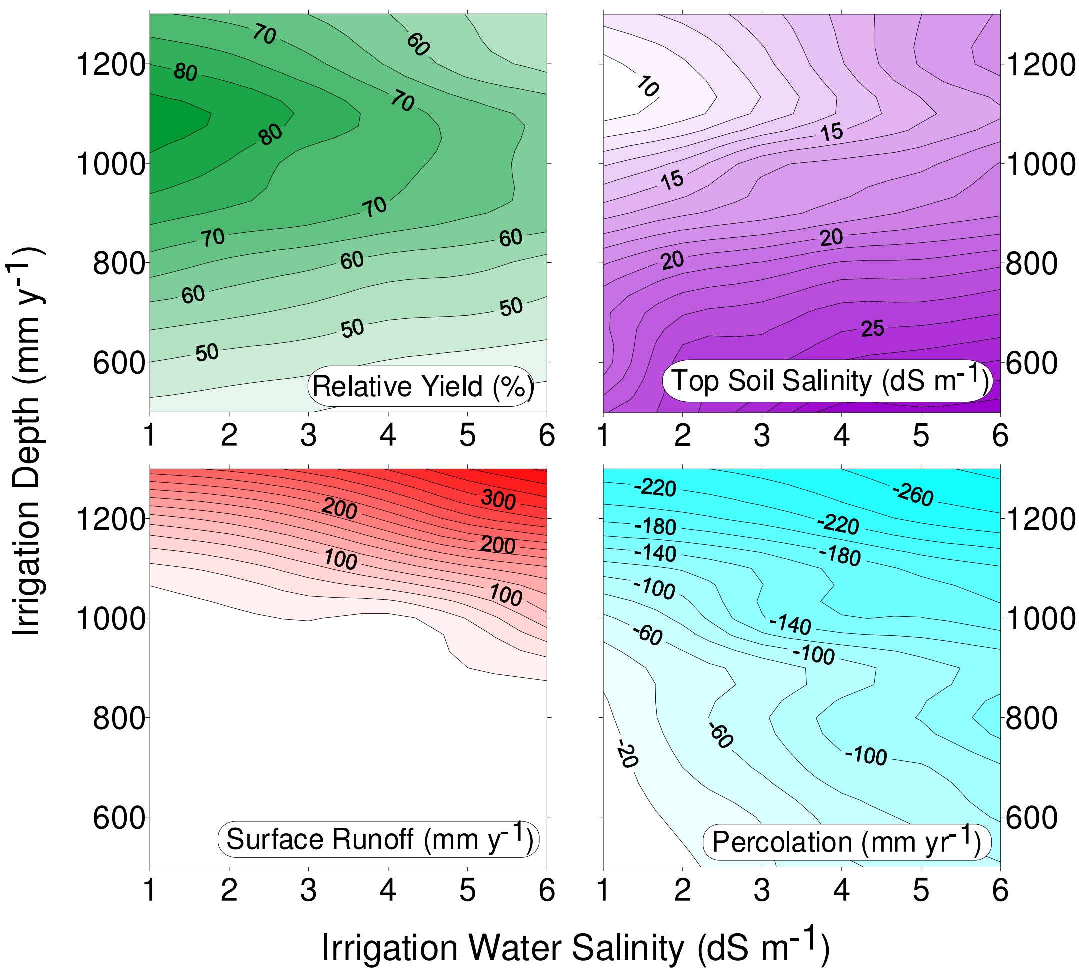

Figure 6. Combined effect of irrigation water quality and quantity on crop yield, top-soil salinity, surface runoff, and percolation.

Changes in water quality

Table 5 shows the effects of changes in water quality in terms of expected crop yields and salt accumulation. Obviously, lower salinity levels result in higher yields and transpiration rates, and lower runoff and soil salinity levels. The increase in percolation can be explained by the fact that water uptake by plant roots is hampered by the high salinity levels, resulting in more water available for percolation. Moreover, due to this lower transpiration the water table will rise and runoff will occur.

Table 5. Effect of the changes in irrigation water quality on yields and salt and water balance. The EC_{soil} reflects the salinity of the top soil (0-100 cm).

dS m^{-1}	PCP	Irr	F_{bot}	Runoff	T_{pot}	T_{act}	E_{pot}	E_{act}	Yield	Salinity
1	118	900	-27	0	922	742	1145	247	77	15.6
2	118	900	-62	0	922	709	1145	248	73	17.6
4	118	900	-130	0	922	640	1145	246	66	19.7
6	118	900	-197	72	922	496	1145	245	51	22.7

Combined effect of water quantity and water quality

The combined effect of changes in water quantity available for irrigation as well as the salinity levels of this water were analyzed using the SWAP model. Figure 6 shows for irrigation depths ranging from 500 to 1300 mm y^{-1} and for salinity levels from 1 to 6 dS m^{-1} the resulting expected relative yields. As can be observed from the figure, the highest yield can be expected for an irrigation depth of 1100 mm with a salinity level of 1 dS m^{-1}. For other combinations of water quantity and quality values, expected yields can be obtained using this figure too. Furthermore, all other terms of the water and salt balance can be analyzed for the different possible water quantity and quality combinations.

In Figure 6 the top soil salinity, surface runoff, and percolation are given as examples. Salinity levels are lowest with irrigation applications of about 1100 mm and increase with higher application rates as a consequence of water logging. As explained before, salinity levels presented here, reflect the top 100 cm average values in the actual soil water, and thus not the levels for a saturated soil.

Below an annual application rate of about 1000 mm surface runoff is negligible, while at higher rates and high salinity levels root water uptake is hampered, water table rises, inducing significant runoff. Finally, expected percolation to the groundwater as function of the annual water application and salinity levels can be observed at the right-bottom in Figure 6. Percolation rates are between almost zero and 280 mm y^{-1}.

Generalization

The SWAP model offers a range of output that can be used to understand processes and to analyze the impact of different scenarios on field water management aspects. In cases where only the relationship between irrigation inputs and yield is required, more generalized and simplified models can be used. Instead of using a classical irrigation research approach involving experimental field trials with different irrigation applications, we used the SWAP model here as a "virtual field". The main advantage over field trials is the unlimited amount of "experiments" that can be performed using the model. For this study 52 different "experiments" have been conducted: the combination of 13 application depths and 4 salinity levels.

A range of regression equations has been tested to relate irrigation applications and salinity levels to relative yields, as simulated by the SWAP model. Table 6 shows the regression equation used, and the resulting Sum Of Squares (SSQ) and the correlation coefficient r^2. Tests with higher degree regression equations did not improve the predictions, but the additional term Salinity times Irrigation, improved the fit substantially. Figure 7 shows the scatter diagram for this regression equation (last equation in Table 6). The obtained functions should be used with care as they are derived from one soil type, one climatological condition, and one crop (cotton). Extension to other crops and soil types are under study.

Table 6. Regression analysis to relate simulated yield to irrigation application depths and salinity levels. *Y* is relative yield (%), *S* is salinity level of irrigation water (dS m^{-1}) and *I* is annual irrigation depth (mm).

Equation	SSQ	r^2
Y = a + bS + cI	4278	0.72
a = 44.415; b = -5.255; c = 0.035		
Y = a + bS + cI + dI^2	2604	0.83
a = 7.993; b = -5.087; c = 0.132; d = -5.6E-05		
Y = a + bS + cI + dS^2	4267	0.73
a = 46.002; b = -6.632; c = 0.035; d = 0.196		
Y = a + bS + cI + dS^2 + eI^2	2588	0.83
a = 5.622; b = -3.718; c = 0.134; d = -0.192; e =-5.7E-05		
Y = a + bS + cI + dS^2 + eI^2 + fSI	813	0.95
a = -32.006; b = 6.891; c = 0.183; d = -0.443; e =-6.5E-05; f = -0.0106		

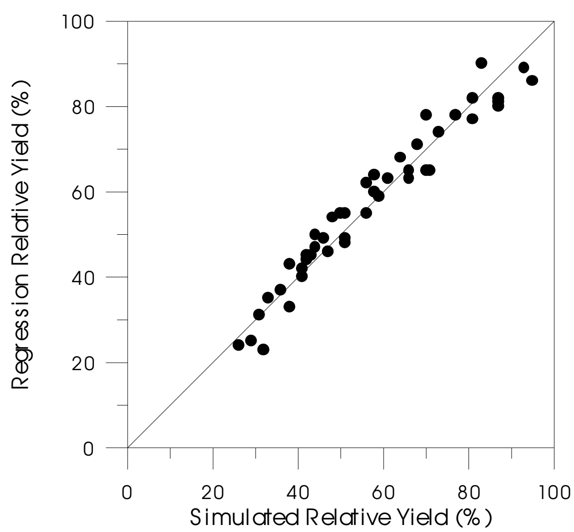

Figure 7. Performance of the last regression equation in Table 6.

Conclusions and recommendations

For the Rudasht area studied here it can be concluded that given the current practice of about 900 mm of irrigation with an average water salinity level of 4 dS m^{-1}, crop yields for cotton are expected to be around 66% of the yield potential of 5000 kg ha^{-1}. Given the current water quality level, changes in the amount of irrigation applied will not change substantially crop yields and the current practice of 900 mm is recommended for cotton.

If water quality improves due to changes in water management upstream of Rudasht to 2 dS m^{-1} or even 1 dS m^{-1}, yields can increase to 73% and 77%, respectively, of the potential value, with the same annual irrigation application of 900 mm. A further increase is possible if along with an improvement in water quality, more water becomes available for irrigation. Expected yields can increase to 87% and 95% for respectively 2 and 1 dS m^{-1}, if an annual application rate of 1100 mm is practiced. A further salinization of irrigation water to 6 dS m^{-1}, will decrease the crop yield for cotton to 51% of potential obtainable.

The results presented here can be used also to assess the effect of sub-optimal irrigation applications on yields and the water and salt balance. Figure 6 top-left can be used as a guideline to estimate expected yields given the salinity level of irrigation water and the annual applied irrigation amount.

Results from this study reflect the situation for the representative soil type considered here and for average farmer practice and weather conditions. Variation in these parameters is likely to change the results and conclusions. However, the input data used here reflects the average conditions and results can be used as general guidelines. Furthermore, limitations as a result of water stress, water logging, and salinity were taken into account, but other possible limitations, such as weeds, diseases, and improper management, were neglected here.

The main advantage of the approach applied here is that it is a nonspecific one and can be easily adapted to other conditions in terms of soil, weather, and crop. The study presented was setup to demonstrate the use of existing models, data, and techniques for a rapid assessment. Input data for the current study was readily available and required data was obtained by converting the existing data to the required ones in stead of starting extensive measurement efforts. The use of an existing well-tested simulation model and well-established data conversion methods was assumed to generate reliable results. The nature of the model, physically based, enabled this approach as no calibration is required by field tests and the input data needed is physically sound.

The model was applied here in an input driven mode, i.e. ignoring the impact of irrigation management on downstream users. As the irrigation scheme studied here was located at the lower part of the river with no downstream users, this downstream effect could be ignored. In cases where downstream users are present and reuse of water is relevant, the evaluation can be extended using output produced by the model, such as surface runoff and percolation in terms of quantity as well as quality.

Besides the benefits of this non-specific approach, the methodology applied here gives a wealth of information in comparison to field trials, in terms of spatial and temporal resolution as well as in terms of difficult to measure processes such as crop transpiration, soil evaporation, and percolation.

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