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Relationships between yield and irrigation with low-quality water — a system approach

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Abstract

With the increasing usage of brackish water in agriculture there is a need to quantify the water quantity and quality relationship during irrigation of crops. A model based on a system approach was developed, where the responses of plants to water and salinity stress are expressed in a structural system of equations. The model was applied to field crops in the Israeli Negev, in three case studies, using existing linear and non-linear relationships between yield and irrigation and between yield and salinity. Model coefficients were estimated from experimental data. Model results were consistent with actual yield of corn and cotton in the single season cases. Simulation of wheat growing in the winter with supplemental irrigation with brackish water for 13 years showed interesting results of accumulation of soil salinity and reduction of yield. The model can be easily applied to other crops and growing areas. It can be used for analysis of long-term soil salinization processes. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: System; Modeling; Response function; Optimization; Management; Irrigation; Brackish water; Estimation

1. Introduction

Limited supply of water has led to the use of low-quality irrigation water in many areas throughout the world. Recycled urban wastewater, agricultural wastewater

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Nomenclature

I	Amount of applied irrigation water during a growing season; cm, exogenous variable
R	Amount of effective rainfall during a growing season; cm
ET	Actual amount of evapotranspiration during a growing season; cm, endogenous variable
D	Amount of water drained below the root zone; cm, endogenous variable
D^p	A predetermined drainage amount; cm
TW	Amount of total water available for uptake by the crop during a growing season; cm, endogenous variable
z	Root zone depth; cm, parameter
$\theta_{wp}, \theta_{fc}, \theta_s$	Volumetric soil moisture content at wilting point, field capacity and saturated soil paste, respectively; fractions, parameters
θ_i	Volumetric soil moisture content at the beginning of the growing season; fractions, exogenous variable
θ_f	Volumetric soil moisture content at the end of a growing season; fractions, endogenous variable
S_i	Soil salinity at the beginning of a growing season; dS/m, exogenous variable
S_f	Soil salinity at the end of a growing season; dS/m, endogenous variable
S_I	Irrigation water salinity; dS/m, exogenous variable
S_D	Drainage water salinity; dS/m endogenous variable
\bar{S}	Seasonal average salinity of the soil; cm, endogenous variable
$Y_s(TW, \bar{S})$	Crop yield as a function of salinity and amount of water; kg/m ² , endogenous variable
$Y_{ns}(TW)$	Crop yield without salinity stress; kg/m ² , endogenous variable
EC	Electrical conductivity of solution; dS/m
EC_e	Electrical conductivity of a saturated soil paste extract; dS/m, parameter
$Y_r(\bar{S})$	Crop yield under salinity stress relative to yield without salinity stress; fraction, endogenous variable
Y_{max}	Maximum attainable yield under no stress; kg/m ² , parameter
ET_{max}	Maximum amount of evapotranspiration without any stress; cm, parameter
Z_o	A minimum amount of water requirement of a crop; cm, parameter

and saline fresh water are sources of low-quality water supplied to agriculture. In many situations farmers have no alternative but to use low-quality water. In other cases, farmers have the alternatives of choosing between low and good quality irrigation water, and of mixing water from different sources.

Using low-quality irrigation water may reduce crop yields or damage the environment, soils, and aquifers. For example, salts applied to soils via irrigation are either left in the soil to affect subsequent crop growth or are leached below the root zone and affect groundwater (Tanji and Yaron, 1994). Also, there can be long-term damage to soils and aquifers that may not be easily recoverable.

There is a possibility for partial substitution of increased quantities of irrigation water for decreased water quality. Since plant roots withstand combined osmotic and matrix stresses, reducing one may compensate for an increase of the other (Feinerman and Yaron, 1983). Moreover, when irrigation plus rainfall exceeds the crop water requirement, excess soil water will drain downward, carrying with it soluble salts (Feinerman and Vaux, 1984; Knapp and Wichelns, 1990).

The objective of this study is to develop a model for prediction of yield levels and soil salinity when irrigating with brackish water. The study is focused on both short-term (1 year) and intermediate-term (several years) effects on agricultural outputs and on interactions between quality and quantity of the irrigation water. The model is based on a system approach to plant–soil–water relationships (Letey and Vaux, 1984).

The model consists of simultaneous equations describing the relationships between crop yield levels, soil-water salt content, drainage-water salt content and subsequent irrigation policies. The functional forms of relationships of yield versus water stress and yield versus salinity stress can be set up by each user of this model. A few examples of existing functional forms are provided in the model application section. The model then can be used to describe the dynamics of the plant–water–soil system over growing seasons. It can also predict increasing or decreasing salinization of the soil as different agronomic and irrigation policies are implemented. Finally, the model can also serve as a tool for measuring the economic value of substituting low-quality water for good-quality water. The general system model, as described before, was then applied in three case studies: corn, cotton and a multi-year simulation.

2. Methods

Consider the water balance of the root zone during a growing season as:

$$z(\theta_f - \theta_i) = I + R - ET - D \quad (1)$$

where z (in cm) is the root zone depth; θ_i and θ_f are the volumetric soil moisture fractions at the beginning and the end of the season, respectively; I is the amount of applied irrigation water during that growing season; R is the effective rainfall during the growing season, ET is the actual amount of evapotranspiration during that season; and D is the amount of water drained below the root zone. The parameters

ET, D , R , and I are expressed in centimeters equivalent to 100 m³ of water per hectare.

Exogenous variables in the plant–soil–water system are those having pre-determined values such as the initial soil water content and salinity level, and the irrigation water amount and salinity level. They are designated in the following equations using specific letters. Endogenous variables are computed values, such as the final soil moisture and salinity levels, the evapotranspiration amount, the drainage water amount and the resultant salinity levels. These are functions of the exogenous variables and of other parameters denoted in the functional expressions.

The total water (TW) available for uptake by the crop during a growing season is:

$$TW = z(\theta_i - \theta_{wp}) + I + R - D \quad (2a)$$

From Eq. (1): $ET = I + R - D - z(\theta_f - \theta_i)$. Thus:

$$TW = ET + z(\theta_f - \theta_{wp}) \quad (2b)$$

Soil saturation (θ_s) is the maximum water content of a soil. Generally it is held in the field for only a short time. In this work θ_s relates to the volumetric water content of a saturated soil paste. Field capacity (θ_{fc}) and wilting point (θ_{wp}) are taken as the maximum and minimum soil moisture limits of the available soil water range, respectively.

Under given climatic conditions, the yield of a crop can be related to the amount of water consumed by evapotranspiration during its growing season. A good correlation has been found between actual evapotranspiration and yield (DeWit, 1958; Solomon, 1985; Letey and Dinar, 1986).

The amount of available water and the concentration of soluble salts in that water affect the yield of the crop. The impact of water and salinity stresses on the crop is considered here assuming that all other growth factors are at their optimal levels. The yield (Y_s) is assumed to be a response function of available water (TW) and of average soil water salinity \bar{S} (Feinerman and Yaron, 1983):

$$Y_s = Y_s(TW, \bar{S}) \quad (3)$$

The salinity term (\bar{S}) in this expression is assumed to represent the seasonal average of the mean salinity in the root zone. It is expressed as the weighted average of the mean soil salinity at the beginning (S_i) and end (S_f) of the growing season:

$$\bar{S} = w_i \times S_i + w_f \times S_f \quad (4)$$

where the respective weights are: $w_f = (I + R)/(I + R + z\theta_i)$ and $w_i = z\theta_i/(I + R + z\theta_i)$. The average salinity (\bar{S}) is greatly dependent on $I + R$. When $I + R$ is much greater than $z\theta_i$, as is generally true in arid and semi-arid regions, $w_f \rightarrow 1$ and $w_i \rightarrow 0$. Therefore, the resultant final soil-salinity level often has a higher impact on average soil-salinity than does the initial salinity level.

The average salinity (\bar{S}) can be expressed either in terms of the concentration of soluble salts in the soil, or by the electrical conductivity (EC) (Jurinak and Suarez, 1990). When salinity is dominated by Na^+ , Ca^{2+} and Mg^{2+} , the solution concentration (C) is typically related to the EC by $C(\text{mmol/l}) \cong 10 \text{ EC (dS/m)}$ at 25°C

(US Salinity Laboratory Staff, 1954). It has been found that the average soil salinity \bar{S} is a good variable for representing salinity effects on crop yield (Maas and Hoffman, 1977; Bresler et al., 1982; Vaux and Prauitt, 1983).

Y_s is commonly described as a separable function of TW, \bar{S} .

$$Y_s = Y_s[Y_{ns}(TW), Y_r(\bar{S})] \quad (5)$$

where $Y_{ns}(TW)$ is the yield response to water stress under non-saline conditions (McNeal and Coleman, 1966; Munns and Termaat, 1986), and the function $Y_r(\bar{S})$ is the relative yield response to salinity. This function is expressed as the ratio between yield attained under a specified salinity stress and yield attainable without salinity stress, keeping all other factors equal.

The response function $Y_{ns}(TW)$ may be expressed using various functional forms or differing parameters. The functional forms and/or parameters may vary under differing conditions, including location, climate, and physiological characteristics of the crop. Generally, $Y_{ns}(TW)$ is a monotonically increasing function of TW (Shalhevet et al., 1986; Maas, 1990; Shalhevet, 1994).

Salts applied to the soil via the irrigation water can either remain in the root zone or be leached downward. The salt balance in the soil is:

$$I \times S_I - D \times S_D = z \times (\theta_f \times S_f - \theta_i \times S_i) \quad (6)$$

The quantities of salts in Eq. (6) are given as the product of salt concentration and amount of water. The difference between the salt input and the amount leached below the root zone [left side of Eq. (6)] is equal to the difference between the amounts of salt in the soil at the end and at the beginning of the period (Bresler, 1967; Bresler and Yaron, 1972; Hoffman, 1990).

While the salinity of the irrigation water (S_I) and the initial soil water salinity (S_i) are prescribed exogenous variables, the salinity of the drainage water (S_D) and the final soil water salinity (S_f) are endogenous variables and must be calculated simultaneously with other unknown variables.

The salinity of the drainage water is assumed to be equal to the seasonal average soil-water salinity:

$$S_D(S_i, S_f) = \bar{S}(S_i, S_f) \quad (7)$$

Hence, for predetermined values of the exogenous variables I , R , S_I , θ_i , and S_i , resultant values of the endogenous variables TW, ET, D , θ_f , S_f , \bar{S} , Y_{ns} and Y_s should satisfy the relation:

$$Y_s(TW, \bar{S}) \equiv Y_{ns}(ET) \quad (8)$$

This relationship states that any yield level that is obtained under conditions of salinity stress can also be obtained under conditions of no salinity stress where $ET \leq TW$ (Letey and Dinar, 1986; Vinten et al., 1991). While the functional form Y_{ns} is given explicitly, there is no explicit form for Y_s . In other words, to obtain a given yield level, water quantity and quality are exchangeable when all other factors are the same. Since $ET \leq TW$ [Eq. (2b)], Eq. (8) can be used to calculate the extra amount of water needed when brackish water replaces non-saline water.

The plant–soil–water–salt system is modeled using Eqs. (1)–(8). The model should be independently provided with the functional forms $Y_{ns}(TW)$ and $Y_f(\bar{S})$, along with their input parameters. These may be existing empirical relationships. The values of I , R , S_I , θ_i and S_i are known, but the values of Y_{ns} , Y_s , ET , D , S_D , θ_f , S_f and \bar{S} must be evaluated by solving the model's equations. The number of unknown variables exceeds the number of equations by one; therefore, the system of equations can be presented as an equation of one variable. One may express the yield Y_s as a function of the drainage amount D and additional site-specific parameters. This is done via the following steps.

For given soil characteristics (θ_{wp}, θ_{fc}) the final soil water content in the root zone, z can be derived from Eq. (1) as a function of ET and D hence, $\theta_f = \theta_f(ET, D)$. Then, $S_D(S_i, S_f)$ [Eq. (7)] and $\theta_f(ET, D)$ can be substituted into Eq. (6) so that S_f can also be defined as a function of ET and D , $S_f(ET, D)$. Substituting $S_f(ET, D)$ into Eq. (4) gives $\bar{S}(ET, D)$.

Next, from Eq. (8), ET can be computed as $ET(D)$. This step requires certain assumptions about the functions Y_s and Y_{ns} in order to give an explicit form of $ET(D)$, but a simple numerical approximation can simplify Eq. (8) and give a good approximation for $ET(D)$. The variable Y_s can be written as a function of D and the predetermined values of parameters such as the initial soil water content and salinity, climatic conditions, soil characteristics ($\theta_{fc}, \theta_{wp}, \theta_s$), etc.:

$$Y_s = Y_s(D | I, R, S_I, \theta_i, S_i, \text{site-specific parameters}) \quad (9)$$

With a given set of constraints on the levels of D , the initial and final soil moisture levels, and the constraint of non-negativity for all variables in the model, the system of equations gives several sets of solutions for ET , D , θ_f , S_f , \bar{S} , and Y_s .

If the management assumption of the decision-maker is to obtain maximum attainable yield, the objective function is:

$$\text{Max}_D Y_s = Y_s(D | I, R, S_I, \theta_i, S_i, \text{site-specific parameters}) \quad (10)$$

which yields the optimal level D^* that maximizes Y_s , subject to:

$$\begin{aligned} 0 &< S_f \\ \theta_{wp} &< \theta_f < \theta_{fc} \\ 0 &< D < I + R \end{aligned} \quad (11)$$

Instead of maximizing yield, other managerial objectives can be assigned as well. For example, it may be desired to reach a certain final soil salinity level (S_f^*) and a certain final water content level (θ_f^*).

Sometimes decision-makers may predetermine an allowed amount of drainage D^p as when assigning the leaching requirement ($D^p/(I + D^p)$). However, in the case presented here the variable D , as well as the other resultant variables, is derived from the simultaneous solution of the system of equations described previously with respect to constraints [Eq. (11)]. The resultant value (D) is not necessarily equal to D^p of any commonly evaluated leaching requirement.

Different functional forms of $Y_{ns}(TW)$ and $Y_r(\bar{S})$ and/or other management assumptions, such as Eq. (10), may be set up by the user of the model for different crops and/or soils.

3. Results

The earlier model was applied to several field crops, using different sets of functional forms for the yield response to water and the yield response to salinity. Other relations among variables in the model are described by relations [Eqs. (2a,b), (4), (5), (7) and (8)] and balance equations [Eqs. (1) and (6)] which do not vary between crops. The model applications described in the following include: (1) annual sweet corn yields and salinity levels using nonlinear functional forms; (2) annual cotton yields and salinity levels using a linear form in a single and in a multi-year framework; and (3) a multi-year simulation for cotton and wheat.

3.1. Application to sweet corn using nonlinear functional forms

We suggest using the following functional form to describe the yield response of corn to water:

$$Y_{ns}(TW) = Y_{max}(1 + a_o TW^{a_1})^{-1} \quad (12)$$

with $TW > 0$, $a_o > 0$ and $a_1 < 0$. This is a continuous, monotonically increasing function. At small values of TW , Y_{ns} is close to zero and, with increasing TW , Y_{ns} asymptotically approaches Y_{max} .

The functional form used for describing the relative-yield response to salinity stress is that of van Genuchten and Hoffman (1984), which was demonstrated on bromegrass:

$$RY(\bar{S}) = (1 + b_o \bar{S}^{b_1})^{-1} \quad (13)$$

with $\bar{S} > 0$ and with the parameters b_o and $b_1 > 0$. This function also decreases monotonically with increase of \bar{S} from a value of one (at very small \bar{S}) to zero. The average soil salinity (\bar{S}) is expressed in terms of the electrical conductivity of a saturated soil extract (EC_e).

The model using these functional forms was applied to sweet corn grown at the Gilat Experimental Station in the southwestern part of Israel. Gilat is located in a semi-arid area with limited rainfall during the winter and a dry summer. Brackish water is used for irrigation because good-quality water is very limited. A detailed description of the experiments, the experimental site and relevant data was provided by Shalhevet et al. (1986). The soil parameters used in this model application were: $\theta_{fc} = 0.21$, $\theta_{wp} = 0.1$ and $\theta_s = 0.4$.

The coefficients a_o , a_1 , b_o , b_1 , Y_{max} of Eqs. (12) and (13) were estimated, using a nonlinear regression methodology, from experimental results for yield levels with respect to different levels of water application and different salinity levels (Shalhevet et al., 1986). Since all experiments were conducted at the same experimental site, the

soil and climatic parameters were assumed to be the same for all experiments. The estimated coefficients and their corresponding t -values (in parentheses) are: $a_0 = 11.18E6$ (0.757); $a_1 = -5.03$ (-4.054); $b_0 = 9.67E-9$ (3.75); $b_1 = 7.6$ (3.82); and $Y_{\max} = 2.96$ (31.26). The computed R^2 was 0.98. The correlation between the experimental yield levels and model-calculated results is illustrated in Fig. 1.

Thus, output yield levels (Y_s) of corn with respect to usage of differing seasonal irrigation water (I) of differing electrical conductivity levels (S_I), assuming $\theta_i = 0.21$ and $S_i = 5$ dS/m, are presented in Fig. 2. When irrigation water was of relatively low salinity, the yield was close to the potential yield, even though the initial soil salinity was assumed to be high ($S_i = 5$ dS/m). With increasing water salinity more irrigation water was needed to maintain that yield level; and when irrigation water salinity was 8 dS/m the potential yield was no longer attainable.

From the same model runs, the dependence of average seasonal \bar{S} on the amount of seasonal I and the water's S_I is shown in Fig. 3. The curves show that, even with non-saline irrigation water, the average soil salinity increases at relatively low seasonal application amounts because of evapotranspiration which increases the concentration of salt in the soil solution in the root zone. This concentration effect diminishes as the amount of applied water increases and salts are leached downward. When the water applied is of low quality the average soil salinity increases sharply as small quantities of water are applied and, with increasing amounts of irrigation, the average soil salinity approaches that of the irrigation water.

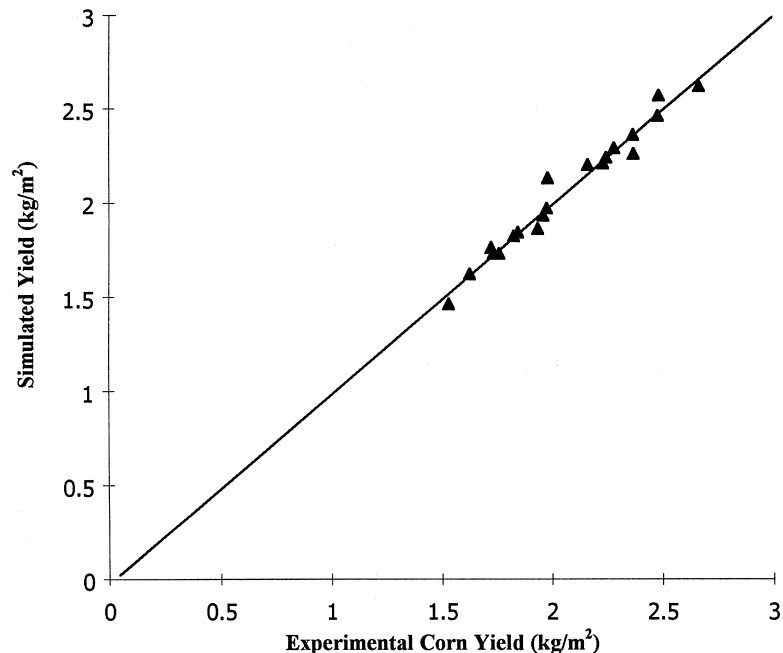


Fig. 1. Corn yield, modeled versus field results.

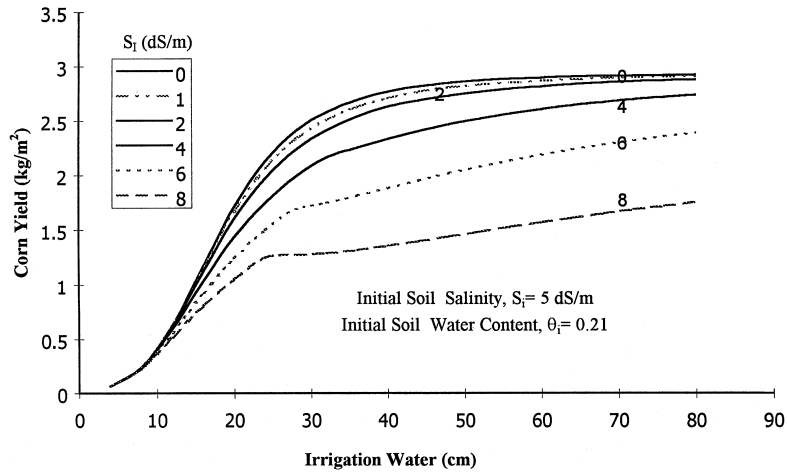


Fig. 2. Calculated corn yield (Y_c) versus amount of irrigation water (I) of different salinity levels (S_f).

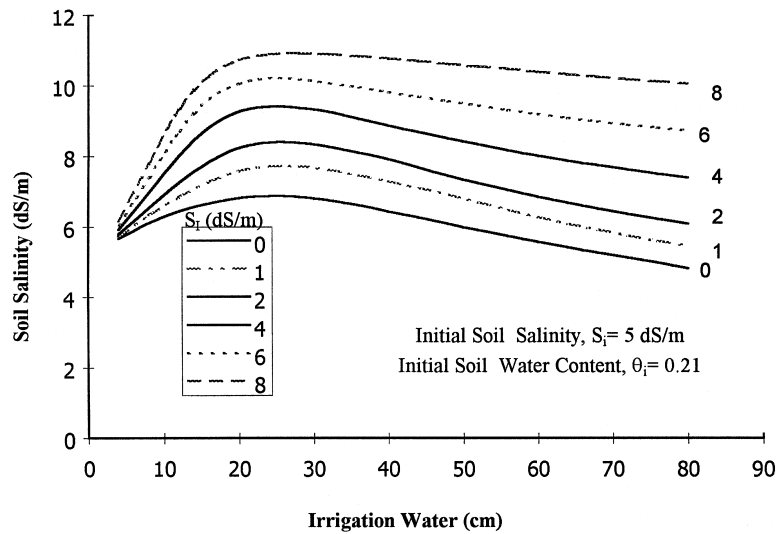


Fig. 3. Calculated average soil salinity level (\bar{S}) as a function of the irrigation water amount (I) and salinity level (S_f).

An attractive use of the model is for farmers who have several sources of water of different qualities and would like to mix them for irrigation. As an example the model was used to simulate yields resulting from a mixture of water having salinities of 5 and 1dS/m, respectively. Isoquants of yield with respect to seasonal amounts of water from the two sources are given in Fig. 4. They are nearly linear, which means that, for a given yield, there is a constant exchange rate between good-quality and low-quality water. The ratio of the exchange increases as greater yield levels are desired.

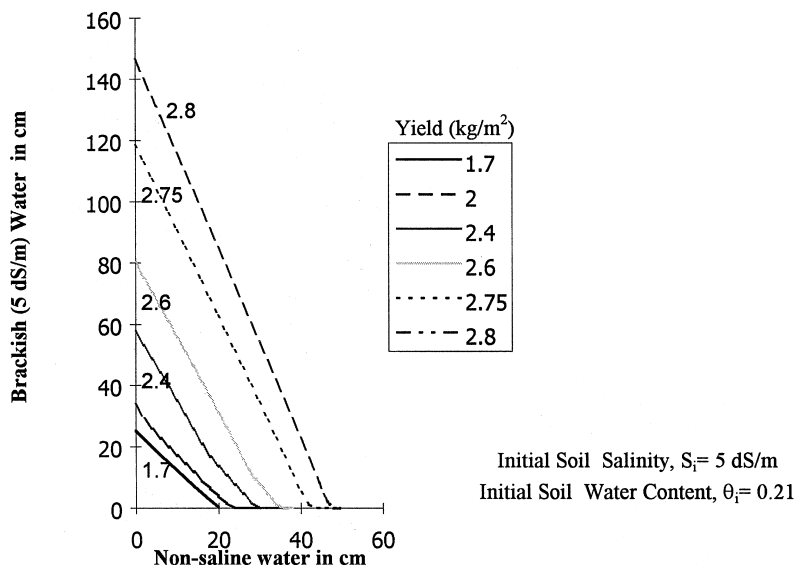


Fig. 4. Calculated isoquant for sweet corn yield (kg/m^2), using mixture of non-saline (1 dS/m) and brackish (5 dS/m) irrigation water.

3.2. Application to cotton using broken-linear functional forms

Broken-linear functional forms are commonly used to describe yield response to water stress and yield response to soil salinity (Maas and Hoffman, 1977). The yield response to water can be described as:

$$Y_{ns}(TW) = \begin{cases} 0, & TW \leq Z_o \\ s(TW - Z_o), & Z_o < TW < ET_{max} \\ Y_{max} & TW \geq ET_{max} \end{cases} \quad (14)$$

where Z_o is the minimum water requirement, ET_{max} is the amount of water required for the maximum attainable (potential) yield, and s is a characteristic coefficient. This functional form, suggested by Letey and Vaux (1984) and used by others (Dinar and Knapp, 1986; Vinten et al., 1991), can be easily adopted for various crops. Because of its linearity it is simple and attractive for computation, but may cause inconvenience because of the non-differentiable singularities in the function.

The corresponding yield response to soil salinity is based on the approach of Maas and Hoffman (1977). A reduction from 100% potential yield (under non-saline conditions) occurs when the \bar{S} is above a crop-specific threshold level. Soil salinity is expressed in terms of the EC_e of the saturated paste extract. The yield response to salinity is given by:

$$Y_r(\bar{S}) = \begin{cases} 1, & \bar{S} \leq c \\ 1 - b(\bar{S} - c), & \bar{S} > c \end{cases} \quad (15)$$

where c is the threshold soil salinity level in dS/m, and b is the rate of decrease in yield per unit increase in the seasonal average soil salinity. Classical coefficients (c , b) compiled by Mass and Hoffman (1977) are available for a variety of crops. Though plants are exposed to a combined stress of salinity and water, the impact of soil water content is accounted for in the average salinity \bar{S} value for Eq. (4). The final (S_f) and initial (S_i) soil salinities are the actual salinity levels at θ_f and θ_i , respectively. Therefore, by introducing Eq. (4) into Eq. (15), the Maas and Hoffman parameters were modified to give:

$$b' = b(\theta_i/\theta_s) \quad \text{and} \quad c' = c(\theta/\theta_i) \quad (16)$$

where θ_s is the volumetric moisture content of the saturated soil paste.

The model using these forms was applied to cotton grown at kibbutz Nir Oz in southwest Israel. Cotton is resistant to soil salinity and is commonly grown when using brackish water. The coefficients for Eqs. (14) and (15), adjusted from Vinten et al. (1991), are: $Z_o = 5.1$, $ET_{\max} = 75.2$, $Y_{\max} = 0.8 \text{ kg/m}^2$, $s = 0.0114$, $c_{M\&H} = 0.069$, and $b_{M\&H} = 0.061$. The soil parameters remain as in the former case.

Results of these simulation runs are presented in Fig. 5 as isoquants of cotton yield levels with respect to irrigation with water of two differing salinities. Here, too, the isoquants are nearly linear but not as steep as those in Fig. 4 for corn (which is more sensitive to salinity stress than cotton). This implies a constant degree of substitution between good- and low-quality irrigation water for a given level of yield. This is not a general conclusion, but applicable only to the specific qualities of irrigation water and initial soil salinity levels in this case.

3.3. Multi-year simulations for wheat and cotton

The model was also used in a multi-year framework by using the final values from the seasonal modeling as initial values for the following season, in order to simulate

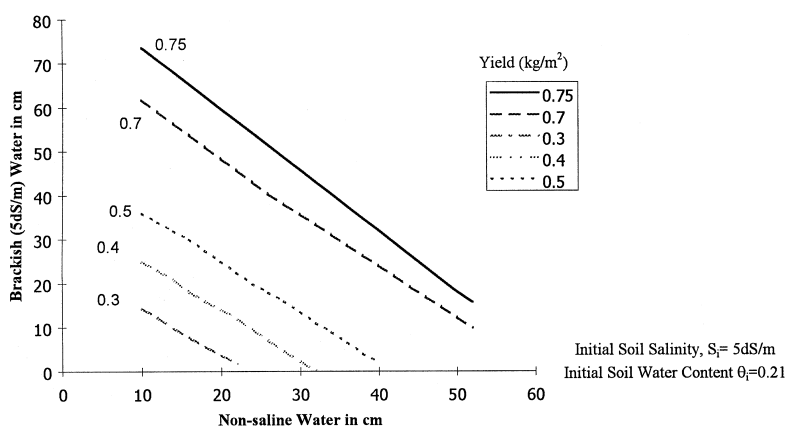


Fig. 5. Calculated isoquants of cotton yield (kg/m^2), using mixture of non-saline (1 dS/m) and brackish (5 dS/m) irrigation water.

system dynamics over a number of years. The model was used to simulate 12 consecutive years of growing cotton using brackish water in the summers and fallow during the winters. The model's performance was compared with data collected by farmers at kibbutz Nir Oz in southwest Israel during the period 1981–92. These include information on annual rainfall, final and initial soil salinities for each growing season, seasonal irrigation amounts and water salinity, and annual yield levels. Model validation was performed by comparing field data on yield and soil salinity levels with model results.

The actual and computed soil salinities at the beginning of each summer (the end of each winter) and at the beginning of each winter (the end of each summer) during the period 1981–92 are presented in Fig. 6. During the winter season the rainfall leaches salts downward. As a result, soil water content is high and soil salinity level is low at the end of the winter. On the other hand, cotton is grown in the summer when there is no rainfall and brackish water is used. Consequently, soil salinity in the fall is higher than in the spring. The RMSE (Root Mean Square Error) of the two series is 2.47 dS/m although, over the years, the difference between predicted and actual salinity levels decreased. Actual cotton yield versus calculated yield is presented in Fig. 7. The RMSE of these two series is 0.0834 kg/m², implying no significant difference between them.

Multi-year simulation can help farmers to predict the effects of long-term irrigation policies on soil salination. For example, farmers may have a strategic question of how to allocate saline and non-saline waters between fields so as to minimize salinization hazards. A hypothetical example of using the multi-year simulation as an aid for decision-making is illustrated in the following. Consider the growth of wheat during the winter over a number of years. Assume that the winter effective rainfall is 25 cm, and that a supplemental irrigation of 5.5 cm water of a 5 dS/m

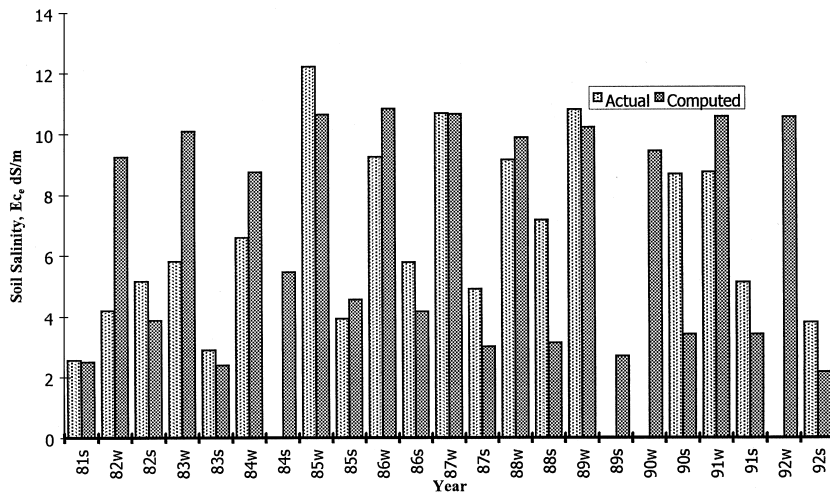


Fig. 6. Computed and actual initial soil salinities during 1981–92 (s, spring; w, fall).

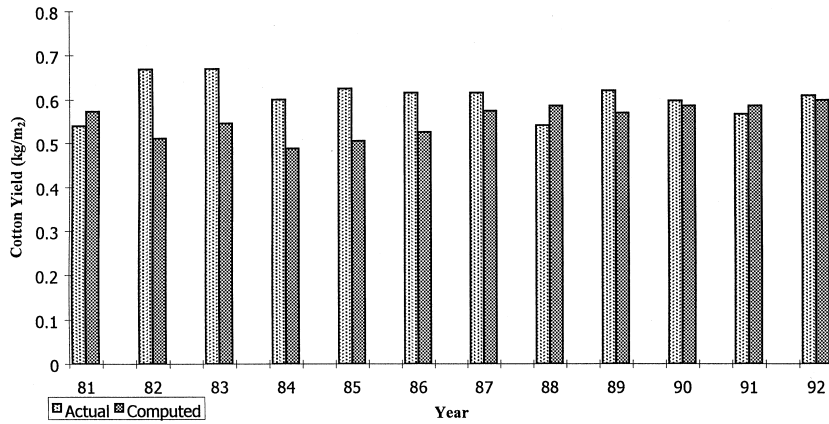


Fig. 7. Computed and actual cotton yields (kg/m²). (Soil salinities as in Fig. 6.)

salinity is applied every winter. This represents, on average, the practice in the southwestern part of Israel.

The coefficients for wheat response to salinity and applied water can be taken from Vinten et al. (1991). The model was run for 13 years and the results of yearly yield and final soil salinity level are presented in Fig. 8. Since the first initial soil salinity was low, irrigating with brackish water did not cause reduction in wheat yield during the first few years because the soil salinity continued to be relatively low. But salt accumulated in the soil, and salinity increased gradually because the rainfall amount was insufficient for leaching the salts. From the seventh year on, one can see a reduction in wheat yield because the soil salinity level is higher than the threshold level to cause salinity stress. Under the saline conditions, growth decreases and less water is used for evapotranspiration, consequently more water is left to

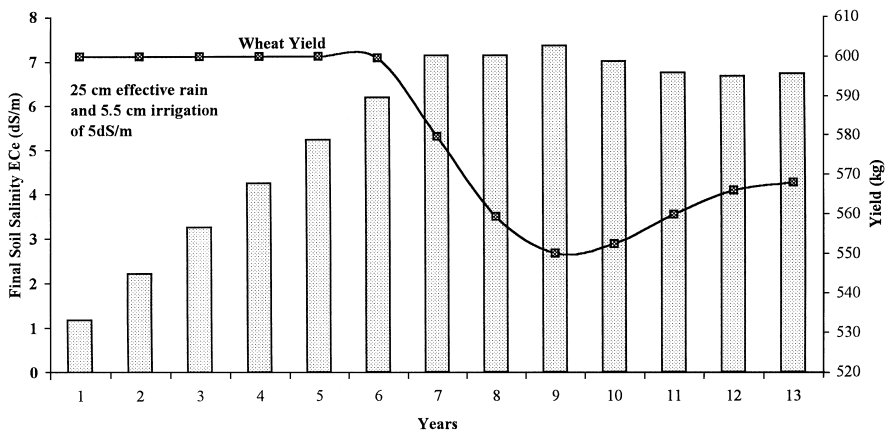


Fig. 8. Computed wheat yield (kg/m²) and final soil salinity levels over time.

drain downward and leach some salts out of the root depth zone. The moderate decrease in soil salinity which occurs, results in a moderate increase of yield up to a level of 0.570 kg/m², compared with 0.600 kg/m² under no-stress conditions. The final soil salinity level seems to reach a steady state when it remains high for the last years of the simulation. This behavior has not yet been verified under controlled experimental condition, but it corresponds with findings reported by local farmers.

The model can be easily adapted to various crops, water qualities, and soil and climatic conditions. It can be used for analysis of long-term salinization processes and for multi-year planning efforts including seasonal time steps. It may be robust for some factors that are sensitive to time steps but it can give good approximation to such variables as yield level and soil salinity. The model requires yield response functional forms and some soil parameters that should be given by the model user. We used existing relationships between yield and salinity and suggested one for the relationship between yield and water amount. Other forms may be introduced.

The model is useful for scientific research and analysis of the economic consequences of using brackish irrigation water over years. This includes governmental intervention in the supply and demand of water, allocation of high- and low-quality water among farmers, better portfolio of crops for irrigation with low-quality water over years.

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