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DRAINKIM: Water Management Model for Assessment of the Re-use of Drainage Water

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Abstract. Investigation of the origin of chemical composition of drainage water, accurate estimation of leaching requirement, and simulation of crop yield response are essentials for effective re-utilization of drainage water for irrigation and salinity control. The comprehensive chemical model SAO (for the chemical evolution of drainage waters and soil solutions) and the leaching requirement model L_rSAO-e (for reactive salt), were verified using a new set of data. The new data are the results of water and soil analysis carried out in a pilot farm during leaching reclamation and by sampling an extension area in Al Hassa, Saudi Arabia. The steady-state SAO model was, originally, based on the changes in irrigation water composition, which occurred due to molecular-water loss, mineral precipitation and dissolution, K^+ fixation, NaCl apparent retention, $MgSO_4^o$ formation, and biological formation of HCO_3^-. Better model predictions were obtained by including $CaSO_4^o$ formation, and soil-Mg hydrolysis. Based on SAO results (EC of soil solution vs concentration factor) the L_rSAO-e model for reactive salt was verified and was able to predict, successfully, the (A_E / EC_i vs L_r) experimental data, where A_E is the crop salt tolerance threshold and EC_i is salinity of irrigation water. The L_rSAO-e model was incorporated with a CROP response code into a water management DRAINKIM program able to predict list of suitable crops, crop yields, leaching requirements, and other management parameters for irrigation-drainage waters. The use of DRAINKIM for the assessment of different scenarios for the re-utilization of drainage water and the selection of management options was demonstrated.

Introduction

Drainage water, a dynamic and open system, is an important water resource in arid land agriculture. Interest in the suitability of drainage water for irrigation dates back a comparatively short time. Hilgard (1886) was among the first to recognize the salinity problems associated with irrigation drainage waters. Many scientists and engineers have since made significant contributions. The

U.S. Salinity Laboratory Staff (1954) have classified irrigation water by electrical conductivity (EC) and sodium adsorption ratio (SAR). Adjusted SAR and pH_c are also important criteria (Suarez, 1981). Bower *et al.* (1969) found crop yield was dependent on average root-zone salinity. Maas and Hoffman (1977) quantified crop salt tolerance using two constants empirical equation.

Investigation of drainage water quality and origin is essential for effective re-utilization of drainage water for irrigation. The processes affecting the composition of these drainage waters have been identified and extensively studied. Recently those processes have become the subjects of comprehensive chemical modeling (Suarez, 1981; Tanji *et al.,* 1972; Rhoades *et al.,* 1973; Mattigod and Sposito, 1979; Robbins *et al.,* 1980; Elprince, 1985; Elprince, 1986).

Presently, it has been realized that the suitability of drainage water for irrigation does not depend only on the quality but it is also related to the chemical and physical properties of the soil, the salt tolerance of the crop grown, the climatic regime of the area, and the method, frequency, and amount of irrigation water applied. This concept was applied by The Bureau de Recherchè Geologiques et Minieres (BRGM 1981) for the re-utilization of drainage water in Al Hassa, Saudi Arabia. The three years study by BRGM, however, did not make any serious attempt to investigate the sources of salinity and origin of the chemical composition of drainage water. The chemical evolution of drainage water in Al Hassa stopped at classification and chemical zonation using the US Salinity Staff diagram and Schoeller Berkallof diagram (BRGM, 1977; BRGM, 1981).

Irrigation drainage water management for salinity control requires an accurate estimation of the leaching requirement, L_r (van Schilfgaade *et al.,* 1974). The L_r is defined as the minimum fraction of infiltrated irrigation water that leaves the bottom of the root-zone to maintain full crop production (US Salinity Lab. Staff, 1954). Over the last several decades, several L_r approaches have been developed for the estimation of L_r as reviewed by Hoffman and van Genuchten (1981). A fundamental approach for the estimation of L_r is the application of solute modeling as done by Hoffman and van Genuchten (1981) for conservative (non-reactive) solute and by Alsaeedi and Elprince (1999) for a reactive solute. The L_rSAO models (Alsaeedi and Elprince, 1999) are the only models, which consider the chemical composition of irrigation water for the estimation of L_r. Thus, the L_rSAO models (Alsaeedi and Elprince, 1999) can be useful for the regional estimation of L_r under the re-utilization of drainage waters.

The objectives of this study were: (i) to verify the chemical model SAO using a new set of data for investigating the origin of chemical composition of drainage waters and soil saturation extracts in Al Hassa; (ii) to verify the leaching requirement model L_rSAO-e; (iii) to combine the L_rSAO-e model with a CROP response code into a water management DRAINKIM program which is able to predict list of suitable crops, crop yields, and their L_r and other management parameters; and (iv) to demonstrate the use of DRAINKIM for the assessment of different irrigation drainage scenarios.

Theoretical

The Chemical Model SAO

The first approximation oasis (FAO) model developed by Elprince (1985) has been based on the changes in irrigation water composition which occur due to molecular-water loss and mineral precipitation. The deviations of measured soil solutions from the computed solution composition have shown that four other primary processes are responsible for the formation of soil solutions from irrigation water under oases conditions. The processes are: K fixation, NaCl apparent retention, $MgSO_4^0$ formation, and biological formation of HCO_3^-. In order to account for these six primary processes a second approximation oasis (SAO) model has been developed. The computer program, which performs these computations, has been named IONIC2. The computational steps, equilibrium equations and analytical expressions are described in details elsewhere (Elprince, 1985).

The L_r Models for conservative and reactive solutes

Hoffman and van Genuchten (1981) used the continuity equation for one-dimensional vertical steady flow of water with a sink term due to exponential water-uptake by plant roots. They have solved it coupled with the steady-state mass balance for salt, neglecting the effects of diffusion-dispersion and chemical reactions. The solution is:

$$EC_e / EC_i = (0.5 / L) + (0.5\,\delta / Z\,L) \ln [\,L + (1\text{-}L) \exp (-Z / \delta)], \qquad (1)$$

where EC_i is irrigation water salt concentration (dS/m), EC_e is mean root-zone saturation-extract salt concentration (dS/m); L is the leaching fraction defined as that fraction of irrigation water that leaves the root-zone as drainage water; Z is the rooting depth (m); and δ is an empirical constant (m^{-1}). The assumption that $EC_e = 0.5\ EC_s$ is inherited in Eq (1), where EC_s is the soil-solution salt concentration (dS/m).

The definition of L_r as the minimum L that maintains full crop production implies L and EC_e in Eq (1) could be, respectively, replaced by L_r and the salt-tolerance threshold (A_L, dSm^{-1}) of the equation of Maas and Hoffman (1977):

$$Y / Y_{max} = 100 - B\,(EC_e - A_L), \qquad (2)$$

where Y / Y_{max} is relative crop yield and B is percent yield decrease per unit salinity increase $[\% \,.\, (dS/m)^{-1}]$. Experimental values of A_L are usually determined at L of about 0.5. As an approximation Hoffman and van Genuchten (1981) assumed:

$$A_L = A_E + EC_e\,(L = .5), \tag{3}$$

where A_E is the experimental threshold and EC_e (L = .5) is mean root-zone saturation-extract at L = 0.5. This approximation is made to account for the observation that plants adjust osmotically as soil salinity increases (Hoffman and van Genuchten, 1981). Subsequently, Eq (1) yields the conservative-salt Hvan-e model (Alsaeedi and Elprince, 1999):

$$A_E / EC_i = (0.5/L_r) + (0.1/L_r).\ \ln(0.0067 + 0.9933\, L_r) - 0.863, \tag{4}$$

where $L_r < 0.5$ with δ is taken equal to 0.2 Z as found by Hoffman and van Genuchten (1981).

As stated above the SAO model predicts the changes in irrigation water composition, which occur due to molecular-water loss and chemical reactions in the root-zone. Subsequently, the SAO model yields the curve:

$$EC / EC_i = f\,(CF), \tag{5}$$

where f (CF) is some regression function of the concentration fraction, CF:

$$EC / EC_i = a_o + a_1\,[\ln CF] + a_2\,[\ln CF]^2 + a_3\,[\ln CF]^3, \tag{6}$$

where a_o, a_1, a_2, and a_3 are regression coefficients (Alsaeedi and Elprince, 1999). The term CF in Eq (6) is a function of soil depth, z and L_r as of the equation:

$$CF = [1 - (1 - L_r) \cdot \{1 - \exp\,(-x / c)\}]^{-1}, \tag{7}$$

where c = δ / Z and x = z / Z (Alsaeedi and Elprince, 1999). Substitution of Eq (7) into Eq (5) gives the L_rSAO-e model:

$$A_E / EC_i = 0.5\, w\, v_{eff}\ \{ 1 / (1 - E)\}\ {}_0\!\int^1 f(CF)\ .\ dx, \tag{8}$$

where w is a weighing factor, E = fraction of irrigation water that is evaporated, and v_{eff} = linearly average root-zone relative effective soil solution volume, which is given by the equation:

$$v_{eff} = 1 / \{ 1 + (Lr / L_{50})^p \}, \tag{9}$$

where L_{50} is L at which the effective volume is half the interstitial, and p is an empirical constant (Alsaeedi and Elprince, 1999).

Materials and Methods

The Al Hassa oasis, Saudi Arabia is situated some 60 km inland of the gulf coast between 25º20′ and 25º40′N Lat and 49º33′ and 49º47′E Long, and covers an area of approximately 20,000 ha, about 7,000 ha of which is cultivated (Fig. 1). Details on the climate, plant resource, water resource, and soil resource of Al Hassa have been given elsewhere (Elprince, 1985).

The Bureau de Recherché Geologiques et Minieres (BRGM) carried out a study from 1978 to 1981 in order to increase the cultivated area in Al Hassa by reutilization of the drainage water coming from the two main drains D1 (5.1 dS/m) and D2 (6.2 dS/m) of the oasis (Fig. 1). A detailed leaching reclamation was carried out in a 12 ha pilot farm, the results of which were extrapolated to two extension areas (Fig.1) where general soil and water studies were made. Standard water analysis was made on drainage waters and soil saturation extracts collected at various times and places during the leaching reclamation in the pilot farm and the soil and water sampling of the extension areas. Results of soil and drainage water analysis were appended. All data in the two appendices (BREGM, 1981) were utilized in the present study after computer elimination of the ones whose EC > 18.9 dS/m and those which deviate from electroneutrality by more than 5%. This elimination was done to compare model prediction using the present set of data with a previous one (Elprince, 1985).

Description of DRAINKIM

Input Parameters

The program DRAINKIM input parameters are the water chemical composition of drainage irrigation water, the soil parameters (soil-extract chemical compositions, mean infiltration rate (mm day^{-1}), I_f and / or mean drainage rate (mm day^{-1}), R_d and partial pressure of CO_2 (atm), P_{CO2} if available); the crop component parameters (A_E, B, and the crop growth stage coefficient K_c); and the climatic component parameter potential evapotranspiration, E_o.

The Algorithm and Output

DRAINKIM uses the IONIC2 program (Elprince, 1985) to perform isothermal deaquation and mineral precipitation and to consider NaCl apparent retention, K fixation, $MgSO_4^o$ and $CaSO_4^o$ ion pairing, soil-Mg hydrolysis, and biological formation of HCO_3^- as of the SAO model. DRAINKIM plot the ionic concentration versus EC showing experimental points and model-predicted curves. Based on this curve fitting DRAINKIM creates the data file (y, L_r), where y = EC_e/EC_i. The CROP code uses the crop data file (A_E, B, and K_c) to

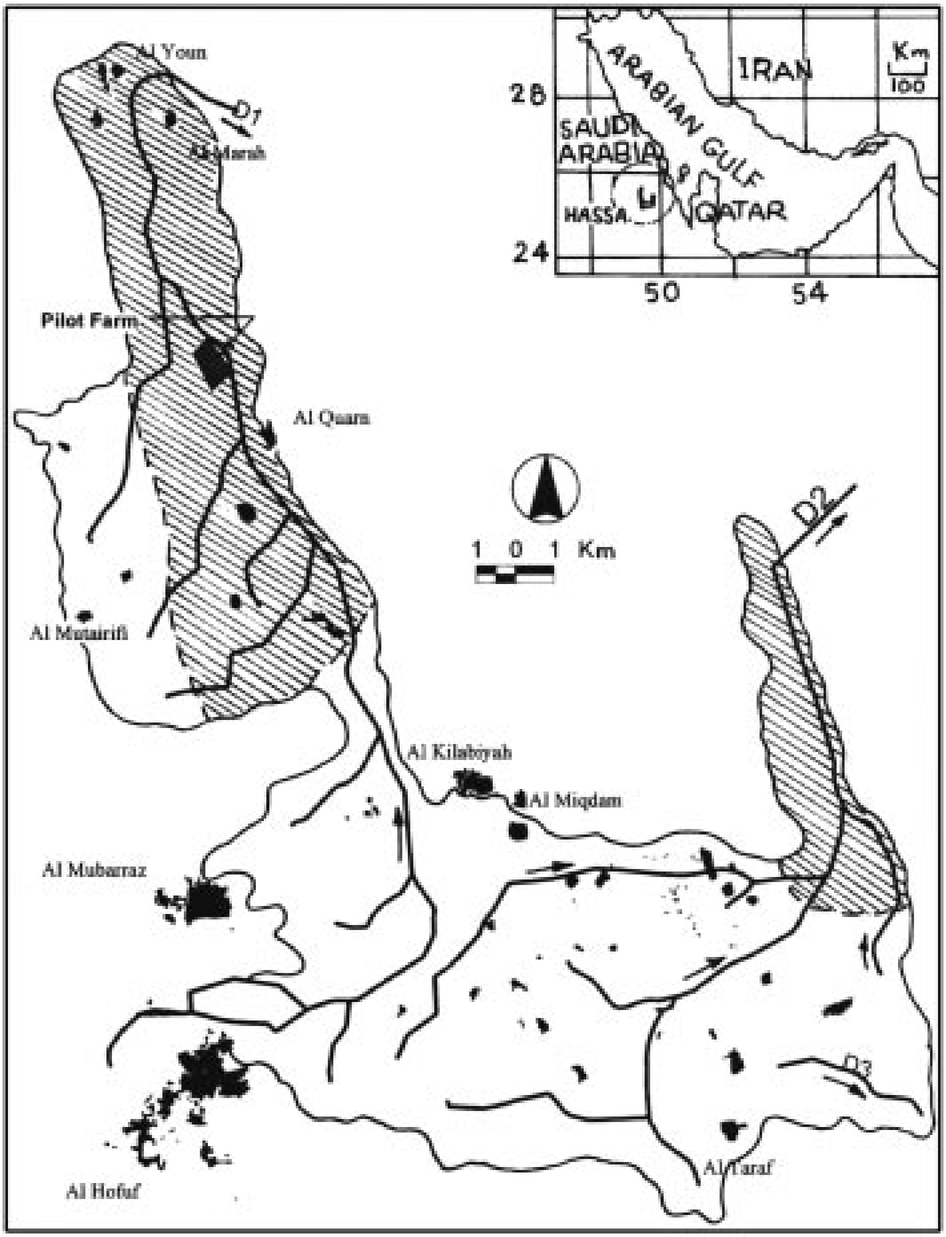

FIG. 1. Location of the pilot farm, extension areas (hatched), and main drains D_1 and D_2. Al Hassa oasis, Eastern Province, Saudi Arabia.

compute for a given EC_i the corresponding L_r value by interpolation of the (y, L_r) data file or/and by solving Eq (4) using the Newton-Raphson modified method (Pennington, 1970). If L_r DRAINKIM considers $y = A_E / EC_i$ and $Y / Y_{max} = 100$. If $L_r > L$ it considers $Y / Y_{max} = 100 - B\,[\,y\,(L).\,EC_i - AE\,]$, where y (L) is the value of y at $L_r = L$ determined from the (y vs L_r) curve. DRAINKIM uses the computed L_r, the soil data I_f and/or R_d to compute the irrigation management parameters:

$$(t_c / t_i)_{max} = (1 - L_r) \,.\, (I_f / ET_r) \;;\; L_r \leq L, \tag{10}$$

$$(ET / t_c)_{max} = [(1 / L_r) - 1) \,.\, R_d, \tag{11}$$

where t_c and t_i are irrigation cycle time (day) and mean infiltration time (day), respectively and ET_r and ET are evapotranspiration rate (mm/day) and evapotranspiration (mm) during t_c, respectively. DRAINKIM outputs a list of crops in descending order with respect to Y / Y_{max} with their L_r, and the maximum permissible $(t_c / t_i)_{max}$ and $(ET/t_c)_{max}$ values for a given EC_i. Subsequently, DRAINKIM can be used to compare different irrigation scenarios for the re-use of drainage water and the selection of management options.

Results and Discussion

Verification of SAO Model Prediction

The original SAO model was first calibrated with chemical analysis of 1:5 soil extracts, drainage waters, and well waters of the Eastern Province (Elprince 1985). Adjusted in the process: the percentage MgS_4^o ion pairing, K fixation, apparent NaCl retention, and biological formation of HCO_3^- . This model is referred to SAO_1 which means SAO applied to set of data number 1.

Figure 2 shows the result of a verification process for SAO using a second set of data where ionic concentrations are plotted versus EC of drainage waters and soil saturation-extracts from the pilot farm and the extension area in Al Hassa. Adjusted, further, in the process the percentage $CaSO_4^o$ ion pairing ($Ca^{2+} + SO_4^{2-} = CaSO_4^o$, $K = 10^{2.23}$ (Lindsay, 1979)); a soil-Mg hydrolysis (soil – Mg + $2H^+$ = soil – H_2 + Mg^{2+}) with $K = 8 \times 10^{12}$ which is within the range of the equilibrium constants for Mg hydrolysis reported by Lindsay (1979); and P_{CO2} is 5 times atmospheric P_{CO2} when $EC \leq 5$ dS/m and 2 times atmospheric P_{CO2} when $EC > 5$ dS/m. As shown in Fig. 2, SAO was successful in predicting the concentration of all the major elements but, to some extent under estimated the concentrations of SO_4^{2-} and Ca^{2+}. This means that these two ions participate in additional processes, other than the ones considered in SAO. This model shall be referred to as SAO_2, which means SAO, applied to set of data number 2.

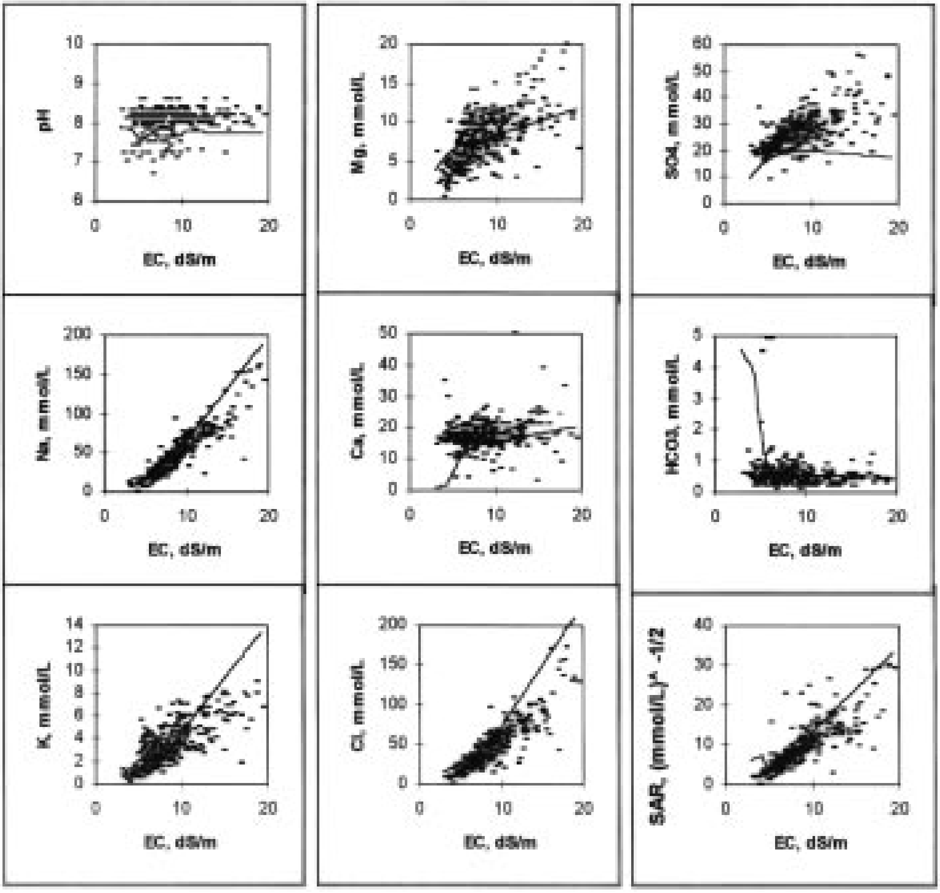

FIG. 2. Results of the chemical analysis of drainage waters and soil saturation-extracts from pilot farm and extension area in Al Hassa oasis. The solid curves are predicted by the SAO2 chemical model.

Model Leaching Requirement Prediction

Table 1 shows EC/EC_i as a function of CF computed from previous set of data according to SAO_1 (Elprince, 1985) and from the present set of data according to SAO_2. Fitting SAO_1 output to the regression given by Eq (6) gives $a_o = 0.861$, $a_1 = 2.131$, $a_2 = -1.069$, $a_3 = 0.375$, and the correlation coefficient square, $R^2 = 0.999$. Similar fitting of the SAO_2 output gives $a_o = 0.655$, $a_1 = 1.944$, $a_2 = -0.397$, $a_3 = 0.191$, and the correlation coefficient square, $R^2 = 0.991$. These data are employed in Fig. 3 which shows A_E / EC_i versus L_r for the reactive-salt model L_rSAO-e, and the conservative-salt Hvan-e model, together with experimental data compiled by Hoffman and van Genunchten (1981).

TABLE 1. Computed EC/EC_i according to SAO model applied to a previous set of chemical composition data (SAO_1) and to the present set of data (SAO_2).

CF	EC / EC_i	
	SAO_1^a	SAO_2
1.2	1.24	1.01
3	2.23	2.13
3.7	2.69	3.31
4	2.88	3.37
7.5	3.93	4.41
10	4.69	5.07
20	7.63	8.40
30	10.56	10.07

[a](Elprince, 1985).

Figure 3 shows the results of a verification process for L_rSAO-e model using the second set of solution composition data. The L_rSAO-e model based on the new set of solution composition data (BREGM, 1981) predicts the experimental data as good as the previous set of solution composition data (Elprince, 1985) using identical input parameter values: $c = 0.27$, $w= 2$, $E = 0$, $p = 1.44$, and $L_{50} = 0.16$. Figure 3, furthermore, indicates that L_rSAO-e model (the SAO_1 and SAO_2 curves) predicts the experimental data as good as the Hvan-e model. It seems that the success of the Hvan-e model in prediction of the L_r experimental data is due to the curve-fitting parameter δ inherited in the model. This parameter seems to account for the chemical reactions involving the water ionic species within the soil root-zone. We conclude that the Hvan-e model by Hoffman and van Genuchten (1981), although derived for a conservative solute, is applicable for reactive solute because of its curve-fitting constant.

Based on the above results, we have incorporated both L_rSAO-e and Hvan-e models into DRAINKIM. The L_rSAO-e model is recommended if regional solution composition data are available for model calibration. In the absence of such data, the Hvan-e model equation is relatively easy. After calibration, both models require the salinity of the applied water and crop salt tolerance threshold as input.

Irrigation Drainage Assessment

As a demonstration DRAINKIM is used to compare the performance of several irrigation drainage scenarios under Al Hassa condition. Three irrigation scenarios using variable irrigation drainage water salinity are considered for the five salt tolerant crops: alfalfa (permanent); wheat (winter); sorghum fodder

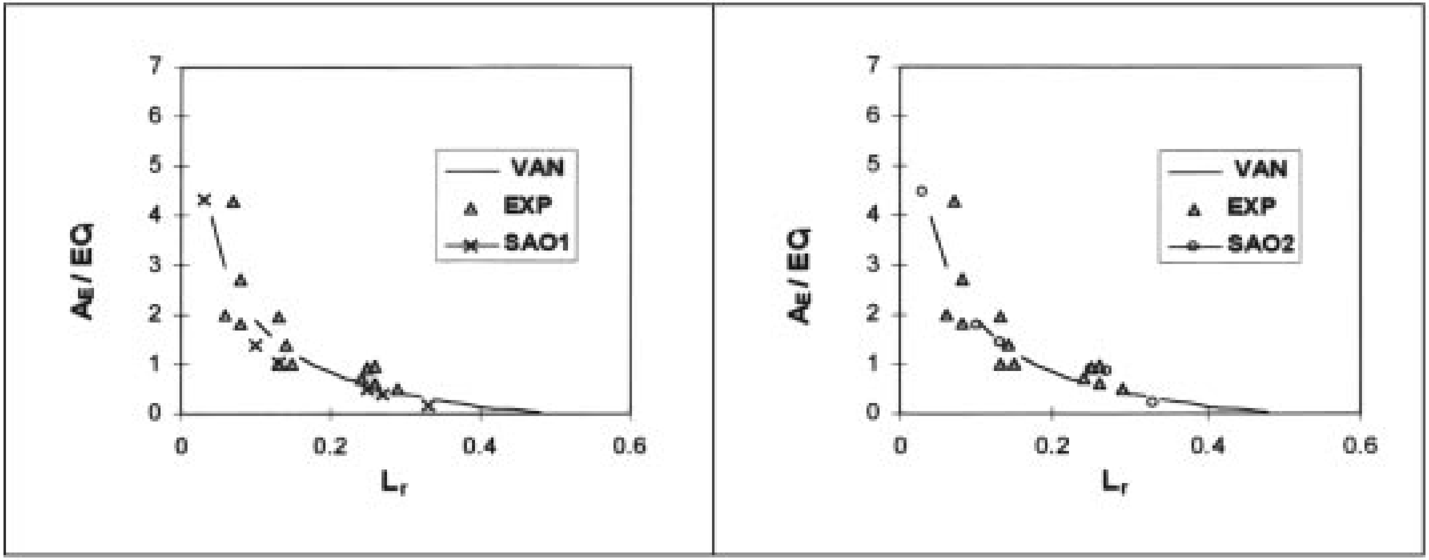

FIG. 3. Experimental and calculated (A_E / EC_i versus L_r) curves. Calculated curves are by the conservative-salt model Hvan-e and by the reactive-salt model L_rSAO-e applied to a previous set of data (SAO_1) and to the present set of data (SAO_2).

(summer); cabbage (winter); and tomato (winter). Table 2 shows values of the crop parameters A_E, B, ET, and length of the growing season used in simulation. In the first, second, and third irrigation scenarios, the irrigation amounts are equal to evapotranspiration requirements by the crops, with the addition of depth of water for leaching equal to 20, 30, and 40 mm/month, respectively. The objective function for these simulations is crop yield.

TABLE 2. Crop parameters used in simulation.

Crop name	Botanical name	A_E dS/m	B % . $(dS/m)^{-1}$	ET mm/season	Season month
Alfalfa[*]	*Medicago sativa*	5.2^a	9.25^a	$2{,}737^b$	12
Wheat	*Triticum aestivum*	6.0^c	7.1^c	612^d	5
Sorghum	*Sorghum bicolor*	6.8^c	16.0^c	954^d	5
Cabbage	*Brassica oleracea capitata*	1.8^c	9.7^c	505^d	5
Tomato	*Lycopersicon lycopersicum*	2.5^c	9.9^c	774^d	5

[a](LIRT, 1972); [b](LIRT, 1973), [c](Maas and Hoffman, 1977); [d](BRGM, 1981);
[*]The local variety Hasawy.

Figure 4 shows Y / Y_{max} for the five crops versus EC_i for the three irrigation scenarios (Fig. 4). If the drainage water of the main drain D_1 in Al Hassa (mean EC_i equal to 5 dS/m) is used for irrigation the following could be concluded from Fig. 4: (i) a complete failure in crop production is expected if the first irrigation scenario (20 mm/month leaching) is adapted. This irrigation scenario resulted in 60% drop in yields of alfalfa and tomato as well as more than 50 and 40% drops in yield of sorghum and cabbage, respectively (Fig. 4); (ii) Crop production under scenario two (30 mm/month leaching) using the 5dS/m drainage water seems equivalent to scenario one (20 mm/month leaching) using 1:1 mixture (3.5 dS/m) made of spring water (2 dS/m) and drainage water (5 dS/m). Both irrigation regimes are successful in producing maximum yield of wheat and sorghum as well as 80, 70, and 65% of maximum yield for cabbage, alfalfa, and tomato, respectively. However, the first irrigation regime consumes no high quality spring water compared to the second one; and (iii) crop production under irrigation scenario three (40-mm/month leaching) exceeds 85% of relative yield for the entire five crop involved in simulation. Subsequently, based on these simulations re-use of Al Hassa drainage water of EC_i equal to 5 dS/m under irrigation scenario three (the irrigation amounts are equal to evapotranspiration requirements by the crop plus leaching depth of 40 mm/month) would be successful in crop production of alfalfa, wheat, sorghum, cabbage, and tomato for the efficient use of the limited water resource and sustainable soil resource.

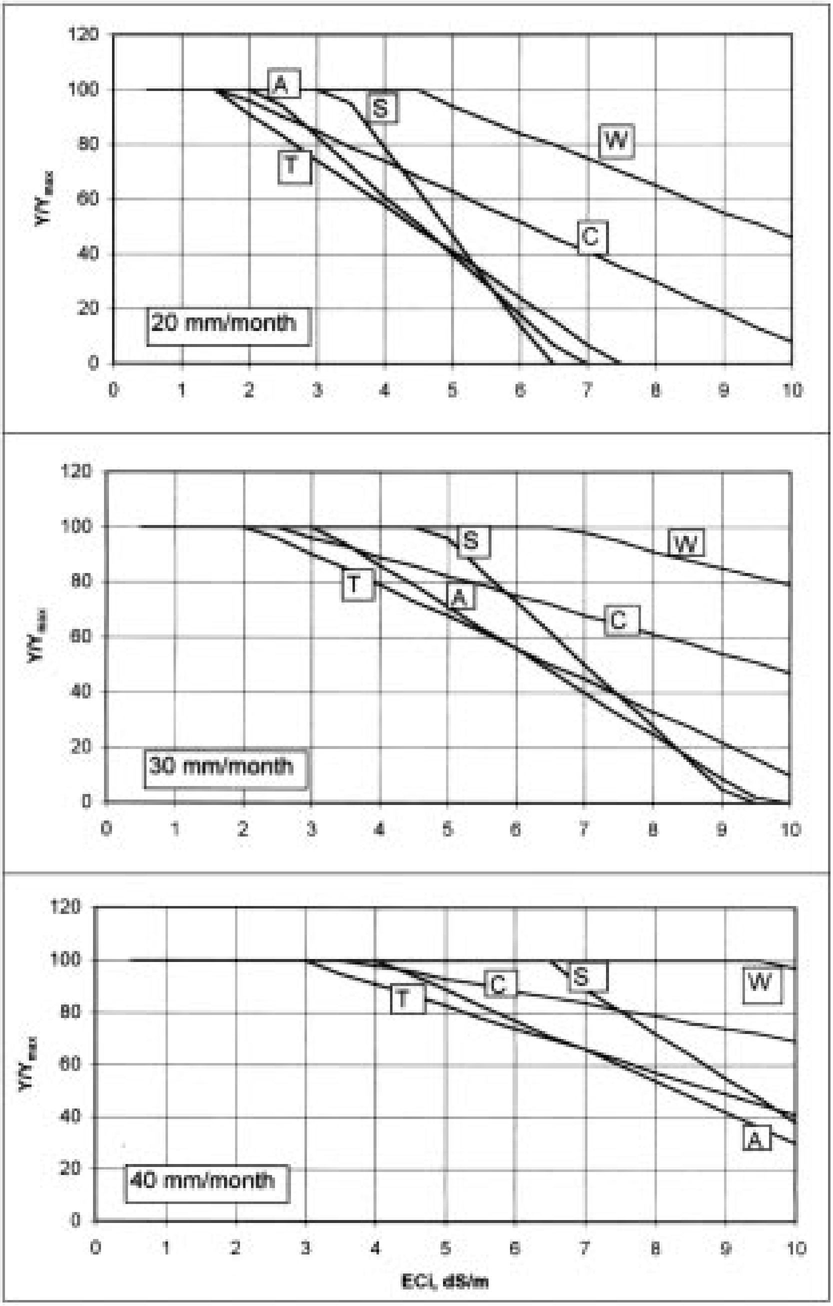

FIG. 4. DRAINKIM simulation of relative crop yield under three irrigation scenarios. The irrigation amounts equal to crop evapotranspiration with the addition of leaching depth of 20, 30, or 40 mm/month applied during the growing season. A = alfalfa; W = wheat; S = sorghum; C = cabbage; and T = tomato.

This example demonstrates that DRAINKIM program is a powerful tool for the assessment of different scenarios for the re-use of drainage waters. This would help planners and decision-makers to re-use, effectively the drainage water resource for sustainable food production.

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درينكم : نموذج إدارة مياه لتقييم إعادة استخدام مياه الصرف الزراعي

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المستخلص . إن بحث نشأة التركيب الكيميائي لمياه الصرف والتقدير الدقيق للاحتياجات الغسيلية للتربة (L_r) ومحاكاة استجابة المحصول لها هي أساسيات هامة لاعادة استخدام مياه الصرف فى الري وللتحكم فى الملوحة بطريقة فعالة . تم تأكيد صحة نموذج الحاسب الآلي « ساو » والخاص بنشأة مياه الصرف الزراعي والمحلول الأرضي وكذلك النموذج L_rSAO-e لحساب الاحتياجات الغسيلية لملح نشط كيميائيا وذلك باستعمال مجموعة جديدة من البيانات الناتجة من تحاليل المياه والتربة لعينات تم الحصول عليها أثناء عملية استصلاح مزرعة تجريبية بالغسيل بغرض التوسع الزراعي فى منطقة الاحساء بالمملكة العربية السعودية . وقد بنى نموذج الحالة المستقرة « ساو » على أساس متابعة التغييرات فى التركيب الكيميائي لمياه الرى والتى تحدث نتيجة فقد جزيئات الماء وترسيب وذوبان المعادن وتثبيت البوتاسيوم والاحتجاز الظاهري لكلوريد الصوديوم وتكوين $MgSO_4^0$ والتكوين البيولوجي لأنيون البيكربونات . وتم الحصول على استنباطات ونتائج أفضل عند أخذ تكوين $CaSO_4^0$ والتحلل المائي لمغنسيوم التربة فى الاعتبار كعمليات أساسية . واستخدمت النتائج المستقاة من « ساو » (ملوحة محلول التربة كدالة لمعامل التركيز) لتأكيد صحة النموذج L_rSAO-e الخاص بحساب الاحتياجات الغسيلية لملح نشط كيميائيا حيث إن هذا النموذج يمكن بواسطته التنبؤ بنجاح بالنتائج التجريبية ممثلة فى شكل المنحنى بين (A_E / EC_i) و L_r حيث A_E تمثل قيمة حد التحمل الملحي للمحصول و EC_i تمثل ملوحة مياه الري . ولقد تم إدماج كل من نموذج L_rSAO-e مع

نموذج الاستجابة المحصولية CROP لاستنباط برنامج « درانكم » لإدارة المياه والذي يمكنه تحديد قائمة بالمحاصيل المناسبة والإنتاجية المحصولية لها واحتياجاتها الغسيلية وغيرها من ثوابت إدارة الري . وتم مناقشة مثال لاستخدام « درانكم » لتقييم سيناريوهات مختلفة لإعادة استخدام مياه الصرف مع تحديد الخيارات المختلفة .