Published November, 1986

Irrigation Management for Soil Salinity Control: Theories and Tests[1]

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ABSTRACT

The steady-state leaching theory and related concepts regarding soil salinity control were evaluated in view of the transient-state theories presented and recent experimental results. Data from small plot experiments to establish the leaching requirement of nine crops and from a rhizotron study on the influence of irrigation frequency on soil salinity control agreed with theoretical, transient-state predictions that consider water flow, salt transport, and water uptake by crop roots, simultaneously. Root water uptake was assumed to depend on matric (water content) and osmotic (soil salinity) potentials, and on a critical root-water potential of about −0.3 MPa. The assumption that the major effect of soil salinity is a reduction in plant water uptake was substantiated. Results show water balance components (for nine crops irrigated several times each day and for grass irrigated with various combinations of quantity, quality, and frequency) deviated significantly from predictions based on the steady-state leaching fraction equation. The deviation was attributed to an increase in soil-water content and transpiration as irrigation applications increased; or conversely, an increase in soil-water content as transpiration decreased because of increased soil salinity. The practical limitations of salinity control in irrigated agriculture based on the steady-state leaching equation were evident even for high frequency irrigation where steady-state conditions should be approached. Measured commercial yields and aboveground dry matter production compared well with yields computed on the assumption that relative crop yield is equivalent to relative transpiration. Both measured and computed results indicated that irrigation water quality and quantity, rather than irrigation frequency, influenced dry matter production of grass.

Additional Index Words: **modeling, steady flow, transient flow, leaching fraction, transient transport.**

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Bresler, E., and G.J. Hoffman. 1986. Irrigation management for soil salinity control: Theories and tests. Soil Sci. Soc. Am. J. 50:1552–1559.

CROP RESPONSE to the space-time distribution of soil water and soil salinity is complex and not well understood. Soil salinity and soil water are interacting variables, thus it is difficult to separate crop response to these two soil variables. Because no salt is transferred to the atmosphere as water evaporates from the soil or transpires from the plant, salts are concentrated in the soil solution. These processes change both the osmotic and matric potentials of the soil solution. These two components of water potential have been shown to be additive in their effect on transpiration (Childs and Hanks, 1975) that in turn has been found to be directly proportional to total dry matter production (De Wit, 1958; Hanks, 1974). However, in conducting water requirement and salt tolerance experiments, researchers have minimized the effect of matric potential when salinity effects are studied (e.g., Bernstein, 1961), and made the osmotic potential negligible when plant response to soil water is of interest (e.g., Shalhevet et al., 1976). Such a sharp differentiation between these two types of experiments is possible only under controlled conditions. In irrigated agriculture where salinity is a hazard, both matric and osmotic potentials must be considered simultaneously. For example, if insufficient amounts of saline irrigation water are applied, matric and osmotic potential will both be low, and transpiration and growth will be reduced.

The primary objective of this study is to reevaluate theories and concepts regarding soil salinity control, in view of recent theories (some of which were summarized by Bresler et al., 1982) and recent research findings (Hoffman et al., 1979, 1983; Jobes et al., 1981; Hoffman and Jobes, 1983). The assumption that the major effect of soil salinity on crop yield reductions is by decreased plant water uptake is tested both theoretically and experimentally. The influence of irrigation frequency as well as the quantity and salt concentration of irrigation waters on grass production are evaluated. Following a brief formulation of the physical-mathematical model for transient conditions, the boundary conditions appropriate to high frequency (nearly continuous) irrigations are presented. Comparisons between computed yield-quantity-quality relationships and the corresponding experimental values are made for nine crops. Model calculations are based on the initial and boundary conditions from the appropriate experiments irrigated frequently. The general transient case, with boundary condition defining a variety of combinations of irrigation water quantity and quality, together with different irrigation frequency treatments to create different soil matric potential profiles, is also evaluated for grass.

PHYSICAL-MATHEMATICAL THEORY FOR TRANSIENT CASE

Unsaturated soil-water flow in a homogeneous field irrigated uniformly at a rate R with water uptake by roots represented by an extraction term S, is given by

$$\frac{\partial\theta}{\partial t} = -\partial q/\partial z - S(z, t) = \frac{\partial}{\partial z}\left\{K[\theta(z, t)]\ \frac{\partial H(\theta)}{\partial z}\right\} - S(z, t)\,. \quad [1]$$

Here, θ is volumetric soil-water content, t is time, q is the specific (Darcy's) water flux, $K(\theta)$ is the hydraulic conductivity function, H is the hydraulic head[3], which is the sum of the soil matric pressure head [$h = h(\theta)$] and the gravitational head, z is the vertical space coordinate positive downward, and S is the volumetric rate of water uptake by plant roots per unit volume of soil. The root extraction term S is expressed here as (Childs and Hanks, 1975; Bresler et al., 1982, p. 139).

$$S(z, t) = -b(z)\ K[\theta(z, t)]\ [\Psi(t) - h(z, t) - \gamma C(z, t)] \quad [2]$$

where $\Psi(t)$ is the total pressure head equivalent in the plant root at the root-soil interface, h is the soil matric pressure head, C is the solute concentration of the soil solution, and γ is a coefficient that transforms salt concentration units into the appropriate pressure head units. The coefficient of proportionality b represents the geometry of the flow to the roots. Note that the term γC represents the osmotic component of the soil-water potential and describes the effect of soil salinity on water uptake by plant roots. When the osmotic potential is low (salt concentration is high), plants may not be able to extract sufficient water to meet transpiration demands. This causes the actual transpiration to be less than the potential and crop yield reductions may occur. For this to occur the value of $\Psi(t)$ in Eq. [2] must be limited (see Eq. [4e]). Similarly, yield reductions occur when the matric potential (pressure head) is low or when both h and γC are low because they are additive in their effect on S.

Neglecting the effects of adsorption, precipitation, dissolution, and salt uptake by plants, the value of $C(z, t)$ in Eq. [2] can be obtained from the solution of the diffusion-convection equation describing transient vertical transport by

$$\frac{\partial(C\theta)}{\partial t} = \frac{\partial}{\partial z}\left[\theta D(\theta, q)\ \frac{\partial C}{\partial z} - qC\right] \quad [3]$$

in which D is the hydrodynamic dispersion coefficient.

Numerical solutions of Eq. [1] to [3] have been obtained for initial and boundary conditions appropriate for irrigation with saline water (e.g., Bresler et al., 1982, p. 116–119). The boundary conditions for Eq. [1] to [3] at $z = 0$ (the soil surface) and at any time $t > 0$ are

$$q(0, t) = -K(\theta)(\partial h/\partial z - 1) \leq R(t) \quad \text{when } h(0, t) \leq 0 \text{ or } \theta(0, t) \leq \theta_s \quad [4a]$$

or

$$q(0, t) \geq R(t) \text{ when } h(0, t) \geq h_d \text{ or } \theta(0, t) \geq \theta_d \quad [4b]$$

$$-\theta(0, t)\ D[\theta(0, t), q(0, t)]\ \partial C/\partial z + q(0, t)\ C(0, t) = q(0, t)\ C_o(t)\,. \quad [4c]$$

These conditions are supplemented by

$$T_r(t) = \int_0^Z -S(z, t)\ dz \quad [4d]$$

$$T_r(t) \leq T_p(t) \text{ and } \Psi(t) \geq h_{cr}\,. \quad [4e]$$

The initial conditions at $t = 0$ are

$$C(z, 0) = C_n(z) \quad [5a]$$

$$\theta(z, 0) = \theta_n(z) \text{ or } h(z, 0) = h_n(z)\,. \quad [5b]$$

Here, $R(t) > 0$ is the rate of water application and $R(t) < 0$ is the maximum possible (prescribed) rate of soil evaporation. The terms h_d and h_n are the water pressure head of air-dry soil and the initial water pressure head; respectively, θ_s, θ_d, and θ_n are saturation, air-dry, and initial soil-water contents; respectively, C_n is the initial soil solution salt concentration, C_o is the salt concentration of the irrigation water ($qC_o = 0$ immediately after an irrigation ceases), Z is the total root zone depth, T_r is the transpiration flux, T_p is the potential (maximum possible) transpiration flux, and h_{cr} is the lowest possible (critical or limiting) value for total plant root potential Ψ. Note in Eq. [2] that when $h(z, t) + \gamma C(z, t) \leq h_{cr}$ then $S = 0$ and water extraction by roots ceases.

SIMPLIFIED THEORY FOR STEADY FLOW AND TRANSPORT

Irrigation systems such as pivot, solid-set sprinkler, or trickle/drip enable one to irrigate very frequently and to control the infiltration rate provided the water application rate is sufficiently low to prevent ponding on the soil surface (the infiltration rate is identical to the application rate). The consequences of high-frequency, low-rate irrigation are that flow may be considered steady at least below a certain shallow soil depth (Rawlins, 1973), because alternate wetting and drying cycles will dampen out with depth. Very high irrigation frequency may be approximated by assuming continuous irrigation so that the flow may be considered as steady. For such a steady water flow and a steady salt transport ($\partial\theta/\partial t = 0$, $\partial C/\partial t = 0$), Eq. [1] and [3] become, respectively,

$$dq/dz = -S(z) \quad [6]$$

$$\frac{\partial}{\partial z}\left[D\theta\frac{\partial C}{\partial z} - qC\right] = 0\,. \quad [7]$$

[3] For convenience, total water potential and its components are expressed on a pressure head equivalence basis. A value of 1 MPa = 10 bars = 1000 J/kg $\simeq$ 102 m.

Table 1. Seasonal averages of irrigation depth (V_i) and drainage depth (V_d) for the six levels of water quantity.†

	1		2		3		4		5		6			
Crop	V_i	V_d	V_i	V_d	V_i	V_d	V_i	V_d	V_i	V_d	V_i	V_d	E_o	U
	mm													
Wheat	579	13	514	74	465	34	444	25	404	15	404	6	720	389
Sorghum	754	34	640	94	603	68	570	48	559	32	432	7	950	515
Lettuce	274	50	245	35	219	22	200	18	208	9	190	5	470	182
Oat	656	16	522	66	426	40	370	28	320	14	279	7	670	272
Tomato	1014	89	878	131	808	86	716	67	669	33	586	3	1030	573
Cauliflower	301	67	283	47	212	24	194	20	202	10	180	6	310	174
Barley	620	16	486	70	458	44	352	38	336	18	313	4	480	309
Cowpea	798	34	668	95	605	48	532	40	433	18	432	8	780	415
Celery	625	24	519	72	471	41	389	34	326	16	300	7	540	293

† Also given are the seasonal class A pan evaporation (E_o) and the steady-state water use (U) for nine experimental crops.

By neglecting diffusion and dispersion Eq. [7] becomes

$$d(qC)/dz = 0. \qquad [8]$$

Integrating Eq. [6] and [8] between $z = 0$ (where $q = R$ and $C = C_o$) and an arbitrary rooting depth X gives

$$q(X) = R - \int_0^X S(z)\,dz = R - T_r(X) \qquad [9]$$

$$q(X) = RC_o/C(X) \qquad [10]$$

where $T_r(X)$ is the transpiration rate that can be accounted for by water extraction by plant roots from the soil surface to the rooting depth X. Under conditions where $R > T_r(X)$ flow is downward through the soil profile and a leaching fraction (L) can be defined from Eq. [9] and [10] as

$$L(X) = q(X)/R = [R - T_r(X)]/R = C_o/C(X). \qquad [11]$$

Equation [11] is useful as long as the transpiration rate $T_r(X)$ is independent of the controllable irrigation variables R and C_o. Employing this assumption and considering several $T_r(z)$ functions, Hoffman and van Genuchten (1983) calculated the average root zone salinity from equations similar to Eq. [9] and [10] in an attempt to relate crop tolerance threshold values to C_o and L.

Based on the assumption that there is a fixed seasonal water consumption (evapotranspiration) $U = [T_r(X) + E]G$ (with E being evaporation flux and G being the length of the growing season), the leaching requirement (L_r) has been derived (van Schilfgaarde et al., 1974) as

$$L_r = V_d/V_i = 1 - (U/V_i) = C_o/C_d \qquad [12]$$

where V_i is the seasonal depth of applied water, and V_d is the required depth of drainage water to pass below the root zone of depth X to prevent yield loss. It should be noted that Eq. [10] to [12] are exact as long as steady flow is maintained, but their practical applications are restricted to the case where T_r or U is independent of C_o and V_i or R. It is also possible to use these equations in practice *if and only if* the dependence of T_r (or U) on R (or V_i) and on C_o is known or can be estimated with the aid of a theory similar to Eq. [2]. The two alternatives of steady and transient cases for the situation in which actual transpiration is less than potential transpiration will be examined in the next section. The trivial case in which actual transpiration equals its potential value so that T_r (or U) is independent of any controllable variable (R, V_i, C_o) need not be examined. It should be noted that one of the most difficult problems is the crop coefficient value that is defined here as the ratio between potential evaporation and potential transpiration for different crops.

EXPERIMENTAL CONDITIONS AND INPUT DATA

In a set of high frequency irrigation experiments (Hoffman et al., 1979; Jobes et al., 1981; Hoffman and Jobes, 1983), L_r was determined experimentally for nine crops. Wheat (*Triticum aestivum*, cv. Siete cerros), grain sorghum (*Sorghum bicolor*, cv. N.K. 125), crisphead lettuce (*Lactuca sativa*, cv. Empire), oat (*Avena sativa*, cv. Montezuma), tomato (*Lycopersicon esculentum*, cv. UC82A), cauliflower (*Brassica oleracea*, Var. Botrytis, cv. Snowball), barley (*Hordeum vulgaris*, cv. California Mariout 67), cowpea (*Vigna unguiculata*, cv. California Blackeye no. 5), and celery (*Apium graviolens* Var. Dulce, cv. Tall Utah 52-70R) were irrigated many times each day with small quantities of water having an electrical conductivity (EC) of $C_o = 2.3$ dS/m. Six levels of water quantity were tested for each crop during two or more irrigation seasons. Irrigation water quantities (V_i) and the corresponding quantity of drainage water (V_d) are summarized in Table 1 along with other variables used in the model. The reader is referred to the research papers for all the input data to the model.

The soil in the experimental plots was assumed homogeneous throughout the soil profile from $z = 0$ to 150 cm with an initial water content (θ_n) of 0.17 (except for $z = 150$ cm where a pressure head of 400 cm of water equivalent to $\theta_n = 0.13$ was applied constantly to extract the drainage water). The very frequent irrigations (many times each day throughout the season) were approximated by assuming continuous irrigation. Continuous irrigation rather than pulse irrigation was selected to save computer time and because preliminary computations showed no significant differences in the results due to the assumption. Hence, water was assumed to be applied uniformly to the surface at a constant rate R throughout the growing season of 90-d duration (G). For simplicity, and to save computer time, the water application rate was obtained by dividing the seasonal water quantity (V_i) by the length of the growing season; i.e., $R = q(0,t) = V_i/G$. Similarly, potential transpiration rate (T_p) to be used in Eq. [4e], subject to the requirements of [4b], was obtained by dividing the cumulative Class A pan evaporation (E_o) (Table 1) by G.

Generally, two values of h_{cr} equivalent to a θ of 0.05 ($h_{cr} = -0.34$ MPa $= -34$ m H_2O) and 0.06 ($h_{cr} = -0.22$ MPa $= -22$ m H_2O) were input for simulation. Lower values of θ were not tested because $\theta_r = 0.04$ and the model does not permit θ to be lower than θ_r(Eq. [14]).

In another experiment, Hoffman et al. (1983) evaluated the influence of the quantity (V_i) and quality (C_o) of irrigation water and irrigation frequency on tall fescue (*Festuca elatior arundinacea*) production in the rhizotron at the U.S. Salinity Laboratory. Two levels of water quantity (equivalent to two leaching fractions), three irrigation frequencies, and two levels of salt in the irrigation water were tested (Table 2). The three levels of irrigation frequency tested were: (i) pulse irrigations with the number of pulses daily depending on Class A pan evaporation (E_o), (ii) irrigations when approximately one-third of the "available" soil water had been depleted with 17 irrigations being applied annually, and (iii) Irrigations when about two-thirds of the available water had been depleted, which resulted in an average of 11

Table 2. Input data of irrigation water salinity (C_o), and irrigation frequency, and annual depths of irrigation water (V_i) and drainage water (V_d).†

Irrigation water salinity, C_o	Irrigation depth, V_i			Drainage depth, V_d			Relative dry matter production, Y_R					
	1978 to 1979	1979 to 1980	1980 to 1981	1978 to 1979	1979 to 1980	1980 to 1981	1978 to 1979		1979 to 1980		1980 to 1981	
							C	M	C	M	C	M
dS/m	cm											
					Daily irrigation							
1	166	193	157	10	20	9	0.90	0.82	0.78	0.74	0.86	0.76
4	137	139	134	24	13	11	0.79	0.76	0.61	0.73	0.76	0.66
1	243	302	244	74	72	73	0.99	1.00	1.00	1.00	1.00	1.00
4	226	184	253	71	62	84	0.88	0.90	0.80	0.73	0.94	0.96
				Irrigation after ⅓ soil water depletion (17 irrigations annually)								
1	176	192	115	9	21	5	0.82	0.92	0.74	0.78	0.56	0.66
4	160	124	101	20	6	8	0.66	0.78	0.57	0.61	0.34	0.45
1	228	225	271	60	58	75	1.00	0.98	1.01	1.00	1.00	1.00
4	218	202	267	59	60	77	0.86	0.90	0.81	0.92	0.92	0.95
				Irrigation after ⅔ soil water depletion (11 irrigations annually)								
1	145	193	140	23	24	4	0.84	0.85	0.66	0.80	0.60	0.68
4	155	154	115	20	13	6	0.70	0.86	0.66	0.82	0.36	0.57
1	238	281	236	57	58	61	0.93	0.96	0.88	0.95	0.97	0.96
4	204	222	222	45	46	57	0.70	0.82	0.87	0.93	0.74	0.82

† Also given are the computed (C) and measured (M) relative dry matter production of tall fescue for 3 yr for 12 treatments.

irrigations annually. Each plot was 3- by 3- by 1.5-m deep and contained Pachappa fine sandy loam (coarse, loamy, mixed, thermic, Mollic Haploxeralfs); the same soil as in the first experiment. A constant suction of about 0.04 MPa was applied to porous ceramic drain lines installed at a depth of 138 cm to extract drainage water.

The rate of irrigation (R), 2.5 mm/h, was considered to be constant with time and less than the saturated hydraulic conductivity (K_s) of the soil so runoff did not occur. Irrigation quantities were fixed in the experiment as well as in the computations by the length of time irrigation water was applied. The annual rate of Class A pan evaporation avg 1825 mm. Initial conditions for $C_n(z)$ and $\theta(z)$ were taken as the measured salinity and volumetric water content profiles prior to the main irrigation season (May) each year. The critical root water potential (Eq. [4e]) was taken to be -1.5 MPa, equivalent to the permanent wilting value.

The solution of the transient model given by Eq. [1] through [5] also requires soil hydraulic characteristics, boundary and initial conditions, and root distribution data. Preliminary results showed that computations of relative transpiration are insensitive to root distribution and depth. Hence, root zone depth (100 cm) and root distribution (50% in the upper third of the root zone, 35% in the middle third, and 15% in the lower third) were assumed to be constant throughout the season. The soil in the experimental plots has soil-water characteristics that may be described by van Genuchten's (1980) equation

$$K(h) = K_s \frac{\{1 - (\alpha h)^{n-1}[1 + (\alpha h)^n]^{-m}\}^2}{[1 + (\alpha h)^n]^{m/2}}; \quad m = 1 - 1/n \qquad [13]$$

$$\theta(h) = \{[1 + (\alpha h)^n]^{-m}\}(\theta_s - \theta_r) + \theta_r \qquad [14]$$

where α and n are fitting parameters, θ_s and θ_r indicate saturation and residual values of θ, respectively, and K_s is saturated K. The best fit of these equations to data for Pachapa soil (Wesseling, 1974) results in the following values: $\alpha = 0.0155$, $n = 1.6648$ ($m = 0.399$), $\theta_s = 0.44$, $\theta_r = 0.04$, and $K_s = 110$ m/s. For the dispersion coefficient, it was assumed that $D = \lambda(q/\theta)$ with the dispersivity parameter λ having the field value of 3 cm (Bresler and Dagan, 1981).

For the practical application of the steady-state model given by Eq. [11] and [12] a constant value of U is generally considered (e.g., van Schilfgaarde et al., 1974). Using a constant U in Eq. [12] requires that any irrigation water quantity in excess of U should drain below the root zone. Hence, the value of U for Eq. [12] was taken as $U = V_i - V_d$ for the treatment with the smallest difference between V_i and V_d (Table 1) for each of the nine crops. It should be noted that any attempt to select a best fit value for U rather than the smallest one would result in values of U, which are larger than V_i for some treatments for each crop. This means that under such conditions the crop consumes water from storage in excess of V_i. This obviously violates the steady-state assumption in Eq. [11] and [12].

RESULTS AND DISCUSSION

Water Balance

The relationship between the relative amount of applied water (V_i) that goes to evapotranspiration (U) and leaching fraction (L) as measured for nine crops is given in Fig. 1. For orientation, values of L as a function of U/V_i calculated from Eq. [11] or [12], with U being constant, are plotted in Fig. 1 as the straight line emanating from $L = 1$ and $V_i = \infty$ and ending at $L = 0$ where $V_i = U$. Examination of Fig. 1 suggests that each of the nine crops reacts differently to the quantities of irrigation water exceeding the steady-state calculation of evapotranspiration. These deviations may be attributed to the increase in transpiration because of the increase in soil-water content as irrigation water quantities increase. These results illustrate that Eq. [11] and [12] cannot be applied in a straightforward manner to resolve practical water management-salinity control situations of the type represented by this study (which was as close to steady state as can be found in the field). This is true even for the simplest case of high frequency (approximately continuous) irrigation partly because steady flow is not assured and partly because U or T_r is not independent of the controllable variables V_i and C_o and depends on the boundary conditions R and C_o. Thus, even in such a simple irrigation scheme, proper irrigation management decisions must emanate from consideration of

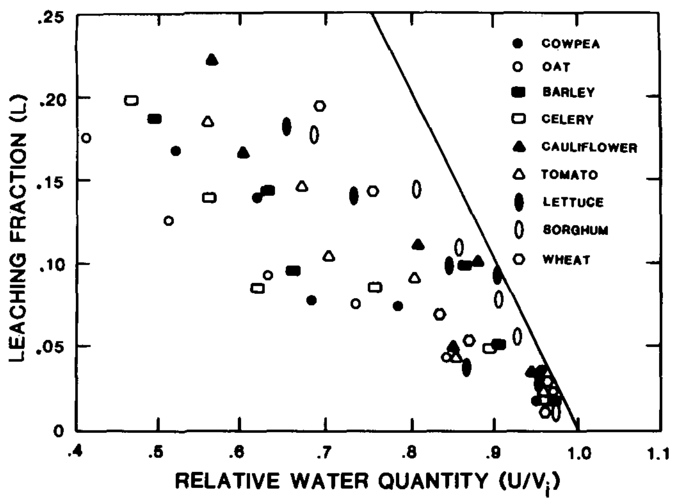

Fig. 1. Leaching fraction ($L = V_d/V_i$) as a function of relative water quantity (U/V_i) for $V_i \geq U$ for nine different crops irrigated frequently (the individual data points). The straight line represents the equation $L = 1 - U/V_i$ assuming U is constant.

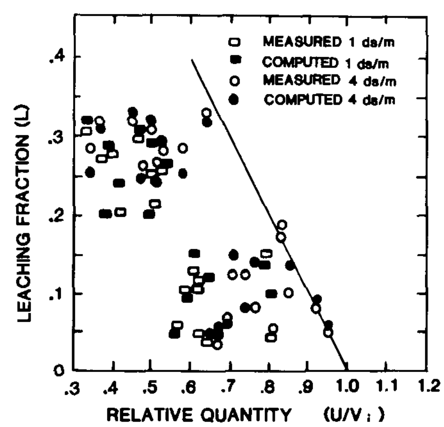

Fig. 2. Measured (open symbols) and computed (closed symbols) leaching fractions (L) as a function of U/V_i for two irrigation water qualities in the tall fescue experiment. The solid straight line represents the equation $L = 1 - U/V_i$ for a constant value of U.

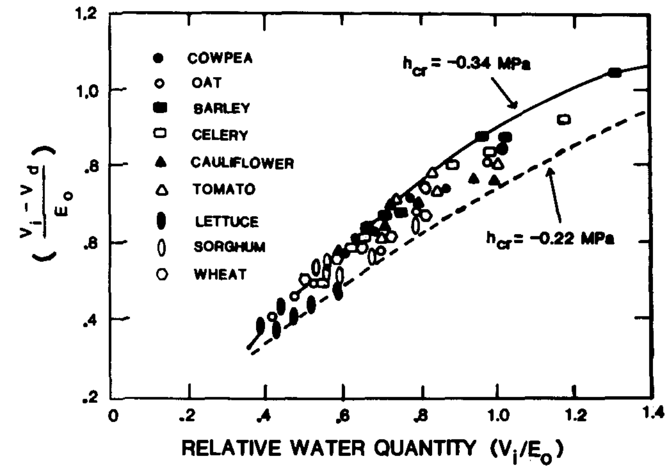

Fig. 3. Measured (data points) and computed (solid and dashed lines) relationships between the annual quantities of irrigation water minus drainage water ($V_i - V_d$) relative to annual Class A pan evaporation (E_o) and V_i/E_o for nine crops the L_r experiments using two values of the critical plant root water potential (h_{cr}) for the transient model.

factors represented in the mathematical expressions of Eq. [1] through [5].

Measured and computed leaching fractions in the tall fescue experiment are plotted in Fig. 2 as a function of U relative to the total irrigation quantity applied (V_i). Here again, the measured value of U was taken as the smallest measured value of the difference between $V_i - V_d$ for each of the three test years and it is actually the sum of evapotranspiration and any change in soil water storage. The measured value of U was taken as 113 cm in 1978 to 1979, 118 cm in 1979 to 1980, and 93 cm in 1980 to 1981. Similar to Fig. 1, the straight line represents the steady-state condition of $L = 1 - U/V_i$ where U is assumed to be constant and the same in each year for all treatments. The points to the left and below this straight line indicate that a part of the irrigation water quantity exceeding U is extracted by the plant roots or stored in the soil or both. Any points above and to the right of this line indicate an annual decrease in soil-water content while the points on the line are those from which the values of U have been taken.

Similar to Fig. 1, the data of Fig. 2 suggest that the results computed from the transient model, as well as measured values, are generally left and below the steady-state condition. The deviation from the steady-state line is generally larger for the less saline irrigation water. This is probably because transpiration is reduced as soil salinity increases; causing more water to be stored in the soil profile. Additional stored water increased the soil-water content, which in turn increased hydraulic conductivity and leaching.

In comparing the theoretical results computed by the transient model with data obtained from the high irrigation frequency experiments for the nine crops during different time periods, the differences in climatic conditions and particularly the evaporative demand must be considered. To overcome these differences and to place measured and computed values on the same scale, we normalized both measured and computed flow variables by dividing them by the value of Class A pan evaporation E_o (Table 1). Measured and computed results of seasonal water quantities utilized for evapotranspiration and storage in the soil profile, calculated from the differences between irrigation (V_i) and drainage (V_d), are given in Fig. 3 as a function of irrigation water quantity (V_i). Note that both ($V_i - V_d$) and V_i are given relative to E_o. An examination of Fig. 3 suggests that the water budget components given by $(V_i - V_d)/E_o$ vs. V_i/E_o, are described reasonably well by the transient model provided that the critical plant root water potential (h_{cr}) is within the two prescribed limits which correspond to a small range of θ (between 0.05–0.06 m^3/m^3).

A key assumption underlying the applicability of Eq. [12] is that $U = V_i - V_d$. This means that there is no increase in water storage in the profile as the controllable variable V_i increases. To test this assumption, water content profiles at the end of the irrigation season were reconstructed from Fig. 7 of Hoffman et al. (1979) and average water content values throughout the irrigation season were taken from Fig. 3 of Hoffman and Jobes (1983) using a bulk density value of 1.3 Mg/m^3. The average θ values measured

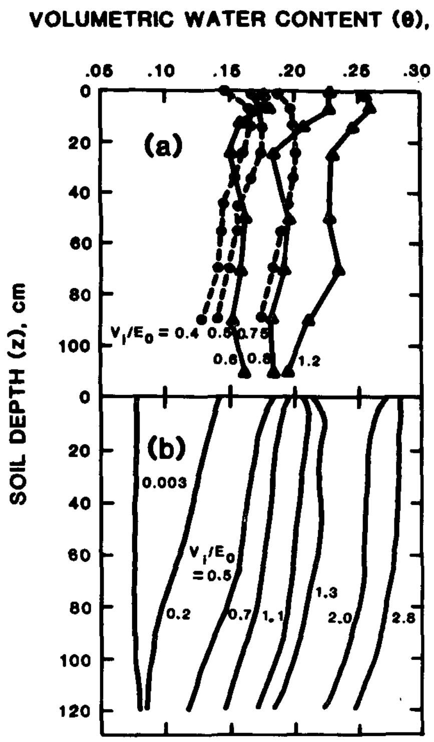

Fig. 4. Time-averaged soil-water content profiles: (a) measured values from Hoffman et al. (1979) denoted by circles connected by dashed lines and from Hoffman and Jobes (1983) denoted by triangles connected by solid lines and (b) values computed from the transient model. The number labeling each of the lines in (a) and (b) denote the value of V_i/E_o.

for various values of V_i/E_o are given in Fig. 4a. Average water content profiles computed from the transient model for different values of V_i/E_o are shown in Fig. 4b. Although the measured water content profiles are not identical to the computed profiles, the curves are very similar. Examination of Fig. 4 shows that measured as well as computed values of θ throughout the profile are higher as water quantities increase. This suggests that the differences in the values of $V_i - V_d$ in Fig. 3 are partly a consequence of the differences in the water content of the soil profile at the end of the season because initial θ profiles ($\theta_n = 0.17$) were identical for all the irrigation treatments. The differences in soil-water content are the result of differences in water application and differences in evapotranspiration. Because soil-water content and transpiration increase as more water is applied, the actual leaching fraction does not increase as rapidly as predicted from steady-state assumptions. This explains why Eq. [12] failed to describe the actual leaching situation and why the actual leaching fraction is always smaller than the steady-state $(1 - U/V_i)$ line as seen in Fig. 1 and 2.

Crop Yield

To compare measured crop yield with a theoretically computed yield, the theory of De Wit (1958), which gives the relationship between transpiration and crop yield, has been used as suggested by Hanks (1974). The model of De Wit (1958) proposes that

$$Y^{DM} = m\ T/E_o \qquad [15]$$

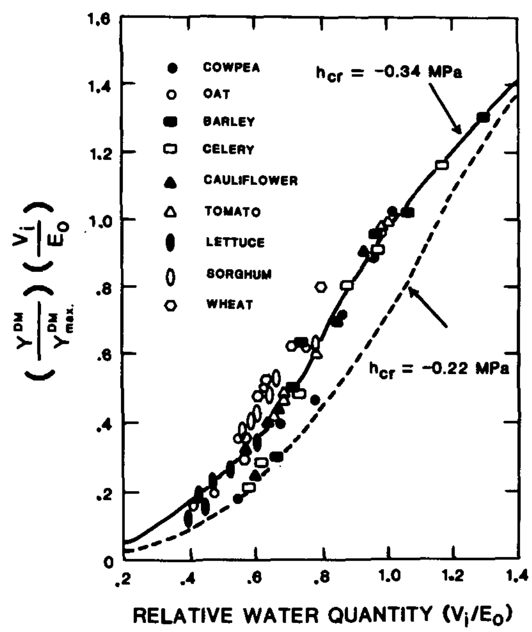

Fig. 5. Measured (data points) and computed (solid and dashed lines) values of relative dry matter production (Y^{DM}/Y^{DM}_{max}) times relative irrigation water quantity (V_i/E_o) as a function of V_i/E_o for the L_r experiments using two values of plant root water potential (h_{cr}) in the transient model.

where Y^{DM} is dry matter production, m is a crop factor, T is seasonal transpiration, and E_o is seasonal free water evaporation (pan evaporation). For a given crop, m is constant and for a given location and season E_o is constant. Thus, relative dry matter production or commercial yield ($Y_R = Y/Y_p$) equals relative transpiration ($T_R = T/T_p$) with the subscript p indicating maximum possible (potential) values. Unfortunately, evapotranspiration was not measured in the high irrigation frequency experiments. Thus, it was impossible to verify De Wit's model with the experimental data. Values of maximum yield (Y_{max}) of each crop, however, were measured in each of the experiments, so that actual yield relative to the maximum experimental yield is available. The actual dry matter production relative to the measured maximum production (Y^{DM}/Y^{DM}_{max}) multipled by the measured V_i/E_o value for each treatment was calculated to normalize the yield for differences in water use among crops. This normalized yield value is given as a function of relative water quantity in Fig. 5. The assumption underlying such a relationship is that the measured value of Y_{max} is proportional to Y_p when measured values of V_i/E_o are proportional to the smallest relative water quantity (V_i/E_o) corresponding to the calculated values of Y_p. In other words, we assumed that maximum crop production as measured in each crop would be identical to its potential production if the crop were irrigated by the smallest relative quantity V_i/E_o, which would give a calculated T_R of 1. Hence, for V_i/E_o of 1.3, $Y^M_{max} = Y_p = Y^C_{max}$ and therefore the measured value of $(Y^M/Y^M_{max})(V_i/E_o)$ should be equal to the computed value of $(Y^C/Y^C_{max})(V_i/E_o)$.

Examination of Fig. 5 suggests that the dry matter production for the nine crops can be calculated as a function of irrigation water quantity for a given water quality (EC = 2.3 dS/m in this case) if the evaporative

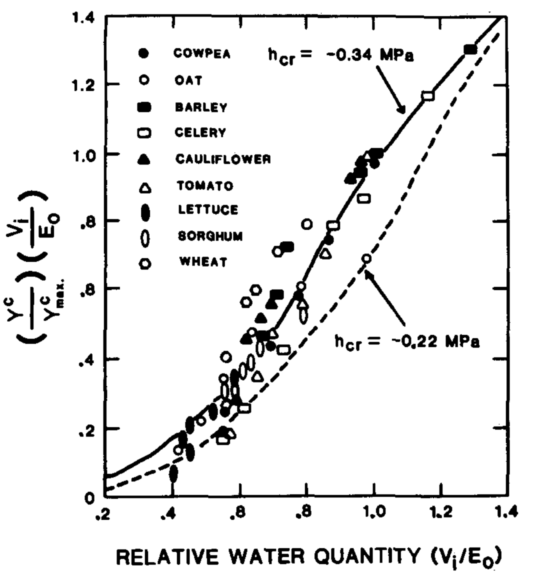

Fig. 6. Measured (data points) and computed (solid and dashed lines) values of relative commercial yield (Y/Y^C_{max}) times relative water quantity (V_i/E_o) as a function of V_i/E_o for the L_r experiment using two values of plant root water potential (h_{cr}) in the transient model.

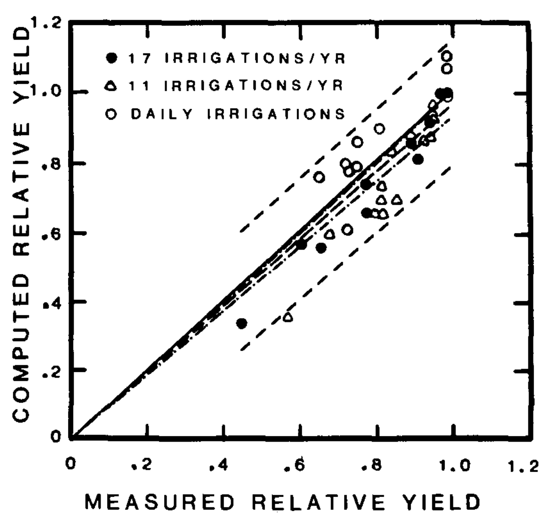

Fig. 7. Relationship between computed and measured relative yield for tall fescue irrigated at three frequencies. The straight solid line represents the 1:1 ratio; the dashed middle line is the best fitted line with β = 0.961; the dashed-dotted lines represents the 95% confidence limits on β; and the two extreme dashed lines are the predicted 95% confidence limits.

conditions and maximum possible (potential) production are known. Experimental data for the commercial yields of each crop are compared with the computed relative yields in Fig. 6. Note that the value assumed for the critical root-water potential (Fig. 5 and 6) is important in the quantitative prediction of crop yield response. A value of h_{cr} of -0.34 MPa fits the experimental data better than -0.22 MPa. A very high correlation ($r^2 = 0.99$) exists between commercial and total dry matter yields and no significant differences between these two yield components can be inferred statistically. This suggests that DeWit's model, which has been verified for dry matter production, may also be applicable to describe commercial yield response under saline conditions.

Results of calculated relative yield vs. measured relative yield for tall fescue are given in Fig. 7 with a few statistically determined lines for illustration. The grass yield of the seventh treatment in Table 2 was chosen as the potential yield each year. Actual yield of this treatment was 2.08, 1.94, and 2.06 kg/m^2 for the years 1978 to 1979, 1979 to 1980, and 1980 to 1981, respectively. To judge the agreement between computed results and measured data, a statistical analysis was performed using the linear regression model of

$$Y^C_R = \beta\, Y^M_R + \epsilon \qquad [16]$$

without an intercept; where superscripts C and M refer to computed and measured, respectively, β is the slope, and ϵ is the residual or error. The determination of Eq. [16] using a least square regression analysis may introduce a bias in the estimated parameter of β. For the parameter estimate to be unbiased the residual terms of the regression model must be uncorrelated and should have a zero mean or nonzero constant mean with a constant variance. Also, a nonstochacity of the explanatory variable (Y^M_R in this case) is required so that the residual terms are independent of Y^M_R. These criteria are met by the measured yield data of Fig. 5, 6, and 7 (or Table 2) because the yield of each treatment represents an average ($\bar{Y}^M_R$) of at least four replications for the tall fescue case and six replications in the L_r experiment. Hence,

$$Y^M_R = \bar{Y}^M_R + \eta \qquad [17]$$

with η being a random error term. Substituting [17] into Eq. [16] yields

$$Y^C_R = \beta\bar{Y}^M_R + \beta\eta + \epsilon = \beta\bar{Y}^M_R + \upsilon \qquad [18]$$

where υ is a random residual (disturbance) term independent of $\bar{Y}^M_R$. For the estimated parameter β from the data, such as in Table 2 (or Fig. 7) to be unbiased the residual terms υ must be uncorrelated. Applying the Durbin-Watson test (Maddala, 1977, p. 284–287) indicates that the disturbance (residual) terms are indeed uncorrelated at 0.01 significant level.

Under these conditions, the least-squares estimator of the regression coefficient is the best linear unbiased estimator of the ratio between calculated and measured data. For the data given in Fig. 7, the value of β was estimated to be 0.961 (illustrated by the middle dashed line of Fig. 7) with an r^2 value of 0.99 and significant β at $P = 0.0001$ level. To illustrate the results for the data of Fig. 7, the limits within which β will lie with probability of 0.95 are plotted as the two dashed-dotted lines in Fig. 7. Also given in Fig. 7 as the solid line is the 1:1 relationship. For most of the data, the model slightly underestimated the yield, but in a few cases, primarily with daily irrigation treatments, the model overestimated relative yield.

Similar to the tall fescue results, a statistical analysis of the agreement between the measured data points and the computed solid lines for h_{cr} = 0.34 MPa for the nine crops in the L_r experiments was performed. For these results the best fitted β is 0.968 (with r^2 = 0.987) for dry matter production (Fig. 5), and 0.971 (with r^2 = 0.977) for commercial yields (Fig. 6).

A response surface analysis made by Hoffman et al. (1983) indicated that irrigation water quality (salin-

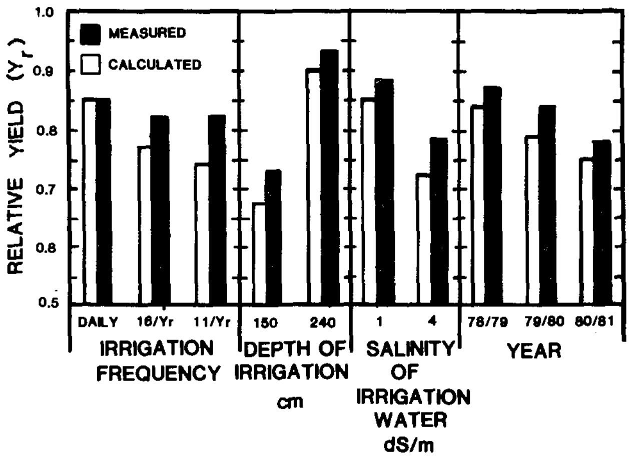

Fig. 8. Measured and calculated relative tall fescue yields averaged over irrigation frequency, irrigation water quantity, irrigation water quality, and time.

ity), irrigation water quantity, and time significantly influenced dry matter production (at probability level of 0.001) but irrigation frequency had no significant effect (the probability of obtaining F was 0.66). These tendencies are illustrated in Fig. 8 for both computed results and measured data by averaging each effect over the other three. Examination of Fig. 8 shows that the results of the analysis made on the measured data are similar to the computed results. In all treatments, yield decline over the years is obvious from both measured and computed data in which $F = 3.53$ (significant at the 0.05 level). Year effect is true except for the treatments in which relative yield was high and remained essentially unchanged and close to 1. The significant effects of both water quantity and quality is also obvious from both measured data and computed results of relative yield (student's t value for water quality is 8.3 and $t = 7.2$ for water quantity both are significant at the 0.0001 level) and is emphasized for the mean values in Fig. 8. While the measured data showed no significant effect of irrigation frequency on relative crop yield the improbable was rejected, but the computed yields show significant differences between the daily irrigation treatment and the two others ($t = 3.5$, significant at 0.05 level). This effect is probably because computations were made assuming all conditions are uniform with no field variations. Hence, computed relative yields are 0.85, 0.77, and 0.74 for daily irrigations, 17 irrigations per year, and 11 irrigations per year, respectively, and the corresponding measured relative yields are 0.85, 0.82, and 0.82, which show small and nonsignificant differences.

These results on the effect of water quantity, water quality, and irrigation frequency on tall fescue yield as measured in a rhizotron and calculated by the transient theory are similar to those observed by Shalhevet et al. (1983) for eggplant (*Solanum Melongena*). Considering the assumptions and approximations made in the theoretical transient model (Eq. [1] through [5]) to calculate relative yield for tall fescue and taking into account the uncertainty involved in the measurements of water inflow and outflow and crop yield, agreement between experimental data and modeling results is quite acceptable.

Two important practical results appear evident from this study: (i) irrigation management for soil salinity control cannot quantitatively be described by the simple steady-state expression as in Eq. [11] or [12], not even for the extreme case of high frequency (continuous) irrigation; and (ii) computed results using a transient model are very similar to measured data for frequent as well as infrequent irrigations. Considering the variability found in the field, there would appear to be no substantial improvement in the accuracy of measured results compared with these calculations.

ACKNOWLEDGMENT

This research was supported in part by a grant from the United States-Israel Binational Agricultural Research and Development Fund (BARD).

APPENDIX

List of Symbols

b = plant root geometry parameter	(1/m^2)
C = solute concentration of the soil solution	(dS/m; mol/m^3)
C_d = solute concentration of soil solution draining below the root zone	(dS/m; mol/m^3)
C_o = solute concentration of irrigation water	(S/m; mol/m^3)
C_n = initial solute concentration of soil solution	(S/m; mol/m^3)
D = hydrodynamic dispersion coefficient	(m^2/s)
EC = electrical conductivity	(S/m)
E_o = seasonal class A pan evaporation	(m)
E = evaporation flux	(m/s)
G = length of growing season	(s)
H = hydraulic head	(m)
h = soil matric pressure (suction) head	(m)
h_d = pressure head of air-dry soil	(m)
h_n = initial pressure head of soil	(m)
h_{cr} = limiting (critical) root pressure head	(m)
K = soil hydraulic conductivity	(m/s)
K_s = saturated soil hydraulic conductivity	(m/s)
L = leaching fraction	
L_r = leaching requirement	
m = fitting parameters for van Genuchten's $K(h)$ and $\theta(h)$ functions	
n = fitting parameter for van Genuchten's K(h) and (h) functions	
q = specific water flux	(m/s)
r^2 = correlation coefficient	
R = rate of water application or rate of soil evaporation	(m/s)
S = Volumetric rate of root water uptake by plant roots	(m/s)
t = time	(s)
T = seasonal transpiration	(m)
T_r = transpiration flux	(m/s)
T_p = maximum possible (potential) transpiration	(m)
T_R = relative transpiration	
U = seasonal water use or evapotranspiration	(m)
V_i = seasonal depth of applied water	(m)
V_d = seasonal depth of drainage water	(m)
X = arbitrary rooting depth	(m)
Y^c = crop commercial yield	(kg/m^2)
Y_p = potential (maximum possible) yield	(kg/m^2)
Y_{max} = maximum experimental yield	(kg/m^2)
Y_R = relative yield	
Y_R^c = computed Y_R	

Y_R^M =	measured Y_R	
Y^{DM} =	crop dry matter production	(kg/m^2)
Y^C =	commercial yield	(kg/m^2)
z =	vertical space coordinate	(m)
Z =	total depth of root zone	(m)
α =	fitting parameter for van Genuchten's K(h) and θ(h) functions	
β =	slope in statistical regression model	
Ψ =	total root water potential, pressure head equivalent	(Pa; m)
ϵ =	residual or error term in statistical regression model	
λ =	dispersivity parameter	(m)
η =	random error term	
γ =	transformation coefficient	(m^4/mol; Pa m^3/mol)
υ =	random residual term	
θ =	volumetric soil water content	(m^3/m^3)
θ_d =	air dry value for θ	(m^3/m^3)
θ_n =	initial value of θ	(m^3/m^3)
θ_r =	residual value of θ	(m^3/m^3)
θ_s =	saturated value of θ	(m^3/m^3)

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