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המרכז למחקר בכלכלה חקלאית

(Hebrew Univ.

THE CENTER FOR AGRICULTURAL ECONOMIC RESEARCH)

Working Paper No. 8304

ECONOMICS OF IRRIGATION WATER MIXING WITHIN A FARM FRAMEWORK

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E. Feinerman & D. Yaron

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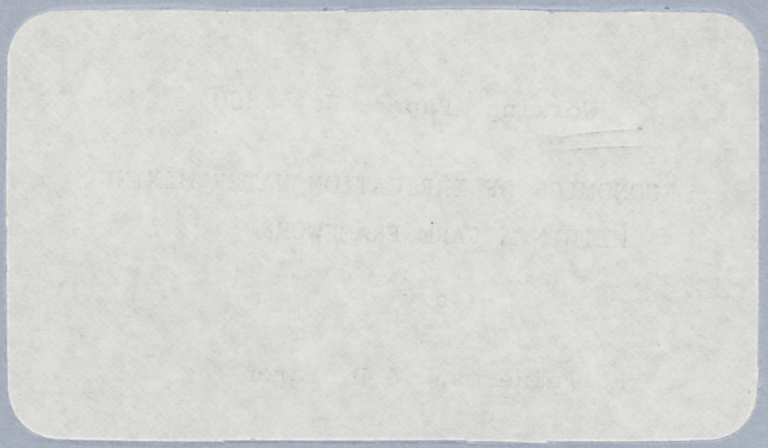

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ECONOMICS OF IRRIGATION WATER MIXING WITHIN A FARM FRAMEWORK

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ECONOMICS OF IRRIGATION WATER MIXING WITHIN A FARM FRAMEWORK

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Running Head: Economics of Irrigation Water Mixing

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ABSTRACT

Linear programming models, deterministic in the short run and stochastic (random rainfall) in the long run, aimed at guiding annual decision-making with regard to crop mix and saline irrigation water mixing from various sources within a farm framework, are presented. The short run model incorporates the physical, biological and economic relationships involved in one endogenous system and enables an in-depth analysis of them, but is limited to a single year. The long run model considers the effects of the short run decisions on the future but several relationships are incorporated exogenously. The short run model's results are utilized for the determination of some of these predetermined relationships. The models are applied to a potential farm situation in southern Israel. The results provide priorities in the allocation of water and soil plots of varying salinity levels and empirical estimates of the shadow prices and the rates of substitution between the limited resources.

INTRODUCTION

Problems of soil salinity and irrigation with saline water are worldwide. It is estimated that one third of the irrigated land in the world is affected by salinity problems [Yaron et al., 1969]. Each year about 40,000 hectares of land throughout the world becomes unfit for agricultural production because of salt accumulation [Evans, 1974].

The sources of water available for agriculture vary in their quantity and salinity levels. The cost of irrigation water is usually an increasing function of its quality. Use of low quality irrigation water may lead to salt accumulation in the soil which in turn may slow down the rate of growth and reduce crop yields. Due to a growing relative scarcity of good quality water for irrigation, the possibility of its partial substitution by relatively saline water is now being discussed in several regions of the world (e.g., Israel [Tahal, 1979], Southern California [Bitoun, 1979]). The expected transition from good quality to saline water necessitates a thorough economic analysis of irrigation with water from various sources, which differ in quality, quantity, and price. Water mixing plants have already been established in the northern coastal plain of Israel to monitor the salinity content of the water of the National Water System. Mixing of irrigation water is also carried out by regional plants not connected to the National Water System and by farms which receive their water supply from different sources (e.g., farms in the Bethshan Valley, farms in the coastal plain).

The econmic literature dealing with irrigation with saline water is still limited. Parkinson et al. [1970], Moore et al. [1974] and Hanks

and Anderson [1981] developed linear programming (LP) models for the determination of an optimal mix of crops in the short-run under conditions of irrigation with saline water. The first two consider mixing of irrigation water from different sources but in predetermined levels. Yaron and Olian [1973] utilized a stochastic dynamic programming for determining the optimal quantity of water for soil leaching (to reduce salinity) of a single perennial crop. The water quality was treated as an exogenous parameter. Their model was extended by Matanga and Marino [1979] who consider the seasonal irrigation depth as an additional decision variable. They combined stochastic dynamic programming and simulation to determine an irrigation policy for several crops, then applied this information in an area allocation LP model among the different crops. The last two papers do not consider mixing of irrigation water from different sources.

This paper considers a single farm with several sources of irrigation water, differing in quantity, quality and price, and several plots of land differing in the initial salinity of the soil solution. First, a short-run (SR) optimization model is presented, its distinctive feature being the incorporation of the economic physical and biological relationships (including mixing irrigation water from various sources, accumulation and leaching of salts in the soil, yield loss due to salinity and net profit for each crop) in one endogenous system. Thus the model provides a framework for an in-depth analysis of the relationships involved, which usually cannot be incorporated in a long-run analysis, due to dimensionality problems, but is limited to a single irrigation season. The objective function is based solely on immediate

profits and ignores the effects of the terminal values of the soil-related state variables on the succeeding seasons. A long-run (LR) model, which refers to the water-soil-crop-farm system over a sequence of several irrigation seasons and utilizes the information provided by the SR model, is presented in the last section of this paper.

With a few empirically justified approximations, the models employ the LP approach and are applied to a potential farm situation in southern Israel.

FORMULATION OF THE SR MODEL

Consider a single irrigation season divided into T subseasons. The farm has at its disposal J sources of water upply, G land plots differing in their initial soil salinity levels, and N cropping alternatives. We first discuss the underlying physical, biological and economic relationships and the linear functions formulated in the process of their adjustment to a linear programming (LP) format.

Irrigation Water Mixing

Let X_{ng} be the number of hectares (ha) of crop n on plot g (henceforth crop ng) and let $\overline{W}_{ng}(t)$ be the total quantity of applied water [m^3] per hectare of crop ng during subseason t (possibly mixed from several sources). It is assumed that $\overline{W}_{ng}(t)$ is predetermined according to the prevailing agricultural practices which are based on detailed

guidelines available to the farmers from research and advisory services and their previous experience. Due to lack of information on the relationships between water quality and the desired irrigation timing, the frequency of irrigation is assumed as a constant. As detailed below, the quantities of water applied for salt leaching are determined endogenously in the model. The quantity and the salinity of the water resulting from mixing several sources are given by (1) and (2) respectively:

$$(1) \qquad \overline{W}_{ng}(t) = \sum_{j=1}^{J} W_{ng}^{j}(t)$$

$$(2) \qquad \overline{W}_{ng}(t)\,\overline{C}_{ng}(t) = \sum_{j} C_{j}(t) W_{ng}^{j}(t)$$

where

$W_{ng}^{j}(t)$ = the quantity of irrigation water in cubic meters [m^3] per hectare of crop ng, from source j, during subseason t;

$C_j(t)$ = the salt concentration in milliequivalent chlorides per liter (meq cl/l) of water source j during subseason t;

$\overline{C}_{ng}(t)$ = the average salt concentration (meq cl/l) of one m^3 of irrigation water, mixed from various sources, allocated to crop ng during subseason t.

Multiplying both sides of (1) and (2) by X_{ng} yields:

$$(3) \qquad \overline{W}_{ng}(t)X_{ng} - \sum_{j}(XW)_{ng}^{j}(t) = 0$$

$$(4) \qquad \overline{W}_{ng}(t)(XC)_{ng}(t) - \sum_j C_j(t)(XW)^j_{ng}(t) = 0$$

where $(XW)^j_{ng}(t) = X_{ng} \cdot W^j_{ng}(t)$ and $(XC)_{ng}(t) = X_{ng} \cdot \overline{C}_{ng}(t)$

It should be emphasized that (XW) and (XC) are incorporated into the LP model as single endogenous variables and not as a product of two endogenous variables. The physical units of (4) are equivalents of chlorides (x 35.5 = kg of chlorides), rather than concentration units.

Accumulation and Leaching of Salts in the Irrigated Plots

Let $S_{ng}(t)$ be the average soil salt concentration (meq Cl/l) at the root zone of plot g, associated with crop n, at the beginning of subseason t. The transformation function from $S_{ng}(t)$ to $S_{ng}(t+1)$ is:

$$(5) \qquad S_{ng}(t+1) = \frac{1}{b^1_{ng}(t)} \sum_j C_j(t)\, W^j_{ng}(t) + \frac{b^2_{ng}(t)}{b^1_{ng}(t)} S_{ng}(t)$$

where

$$b^1_{ng} = V_g + \frac{\beta_g}{2}(\overline{W}_{ng}(t) + R(t)) \quad \text{and} \quad b^2_{ng}(t) = V_g - \frac{\beta_g}{2}(\overline{W}_{ng}(t) + R(t))$$

where

β_g = the fraction of applied irrigation water leached out of the root zone of soil plot g (soil parameter);

V_g = the average amount of water [m^3/ha] contained in the root zone of soil plot g (soil parameter);

$R(t)$ = the rainfall level [m^3/ha] during subseason t.

Relationship (5) is based on the law of mass conservation and was found to serve as a good approximation of salt accumulation and leaching processes [Yaron and Bresler, 1970; Yaron and Olian, 1973].

Multiplying both sides of (5) by X_{ng} yields:

$$(6) \qquad \frac{b^2_{ng}(t)}{b^1_{ng}(t)} (XS)_{ng}(t) + \frac{1}{b^1_{ng}(t)} \sum_j C_j(t)(XW)^j_{ng}(t) - (XS)_{ng}(t+1) = 0$$

where $(XS)_{ng}(t) = X_{ng}\ S_{ng}(t)$ (regarded as one endogenous variable). $b^1_{ng}(t)$ and $b^2_{ng}(t)$ are given parameters due to the assumption that $\overline{W}_{ng}(t)$ is predetermined. This assumption is needed to ensure that (6) is a linear function of (XS) and (XW). The units of (6) are [(meq Cl/l)·ha] and have no physical meaning. (Note that multiplying (6) by the constant V_g will change its units to quantities of chlorides (35.5 kg Cl). This multiplication, however, is not needed for using (6) in the LP model.)

We refer to salt leaching with reference to field crops as pre-irrigation with water of low salinity level in order to decrease the salt concentration of the soil solution before planting. Regarding fruit groves, we refer to leaching as a specific irrigation application with water of low salt concentration over and above the conventional practice. (The model enables us to include leaching activities with

water from each source at each subseason. The simplified assumptions are based on the empirical application of the model.)

Let S_g be the initial known salt concentration of the soil solution in plot g, t_n^* the subseason in which leaching associated with crop n is performed and $S_{ng}(t_n^*)$ be the salinity of soil solution of plot g planted with crop n, after leaching. We assume that leaching irrigation, if any, will be applied using water of lower salinity than S_g. Denote by $(SWL)^1_{ng}(t_n^*)$ the quantity of leaching water from source 1 applied to one hectare of plot g to be allocated to crop n, (assuming that the leaching is performed with water from source 1). We approximate the relationship between $S_{ng}(t_n^*)$ and S_g by the following expression:

$$(7) \qquad S_{ng}(t_n^*) = S_g + \alpha_g (WL)^1_{ng}(t_n^*)$$

Multiplying both sides of (7) by X_{ng} and rearranging yields:

$$(8) \qquad \alpha_g (XWL)^1_{ng}(t_n^*) + S_g X_{ng} - (XS)_{ng}(t_n^*) = 0$$

where: $(XWL)^1_{ng}(t_n^*) = X_{ng}(WL)^1_{ng}(t_n^*)$ (regarded as one endogenous variable) and α_g is an empirical parameter. The quantity of water for leaching is assumed to be restricted and not exceeding some predetermined value $\overline{WL}$ (m^3/ha):

$$(9) \qquad (XWL)^1_{ng}(t_n^*) - \overline{WL} \cdot X_{ng} \leq 0$$

Yield Loss

It is assumed that the reduction in yield of crop ng, if any, is

due only to the osmotic (salinity) effect of the soil solution. This approach assumes that the predetermined values of $\overline{W}_{ng}(t)$ assure an irrigation regime in which the possibility of a soil moisure deficiency is eliminated. A similar approach has been adopted by Maas and Hoffman [1977] and Bernstein [1981].

We adopt the specification of the yield loss function which suggests that below a given soil salinity threshold the yield of a crop is not affected, while above this threshold the yield decreases linearly with soil salinity [Maas and Hoffman, 1977]. Formally, the yield loss function can be stated as follows:

$$(10) \qquad L_{ng} = \begin{cases} \gamma_n + \delta_n S_{ng} & \text{if } S_{ng} > \overline{S}_n \\ 0 & \text{otherwise} \end{cases}$$

where L_{ng} is percentage loss of yield of crop ng, $\gamma_n < 0$ and $\delta_n > 0$ are given parameters, $S_{ng} = \dfrac{S_{ng}(t_n^*) + S_{ng}(t_n^* + 1) + .. + S_{ng}(\overline{t}_n)}{(\overline{t}_n + 2 - t_n^*)}$ is the average salt concentration (meq Cl/l) of the soil solution in the root zone during the growth period, $\overline{t}_n$ is the subseason in which the harvest is performed, and $\overline{S}_n$ is the critical salinity level expressed in terms of average salinity throughout the season.

The yield loss function is depicted in Figure 1.

Note that sign $\{\gamma_n + \delta_n S_{ng}\}$ = sign $\{S_{ng} - \overline{S}_n\}$.

To incorporate (10) in the LP model, we rewrite it as:

$$(11) \qquad L_{ng} \geq \gamma_n + \delta_n S_{ng}$$

and restrict L_{ng} to be non-negative in the LP model. Since the planning problem is a maximization problem, it's clear from (11) that the level of L_{ng} in the optimal solution will be equal to max $\{0, \gamma_n + \delta_n S_{ng}\}$.

Multiplying both sides of (11) by X_{ng} and substituting for S_{ng} yields:

$$(12) \qquad \gamma_n X_{ng} + \bar{\delta}_n (XS)_{ng}(t_n^*) + \ldots + \bar{\delta}_n (XS)_{ng}(\bar{t}_n) - (XL)_{ng} \leq 0$$

where $(XL)_{ng} = X_{ng} \cdot L_{ng}$ (regarded as one endogenous variable) and

$$\bar{\delta}_n = \frac{\delta_n}{(\bar{t}_n + 2 - t_n^*)}$$

Since $L_{ng} \leq 100$, we have to formulate:

$$(13) \qquad 0.01\,(XL)_{ng} - X_{ng} \leq 0$$

Net Profit

Let $(YS)_{ng}$ be the yield in physical units per hectare of crop ng with no loss incurred ($(XL)_{ng} = 0$). Accordingly, the actual yield Y_{ng} will be,

$$(14) \qquad Y_{ng} = (YS)_{ng} - 0.01(YS)_{ng} L_{ng}$$

and the net profit per hectare (water cost excluded) will be,

$$(15) \qquad \pi_{ng} = \theta_{ng} Y_{ng} - \eta_{ng} = \theta_{ng}((YS)_{ng} - 0.01(YS)_{ng} L_{ng}) - \eta_{ng}$$

where:

θ_{ng} = income (dollars/ton) net of non-water variable costs directly related to yield (e.g., harvesting, grading, packing and transportation).

η_{ng} = variable costs in dollars/ha, independent of yield.

Multiplying both sides of (15) by X_{ng} yields:

$$(16) \qquad (\theta_{ng}(YS)_{ng} - \eta_{ng})\, X_{ng} - 0.01(YS)_{ng}\theta_{ng}(XL)_{ng} - (X\pi)_{ng} = 0$$

where $(X\pi)_{ng} = X_{ng} \cdot \pi_{ng}$ (regarded as one endogenous variable).

The above relationships are combined to get the following LP model:

$$\max Z = \sum_{n=1}^{N} \sum_{g=1}^{G} (X\pi)_{ng} - \sum_{j=1}^{J} \sum_{t=1}^{T} D_j(t)\, P_j(t)$$

subject to:

		Shadow Price Notation	Restriction Notation
$\forall j,t$	$D_j(t) \leq A_j(t)$	$U_j^1(t)$	$F_j^1(t)$
$\forall j,t$	$\sum_n \sum_g [(XW)_{ng}^j(t) + (XWL)_{ng}^1(t_n^*).I_n^1(t)] - D_j(t) = 0$	$U_j^2(t)$	$F_j^2(t)$
$\forall g$	$X_{ng} \leq H_g$	U_g	F_g
$\forall n,g,t\in[t_n^*,\bar{t}_n]$	$\bar{W}_{ng}(t)\, X_{ng} - \sum_j (XW)_{ng}^j(t) = 0$	$U_{ng}^3(t)$	$F_{ng}^3(t)$
$\forall n,g,t\in[t_n^*,\bar{t}_n]$	$\bar{W}_{ng}(t)(XC)_{ng}(t) - \sum_j C_j(t)(XW)_{ng}^j(t) = 0$	$U_{ng}^4(t)$	$F_{ng}^4(t)$
$\forall n,g,t_n^*$	$(XWL)_{ng}^1(t_n^*) - \overline{WL}\, X_{ng} \leq 0$	$U_{ng}^5(t_n^*)$	$F_{ng}^5(t_n^*)$
$\forall n,g,t_n^*$	$S_g X_{ng} + \alpha_g (XWL)_{ng}^1(t_n^*) - (XS)_{ng}(t_n^*) = 0$	$U_{ng}^6(t_n^*)$	$F_{ng}^6(t_n^*)$
$\forall n,g,t\in[t_n^*,\bar{t}_n]$	$\frac{b_{ng}^2(t)}{b_{ng}^1(t)} (XS)_{ng}(t) + \frac{1}{b_{ng}^1(t)} \sum_j C_j(t)(XW)_{ng}^j(t) - (XS)_{ng}(t+1) = 0$	$U_{ng}^7(t)$	$F_{ng}^7(t)$
$\forall n,g,t_n^*,\bar{t}_n$	$\gamma_n X_{ng} + \bar{\delta}_n (XS)_{ng}(t_n^*) + \ldots + \bar{\delta}_n (XS)_{ng}(\bar{t}_n) - (XL)_{ng} \leq 0$	U_{ng}^8	F_{ng}^8
$\forall n,g$	$0.01(XL)_{ng} - X_{ng} \leq 0$	U_{ng}^9	F_{ng}^9
$\forall n,g$	$(\theta_{ng}(YS)_{ng} - \eta_{ng})\, X_{ng} - 0.01(YS)_{ng}\, \theta_{ng}(XL)_{ng} - (X\pi)_{ng} = 0$	U_{ng}^{10}	F_{ng}^{10}
$\forall n,g,j,t$	$D_j(t), (XW)_{ng}^j(t), (XWL)_{ng}^1(t_n^*), X_{ng}, (XC)_{ng}(t), (XS)_{ng}(t), (XL)_{ng}, (X\pi)_{ng} \geq 0$		F^{11}

where:

$D_j(t)$ = the quantity of irrigation water from source j actually used for irrigation during subseason t [m^3];

$P_j(t)$ = the cost of water from source j, in subseason t [$/$m^3$];

$A_j(t)$ = the quantity of irrigation water available from source j during subseason t [m^3];

$I_n^1(t)$ = an indicator function which takes values of 0 or 1 as follows:

$$I_n^1(t) = \begin{cases} 1 & \text{if } j=1 \text{ and } t=t_n^* \\ 0 & \text{otherwise} \end{cases}$$

H_g = the area of plot g (hectares)

The decision variables of the model are: X_{ng}, $(XW)_{ng}^j(t)$, and $(XWL)_{ng}^1(t_n^*)$ while the parameters $A_j(t)$, H_g, $C_j(t)$, $\overline{W}_{ng}(t)$, $\overline{WL}$, $(YS)_{ng}$ and $P_j(t)$ are predetermined. $M_j(t)$, $(XC)_{ng}(t)$, $(XS)_{ng}(t)$, $(XL)_{ng}$ and $(X\pi)_{ng}$ are state variables determined endogenously in the model.

The restrictions $F_j^1(t)$ and $F_j^2(t)$ represent the supply and use of irrigation water, F_g represents supply and use of land (if some mature perennial crops are included in the cropping alternatives, equality constraints have to be added, taking into account their given constant areas). The restrictions $F_{ng}^3(t)$, $F_{ng}^4(t)$, $F_{ng}^5(t_n^*)$, $F_{ng}^6(t_n^*)$, $F_{ng}^7(t)$, F_{ng}^8, F_{ng}^9, and F_{ng}^{10} are identical to the relationships (3), (4), (9), (8), (6), (12), (13), and (16), respectively.

The variable $(XW)^{j}_{ng}(t)$ ($(XWL)^{l}_{ng}(t^{*}_{n})$) represents the total quantity of irrigation (leaching) water [m^3] from source j, applied to X_{ng} hectares of crop ng during subseason-t. The variable $(X\pi)_{ng}$ represents the total net profits (water cost excluded) per X_{ng} hectares of crop ng. The units of (XC), (XS), and (XL) have no physical meaning. Since the (nonlinear) definitional constraints ($(XW)^{j}_{ng}(t) = X_{ng}W^{j}_{ng}(t)$, etc.) are not included in the LP model, the optimal values of $W^{j}_{ng}(t)$, $WL^{l}_{ng}(t^{*}_{n})$, π_{ng}, $\overline{C}_{ng}(t)$, $S_{ng}(t)$ and L_{ng} are not directly determined by its solution. However, their values can be computed respectively as the optimal levels of (XW), (XWL), $X\pi$), (XC), (XS) and (XL) divided by the optimal level of X_{ng}.

Keeping in mind the non negativity restrictions (F^{11}), note that $X_{ng}=0$ implies: (I) $(XW)^{j}_{ng}(t) = 0$ $\forall j,t$ (see $F^{3}_{ng}(t)$) and hence $(XC)_{ng}(t) = 0$ $\forall t$ ($F^{4}_{ng}(t)$). (II) $(XWL)^{l}_{ng}(t^{*}_{n}) = 0$ $\forall t^{*}_{n}$ ($F^{5}_{ng}(t^{*}_{n})$) and hence $(XS)_{ng}(t^{*}_{n}) = 0$ $\forall t^{*}_{n}$ ($F^{6}_{ng}(t^{*}_{n})$). (III) $(XL)_{ng} = 0$ (F^{9}_{ng}) and hence $(XS)_{ng}(t) = 0$ $\forall t$ (F^{8}_{ng}); $(X\pi)_{ng} = 0$ (F^{10}_{ng}).

It should also be noted that $(XL)_{ng} = 0$ and/or $(XWL)^{l}_{ng}(t^{*}_{n}) = 0$ do not necessarily imply $X_{ng} = 0$ (the sign of X_{ng} in the nonequality constraints $F^{5}_{ng}(t^{*}_{n})$, F^{8}_{ng} and F^{3}_{ng} is negative ($\gamma_{n} < 0$)). This fact is demonstrated in the next empirical section.

The model assumes that each crop can be grown only once (on each plot) during the single irrigation season and that there is no possibility of "double-cropping". However, these assumptions can be easily modified.

The economic interpretations of some of the shadow prices are summarized in Table 1.

The marginal rate of substitution between two variables equals the negative of the ratio between their marginal productivity values (represented by the shadow prices). The marginal rate of substitution between water from the various sources in different subseasons, needed to maintain a constant level of farm income, is given by

$$\frac{dW_{ng}^{j'}(t')}{dW_{ng}^{j}(t)} = -\frac{U_j^2(t)}{U_{j'}^2(t')} \tag{17}$$

As mentioned, the issue of substitution of good quality water by relatively saline water in agriculture is now discussed in several regions in the world. The proper substitution quotas needed to compensate farmers for deteriorating irrigation water qualities can be based on (17). However, these rates of substitution are valid only for the optimal solution values and their vicinity with the widths of the margins not being established in this paper. Nevertheless, they might indicate the order of magnitude relevant to policy decisions with respect to farms in the region under consideration.

EMPIRICAL APPLICATION OF THE SR MODEL

In the following, all monetary units are expressed in dollars at January 1978 price levels. Land areas are in hectares and salt concentrations are in terms of milliequivalent chlorides per liter (meq Cl/l).

The empirical application of the model is based on data for a Kibbutz farm in southern Israel. An irrigation season is defined as one year and is subdivided into two subseasons: t=1, spring-summer (May-October); t=2, autumn-winter (November-April). The farm has three water supply sources with varying levels of quantities ((100, 350, 400) thousands m^3 respectively in t=1 and (110, 375, 400) thousands m^3 respectively in t=2), salt concentrations (5, 10, 25 meq cl/l respectively) and costs (0.10, 0.07, 0.06 $/m^3$ respectively). Five soil plots (Plot A - Plot E) with different areas (50, 50, 50, 60, 60 hectares respectively) and initial soil salinity levels (5, 10, 15, 20, 25 meq Cl/l respectively) are distinguished.

The cropping alternatives of the farm are: fall potatoes, fall carrots, cotton and a mature grapefruit grove. The yields of these crops (except cotton) are sensitive to soil salinity. The land area of the grapefruit grove is 50 hectares, presently 10 in each soil plot. The farm faces yearly quotas for potatoes (100 hectares) and carrots (60 hectares). Field crops are sown in t=1 and all crops are harvested in t=2.

Quantities of irrigation water and parameters of yield-loss functions due to salinity for the various crops are shown in Table 2. The parameters of the yield-loss functions for potatoes and grapefruits were estimated by a switching regression approach [see Feinerman et al., 1982] on the basis of original experiments of the soil researches Sadan and Berglas [1980] and Bielorai [1980] respectively. The parameters for carrots are based on Maas and Hoffman [1977]. It is assumed that leaching irrigation, if any, would be performed by applying water from source

1 (salinity level of 5 meq Cl/l). It is also assumed that all rainfall occurs during t=2 at a "moderate" amount of 2600 [m^3/ha].

Selected results are presented in Tables 3-5. Additionally, the shadow prices ($/ha) of the land area restrictions associated with plots A-E are, respectively, (2437, 1884, 1092, 1091, 1091), and the shadow prices ($/$m^3$) of the water supply restrictions associated with sources 1-3 are, respectively, (0.36, 0.27, 0.17) in t=1 and (0.18, 0.13, 0.06) in t=2. The results suggest that the three crops sensitive to salinity can be ranked according to their net profit/ha level and the shadow prices of the yield-loss balance equations as follows: potatoes, grapefruits and carrots, in order of decreasing profitability. This ranking clarifies the priorities with respect to the allocation of limited resources (water and land) to these crops.

All high quality water from source 1 was allocated by the program to the most profitable crop -- potatoes. The remaining water needed for this crop was supplemented from source 2. The grapefruit grove should be irrigated according to the program mainly by water from source 2, while carrots, the least profitable out of the three, should be irrigated by water from source 3, utilizing, if possible, residual quantities from source 2.

The priorities in allocation of land are clear cut as well. Note that the grapefruit grove was restricted to 10 hectares on each of the five plots (varying by their salinity levels). Accordingly, land allocation was relevant only with respect to the field crops. The least saline plots (in terms of initial soil salinity) were allocated by the program to potatoes, namely 80 hectares from plots 1 and 2 and

20 hectares from plot 3. Carrots were planted on the residual of plots 3 and 4. The most saline plots were allocated by the program, as expected, to cotton. Cotton should be irrigated as well by the most saline water.

The results do not recommend leaching of the soil whatsoever. This is explained by the fact that the alternative cost of water suitable for leaching (source 1) is higher than its contribution to the reduction of soil salinity levels on the relevant plots. (For example: an empirical estimation of the linear relationships between soil salinities before and after leaching shows that one m^3 of leaching water from source 1 reduces the initial salinity of plot A by 0.0033 meq Cl/l. The contribution of applying this one m^3 of leaching water to potatoes (or grapefruits) associated with plot A equals (Table 4) 0.0033 x 11.04 = 0.036 dollars (or 0.0033 x 3.99 = 0.013 dollars) while its shadow price is much higher: 0.36 dollars).

The marginal rates of substitution between water from the various sources in different subseasons can be easily computed using the estimated shadow prices of the water supply restrictions and eq. (17).

THE LONG-RUN ANALYSIS

The LR model refers to the water-soil-crop-farm system over a sequence of several irrigation seasons and considers rainfall uncertainty which are assumed away in the SR model. Conceptually it is an extension of the two stage LP model under uncertainty (Dantzig and Madansky, 1961; El Agizy, 1967). The objective function is to maximize the present value of the expected net profits from the yields of crops over the time horizon subject to total water and land supplies, quotas for

potatoes and carrots and linear balance equations which describe ther evolvement of the (soil related) state variables over time.

Obviously, the optimal solution of each season of the LR model depends on all future parameters of the system representation. As we progress over the planning horizon, however, additional data and information become available and can be used to update the model's parameters. The revised parameters are then employed as a priori information for the next model's solution (typically an agricultural production system is relatively flexible and can accommodate itself to changing conditions at a relatively low cost). The main goal of the LR model, presented here, is to provide a framework for decision making in the short-run taking into account the future. Let us first present and discuss some of the underlying assumptions and data of the LR model:

The farm's planning horizon consists of 4 years with each subdivided into two subseasons. Rain occurs in the 2nd subseason (winter) only and is regarded as a single discrete random variable. Three winter-types -- "dry", "moderate", and "wet" -- with probabilities of 0.40, 0.33, 0.27 and rainfall levels (m^3/ha] of 1400, 2600 and 3300 respectively (based on 22 years' rainfall sample data) are assumed.

The quantities of irrigation water per hectare for each crop in the second subseason are dependent on the "winter type". The mixes of water from the various sources and the quantity of leaching water for each crop are predetermined. For each crop some different (10 for potatoes and carrots, 7 for grapefruit and 3 for cotton) "irrigation alternatives" -- different ways of mixing the irrigation water and different quantities (including zero) of leaching water -- are specified using the results

(Table 3) of the SR model. (In the SR model these quantities are determined endogenously.)

Initially (as in the SR model), only 5 soil plots are distinguished (Plot A-plot E), but from the end of year 1 (= beginning of year 2) and on, 11 soil plots are asumed (henceforth Plot I - Plot XI), each characterized by a given range of salt concentrations [(4-5), (5-7), ..., (23-26) meq Cl/l]. The salinity of each subrange represented by a unique number (a simple average of its bounds). Assume a specific crop which is irrigated by a given "irrigation alternative" and grown on a given plot, with known salinity level at the beginning of the growing season The salinity level of the plot at the end of the growing season is dependent on the "winter-type" rainfall level. As an example, consider potatoes which are sown on soil plot II (with salt concentration of 6 meq Cl/l) and irrigated by the 1st irrigation alternative. The salt concentration of this plot at the end of the growing season is included in the salinity range of soil plot IV if the winter is "Dry" (probability of 0.4), in that of soil plot III if the winter is "Moderate" (probability of 0.33), and in that of soil plot II if the winter is "Wet" (probability of 0.27). The expected area that will be transferred by one hectare of potatoes to soil plots IV, III and II are 0.4, 0.33, and 0.27 hectares respectively. The expected areas of the soil plots at the end of each year are the state variables of the LR model.

A segment of the LR planning matrix, considering potatoes which are irrigated by its 1st irrigation alternative and is sown on soil plot A (with salt concentration of 5 meq Cl/l) in year 1 (activity P_1) and on soil plot II (with salt concentration of 6 meq Cl/l) in years 2-4

(activities P_2-P_4) respectively) is presented in Table 6.

When the (finite) time horizon is very long, it is empirically justified to assume that the terminal values of the state variables -- the expected areas of the field plots at the end of the time horizon-- are zero. However, this is not the case under consideration. Hence, while applying the LR model, the terminal values of the model's state variables at the end of year 4, are approximated by following these stages: a) Running the model with zero terminal values ("Run-a"); b) updating the net profits of the 4th year's crops with terminal values, based on the shadow prices of the soil balance constraints at the beginning of year 2 and running the model again ("Run-b"); c) running sensitivity analyses with regard to the terminal values. As an example, consider activity P_4 of Table 6 and let λ_ℓ, $\ell = 1,\ldots,30$ be the sahdow price of the ℓ's constraint. The potatoes transfers expected areas of 0.27, 0.33, and 0.40 hectares to soil plots II, III and IV respectively at the end of year 4. Accordingly, $[0.27 \times \lambda_7 + 0.33 \times \lambda_8 + 0.40 \times \lambda_9]$ dollars have to be added to its expected net profits. (Since only 5 soil plots (Plot A - Plot E) are assumed in the beginning of year 1 (initial conditions), which are different in their salt concentrations from soil plots I-XI as defined in years 2-4, it is impossible to use their shadow prices for the updating process.) This addition can be interpreted as crediting P_4 with approximate expected future net income (adjusted for present value) over 3 more years. Following the above stages, the sensitivity of the optimal activities' level (especially in year 1) to changes in the terminal values was found to be relatively low. In the following, all the results presented are those of "Run-b".

As mentioned, the operative goal of the LR model is planning the short-run taking the future into account. The allocation of land and the allocation of water to the crops in the 1st year of the planning horizon are respectively presented, in parentheses, in the 2nd column of Table 3 and in Table 5. Additionally, the shadow prices ($/ha) of the land are restrictions (in the 1st year) associated with plots A-E are respectively (9620, 9040, 8370, 8090, 8090), and the shadow prices ($/$m^3$) of the water supply restrictions associated with sources 1-3 are respectively (0.42, 0.33, 0.19) in t=1 and (0.26, 0.14, 0.0) in t=2. The results shows that the SR model's priorities in allocating water and land to the sensitive crops (potatoes, grapefruits, carrots in a decreasing order) are preserved in the LR model too but are less clear-cut. For example: in the LR model high quality water from source 1 is allocated to carrots and 2.5 hectares of potatoes are grown on (the saline) soil plot D; while in the SR model all the water from source 1 were allocated to potatoes (the most profitable crop) and it was grown only in Plots A-C. The SR model's objective function is based solely on the immediate profits and the allocation of the limited resources depends heavily on the relative profitabilities. The LR model considers the effects of the short-run decisions on the succeeding years as well and, hence, the improtance of the immediate profits for the allocation process is decreased. Obviously the big differences between the shadow prices of the land area restrictions emerge from the fact that additional soil areas at the beginning of the time horizon will "serve" the farm a single year in the SR model and several years

in the LR model (7 years taking into account the terminal values). As in the SR model, the results suggest zero leaching of the soil.

It is expected a priori that the soil sainity at the end of year 1 as derived from the SR model, which ignores the (negative) effects of its terminal soil salinities' levels on the future, will be higher than that derived from the LR model. But the basis for such a comparison is not accurate. In the SR model a "Moderate" winter is assumed. In the LR model two additional "winter types" are added and the probability of the "Dry" winter (0.4) - which leads to higher soil salinity levels - is 1.48 times greater than the probability of the "Wet" winter (0.27). If, however, the total area (270 hectares) of the farm is subdivided into "non-saline soils" with salinity levels less than or equal to 16 meq Cl/l (Plots I-VII in the LR model), and "saline soils" with salinity levels greater than 16 meq Cl/l (Plots VIII-XI in the LR model), the following results at the end of year 1 are obtained:

	"Non-Saline Sols" (ha)	"Saline Soils" (ha)
The SR Model	150	120
The LR Model	168.5	101.5

Despite the offsetting effect caused by the relatively high probability of "Dry" winter, the expected results are obtained.

Other results of interest are:

	"Non-Saline Sols" (ha)	"Saline Soils" (ha)
Crop fields' area, end of year 1	120.4	99.6
Crop fields' area, end of year 4	122.7	97.3
Grapefruits' area, end of year 1	48.1	1.9
Grapefruits' area, end of year 4	48.3	1.7

The state variables' levels (the expected areas of the different soil plots for field crops and grapefruits) at the end of the time horizon are very similar to their levels at the end of year 1. The assumptions of static technology, constant relative prices and given cropping alternatives over the 4 years' time horizon are the main reasons that the fluctuations in the state variables' levels are relatively small.

SUMMARY

This paper presents deterministic short-run and stochastic long-run LP models for the analysis of the complex relationships involved in irrigation water of varying salinity concentrations and the optimization of their use within a framework of a single farm. The incorporation of economic physical and biological relationships in one endogenous system seems to be the main advantage of the short-run model. It leads to better understanding of the economic significance of the various parameters, the optimal solution values, the shadow prices and the

rates of substitution between the limited resources. The stochastic long-run model considers the effects of the short-run decisions on the stream of future profits and rainfall uncertainty which assumed away in the short-run model. On the other hand, some of the relationships involved (like irrigation-water mixing, soil salinity ranges, crop yields and net profits) are incorporated exogenously in the model. The SR model's results are utilized for the formulation of the various relevant irrigation water mixing alternatives of the LR model. In Practice, the values of the models' parameters are updated in each short run and new solutions are obtained by solving the SR model first and then the LR model.

The empirical application provides priorities in the allocation of water and soil plots to the farm's crops, empirical estimates of shadow prices of soil plots of varying salinity levels, empirical estimates of shadow prices of water from different sources and the rates of substitution between them.

Linear programming is a powerful approach to the study of irrigation with saline water within the framework of a complex system, such as a farm. It directly and sharply clarifies and estimates the relationships between the variables involved on the one hand and is an easily applicable approach with relatively low cost on the other hand.

Recently, considerable research dealing with the technical aspects of using the dilution process (mixing different kidns of water in a single water distribution system) within water distribution networks as a practical tool to control the quality of water for irrigation, has been pursued (e.g., Jury et al. (1980)). Accounting for technical and

hydrological restrictions is a subject which calls for an extension of the analysis here presented. Other directions into which the analysis might profitably be extended, include: incorporation of seasonal irrigation depth as an additional decision variable and soil moisture content as an additional state variable; incorporation of additional stochastic elements subject to uncertainty like evapotranspiration [Rhenals and Bras, 1981], biological and physical parameters, etc., and the analysis the value of additional information [Feinerman and Yaron, 1982].

Finally, inter-farm/regional and inter-regional analysis [Scherer, 1977] have to be performed (taking into account externalities created by use of saline water, equity and distributional considerations) in order to provide a sound basis for policy decisions. The models presented in this paper can serve as building block in such analysis.

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Figure Legends

Figure 1. The yield loss function.

TABLE 1. The Shadow Prices of the Limited Resources and Other Constraints in the SR Model.

Shadow Prices' Notations and Signs	Interpretation of Shadow Prices	Unit
$U_j^2(t) \geq 0$	Change in value of the objective function in response to the addition of one m^3 of water from source J in subseason t (Note: $U_j^1(t) = U_j^2(t) - P_j(t)$)	$\$/m^3$
$U_{ng}^3(t) \geq 0$	Change in value of the objective function in response to the addition of one m^3 of (optimally mixed) water to crop ng in subseason t	$\$/m^3$
$U_{ng}^4(t) \leq 0$	Change in value of the objective function in response to the addition of 35.5 kg Cl to the mixed water allocated to crop ng in subseason t	\$/(35.5 kg Cl)
$U_{ng}^7(t) \geq 0$	Change in value of the objective function in response to a downward change in the salinity of the soil solution of plot g with crop n at the end of subseason t by $1/X_{ng}$ concentration units	$\$/(\frac{\text{meq.Cl}}{\text{liter}})$
$U_{ng}^8 \geq 0$	Change in value of the objective function in response to the reduction in the physical loss in yield of crop ng by $1/X_{ng}$ percents	(\$/percent)

TABLE 2. Quantities of Irrigation Water and Yield Loss Function.

Crop	Irrigation Water [m^3/ha]		Parameters of Yield Loss Functions		
			Salinity Threshold	Linear Increasing Segment	
	t=1	t=2	(meq Cl/l)	Intercept	Slope
Potatoes	1500	4000	6.05	-14.34	2.37
Carrots	2100	3200	2.78	- 5.34	1.92
Grapefruits	6400	800	10.28	-18.61	1.81
Cotton	4000	1750	Non-Sensitive in the Relevant Range		

TABLE 3. Activity Levels at the Optimal Solution of the SR Model.

Soil Plots and Their Associated Crops	Area		Applied Irrigation Water: The Supplying Sources at t=1 (1)	(2)	(3)	The Supplying Sources at t=2 (1)	(2)	(3)	Quantity of Salts in the Mixed Water t=1	t=2	Salinity of the Mixed Water t=1	t=2	Leaching Water	Soil Salinity Con'c. After Leaching	End of t=1	End of t=2	Loss of Crop Yield	Loss of Net Income	Net Income
	(ha)		m^3/ha						10^3 x meq Cl/l		meq Cl/l		m^3/ha	meq Cl/l			%	%	$/ha
Plot A																			
Potatoes	40	(40)	1250	250	0	0	4000	0	875	4000	5.8	10	0	5	5.9	8	0.6	0.8	5130
Grapefruits	10	(10)	0	4750	1650	0	800	0	8872	800	13.9	10	0	5	16.2	9.6	0	0	3670
Plot B																			
Potatoes	40	(40)	1500	0	0	2500	1500	0	750	2750	5	6.9	0	10	9.3	6.6	6.1	8.7	4720
Grapefruits	10	(10)	0	6400	0	0	800	0	6400	800	10	10	0	10	13.1	8.1	0.2	0.4	3650
Plot C																			
Potatoes	20	(17.5)	0	1500	0	0	4000	0	1500	4000	10	10	0	15	14.8	9.8	17	24.3	3910
Carrots	20	(22.3)	0	1570	530	0	500	2700	2895	7250	13.8	22.7	0	15	16.3	17.0	25.8	32.9	2070
Grapefruits	10	(10)	0	6400	0	0	800	0	6400	800	10	10	0	15	14.2	8.7	4.2	7.7	3380
Plot D																			
Potatoes	0	(2.5)																	
Carrots	14.2	(3.7)	0	0	2100	0	0	3200	5250	8000	25	25	0	20	25.7	21.2	37.4	47.6	1610
Grapefruits	10	(10)	0	6400	0	0	800	0	6400	800	10	10	0	20	15.3	9.2	8.2	15	3120
Cotton	35.8	(44)	0	0	4000	0	0	1750									0	0	1820
Plot E																			
Grapefruits	10	(10)	0	6400	0	0	800	0	6400	800	10	10	0	25	16.3	9.7	11.9	21.8	2870
Cotton	50	(50)	0	0	4000	0	0	750									0	0	1820

( ) - Allocation of the soil plots in the 1st year of the LR model.

TABLE 4. Shadow Prices of Some Balance Restrictions of the SR Model.

Shadow Price Interpretation: Change in Value of the Objective Function in Response to...	Crops and Their Associated Plots The Balance Restriction	Potatoes on Plots A, B & C	Carrots on Plots C & D	Grapefruits on Plot A	Grapefruits on Plots B, C, D & E
...The addition of one m^3 of (optimally mixed) irrigation water to crop n* on soil plot g** (crop ng) in subseason t.	Irrig. Water Mixing				
	t = 1 ($/$m^3$)	0.44	0.34	0.34	0.37
	t = 2 ($/$m^3$)	0.23	0.19	0.20	0.34
...The addition of 35.5 kg Cl to the mixed water allocated to crop ng in subseason t.	Quantity of Salts in the Mixed Water				
	t = 1 ($/35.5 kg Cl)	-0.02	-0.006	-0.008	-0.01
	t = 2 ($/35.5 kg Cl)	-0.01	-0.005	-0.006	-0.009
...A downward change in the salinity of plot g with crop n at the end of t by $1/X_{ng}$*** concentration units.	Soil Salinity Equations ($/(meq Cl/l))				
	After Leaching	11.04	4.5	3.99	5.35
	End of t = 1	7.04	3.18	4.49	6.01
	End of t = 2	5.84	2.51	3.01	4.03
...The reduction in the physical yield loss of crop ng by $1/X_{ng}$ percent.	Yield Loss Function ($/Percent)	7.38	3.93	4.99	6.68

*The crop symbol n stands for one of the three crops (potatoes, carrots, grapefruits).

**The soil plot symbol g stands for one of the five plots (Plot A, ..., Plot E).

***X_{ng} is the number of hectares of crop ng.

TABLE 5. Allocation of Water from the Various Sources to Salinity-Sensitive Crops (percentage) in the SR Model.

Crop	t = 1				t = 2			
	Source 1	Source 2	Source 3	Total	Source 1	Source 2	Source 3	Total
Potatoes	73	27	0	100	25	75	0	100
	(61.3)	(38.7)	(0)	(100)	(23.3)	(76.7)	(0)	(100)
Grape-fruits Grove	0	95	5	100	0	100	0	100
	(0)	(96.3)	(3.7)	(100)	(0)	(95)	(5)	(100)
Carrots	0	44	56	100	0	9	91	100
	(14.8)	(61.8)	(23.4)	(100)	(1.9)	(15.4)	(82.7)	(100)

( ) -- Allocation of water in the 1st year of the LR model.

TABLE 6. A segment of the LR Planning Matrix, Considering Potatoes Which are Irrigated by its First Irrigation Alternative and Grown on Plot A* in Year 1 (P_1) and on Plot II** in Years 2-4 (P_2-P_4 respectively).

Restrictions' Description		Restrictions' Units and Levels	Activities Ordinal No.	P_1	P_2	P_3	P_4
Year 1							
	Soil Plot A	(ha) 50≥	1	1			
t=1	Water Source 1	(m^3)100000≥	2	500			
	Water Source 2	" 350000≥	3	1000			
t=2	Water Source 1	" 110000≥	4	420			
	Water Source 2	" 375000≥	5	3690			
	Annual Quota	(ha) 100≥	6	1			
Year 2							
	Balance of Plot II (Field Crops)	(ha) 0 ≥	7	-0.27	1		
	Balance of Plot III (Field Crops)	" 0 ≥	8	-0.33			
	Balance of Plot IV (Field Crops)	" 0 ≥	9	-0.40			
t=1	Water Source 1	(m^3)100000≥	10		500		
	Water Source 2	" 400000≥	11		1000		
t=2	Water Source 1	" 100000≥	12		420		
	Water Source 2	" 400000≥	13		3690		
	Annual Quota	(ha) 100≥	14		1		
Year 3							
	Balance of Plot II (Field Crops)	(ha) 0 ≥	15		-0.27	1	
	Balance of Plot III (Field Crops)	" 0 ≥	16		-0.33		
	Balance of Plot IV (Field Crops)	" 0 ≥	17		-0.40		
t=1	Water Source 1	(m^3)100000≥	18			500	
	Water Source 2	" 400000≥	19			1000	
t=2	Water Source 1	" 100000≥	20			420	
	Water Source 2	" 400000≥	21			3690	
	Annual Quota	(ha) 100≥	22			1	
Year 4							
	Balance of Plot II (Field Crops)	(ha) 0 ≥	23			-0.27	1
	Balance of Plot III (Field Crops)	" 0 ≥	24			-0.33	
	Balance of Plot IV (Field Crops)	" 0 ≥	25			-0.40	
t=1	Water Source 1	(m^3)100000≥	26				500
	Water Source 2	" 400000≥	27				1000
	Water Source 1	" 100000≥	28				420
	Water Source 2	" 400000≥	29				3690
	Annual Quota	(ha) 100≥	30				1

*Soil salinity level of 5 meq Cl/l.
**Soil salinity level of 6 meq Cl/l.

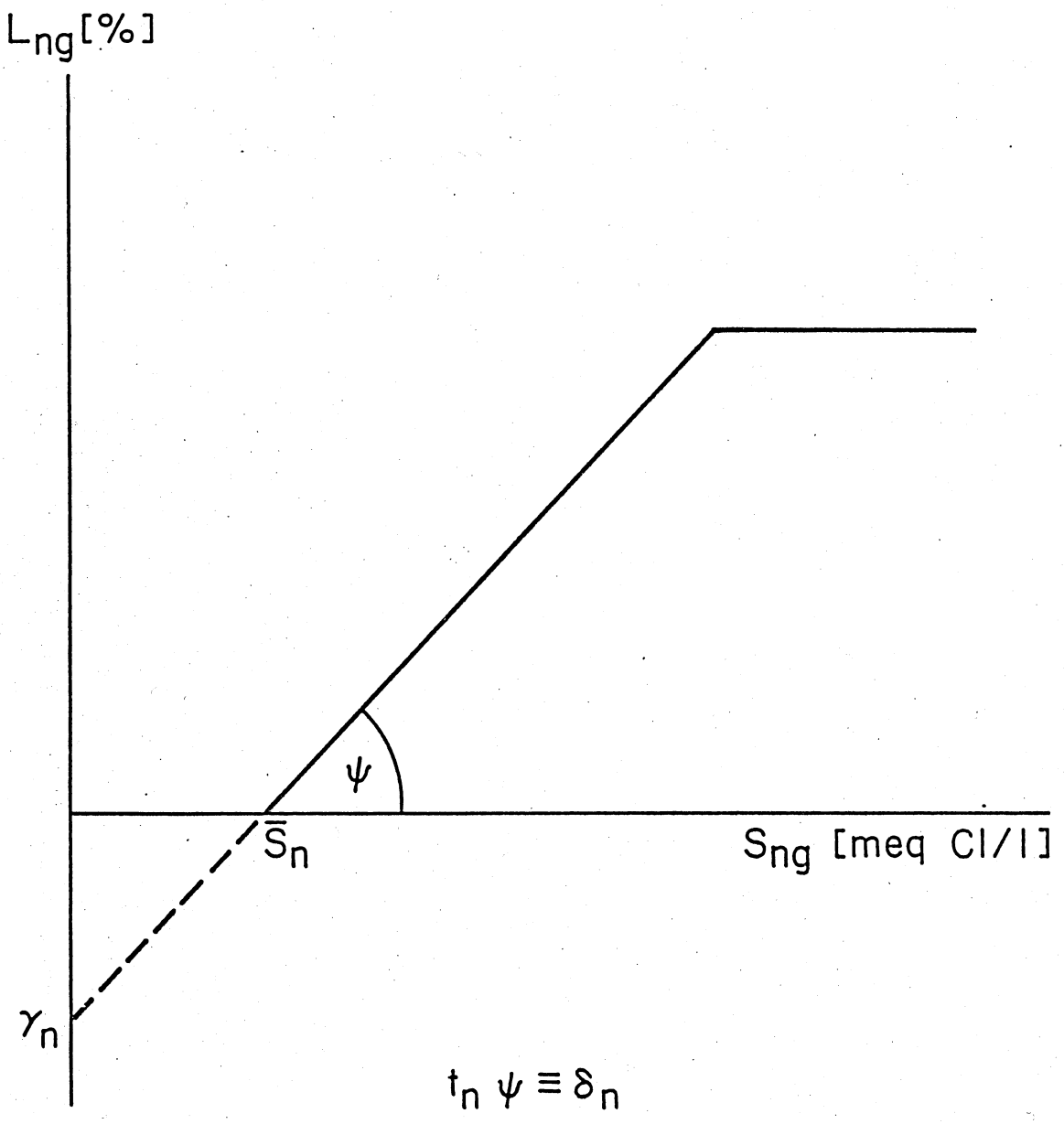

Figure 1. The yield loss function.

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