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A Model to Predict the Effect of Salinity on Crop Growth

Stuart W. Childs

A MODEL TO PREDICT THE EFFECT OF SALINITY ON CROP GROWTH

by

Stuart W. Childs

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Stuart W. Childs

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ABSTRACT

A Model to Predict the Effect of

Salinity on Crop Growth

by

Stuart W. Childs, Master of Science

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Major Professor: Dr. R. J. Hanks
Department: Soil Science and Biometeorology

A model is developed to predict the effects of soil salinity on crop growth. As an outgrowth and extension of the modelling efforts of Nimah and Hanks (1973a) and Gupta (1972), this model makes these principal assumptions in order to arrive at a quantitative relationship: 1) Relative yield for a growing season is directly related to the ratio of actual and potential transpiration. 2) Water uptake by plants is in response to the water potential gradient between the plant at the soil surface and the soil surrounding the plant roots. 3) The effect of salinity on crop growth is solely due to the effect of osmotic potential in decreasing the water potential gradient. In addition, minor assumptions are made regarding plant cover growth, plant root growth, and the separation of E and T from ET.

The model was tested to assess its accuracy and was then used to make calculations regarding the relationships of plant growth, irrigation amount and water quality, initial soil salinity, and crop type. Due to the presence of a water table at two meters in the simulations, deep rooted crops showed the best growth under most conditions. Decreases in

irrigation and increases in soil salinity were detrimental to crop growth. Irrigation water quality was not effective in decreasing crop growth in one season but was shown to be a factor in long term calculations. Simulations of ten-year management schemes are shown in order to demonstrate long term effects. Finally, a method is presented to evaluate different irrigation systems and calculations are made which compare a flood irrigation system and a sprinkler system.

(108 pages)

INTRODUCTION

In recent years increasing importance has been placed on the development of agricultural production capacity. Developments involve either increasing the amount of land in use or increasing production on lands already used. These solutions may be implemented with improved crop varieties, farming techniques, or land management schemes. In the arid western United States, where irrigated agriculture is the largest consumer of public water supplies (Nimah, 1972), attention is often focused on water use and the technology of irrigated agriculture. For the western United States, the major planning consideration for agriculture has traditionally been the stimulation of crop yields in the face of limitations of water and potentially harmful salinity conditions. As a result of increased public awareness of and concern over environmental quality, other aspects of land management planning have become important. Agricultural technology and particularly irrigation technology is aimed towards increasing control of the soil-plant system to avoid waste of water and environmental degradation while maximizing crop production. In 1970, a project was initiated in Vernal, Utah, to develop techniques to predict and control irrigation return flow. The results of this study stimulated enough interest to justify a project designed to perform an economic analysis of land management factors. To facilitate the evaluation, a quantitative assessment of various soil-plant factors is required. This research project was initiated in order to fulfill this need.

The general objective of the project is to develop predictions of crop yield and irrigation return flow under various management options available to the farm operator. A computer technique seems warranted because of the number of potentially important variables. In addition to the computations required to obtain quantitative predictions, theoretical relationships between system parameters must be established or assumed. The major assumptions needed are:

1. The relationship between plant water use and crop growth.
2. The relationship between soil water status and water uptake.
3. A mechanism for plant water uptake.

Objectives

This research is intended to fulfill the following objectives:

1. Develop a model to predict the effects of salinity and irrigation practices on crop growth.
2. Test the assumptions of the resultant model regarding the relationships between salinity and crop growth.
3. Make predictions using the model for a variety of plausible field situations.
4. Analyze predictions to determine whether practical, quantitative relationships can be inferred which will be of use in irrigation and crop planning.

LITERATURE REVIEW

Two bodies of literature are pertinent to this project: that concerning the development of models to predict salt and water movements in soils and that concerning the experimental and theoretical relationships of salinity, soil water, and plant growth. While the latter topic is integral to the former, they may be separated in that modelling implies an application of theoretically or experimentally derived concepts.

Crop growth and salinity

Since the relationship between crop growth and salinity is generally known to be complex, an empirical approach is often used to quantify the relationship (Bernstein, 1964). This approach is the measurement of salt tolerance for various crops through field or laboratory experiments. The resultant data may be shown as a graph of relative yield versus average electrical conductivity of the soil extract. These data are difficult to use with confidence because many of the factors contributing to plant salt tolerance are either not specified or are arbitrarily set. Since plant responses to soil salinity are affected by environmental demand, basic soil properties, available soil water, the distribution of salt in the soil profile, and plant characteristics, salt tolerance information can be regarded only as a generalized estimate. Furthermore, since much research has been done concerning various aspects of the salinity-crop growth problem, an approach which treats the effects of specific factors can be readily used with less recourse to general assumptions.

Relationship of plant water use and transpiration. A basic premise for much of the work in this area is embodied in papers by deWit (1958) and Arkley (1963). They presented statistical treatments of data from several world locations to document the linear relationship between transpiration (T) and yield (Y). Shalhevet and Bernstein (1968) presented data to show that, although both T and Y change substantially under different salinity regimes their ratio is nearly constant. The data presented in these three papers suggest that good yield estimates can be made knowing T once a relationship between potential transpiration (Tp) and maximum yield (Ym) is known for a specific location.

The work of Lagerwerff and Eagle (1961) is an exception to this hypothesis. Their experiments growing beans in saline media showed that water use efficiency increased with increasing salinity. In other words, under saline conditions, the ratio of T/Tp may not be a good indicator of relative yield. It is unfortunate that the authors did not provide enough of their basic data to afford a test of this hypothesis.

Relationship of soil water potential to transpiration. Denmead and Shaw (1962) provided evidence that plant transpiration was decreased under conditions of low soil water potential. The amount of reduction in T was dependent upon both the magnitude of Tp and soil water conditions. Lagerwerff and Eagle (1961) presented data to show that, at root medium potentials of three bars or less, Tp was the single important factor.

The effect of osmotic potential on transpiration has been studied extensively under greenhouse conditions in order to relate soil salinity and plant water use. Early work by Eaton (1941) involved salinization of one half of a plant root zone in order to measure differential water

uptake and root growth. As expected, water uptake was greater for roots in the non-saline medium. Root growth was also greater in this zone. In addition to these findings, Eaton also postulated that the primary effect of salt on transpiration was through its contribution of osmotic potential to the total soil water potential. By performing the necessary calculations for a mean plant water potential, he also implied that differential water absorption by roots subject to different soil salinities could be predicted from a calculation of the water potential gradient between the plant and each zone of the soil.

Wadleigh et al. (1947) performed experiments which indicated that the presence of salt in the soil water made water less available for transpiration and also hindered root penetration. Because their data showed differential water uptake, the authors concluded that zonal salt storage would be a useful soil management technique.

In a treatment of physiological aspects of salt tolerance, Bernstein and Hayward (1958) divided the effects of salinity on crop growth into osmotic effects and the specific ion effects of toxicity and nutritional imbalance. He cited similar growth retarding effects for isosmotic concentrations of various salts as evidence that decreased water availability to plants in saline soils is primarily due to low osmotic potentials in the soil. In 1961, Bernstein strengthened this view by reporting measurements showing osmotic adjustments by plants in order to create a favorable water potential gradient for plant water extraction. He also cautioned, however, that water uptake may be affected by salinity in two other ways (1958):

1. Decrease in transpirational demand due to decreased leaf area of salt-affected plants.

2. Decreased root growth as noted by Eaton (1941) and Wadleigh et al. (1947).

Zonal management of salt in the soil profile. While the literature relating plant physiology and salt tolerance has generally been directed towards the study of plant mechanisms that cope with salinity conditions, there have been several attempts to measure plant responses to soil salinity conditions which are variable through the root zone. Shalhevet and Bernstein (1968) performed long term growth experiments with divided root zones and different soil salinity levels. Their results showed that the resultant differential water absorption from portions of the root zone could be explained fairly accurately by the smaller water potential gradient between plants and saline substrates. They found, though, that water absorption from a zone never ceased, even under highly saline conditions where water was more readily available from another depth zone. This result showed that the process of water uptake is more complicated than the simple theory of water uptake solely in response to water potetial gradients. A final conclusion of this research was that total water uptake correlated well with average soil salinity.

Other studies (Lunin and Gallatin, 1965; Bingham and Garber, 1970), have shown that water uptake is proportional to the largest water potential gradient present and, therefore, correlates with minimum salinity. It should be noted that the three papers mentioned above worked with osmotic potential limitations to water uptake. Differences in matric potential in the various treatments were minimized by maintaining high water contents in all layers.

A final significant conclusion reached both by Lunin and Gallatin (1965) and Shalhevet and Bernstein (1968) was that water use efficiency

did not change with soil salinity under zonal management. It should be noted that this conclusion is not in conflict with the findings of Lagerwerff and Eagle (1961). The findings of these latter authors relate to plants grown in substrates of uniform salinity and, therefore, did not have the non-saline water source which was available in the two zonal salinity studies.

Irrigation management studies. Since irrigation frequency and amount are relatively easy to control, considerable research has been done in order to quantify the effects of leaching fraction and irrigation water quality on plant growth (Allison, 1964; Bower et al., 1969). Bower et al. show the effects of irrigation amount and quality on crop growth through an easily measureable quantity: average electrical conductivity of the soil. Although they also collected data showing the establishment of steady state salt profiles, little use was made of this detailed information. Bernstein and Francois (1973) performed the same kind of experiment in a much more exhaustive manner. Their data show that very small leaching fractions, if obtainable, are adequate to ensure maximum crop growth. Storage of salt in the lower portion of the root zone has only small effects on crop growth while increased salinity in the upper portion will be more important.

Simulation modelling

Modelling will be treated here in two phases: root extraction models and salt flow models. Water flow modelling will be discussed only in relation to root extraction.

Root extraction models. Plant water use modelling efforts can be separated into two broad approaches: macroscopic and microscopic. The

microscopic approach involves the calculation of water uptake for a single root. Total plant transpiration is then obtained by multiplying the single root result by an appropriate root density. Examples of this approach are the works of Gardner (1960) and Molz et al. (1968). Both involve solutions of partial differential equations in cylindrical coordinates and require a detailed knowledge of root diameters, resistance, spatial distribution, and volume of effective water absorption. The difficulties associated with this approach has resulted in a change of emphasis from microscopic to macroscopic work.

The macroscopic approach to root water extraction considers various depth zones for roots and extracts water from these zones according to an established scheme. In accordance with early work on salinity-transpiration relations (Eaton, 1941; Bernstein and Hayward, 1958), many models base root extraction on water potential gradients between plant and soil. Gardner (1960) has outlined the theory of root extraction using the following equation:

$$W = \frac{(\delta - \sigma)}{Ip + Is} \qquad (1)$$

where:

W = water uptake as vol./time/vol.soil

δ = plant water potential

σ = soil matric potential

Ip = Plant flow resistance

Is = Soil flow resistance

A more general treatment would replace matric potential (σ) with total soil water potential in order to include the effects of the osmotic and gravitational potentials (Gardner, 1964). Gardner (1960) next assumed soil resistance (Is) to be proportional to the reciprocal of the soil water conductivity times a root density function. With the addition of measurements to show that plant flow resistance (Ip) is negligible under most

circumstances (Gardner and Ehlig, 1962), a water extraction model can be presented:

$$W = (\delta - \psi_t) * K(z) * R(z) * h * B \quad (2)$$

where all previously defined symbols are the same and:

ψ_t = Total soil water potential

K(z) = Hydraulic conductivity at depth z

R(z) = Root density function at depth z

h = thickness of soil layer

B = Proportionality constant

* = Denotes multiplication

For total transpiration:

$$q = \sum_{i=1}^{n} W_i = h * B \sum_{i=1}^{n} (\delta - \psi_t) * K(z_i) * R(z_i) \quad (3)$$

where: q = total transpiration

Gardner (1964) used this equation to calculate water uptake with reasonable success. He assumed that, below field capacity, soil water flow was negligible. Whisler, Klute, and Millington (1968) used Gardner's extraction term with the unsaturated flow equation to predict water movement for their laboratory experiments.

Another approach to root extraction modelling on the macroscopic scale has been used by Dutt, Shaffer and Moore (1972) and Molz and Remson (1970, 1971). Their approach is to compute root extraction by depth without regard to soil water conditions. The root extraction is based solely on transpiration and root distribution. Molz and Remson (1970) assumed a root distribution for the four quarters of the root zone (40%, 30%, 20%, 10%) and were able to calculate water uptake for laboratory data with moderate accuracy.

A final approach which has been used is that of Nimah and Hanks (1973a). Their approach involves modification of Gardner's (1964) extraction term coupled with the unsaturated flow equation. Their modification is the addition of a plant flow resistance term as well as a different approach to solution of the term. The solution procedure is to pick a plant water potential and calculate transpiration using eq. (3). If transpiration is less than Tp, a lower value for plant water potential is tried. Thus, the water potential gradient is adjusted to meet Tp. Specification of a minimum plant water potential forces T to be less than Tp under conditions of low soil water potential. This minimum value corresponds to the concept of plant wilting point. When Tp cannot be met, damage is done to the plant and a reduction in yield occurs.

The difference between this approach and that of Gardner is that Gardner requires that T be known and cancels the plant water potential term out of his solution. Nimah and Hanks require Tp as input and solve by trial and error for both transpiration and plant water potential.

While each root extraction model discussed has its own particular strength, the common weakness of all is the need for root distribution (1972) have presented data to show that water absorption from the soil does not correlate well with root distribution. Because "effective" root distributions are difficult to measure and have not been adequately related to measureable quantities such as root weight, volume, or length; root extraction models are only approximate predictive tools.

Salt flow modelling. In the past, two major approaches to salt flow modelling have been used: rate theory and plate theory. Rate theories

involve the solution of equations in which rate of movement of solute is of primary concern and is specified. In plate theory, the fundamental concern is with the establishment of thin, homogeneous plates of soil which are assumed to be in equilibrium at any time. Gupta (1972) and Frissel and Poelstra (1967) provide excellent reviews of literature and comparisons of these approaches.

Most recent work has been done with either plate theory or a combination of rate and plate theories. Three important approaches will be discussed here. First, Terkeltoub and Babcock (1971), primarily interested in the calculation of leaching requirements, have presented a plate model which involves salt movement through mass flow alone. Salt is treated as a bulk constituent and precipitation and dissolution are not considered. Their procedure is to add enough water to saturate the first plate and then bring it into equilibrium with the second plate. The second is equilibrated with the third, the third with the fourth and so forth until the bottom of the profile is reached. Another increment of water is added at the surface and the entire procedure is repeated until a specified irrigation has been applied. The authors have shown that adequate results can be obtained with this technique and also found that their calculations were relatively insensitive to plate size change.

Dutt, Shaffer, and Moore (1972) used a model with more sophistication to achieve comparable accuracy. Their technique involves the treatment of salt movement as a mass flow process based on the water flow calculations from an accompanying water flow model. While their results were fairly accurate, they showed an effect of unknown dispersion even in the absence of diffusion and hydrodynamic dispersion in the solution equations. This may be due to a departure from actual plate theory.

The theory requires that plate size be determined so that the interval is homogeneous and in mutual equilibrium throughout its entire volume (Frissel and Poelstra, 1967). The use of fixed and equal plate heights coupled with the finite difference solution of this model may be the source of the unknown dispersion.

Perhaps the most significant assets of Dutt's model (Dutt, Shaffer, and Moore, 1972) are the treatment of individual cations and anions and the calculation of equilibrium between the soil solution and the soil. The model treats NaCl, $CaCo_3$, $MgSO_4$, and associated salts, ions, and ion pairs. The addition of dissolution and precipitation of constituents allows a calculation of equilibrium for each plate. The solution of a complicated set of simultaneous differential equations is performed in iterative fashion for each plate.

A final approach is that of Bresler and Hanks (1969), Bresler (1973), and Gupta (1972). Bresler and Hanks (1969) modelled the flow of total salt by assuming salt flow to be a combination of mass flow and diffusion, but allowing no dissolution or precipitation. Laboratory experimental data has been modelled successfully but there was some numerical dispersion present. Gupta (1972) combined the model of Dutt, Shaffer and Moore (1972) with Bresler and Hanks (1969). The resultant model gave acceptable results for laboratory experiments but was not accurate in the simulation of field experiments. Bresler (1973), still working with total salt flow without precipitation and dissolution, updated his previous work with the addition of a hydrodynamic dispersion term. To alleviate the problem of numerical dispersion, he used second order finite difference approximations for first derivatives and third order approximations for second

derivatives in his solution equation. These modifications have improved his calculations enough to be close to the accuracy of his diffusion and dispersion coefficients.

DEVELOPMENT OF THE MODEL

General approach and assumptions

This model is a modification of the soil water flow and root extraction model of Nimah and Hanks (1973a). Unsaturated water flow is calculated from a finite difference solution to the following equation:

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\Theta)\frac{H}{z}\right) + A(z) \qquad (4)$$

where: $K(\Theta)$ = Hydraulic conductivity

H = Hydraulic potential

z = Depth

t = Time

Θ = Water content by volume

$A(z)$ = Root extraction term

Use of the above equation implies the following assumptions:

1. Since the equation is one dimensional, vertical water flow is assumed to be of dominant importance.

2. The soil is homogeneous, isothermal, and has basic properties which are constant with time.

3. Hysteresis of soil properties can be neglected.

The root extraction scheme, as discussed previously is:

$$A(z) = \frac{(Hroot - Rres*z - h - s)*K(z)*RDF(z)}{x * z}$$

where: Hroot = Plant water potential at the soil surface

Rres = Root resistance term

RDF(z) = Root density function by depth

x = Distance of effective root water extraction

h = Soil matric potential

z = Size of depth increment

s = Soil osmotic potential

The modifications to this basic model are:

1. The salt flow approach of Bresler (1973) has been modified for use in this program. The principal modification is the allowance for unequal plate heights in the soil. This technique has been selected instead of the single ion approach for two reasons: 1) Detailed information on salt concentrations is not being considered here. The salt flow portion of the program is used in the calculation of osmotic potentials in each depth zone while toxicity due to specific ion concentrations is not considered, and 2) The work of Gupta (1972) showed that the single ion approach did not yield accurate results for the field area considered in this work. Furthermore, adequate results have been obtained with Bresler's total salt model.

2. The static root density assumption has been modified to allow for simulation of root growth.

3. Some improvement has been made in the separation of Ep and Tp from ETp for surface flux conditions. The assumption is made that crop cover can be used as a measure of the ratio of Tp to ETp.

4. Provision has been made for the calculation of realistic hourly ETp values from field measurements taken over longer periods of time. It is assumed that ETp rates vary sinusoidally during daylight hours and are zero at night.

5. Assumptions have been made to allow the prediction of yield to be made from output concerning potential and actual transpiration.

6. The effect of salinity on crop growth is assumed to be solely the result of decreased water availability due to the lower osmotic potentials in saline soils.

Modification of the Nimah and Hanks (1973a) model

Water flow. This portion of the program has been modified by the addition of a calculation of osmotic potential. The calculation is made from salt flow calculations for each depth. Salt flow output in millequivalents/liter is converted to osmotic potential (in centimeters of water) by the following equation:

$$S(z) = SE(z)/10. *0.36 * 1030 \quad (6)$$

where: SE(z) = Salt concentration in meq./l.

Conversion from concentration to electrical conductivity in millimhos is accomplished by division by 10 (U.S.D.A. 1954). The range of validity for this conversion is from 0.1 to 5.0 mmho. Multiplication of mmhos by 0.36 gives an osmotic potential in atmospheres (U.S.D.A., 1954). The range of validity for this conversion is 3 - 30 mmhos, essentially the range of conductivities in which plant growth occurs. Multiplication by 1030 gives a value for osmotic potential in centimeters of water. The limitation in this calculation is in the conversion from concentration to electrical conductivity. Above 5 mmho the conductivity is overestimated by the above procedure.

Salt flow. The calculation of salt flow involves the solution of the following equation (Bresler, 1973):

$$\frac{\partial}{\partial t}(C) = \frac{\partial}{\partial z}\left(D(\theta,V)\frac{\partial C}{\partial z} - qC\right) \quad (7)$$

where: C = concentration in meq/l.

θ = Water content cm^3/cm^3

q = Flow rate cm/hr.

$$D(\theta,V) = D_0 * a * e^{b\theta} + D_k(V) \quad (8)$$

where: V = Average flow velocity

D_0 = Diffusion coefficient in pure water

a, b = constants

D_k = Hydrodynamic dispersion coefficient

$= \lambda|V|$

λ = Constant

The equation is solved for all depths using a Crank-Nicolson solution. The finite differencing technique has been expanded to alleviate the problem of numerical dispersion. This is accomplished through the use of second order differences to approximate first derivatives and third order differences to approximate second order derivatives. This procedure is fully described by Bresler (1973). The only departures from his work are the inclusion of unequal depth increments and the use of mass flow alone between the soil surface and the first depth zone.

Root distribution. Although a static root density function was found to be adequate for established perennial crops like alfalfa (Nimah and Hanks, 1973b), a root growth calculation was introduced to allow the simulation of annual crop growth. In the absence of adequate data on effective root density, a root distribution calculation was performed which scaled the mature root distribution to various soil depths according to time in the growing season. A graph of root zone depth versus time

was assumed to describe a sigmoid curve with no roots at the time of planting and no change in root depth after the time of root profile maturity. The equation for calculation of root depth versus time is:

$$droot = DD(kk)/(1.0+\exp(6.0-12.0*\frac{Time}{Rdfday})) \quad (9)$$

where: droot = depth of rooting in cm

Time = Time in days

DD(kk) = Depth of root zone at maturity

Rdfday = Number of days to root profile maturity

It can be seen that, when Time equals 0, droot equals $DD(kk)/-(1.+e^{+6})$, essentially zero. At Time equals Rdfday, the time to root profile maturity, droot equals $DD(kk)/(1.+e^{-6})$, essentially DD(kk). The distribution of roots for any value of droot is an algebraic scaling of the mature root density profile to fit a smaller depth.

Separation of potential evaporation (Ep) and potential transpiration (Tp) from potential evapotranspiration (ETp). Since the environmental evapotranspiration demand on the plant and soil system can be satisfied either by E or T, a separation of potential rates for these two components is necessary. This was performed for this study by assuming that the ratio Tp/ETp was equal to the per cent crop cover at any time. Because adequate detailed information was not available, the following computational scheme was adopted:

1. Three input parameters were required: time from planting to seedling emergence, time from planting to crop cover maturity, and per cent crop cover at maturity.

2. From the time of planting to the time of seedling emergence, Ep = ETp.

3. From seedling emergence until the time of crop cover maturity, crop cover growth versus time was assumed to be described by a sigmoid curve. Ep and Tp were separated in the following manner:

$$Tp = ETp*\left(\frac{Cover}{1.+\exp\left(6.-\frac{(Time-Estart)*12.}{(Estop-Estart)}\right)}\right) \quad (10)$$

where: Estop = Time in days from planting to crop cover maturity

Estart = Time in days from planting to seedling emergence

Cover = Per cent crop cover at maturity as a fraction.

When time equals Estart, Tp equals 0 as required. At Time equals Estop, Tp = ETp*Cover. Ep is always calculated as the difference between ETp and Tp.

4. After the time of crop cover maturity (Estop), the ratio of Ep to Tp is constant.

5. An additional provision was made for the phenomenon of increased transpiration when E does not reach Ep due to soil moisture constraints (Hanks et al., 1971). In this event, Tp is increased to either the limit of plant transpiration or the quantity (ETp-E), whichever is smaller. The limit of plant transpiration is calculated in the same manner as Tp in equation (10) by replacing Cover with an input quantity related to the magnitude of additional transpiration allowed.

Calculation of hourly Ep and Tp rates. Since ETp data are often collected on a daily or bi-daily basis, a calculation was required to convert these long term rates into realistic hourly values. The calculation of rates for shorter time periods is necessary to simulate the high demands which occur at midday and the near zero demands at night. In order to calculate the proper fluxes for any time step size, the following technique was used:

1. It was assumed that zero time was 8 a.m.

2. The pattern of water use was distributed by assuming that daily rates varies sinusoidally with time. Daytime rates (8 a.m. to 8 p.m.) were described as the positive portion of a sine wave while nighttime rates were set equal to zero.

3. For a given day, total water use was set equal to the area under the sine curve. With this relationship established, rates for any time step were calculated by integrating the sine curve between the beginning and end of the time step and dividing by the time step:

$$ETp = \frac{\cos(Timed*6.2832) - \cos(Timea*6.2832)}{-2.0} \frac{*Watuse}{(Timed-Timea)} \quad (11)$$

where: Timed = Fraction of a day at the end of time step

Timea = Fraction of a day at beginning of time step

Watuse = Total water use for the day

4. This pattern of surface flux calculation set the maximum time step as 12 hours. This step size is seldom reached, however, because the water flow model keeps the step size smaller by setting a maximum allowable water content change per time step.

Estimation of crop growth. The approach used in this model for the calculation of crop yields is based on the assumed equivalence of relative yield and the transpiration ratio: Y/Ymax = T/Tp. This assumption is discussed in detail by Hanks (1974).

Once this relationship is assumed, crop yields can be calculated if a maximum yield value is available.

Effect of soil salinity on crop growth. Salinity is related to crop growth through its effect on transpiration. As described previously, the calculation of osmotic potential in the root extraction term provides

an input of salt concentration to the transpiration process. It is assumed that, for any practical salt management schemes, this influence of salinity is of primary importance. Effects of toxicity and nutritional imbalance are ignored.

TESTING THE MODEL

Testing of the model was accomplished by a series of checks against existing field data pertaining to various assumptions in the model. Because of the large amount of detailed field data required to test the model as a whole, a total test could not be performed. The check tests performed were:

1. Relationship of T/Tp to Y/Ymax.
2. Relationship of soil salinity to water uptake.
3. Solute flow.
4. Soil Water flow.
5. Root Extraction

Relationship of transpiration to yield. Data are available in the literature to verify that transpiration provides a useful and accurate measure of yield. Figure 1 is a plot of yield versus transpiration after Arkley (1963). An excellent linear relationship is shown for barley varieties grown in Colorado. Evidence of this type has made this relationship a generally accepted fact. Figure 2 shows a more important relationship for the purposes of this project. It shows similar results for experiments performed with zonal salt treatments in the soil. The experimental data shown are all from greenhouse studies of differential water uptake by corn and alfalfa due to osmotic potential differences in the root zone. The data plotted were derived from the basic data in the literature by setting the highest recorded yield equal to Ymax. Its

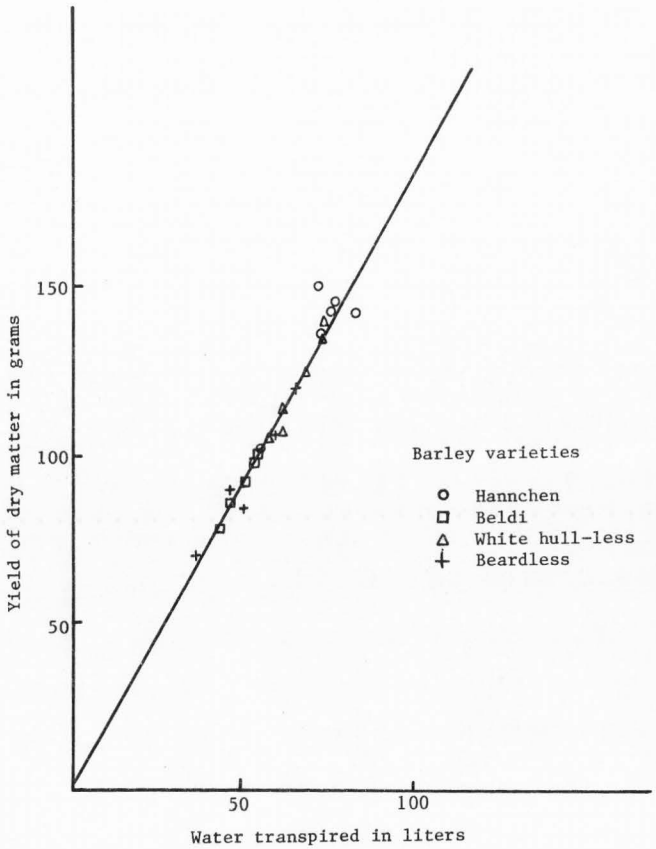


Figure 1: Dry matter yield versus water transpired for barley. From Arkley (1963).

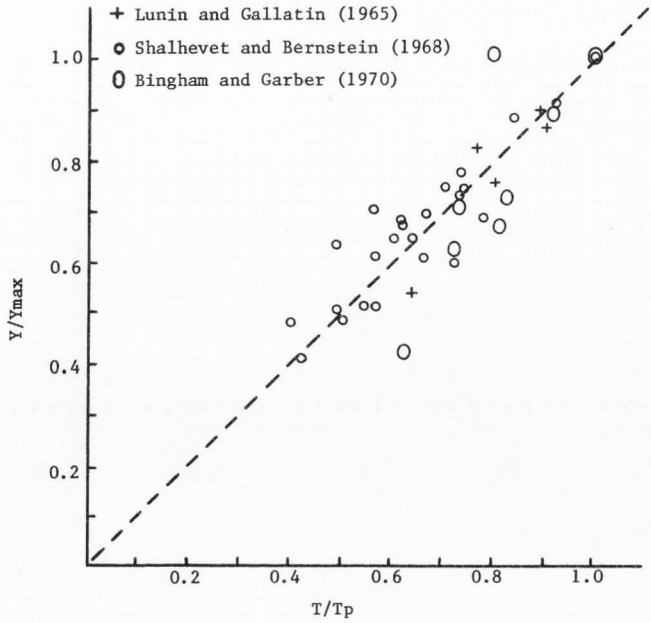


Figure 2: Relative yield versus transpiration ratio under saline conditions. Results of three experiments.

accompanying water use figure was assumed to be Tp. The remaining treatments in each experiment were used to calculate the ratios Y/Ymax and T/Tp. The data clearly show that T/Tp is a valuable indicator of relative dry matter crop yield.

Another facet of the relationship between T and Y, mentioned earlier, is the relationship between the magnitude of Tp and the ability of the soil plant system to meet the demand. Denmead and Shaw (1962) gave examples of this relationship by plotting transpiration versus soil water content for various Tp values. The same trends can be shown using the predictions of this model, as in Figure 3. The transpiration rates used here are actual measured values for various climatic conditions at Vernal, Utah. These data were used as a basis for the crop growth predictions which follow. The curves shown were constructed from two day simulations of transpiration from oats at four Tp values and various water contents. As discussed earlier, hourly rates changed throughout the day and were zero at night. Several facets of the predicted transpirational patterns are of interest. First, it can be seen that higher transpiration rates require higher soil water contents if they are to be met. The relationship is clear between the growth limiting effects of soil water availability and environmental demand. Availability of water depends both upon the supply of water and the amount needed. If Tp is low enough, it can be met until the soil is dry almost to the wilting point of the plant.

Another point of interest is the shape of the transpiration curves after they fall below Tp. The curves roughly outline a linear decrease in Transpiration with decreasing water content. As Denmead and Shaw show

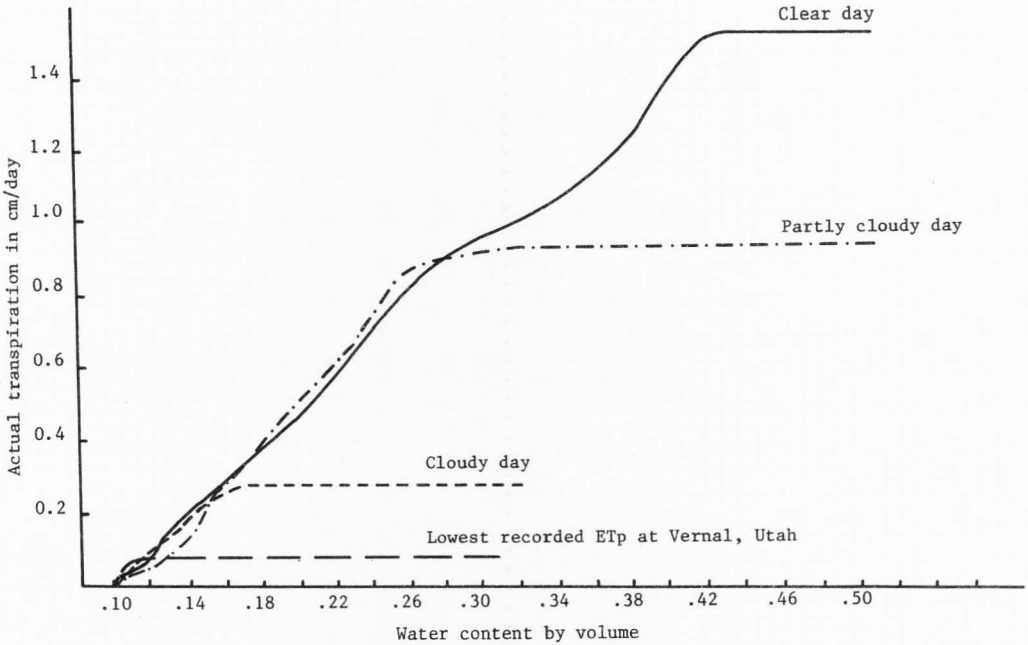


Figure 3: Prediction of actual transpiration versus soil water content at several potential transpiration rates at Vernal, Utah.

in their data, a lower Tp rate performs slightly better than higher rates when T does not equal Tp. This may be due in part to the fact that evaporational demand is less for lower Tp rates. Another contributing factor is the ability of the soil profile to redistribute water to meet requirements when extraction occurs at a lower rate.

In all, the results shown here are encouraging because they show the same trends as data available in the literature and, therefore, on a general level, validate the calculations of the root extraction term.

Relationship of soil salinity to water uptake. Two greenhouse experiments (Lunin and Gallatin, 1964; Bingham and Garber, 1970) involving transpiration from soils with zonal salinity treatments were simulated to test the accuracy of the model in predicting differential water uptake. The assumptions and data inputs required for the testing procedures were as follows:

1. Root distribution functions were developed from water uptake data for the experimental plants in non-saline soil.
2. Hydraulic conductivity in the soil was assumed to be 0.5cm/hr.
3. Soil salinity treatments were given.
4. The lowest allowable plant water potential was -10 bars in Figure 5 and -15 bars in Figure 4.
5. Tp was taken as the average rate for the control plants in each experiment.

Figures 4 and 5 show actual and predicted results for these experiments. The agreement is, in general, good. It should be noted that, in the presence of high soil salinity, water use was always underestimated. This may be attributed to the inaccuracy at high salinities of the relationship used to calculate osmotic potential from soil salinity.

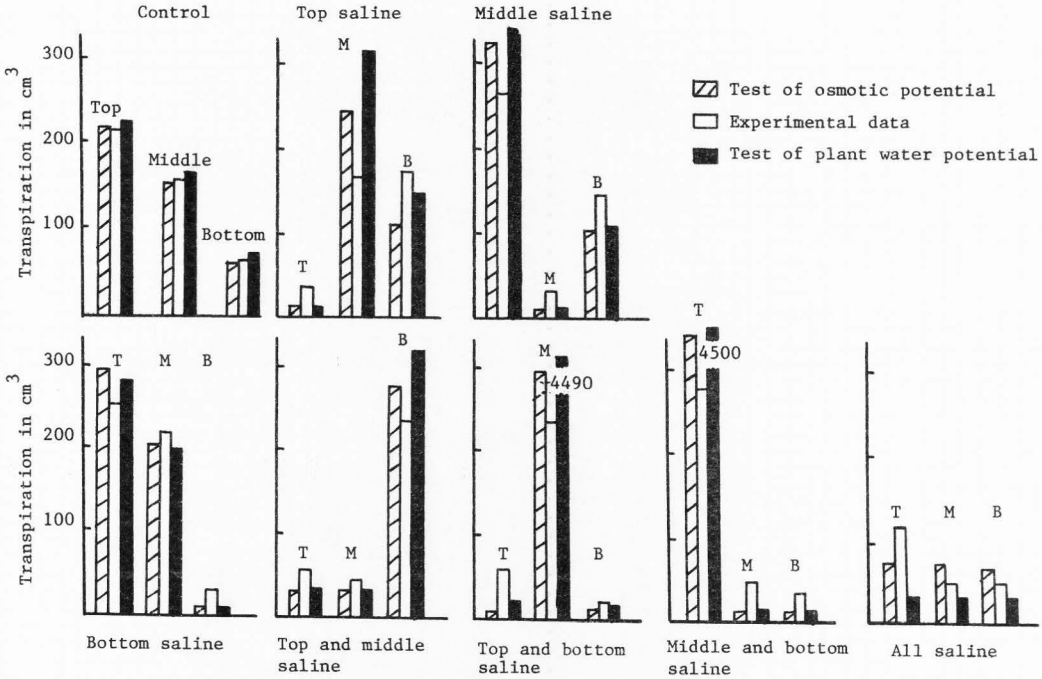


Figure 4: Predicted and actual water use by depth for various salinity conditions. Data of Bingham and Garber (1970).

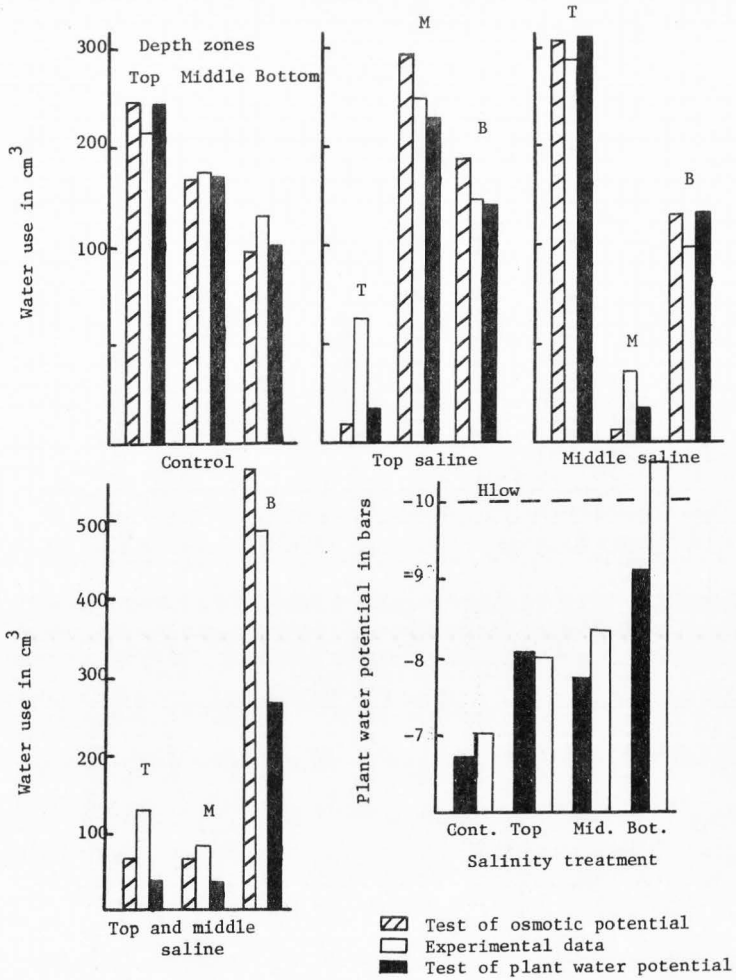


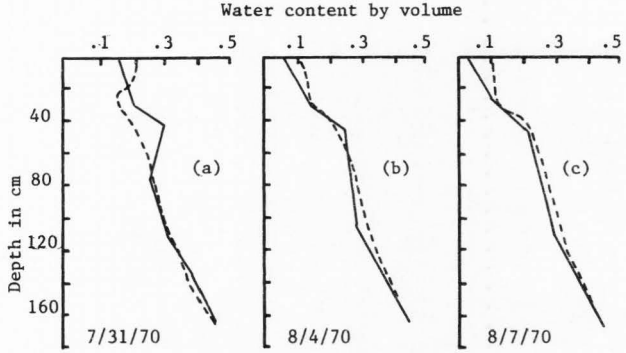
Figure 5: Predicted and actual water use by depth for various salinity conditions from Lunin and Gallatin (1965).

The simulation data presented are of two types. The column to the left in each group of three in both figures is the result of a simulation of the relationship between water uptake and osmotic potential in the soil. For these calculations, approximate actual transpiration values were supplied. The point of the tests was to see whether the model theory would predict the actual results.

The columns on the right in every group are results from a test of the entire root extraction term. This test forced total water use to be calculated from Tp and the prevailing soil water conditions. While the left hand columns are designed to test only the zonal distribution of water uptake, the right hand columns test not only zonal distribution but also total water use. It can be seen from the figures that total water use is accurately predicted in all cases except for the "Top and Middle Salinized" situation of Figure 5. Zonal distributions are again good approximations.

An additional evaluation has been made using the data of Lunin and Gallatin (1965) and is shown in Figure 5. Plant water potentials calculated in the simulations are compared to measured stem water potentials. While the comparison is fairly close, the simulated values are generally slightly lower.

Water flow modelling. Nimah and Hanks (1973a) have tested the soil water flow and root extraction model and found that results agree closely with those measured in the field. Figure 6 shows their soil water data and simulations for a 10-day field test. Also included in the figure is a graph showing predicted versus actual transpiration for the period. These data provide a test of the root extraction term by showing its ability to predict actual transpiration with good accuracy. Other



Comparison of the water content profiles as predicted and measured for oats in 1970
(a) 24 hours
(b) 144 hours
(c) 216 hours

—— Actual
---- Predicted

Comparison of actual, predicted, and potential evapotranspiration during the nine day period for oats in 1970

Predicted evapotranspiration
Actual evapotranspiration
Potential evapotranspiration

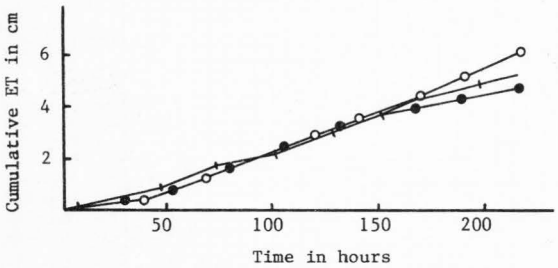


Figure 6: Field test of water flow model from Nimah and Hanks (1973a).

tests are given by Nimah and Hanks (1973b). It should be noted that the experiments reported in this latter paper use the same data which were used to make predictions for this project.

Another test of the water flow model is shown in Figure 7. Simulations are for the data of Warrick et al. (1971) as presented by Bresler (1973). The simulation is accurate except for the cases at 11 and 17 hours. At these times the measured water contents exceed the saturated water content used in the modelling procedure. With the exception of the 17 hour prediction, the wetting fronts are accurately predicted. A further description of this test will be given shortly.

Salt flow modelling. In order to test the salt flow calculations used in this model, two data sets were simulated. The first experiment simulated data obtained in Vernal, Utah. The field experiment was designed to study leaching phenomena by irrigating twice in two days, first with saline water, then with water of good quality. Soil solution conductivity was measured at various times during the test. These data are shown in Figure 8. For simulation, the model was initialized with field data and run for the two day irrigation and evaporation sequence. The model predictions, although they agree well when compared with each other, show no similarities to the field results. It is presumed that the poorness in fit is due to the presence of conditions in the field which allow the precipitation and dissolution of salt constituents. The degree to which the soil solution salinity resists change lends support to this assumption. Since the salt flow approach used here does not account for the sink and source terms associated with large amounts of salt in the exchange phase, the predictions are poor.

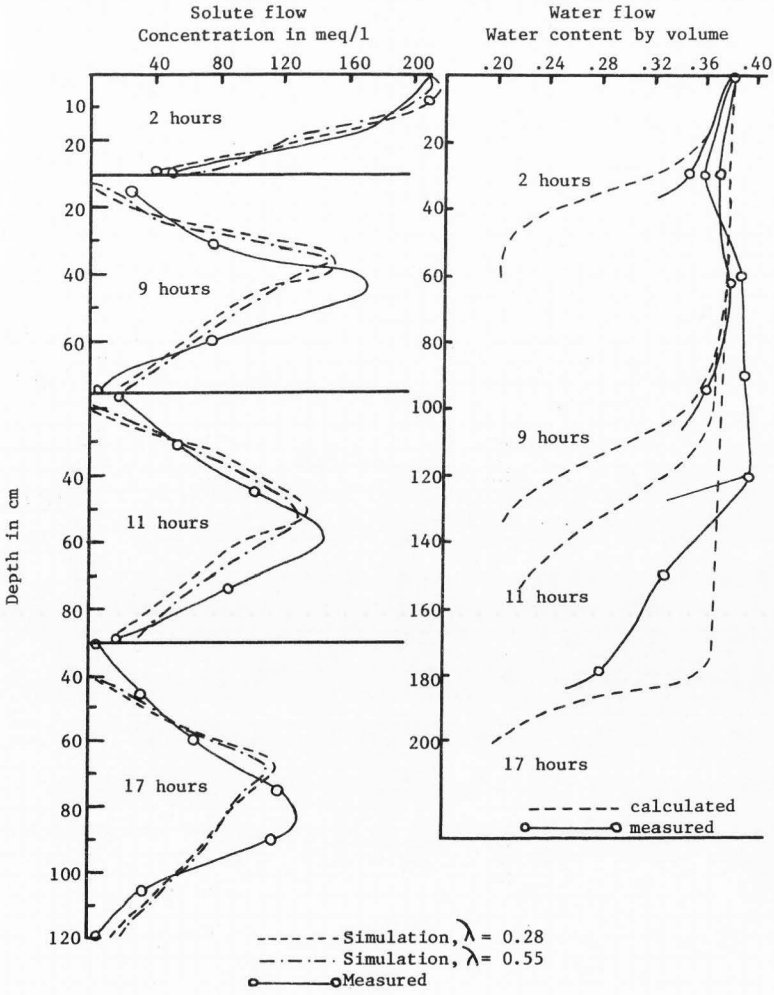


Figure 7: Field test of salt and water flow model after Bresler (1973). Data of Warrick et al. (1971).

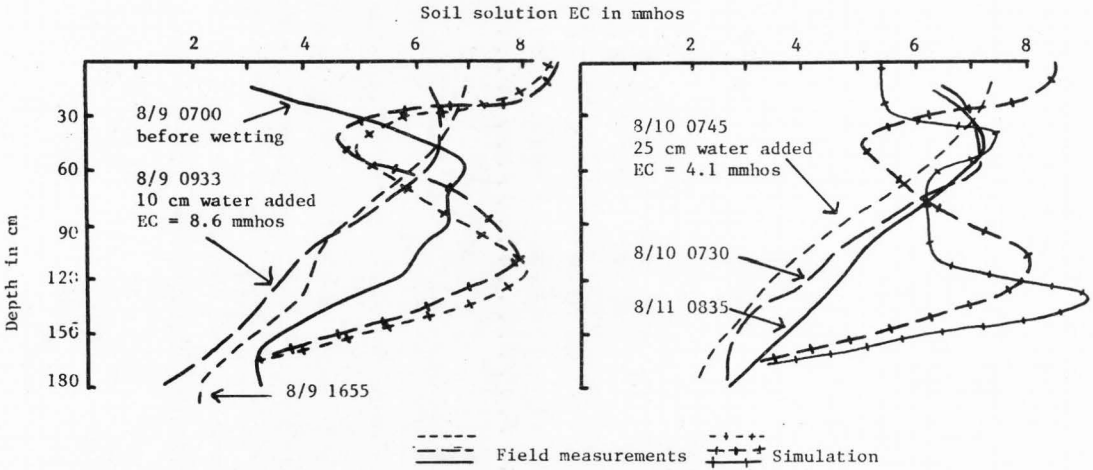


Figure 8: Field test of salt flow model at Vernal, Utah. Soil solution EC versus depth at several times.

A second test of salt flow was conducted using data from Warrick et al. (1971) for both water and salt flow data during a 17 hour irrigation experiment. 7.62 cm of water containing 209 meq/l $CaCl_2$ was applied followed by good quality water for the duration of the experiment. The procedure for modelling is given by Bresler (1973). His input conditions were used with the exception of hydraulic conductivity data and boundary conditions. Hydraulic conductivity values were calculated using the method of Millington and Quirk as modified by Kunze et al. (1968). A value for saturated conductivity was obtained from the water application and timing information given by Warrick et al. Figure 7 shows experimental data and model simulations for four times during the test. The water flow data has been discussed previously. The predictions for salt flow are quite good. A systematic error can be seen in that the predicted peak concentrations occur slightly higher in the profile than the measured peaks. In addition, the upper boundary of each predicted peak is somewhat sharper than the actual data. The lower boundaries are somewhat more diffuse.

Two simulations have been included in Figure 7 in order to show the effect of hydrodynamic dispersion on the predictions. The larger value of λ increased dispersion almost two fold (Equation 8). The effect of the increase on the predicted profiles is to broaden the concentration peak only slighty. A similar test of the effect of D_0, the diffusion coefficient, showed no change, even when D_0 was changed by an order of magnitude. While the combined effects of diffusion and dispersion were not great in this case, they would probably increase in importance under lower water flow conditions such as evaporation.

In conclusion, it appear that the salt flow calculations were adequate for field situations which do not involve precipitation or dissolution of salt. Modifications must be made in order to model these phenomena. The present model has been shown to be accurate for infiltration calculations and is probably accurate for the slower flow cases of evaporation or redistribution.

PREDICTIONS OF THE MODEL

Basic data and scope of the predictions

Application of the model described here resulted in a series of predictions of crop growth and water and salt flow under the influence of a range of input parameters. The utility of the modelling approach lies in the fact that the resultant predictions help to isolate effects of each system parameter studied. This is done by holding all factors but one constant and incrementing the parameter of interest in order to assess its specific effect. In this manner, the following parameters were studied:

1. Amount of irrigation water applied. Six levels were used ranging from no irrigation to an irrigation 30% greater than potential evapotranspiration.

2. Quality of irrigation water applied. Three levels were used ranging from good quality water which is presently used at the Vernal experimental farm to water with a conductivity of 9 millimhos.

3. Crop type. Three crops were considered: oats, alfalfa, and corn.

4. Initial soil salinity. Three initial concentrations were used: 20, 50, and 200 meq/l. The levels may be construed either as lands of different qualities or lands having undergone different kinds of management.

Two other investigations were conducted using the predictions supplied by the above tests:

1. Calculations were linked in order to simulate multiple year management practices.

2. Irrigation amount and initial soil salinity calculations were combined in order to assess the effects of uniformity of water distribution on crop growth and soil salinity status.

Basic data. The basic physical data used for predictions was obtained on an experimental farm at Vernal, Utah. King and Hanks (1973) discuss the setting and give the necessary data required for simulation. The required input data are:

1. The basic soil properties of hydraulic conductivity and matric potential in relation to soil water content. The soil is Mesa Sandy Clay.

2. Surface boundary flux conditions and times over which they apply. An actual irrigation schedule together with rains and daily lysimeter measurements of potential evapotranspiration were used (King and Hanks, 1973). Water levels were changed in the prediction tests by changing water application rates for irrigation while leaving the other data unchanged. The surface flux data also include the quality of irrigation water and rain.

3. Soil water content, soil salinity, and root distributions were taken from King and Hanks (1973). Soil salinity was manipulated as a test parameter and was assumed to be initially constant with depth. The three root distributions at maturity used in the model are shown in Figure 9. The distributions roughly fit the descriptions of shallow, medium and deep. The medium profile was used for the simulation of alfalfa growth, the shallow profile for oats, and the deep profile for corn. Because the relationships between the crop root distributions may not be valid in

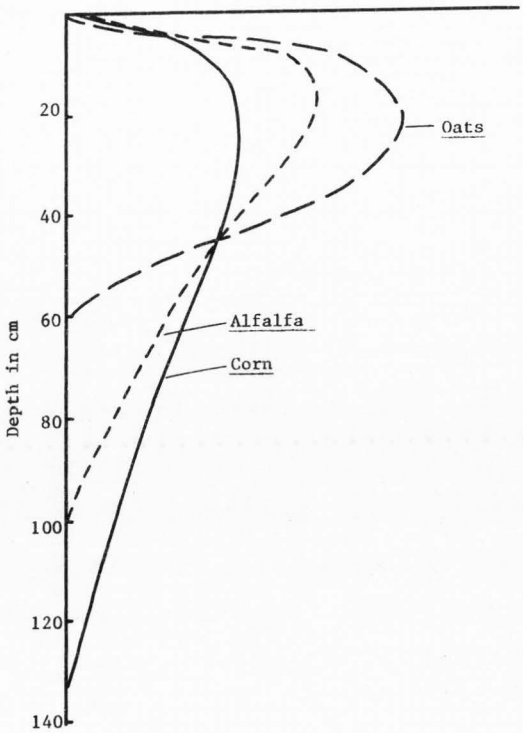


Figure 9: Relative root distributions for various crops.

many areas, it may be better to view the predictions as pertaining to rooting pattern rather than crop type.

4. Table 1 gives values for other input requirements related to soil properties and model operation.

Table 1. Various input data for model control and soil properties

Variable name	Function of variable	Value
DETT	Smallest time step to use for a single calculation	0.024 hour
CONQ	Maximum allowable water content change during one time step	0.03
RRES	Root flow resistance term	0.05 * depth of root in cm
HDRY	Matric potential at air dry water content	-82,000 cm
HWET	Maximum allowable matric potential	0.0 cm
HLOW	Plant wilting potential	-15,000 cm
HHIGH	Maximum plant water potential	0.0 cm
ALAMBA	Solute dispersion coefficient	0.40
DIFO	Free water diffusion coefficient	0.05
DIFA	Diffusion constant	0.002
DIFB	Diffusion constant	10.0
ISALT	Conversion factor between meq/l and T/ac	0.00387

5. Table 2 gives inputs for the three crops concerning root and crop growth.

Table 2. Input values required for crop and root growth

Variable	Function	Value Corn	Alfalfa	Oats
RDFDAY	Number of days to root profile maturity	144	0	132
ESTART	Number of days to seedling emergence	15	0	5
ESTOP	Number of days to crop cover maturity	60	1	50
AK1	Crop cover at maturity	0.8	0.9	0.8
AK2	Maximum T/ET ratio allowed	1.0	0.9	1.0

Output of the model and predicted relationships

The output data are grouped as tables showing different water levels and initial soil salinities for each combination of crop type and irrigation water quality. An example for corn irrigated with 0.6 mmho/cm water is shown in Table 3. Since the data in this table show typical relationships for all the data, the additional tables of similar data are presented in the Appendix.

Many of the relationships shown in the raw data are amenable to graphical presentation and will be discussed in that manner. There are, however, several other things of note in the tables:

1. Notice that irrigation and rain starts at 5.6 cm. This level has no irrigation; 5.6 cm of rain was delivered during the growing season.

2. A fact not immediately obvious in the data as presented is the change in Tp with level of irrigation. At 5.6 cm of water applied, Tp

Table 3. Comparison of irrigation water applied and initial salt concentration on relative transpiration of corn T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality = 63.5 meq/l

Irrig. and rain cm	Tp	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l	Final salt concentration average meq/l
5.6	42.1	36.2	.86	-16.6	-	20	53
5.6	41.8	35.1	.84	-16.5	-	50	121
5.6	41.3	22.3	.54	-13.2	-	200	328
10.3	38.8	36.1	.93	-16.3	-	20	51
10.3	35.9	35.0	.90	-16.3	-	50	117
10.3	38.3	22.6	.59	-13.0	-	200	315
15.0	37.4	37.4	1.00	-16.1	-	20	48
15.0	37.4	36.7	.98	-15.9	-	50	112
15.0	37.6	24.8	.66	-12.9	-	200	307
21.4	35	35.0	1.00	-14.6	-	20	36
24.4	35	35.0	1.00	-14.2	-	50	84
24.4	35	31.1	.88	-12.4	-	200	300
43.2	34.0	34.0	1.00	- 7.6	-	20	26
43.2	34.4	34.4	1.00	- 7.1	-	50	60
43.2	34.8	34.8	1.00	- 6.3	-	200	230
56.4	35.3	35.3	1.00	- .7	-	20	23
56.4	35.3	35.3	1.00	- .5	-	50	52
56.4	35.4	35.4	1.00	- .39	-	200	195
66.7	35.0	35.0	1.00	8.8	.69	20	21
66.7	35.0	35.0	1.00	8.9	1.72	50	44

is 42.1 cm while at 56.4 cm of water applied, Tp = 35.3 cm. This increase at low irrigation is due to the inability of the soil near the surface to meet Ep. As discussed earlier, Tp will be increased in this event.

3. The column marked drainage shows a large quantity of upward flow (negative drainage) at the lower water levels. The magnitude of these figures is due to the presence of a water-table at approximately 2 m. While this is the field situation at Vernal, Utah, and is a reasonable quantity, it should be acknowledged that this factor influences predictions markedly. Many other soils will not show this feature.

4. Salt flow to the groundwater is often zero because of the frequency of upward flow conditions.

5. Average final salt concentrations are shown in the table as a general guideline only. More detailed information is available which shows zonal effects.

Graphical analyses

Crop yield. Figure 10 shows relationships between yield and water applied for three crops. The effect of initial soil salinity is also visible. The lines marked 20 meq/l. initial salt can be considered to show effects due to water supply only. At this initial salinity level, the soil solution never concentrates enough to become harmful. It can be seen that salinity effects are most harmful when yield is already depressed because water is already in short supply. Also, there is a water level which overcomes the adverse effects of high soil salinity.

Comparisons among graphs show other effects. Comparison of the three curves for low initial salinity shows that root depth has a strong influence on transpiration. This effect is due to two advantages for deep

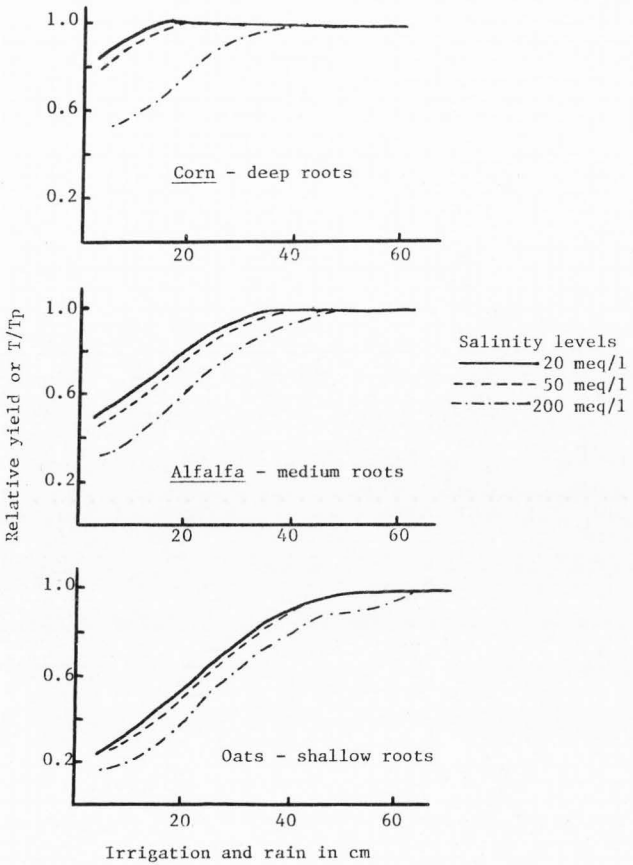


Figure 10: Yield versus irrigation and rain for three crops and three initial soil salinities.

roots over shallow roots. Deeper roots allow the plant to tap a larger volume of the root zone making more water available. Also, deep roots are nearer to the water table and can take greater advantage of this resource. The data shown in Figure 11 show that this latter phenomenon is of primary importance here. At low water application levels, corn can draw almost twice as much upward flow as alfalfa and four times as much as oats.

A final point of interest in Figure 10 is the differential effect of soil salinity on crops. Corn is affected more strongly than alfalfa or oats. This is presumably due to the fact that the deeper rooted crop uses the saline water available at depth while the shallow root system of oats transpires primarily the good quality water which enters the soil as irrigation or rain. The effect of soil salinity on oats is seen to be uniform over a wide range of water applications while the effect on corn is continually changing. The effect of soil salinity on oats, a shallow rooted crop, can be viewed as a shift in the curve for low salinity effects of water supply only. Corn, however, cannot be viewed in this manner. In other words, oats is primarily dependent upon irrigation and rain for growth and, therefore, will be only slightly affected by soil salinity. A deep rooted crop, on the other hand, is primarily dependent upon stored soil water and will be more strongly affected by soil salinity. This line of reasoning suggests that a shallow rooted crop will be more strongly affected by irrigation water quality than a deep rooted crop.

Drainage and upward flow. As seen in Figure 11, upward flow is often important in the presence of a shallow water table. Upward flow can enhance yields and may be desirable. The case of drainage has other implications. Since, under saline conditions, drainage will be accompanied

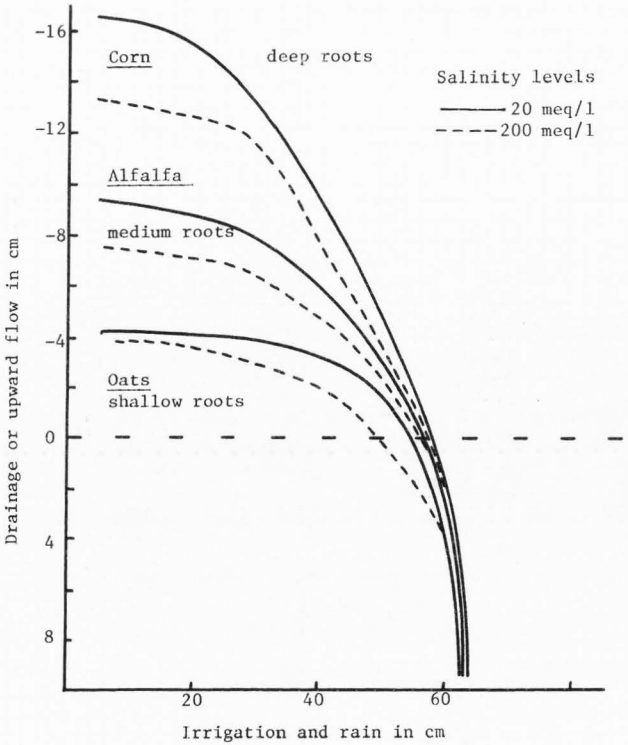


Figure 11: Upward flow versus irrigation and rain for three crops and three initial soil salinities.

by salt outflow, this effect should be considered. Table 3 shows values for salt outflow in T/ac which range from 0.69 to 1.72.

Salinity profiles in the soil. The relationships of yield, salt outflow, and irrigation rate are all influenced by the soil salinity profile. Figure 12 shows final soil salinity for various crops, irrigation amounts and initial soil salinity conditions. Each graph shows the effect of water applied on leaching and salt buildup. Although the trends are expected, these predictions provide interesting and useful quantification. While the curves for high initial soil salinity show the greatest variation in final salinity, the curves for low initial salinity actually have the largest percentage change. It is of interest, though, that because of the difficulty involved in leaching a soil profile initially low in salinity, the greatest range in per cent change of salinity between high and low irrigation levels is seen at the intermediate initial salinity levels. Since soil salinity restricts plant water use and, therefore, increases the soil water content, the high initial salt levels show drainage and leaching before the lower ones. At the lowest level, leaching does not occur although a steady state condition of no salt buildup is reached.

As before, comparisons among the three graphs show the effect of crop. Corn, as a deep rooted crop, is most effective in concentrating the soil solution because it can take water from a larger zone than the other crops. As a result of the same effect, oats show smaller buildups. Also, leaching occurs at a lower water level because water is less available to a shallow root system. These explanations can be clarified by examining the soil salinity profiles shown in Figures 13 and 14. The

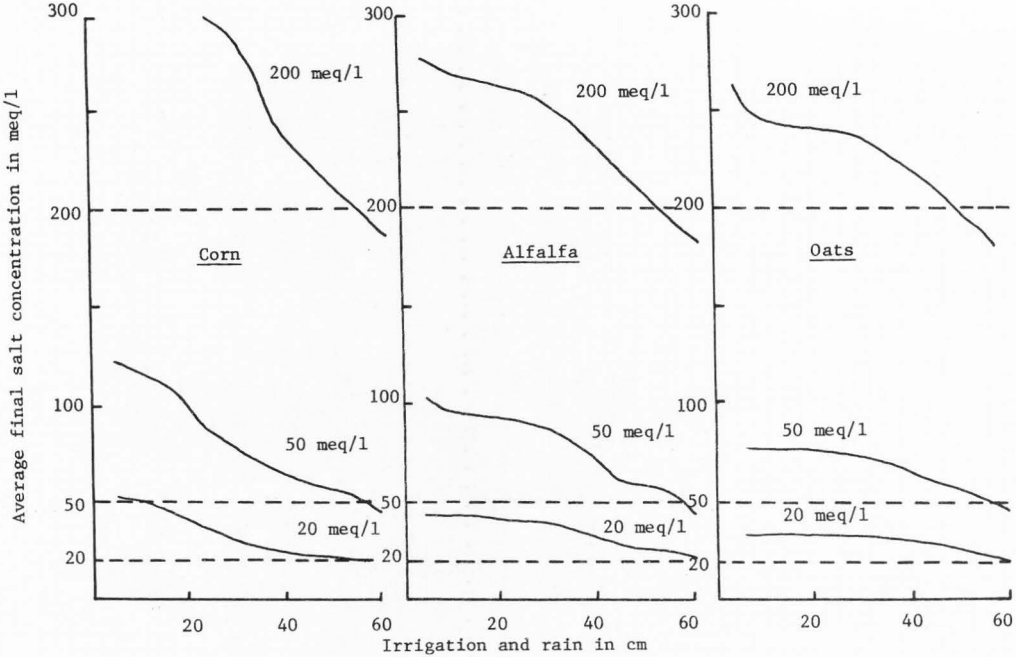


Figure 12: Final soil salinity versus irrigation and rain for three crops and three initial soil salinities.

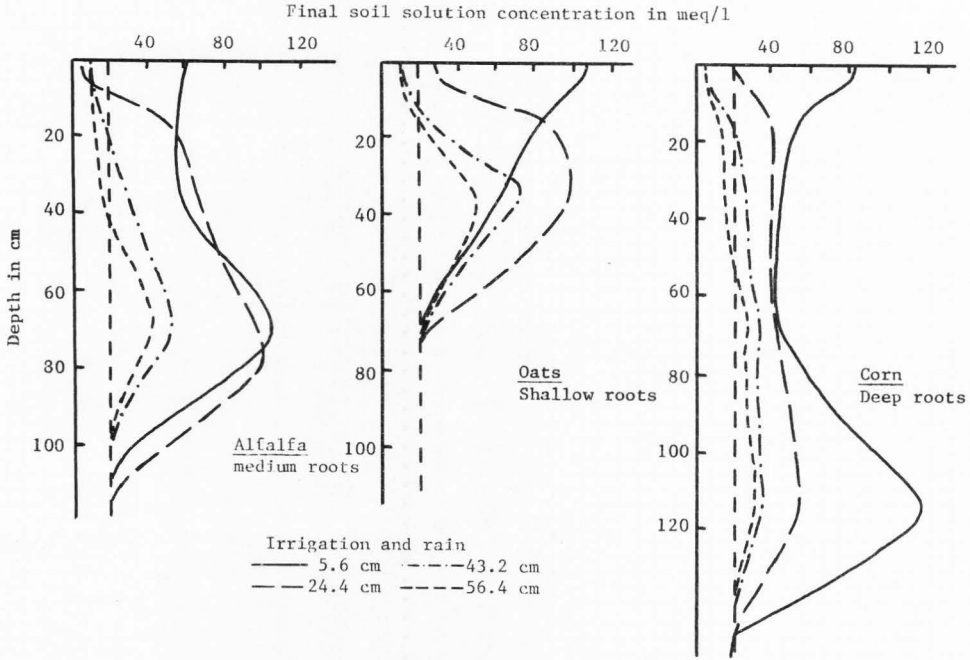


Figure 13: Final soil salinity versus depth for three crops and various water levels. Initial soil salinity = 20 meq/l.

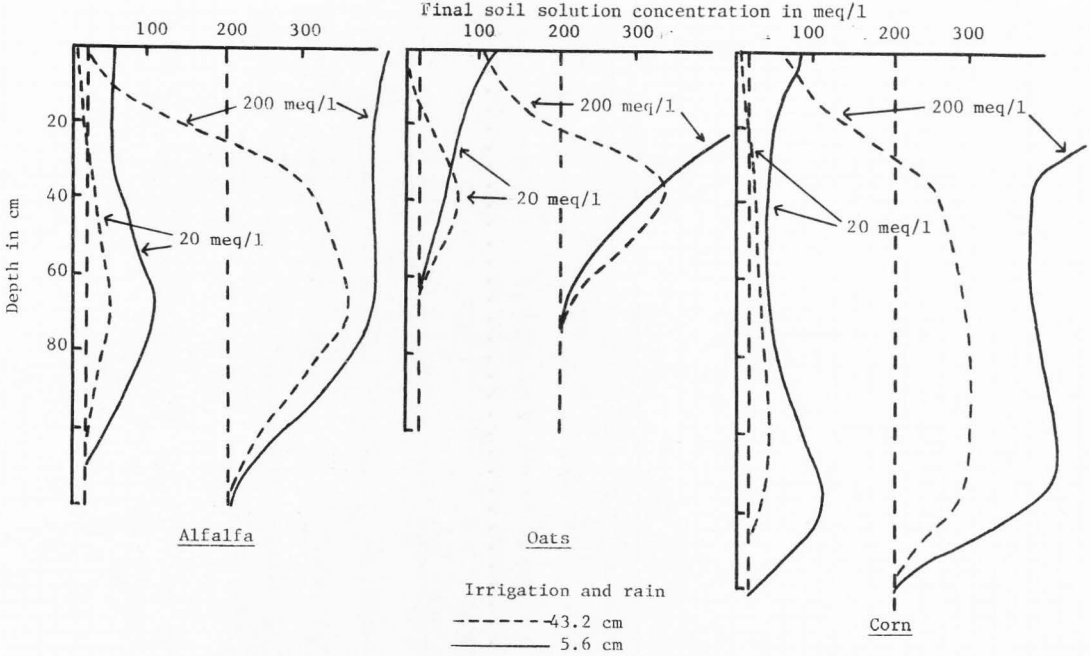


Figure 14: Final soil salinity versus depth for three crops and various water and initial salinity conditions.

first figure shows a marked effect of root depth on salt buildup. Each graph shows a concentration due to evaporation at the soil surface for the lowest water level. The other water levels in each graph show decreasing upper profile salinity with increasing irrigation. All graphs show a peak in salt concentration at the bottom of the root zone. Figure 14 shows the effect of initial salinity on soil salinity profiles. Concentrations at the surface due to evaporation are enormous at high initial salinities but are generally proportional to the curves for low initial salinity. The relationship of each concentration profile to its initial concentration profile is not the same for the high and low initial salinity conditions. The difference results from the unavailability of water for plant transpiration at the higher level. Because there is more water present in the soil, the concentration doesn't show the same proportional increase as at the lower level. The proportional increases in total salt for the two initial salinity levels are, however, similar. Since plant transpiration is in response to the soil solution concentration, the curves drawn for concentration are pertinent.

Irrigation water quality. The basic relationships between soil salinity, water application, and crop growth cannot be changed but may be manipulated through irrigation water quality control. Although good quality water is most desirable, the model predictions show that low quality waters can be managed to provide adequate growth. Figure 15 shows results which indicate that excellent growth can be maintained even with irrigation water with an osmotic potential of -3.2 bars. It can be seen that a shallow rooted crop is more strongly influenced by irrigation than deeper rooted crops. This is evidenced by the effect on oat yield of low quality irrigation water. The detrimental

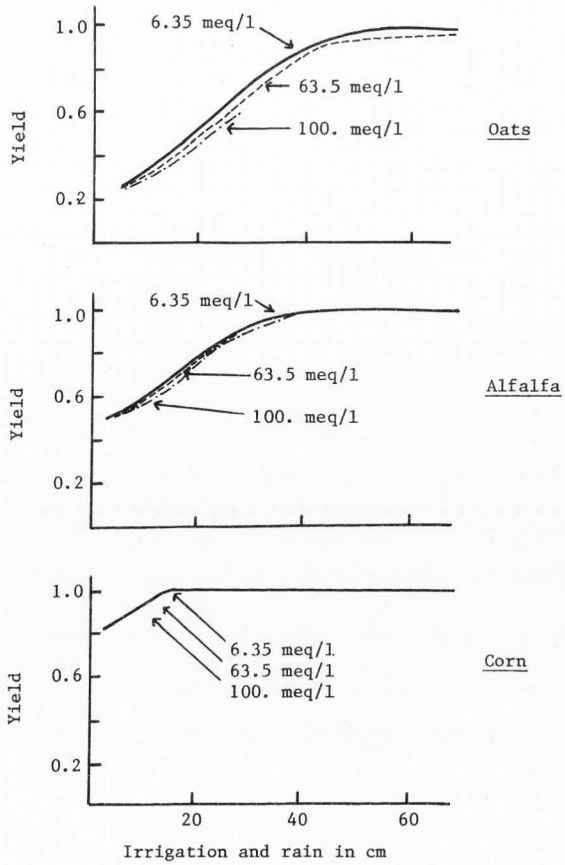


Figure 15: Yield versus irrigation and rain for three crops and three water qualities. Initial salinity: 20 meq/1

effects of saline irrigation water are amplified by initially saline soil conditions. Figure 16 shows that this effect, however, is secondary to the effect of the initial soil conditions. It is also interesting to note that the effect of water quality is greater between the extreme values of maximum and minimum yield rather than at the minimum end.

When saline water is used, upward flow becomes more important for plant growth. Figure 17 shows this phenomenon for corn which, due to the depth of its root zone, shows the largest effect of the three crops. It can also be seen that drainage relations are not changed substantially by irrigation water quality. Since the effects of increased salt output are not seen in drainage waters, soil salinity profiles must show the effects. Average soil profile salinity is shown in Figure 18 for three initial salinity levels. Soil salinity increases with incoming salt, as expected. In addition, it is of note that soil salinity decreases from its initial value only at the highest irrigation levels of good quality water. Although water quality does not affect yield in one year, the buildup of soil salinity indicates that it will eventually have an effect.

The graphs of soil profile salinity in Figure 18 show other interesting effects. The curves for corn grown at 200 meq/l. initial salinity show the effects of water uptake on soil solution concentration. At low irrigation rates soil salinity decreases for two reasons. First, there is a large upward flow component at these levels and, second, plant transpiration is not reaching potential. This means that soil solution concentration due to uptake of pure water by plants is not a large factor. With increasing irrigation, plant transpiration increases. This allows increased concentration of the soil solution. At a certain level of irrigation, however, enough irrigation water is available to allow plants

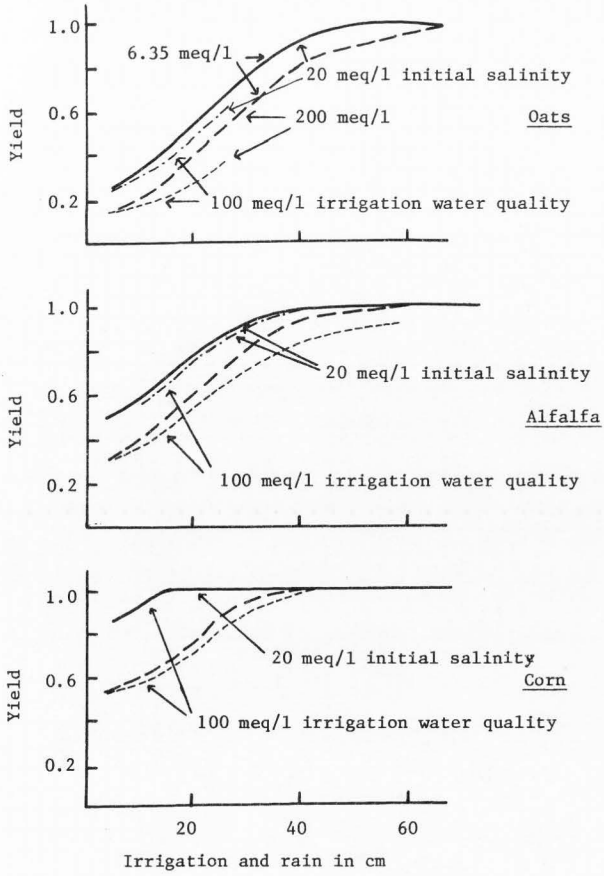


Figure 16: Yield versus irrigation and rain for three crops at two initial soil salinities and two irrigation water qualities.

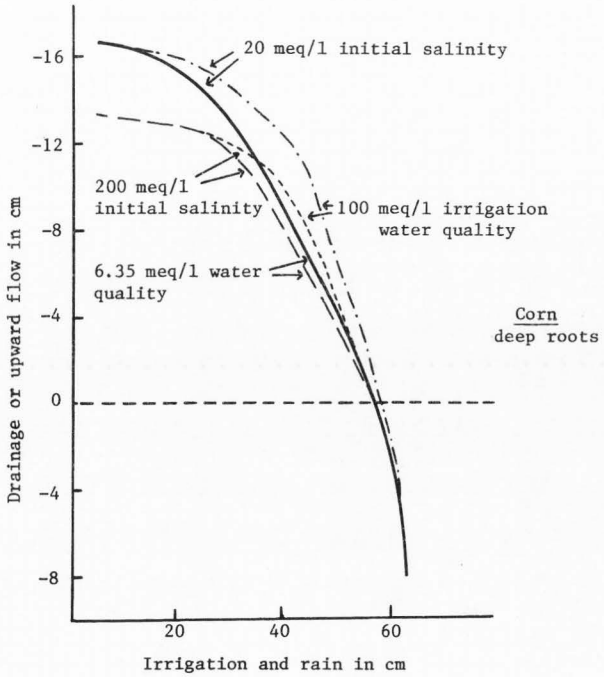


Figure 17: Upward flow and drainage versus irrigation and rain for corn at two water qualities and two initial soil salinities.

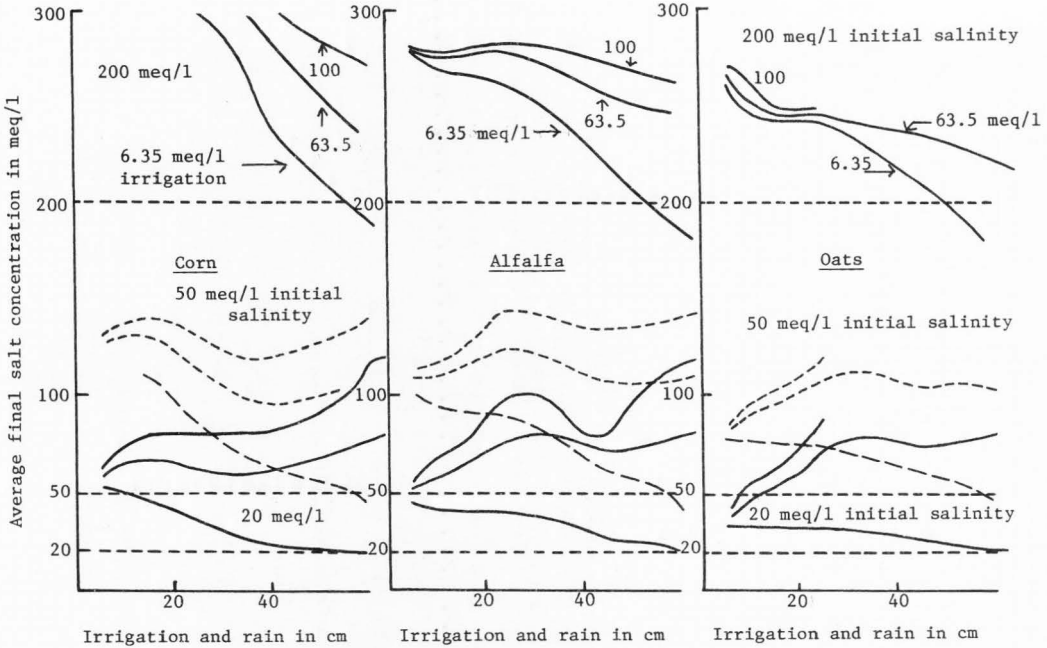


Figure 18: Final soil salinity versus irrigation and rain for three initial salinities and three water qualities.

to transpire at potential without depleting the entire soil water supply. Even though the plant is effectively concentrating the soil solution, enough soil water is available from irrigation to show a net decrease in soil salinity. If enough water were supplied, the soil solution would ultimately reach the same concentration as the incoming water. These relationships for corn are also noticeable to a lesser extent in both alfalfa and oats.

At initial salinity conditions of 50 meq/l, the effects of irrigation are slightly different because the higher water qualities are higher than the initial salinity of the soil solution. For this reason, as well as the higher transpiration rates which prevail, the soil solution shows an increase in salinity as irrigation increases. This concentration is also affected by the decrease in upward flow which occurs with increasing irrigation. At a certain irrigation, soil salinity shows a decrease. This is the result of increased water supply without increased transpiration and with only a minor decrease in upward flow. The rise in salinity at higher irrigations is due to the marked decrease in upward flow and the eventual change to drainage. As is the case for all irrigation water qualities when initial salinity is 200 meq/l, the lowest irrigation water quality is lower than the initial soil salinity. In this instance, there is no increase in salinity at the higher irrigation levels.

For the case of 20 meq/l initial salinity, the same reasoning applies as for the previous case. It is of note, though, that the curves for each irrigation water quality appear to be reaching steady state salinities. The curve for alfalfa at 100 meq/l water quality is also of interest. It shows a marked initial rise due to rapidly increasing transpiration. It

also shows a strong decrease in salinity as transpiration stabilizes and a final rise as upward flow ceases. The magnitude of the effects shown is due to the large range of transpiration values which are associated with this curve. Figure 19 shows transpiration curves for three crops. Alfalfa displays a greater range because, as a perennial crop, it has an established root system at the beginning of the growing season. This allows transpiration at a time when there is none for the two annual crops.

An additional effect of irrigation water quality is its effect on the general shape of the soil salinity profile. Relationships between the salinity profile and water quality, amount of irrigation and initial salinity are shown in Figures 20 and 21. Figure 20 shows the effects of water quality under different irrigation rates. Under low irrigation, large near surface concentrations are established while the remainder of the salinity profile is shifted slightly. At high irrigation rates, the tendency is to form steady concentrations with depth. There is, in general, no accumulation of salt at the base of the root zone. Figure 21 shows the effect of water quality at two initial salinities under high irrigation. The results for the low initial salinity are as before. The higher level of initial salt is different in that the irrigation waters are all less saline than the soil solution. For this reason, the upper portion of the profile is somewhat lower in concentration than the rest of the root zone. This is a product of the leaching effect of the irrigation waters regardless of their quality. It is true, though, that the best quality irrigation water is most efficient in this leaching process.

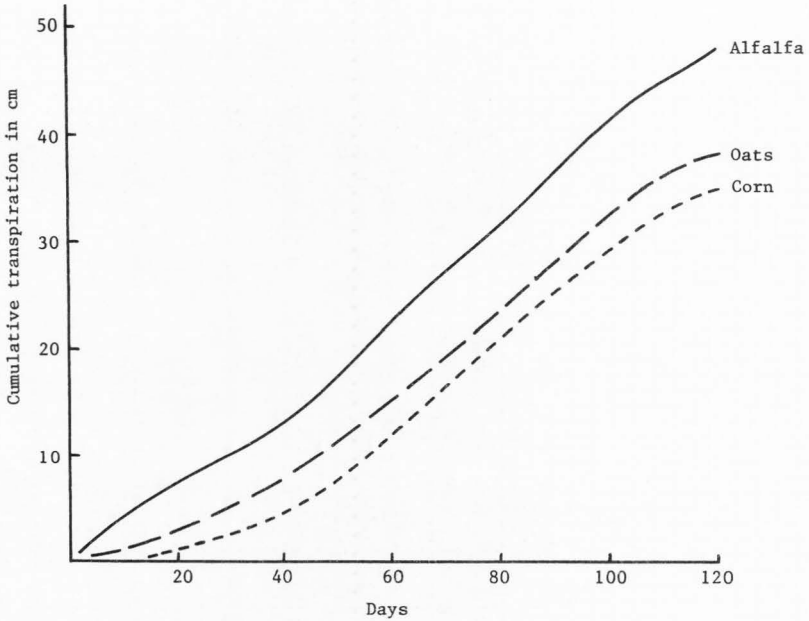


Figure 19: Cumulative transpiration versus time.
Initial soil salinity = 20 meq/1.

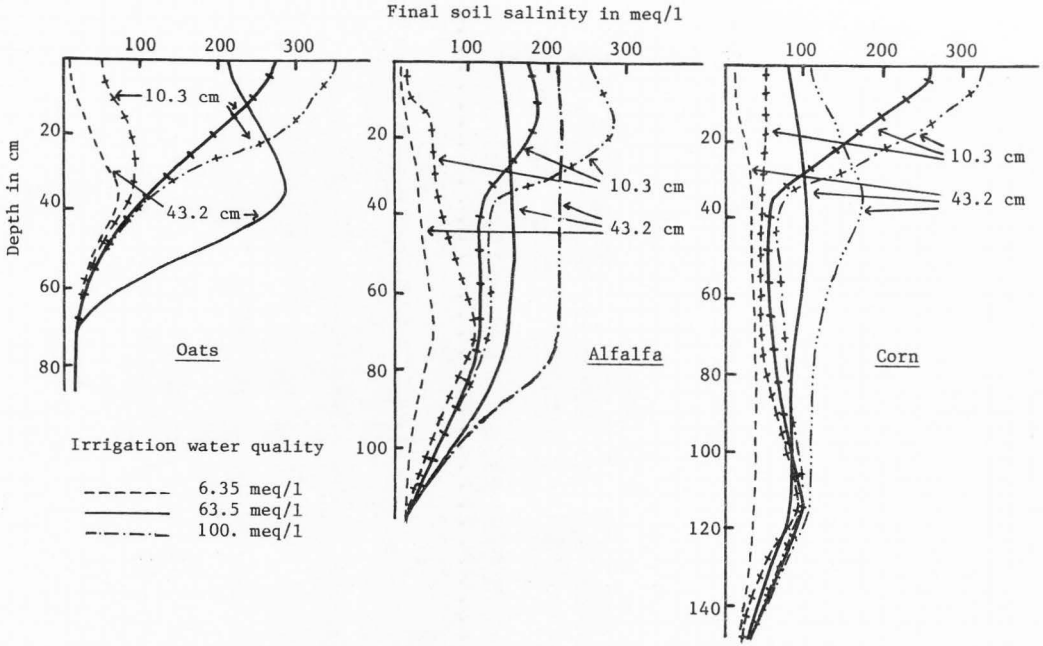


Figure 20: Final soil salinity versus depth for three crops at three irrigation water qualities and two water levels.

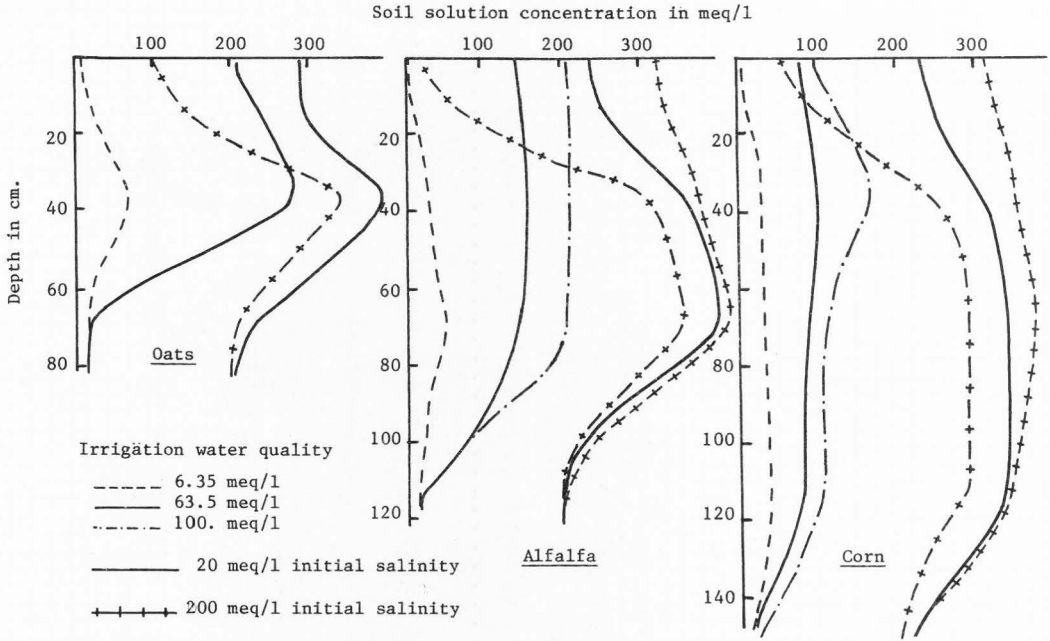


Figure 21: Final soil salinity versus depth for three crops at three irrigation qualities and two initial salinities. Irrigation and rain= 43.2 cm.

Summary of basic predictions

The primary aim in the development of this model is the prediction of the effects of salinity and water on crop growth. To fulfill this objective, data have been presented which treat the relationships among 3 crop types, 7 irrigation amounts, 3 initial soil salinities, and 3 irrigation water qualities. These parameters have all been related to yield and provide a means of quantifying their effects. In addition, the parameters have been related to various other soil conditions in order to better assess their effects. Examination of these related phenomena has stimulated additional investigation in two areas. The simulations show that, although yield is not affected immediately, substantial increases in soil salinity occur under some conditions of water and salt management. If these conditions are viewed as farm operation schemes, it is clear that yield for a single season cannot be the only criterion in choosing water and salt treatments. In order to examine the long term effects, predictions have been made in cumulative fashion for 10 year periods. This provides a means of assessing the importance of various soil water management variables in long term planning.

A final investigation concerning the effects of various irrigation practices has also been made. Since it is unrealistic to specify narrowly restricted conditions in order to maximize crop production, predictions have been modified to account for variability of management control in field practices.

Multiyear calculations

Assessment of long term effects of various management practices was accomplished by using the final conditions of a one-year run as initial

conditions for the following year. Boundary conditions for irrigation, rain, and Etp remained the same; soil water content was assumed to be roughly at field capacity at the start of each new year. Figure 22 shows typical results for several 10-year sequences. Relative yield and final soil salinity are plotted together in order to show the close relationship which exists. It is apparent that until leaching occurs, additional irrigation will allow soil salinity to build to higher levels without any effect on yield. The two lower irrigation levels can also be seen to have stabilized in yield and soil salinity. Yield at the highest irrigation level is not affected in the 10-year period shown. Soil salinity is not only low but is also increasing at a slow rate. A minor effect of soil salinity can be seen in the graph of upward flow. At the end of the 10-year period, upward flow for the case of high irrigation is increasing. This is presumably due to the increasing amount of salt in the soil profile which makes the soil water less available. The lower irrigation rates show a decrease in upward flow as the demand for water by the crop decreases.

A comparison among crops can be made using the data in Figure 23. The curves for upward flow are quite straightforward. As shown previously, decreases in upward flow occur as yield decreases but will remain steady if yield does. In addition, there is a noticeable effect of crop rooting depth on upward flow. This effect is noticeable also in the yield and soil salinity curves. The salinity curves show that deep roots allow greater concentration of the soil solution without detrimental effects. It is interesting to note that, at the high irrigation level, alfalfa is concentrating the soil solution more than corn. This

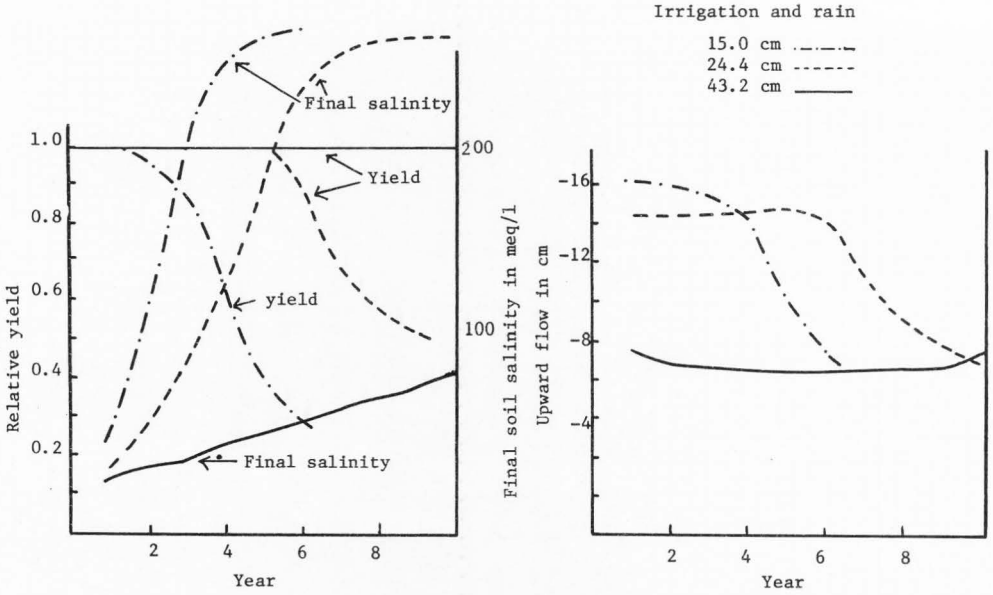


Figure 22: Relative yield, final salinity, and upward flow versus time for corn. Irrigation water quality: 6.35 meq/l

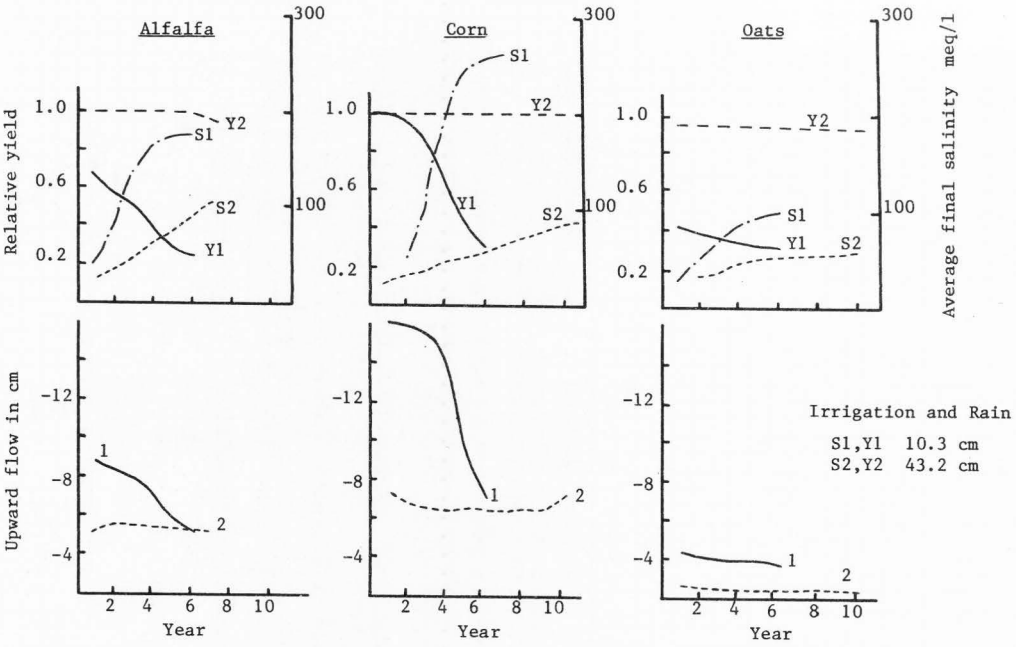


Figure 23: Relative yield, final soil salinity, and upward flow versus time for three crops and two water levels.

is a result of the larger upward flow to corn as well as the smaller total transpiration values for corn (Figure 19).

Figure 24 shows the effects of irrigation quality over several years for alfalfa. Although, as expected, higher irrigation water salinity gives poor growth, there are some interesting interrelationships present. First, irrigation water quality is not immediately important. At high irrigation levels, its effect can be seen after 2 or 3 years depending on the quality of water. At the low irrigation rates, substantial differences in yield cannot be seen until the fourth year. In fact, poorer quality water actually shows less decrease in yield after 2 years. This effect is due to increased upward flow when irrigation water is salty. Soil salinity increases more for salty irrigation water at high irrigation rates than for good quality water. At low rates, the buildup of soil salinity is almost identical for all water qualities.

Upward flow is the most striking feature of Figure 24. At low irrigation rates upward flow is influenced strongly by water quality. At high irrigation rates it is also affected and results in drainage to the watertable as plant water uptake decreases. While drainage itself has no effect on plant growth, it is nevertheless of concern to the land manager because it is necessary to remove salt from the soil profile.

Figures 25 and 26 show final soil salinity profiles versus time. All of these graphs show expected trends. Crops increase soil salinity almost uniformly through their root zones. The effect of irrigation water salinity is to hasten salinization of the soil profile and raise the maximum concentrations.

The calculations for multiyear prediction contained in Figures 22 through 26 show cumulative effects of soil and irrigation salinity which

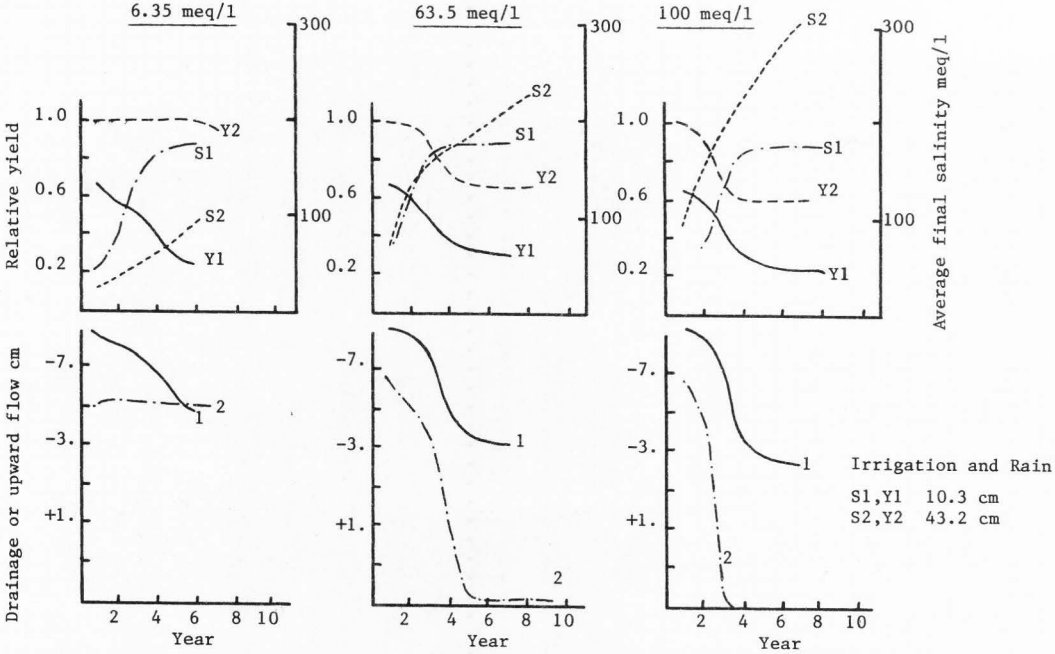


Figure 24: Relative yield, final soil salinity, and upward flow versus time for alfalfa at three irrigation water qualities and two water levels.

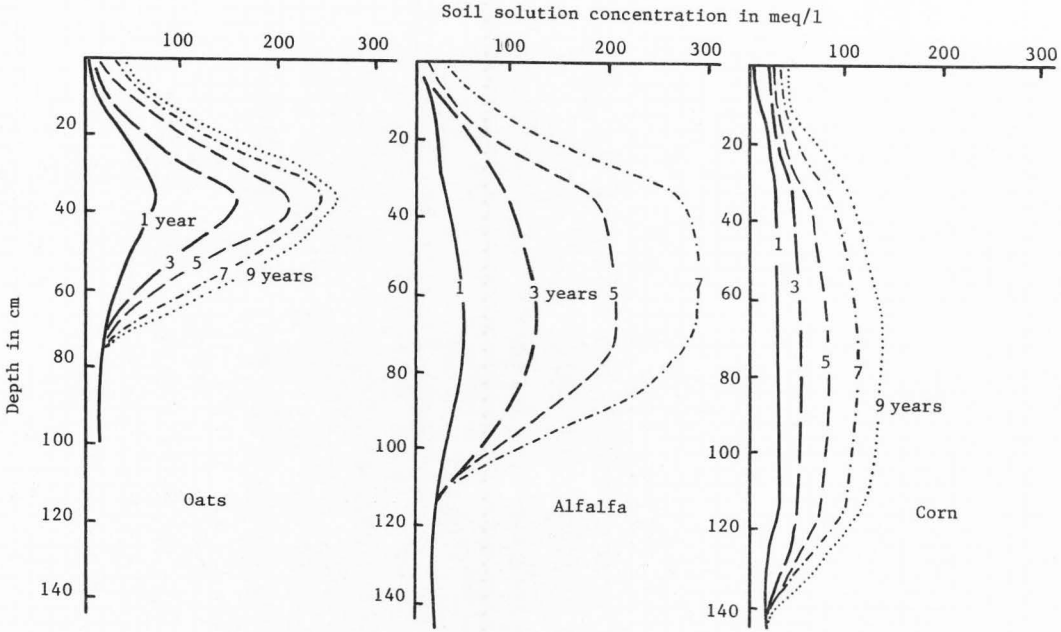


Figure 25: Final soil salinity versus depth for three crops at various times.

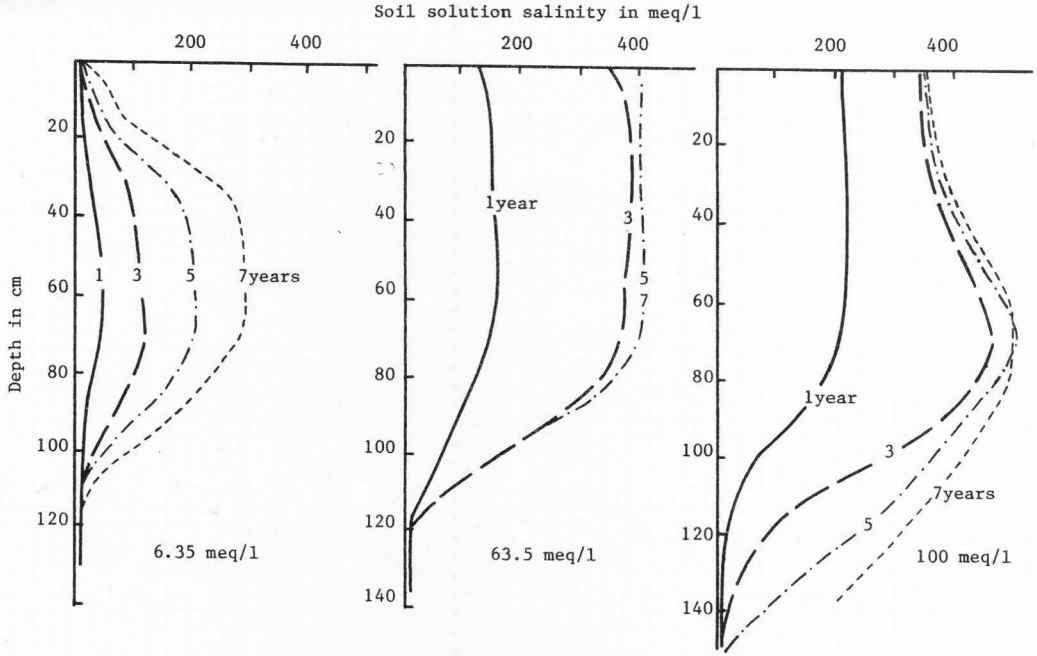


Figure 26: Final soil salinity versus depth for alfalfa at various times. Three irrigation water qualities.

are of practical significance. The resultant data indicate that management practices must be based upon consideration of more than maximum yields and minimum costs. At the same time, however, these data may also be used to predict minimum irrigation required to operate at maximum yield. If environmental degradation is a concern of the land manager, salt outflow and drainage calculations can provide the necessary figures on which to base decisions.

Calculations regarding uniformity of water application. A final arrangement of the basic data was made in order to show the effects on yield of uniformity of water application. While the predictions of this model can show that a particular irrigation rate is ideal for a given situation of soil salinity, irrigation water quality, and crop type, application of that precise amount of water everywhere in a field is virtually impossible. In order to account for this variability, a measure of uniformity of water application was required. The approach used was to segregate an area into zones receiving differing amounts of irrigation according to the uniformity afforded by the water application system. Calculations were carried out for each of these zones and then combined to give general results for the entire area. The measure of water application uniformity commonly used is:

$$Cu = 1 - \frac{D}{M}$$

where: Cu = Coefficient of Uniformity

M = Average or Ideal Irrigation

D = Average Deviation from M (disregarding sign)

When this coefficient equals 1, the average deviation is zero and irrigation is applied everywhere at the ideal amount. A rule of thumb

to clarify this concept is: Approximately 79 per cent of the aread under irrigation receives an irrigation equal to or greater than the amount Cu*M.

In order to completely specify an irrigation level, the pattern of distribution of the applications within that 79 per cent must be known. For the purposes of this project, two patterns of distribution were considered: rectangular and parabolic (Figure 27). For the case of the rectangular distribution, the same amount of area receives minimum irrigation as that which receives the ideal amount. The parabolic distribution has most of its applications clustered near the ideal. In other words, given the same Value for Cu, a parabolic distribution will have more of the total land receiving nearly ideal irrigation than the rectangular distribution.

Using the concept of coefficient of uniformity and pattern of distribution, a variety of probable irrigation patterns were investigated. The sprinkler system for the experimental farm at Vernal, Utah, has a measured Cu value of 0.88, (L. G. King, personal communication). It can also be approximated by a parabolic distribution pattern. This was the most controlled irrigation application considered. The other extreme of the range of uniformities was a rectangular distribution with Cu = 0.42. This option was assumed to simulate the flood irrigation system previously in use at Vernal, Utah, (Hanks and King, personal communication).

Table 4 shows the technique used for calculations which consider uniformity. Total area is divided into 5 blocks with different irrigation levels. A comparison of the amounts in the two portions of the table shows that low uniformity requires a large range in applications. Comparison of the figures for area shows that, in addition to the wide range of the irrigation levels for Cu = 0.42, the extremes comprise more of the area. The

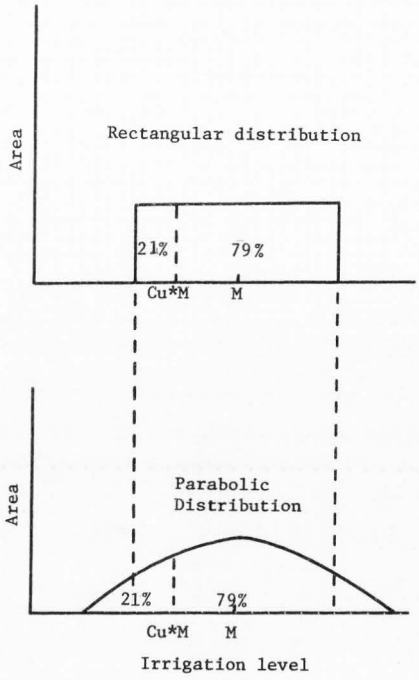


Figure 27: Patterns of distribution for uniformity calculations.

Table 4. Example of uniformity calculations - 5-year sequence for oats

Irrig. and rain cm	% Area	Rel. yield	Salt outflow T/ac	Final soil salinity meq/l	Rel. yield	Salt outflow T/ac	Final soil salinity meq/l
		YEAR 1			YEAR 5		
Cu = 0.88 Parabolic distribution				Irrigation and rain: 53.1 cm			
40.4	10.4	.85	-	27.6	.84	-	70.8
46.7	24.8	.92	-	25.7	.91	-	52.5
53.1	29.6	.96	-	23.9	.96	-	38.7
59.5	24.8	.99	.23	22.4	.99	.03	29.6
65.8	10.4	1.00	.55	21.2	.99	.64	24.0
AVERAGE		.95	.11		.95	.14	
Cu = 0.42 Rectangular distribution				Irrigation and rain: 53.1 cm			
10.6	20.0	.50	-	32.3	.39	-	161.6
31.9	20.00	.75	-	29.9	.68	-	50.5
53.1	20.00	.96	-	23.9	.96	-	38.7
74.3	20.00	.96	1.14	20.4	.96	1.19	21.1
95.6	20.00	1.00	3.63	20.0	1.00	3.86	20.0
AVERAGE		.83	.97		.80	1.02	

areas are used to weight the results for each irrigation level in order to obtain an average figure. The remainder of the table shows the individual results and averages for two times. Initially, a change from flood irrigation to sprinkler irrigation boosts yield from 83 to 95 per cent of maximum yield. After 5 years, yield is still at 95 per cent under sprinkler irrigation while the yield under flooding has dropped to 80 per cent. Another advantage to the sprinkler system can be seen in the figures for salt outflow. Better irrigation management gives better drainage water management. The calculations show a decrease in salt flow to the groundwater of 0.87 T/ac over a five-year period.

Calculations regarding Cu all show effects on drainage and upward flow. Yield changes are evident in a few cases but the significance of careful irrigation management is more often related to environmental quality and long term planning. Table 5 supports this conclusion with data comparing yields under different uniformity conditions. For the first three irrigation levels, there is no effect of uniformity on yield. The three higher levels show yield differences among coefficients of uniformity. The effect of distribution pattern is only slight and shows that yield is better for a rectangular type distribution. All the effects regarding yield can be related to the shapes of the basic yield curves shown in Figure 10. When water application is low, increased yield for irrigation above the mean rate is offset by decreased yield at irrigation below the mean rate. As the mean irrigation is increased, the linear relation between irrigation and yield no longer applies. At this point, yield decreases below the mean are not offset by corresponding increases above the mean and total yield shows a net decrease. The slight increase in yield for a rectangular distribution versus a parabolic distribution at the same Cu

Table 5. Comparison of yields under various coefficients of uniformity and distribution patterns. Calculations for oats under various water levels and initial salinity conditions

Irrig. and rain cm	Init. salinity meq/l	Cu = 0.88 Parabolic rel. yld.	salt T/ac	Rectangular rel. yld.	salt T/ac	Cu = 0.60 Parabolic rel. yld.	salt T/ac	Rectangular rel. yld.	salt T/ac	Cu = 0.42 Rectangular rel. yld.	salt T/ac
10.3	20	.37	-	.37	-	.37	-	.37	-	.37	-
	50	.36	-	.36	-	.36	-	.36	-	.36	-
	200	.24	-	.24	-	.24	-	.24	-	.24	-
15.0	20	.45	-	.45	-	.45	-	.45	-	.45	-
	50	.43	-	.43	-	.43	-	.43	-	.43	-
	200	.31	-	.31	-	.32	-	.31	-	.32	
22.0	20	.61	-	.61	-	.60	-	.60	-	.60	-
	50	.59	-	.59	-	.59	-	.59	-	.59	-
	200	.47	-	.47	-	.47	-	.47	-	.48	-
40.8	20	.87	-	.87	-	.82	.18	.83	.13	.79	.33
	50	.87	-	.87	-	.81	.44	.82	.32	.78	.81
	200	.78	.07	.78	.02	.74	1.9	.75	1.5	.71	3.2
56.4	20	.97	.24	.97	.22	.89	.94	.90	.80	.84	1.4
	50	.97	.61	.97	.56	.89	2.4	.90	2.0	.84	3.6
	200	.93	2.9	.93	2.7	.84	8.5	.85	7.3	.79	12.2
66.7	20	.99	.87	.99	.84	.92	2.1	.93	1.9	.87	3.1
	50	.99	2.2	.99	2.1	.92	5.4	.93	4.7	.87	7.6
	200	.98	8.4	.98	8.2	.88	18.2	.90	16.0	.82	25.1

can be explained with reference to Figure 27. The distributions shown in this figure are drawn for the same Cu. It can be seen that the range of irrigation levels is greater for the parabolic distribution and will, therefore, make yield slightly lower than the rectangular pattern when the higher irrigation levels are in the region of maximum yield.

While the yield difference between distribution patterns at the same Cu is slight, the effect on salt outflow is more substantial. Table 5 shows that salt outflow increases as Cu decreases. For the reason discussed above, salt outflow is larger for parabolic distributions than for rectangular.

The same kinds of comparisons can be made for different crops using the data in Table 6. Effects of uniformity are seen to be important for Cu = 0.42. The increase in yield at low irrigation rates for lower Cu is only present for oats where yield is most strongly dependent on surface irrigation. Salt outflow, however, is strongly affected by Cu and not by crop. The difference between the low uniformity and the high uniformity systems is approximately one order of magnitude. It is an obvious conclusion that irrigation systems with high uniformity have definite value for environmental concerns if not also for yield.

The final evaluation of the effect irrigation uniformity is performed as a multiyear sequence of calculations. The qualitative effects are obvious but the presentation of predictions from the model gives a feeling for the qualitative relationships. Figure 28 gives comparisons between uniformities for a 10-year period. For the simulation of a poor quality flood irrigation system, yield starts lower than for the simulation of sprinkler irrigation and also changes as much over time. In addition salt flow to

Table 6. Changes in yield and salt outflow with uniformity for three crops *

Irrig. and rain cm	Init. salinity meq/l	Oats				Alfalfa				Corn			
		Cu = 0.88		Cu = 0.42		Cu = 0.88		Cu = 0.42		Cu = 0.88		Cu = 0.42	
		rel. yld.	Salt T/ac	rel. yld.	Salt T/ac	rel. yld.	Salt T/ac	rel. yld.	Salt T/ac	rel. yld.	Salt T/ac	rel. yld.	Salt T/ac
22.0	20	+.02		+.01		+.01		-.01		+.01		-.01	
	50	+.01		+.01		+.01		-.01		+.01		-.01	
	200	+.01		+.02		+.01		+.01				-.02	
40.8	20	-.02		-.04	+.33	-.02		-.10	+.33	+.01		-.01	+.34
	50	-.01		-.10	+.81	-.03		-.11	+.82	+.01		-.01	+.84
	200	-.02	+.07	-.09	+3.2	-.02		-.12	+3.1	-.01		-.09	+3.8
56.4	20		+.14	-.13	+1.3		+.70	-.08	+1.7		+.16	-.01	+1.3
	50	-.01	+3.7	-.14	+3.4		+.03	-.08	+3.8	-.01	+.42	-.02	+3.0
	200		+1.0	-.14	+10.3	-.01	+1.7	-.14	+13.3		+1.7	-.09	+13.3
66.7	20		+.10	-.12	+2.3		+.21	-.06	+3.2		+.11	-.01	+1.9
	50		+3.0	-.12	+5.7		+4.0	-.17	+6.4		+.10	-.02	+4.0
	200	-.01	+.80	-.17	+17.5		+1.1	-.11	+20.6		+.90	-.08	+19.1

*Cu = 1.0 used as standard.

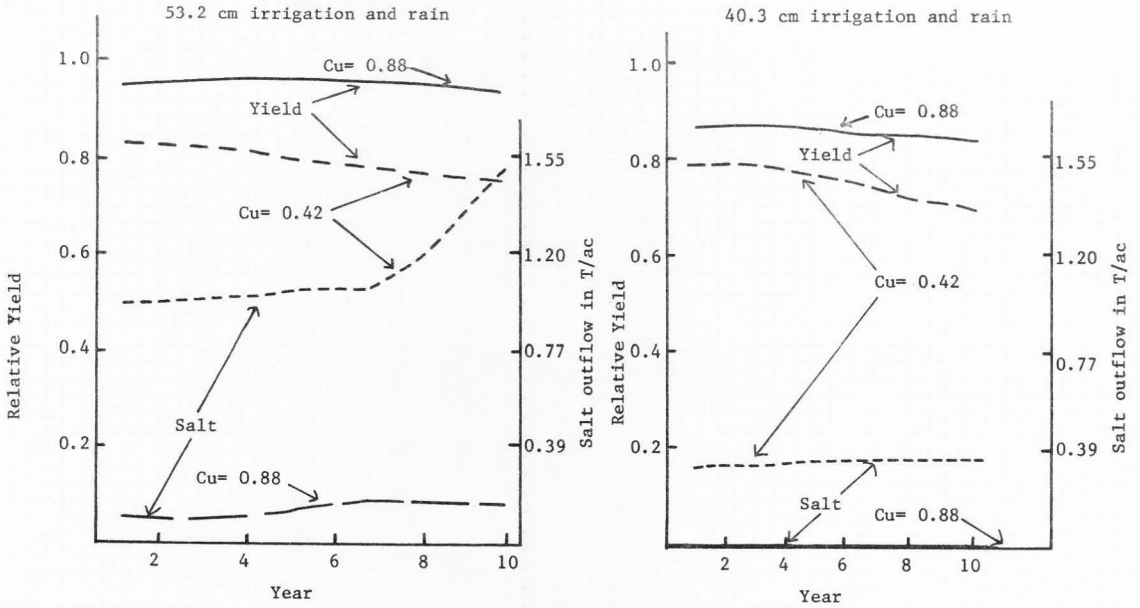


Figure 28: Relative yield and final soil salinity versus time for two coefficients of uniformity and two water levels.

the watertable cannot be managed as closely under the flood system. For the sprinkler simulation, salt outflow is seen to stabilize at a low value (less than 0.2 T/ac.). In fact, one of the graphs shows that the sprinkler irrigation system allows the entire area to operate under an upward flow situation. The flood situations show differing results. In one case, salt flow is steady at a low rate. This may change, however, because yield and water uptake are decreasing. For the flood irrigation case with 53.2 cm irrigation plus rain, outflow changes markedly after seven years. It is apparent that this situation could be avoided by irrigating less or by changing the irrigation uniformity before eight year's time.

Uniformity options as presented above can be considered in relation to all soil-plant phenomena treated in this project and should be used as another management option in planning. Uniformity can generally be seen to be a measure of control of the soil-plant system. For precise management of an area, the above results indicate that the coefficient of uniformity should be high. At the same time, it can be seen that the model allows calculations of intermediate schemes of uniformity, water application, and salt management. These schemes need not be concerned with only achieving ideals but may also be used to predict the consequences of various existing or proposed management schemes. This kind of data would also be useful in planning a minimum cost irrigation system which will meet given production, environmental quality, and water specifications.

SUMMARY AND CONCLUSIONS

Development of the model

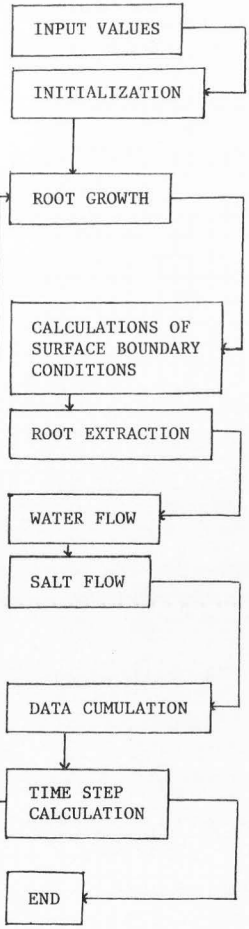
The most basic objective of this research has been to develop a model that would produce a quantitative method to relate crop production and salinity under different levels of water management. In the fulfillment of this objective, consideration has been given to various processes essential to plant growth. This allows assessment of their relationships in order to arrive at a quantitative description of the whole system. In an attempt to summarize the calculations and assumptions of the model, a flow chart is given in Figure 29. The comments included show where the basic assumptions are implemented. The two most critical assumptions are:

1. $Y/Ymax = T/Tp$
2. The effect of salinity on crop growth is only through the effect of soil osmotic potential on water availability.

Tests were conducted for various portions of the model. The tests concerned both validation of the assumptions made and the implementation of those assumptions. The model and assumptions were shown to be satisfactory for calculations concerning water flow, salt flow, root extraction, prediction of relative yield, and plant water potential. The model was shown to be insufficient, though, when precipitation and dissolution of salts in the soil were important.

Basic predictions of the model

Transpiration, soil salinity, and drainage or upward flow of water and salt were tabulated in order to quantify their relationships to different



1. Input values for ET must be separated into components of E and T. Inherent assumptions here are: 1) Relationship between crop cover growth versus time.
2. Roots are lengthened with time according to crop characteristics. A sigmoid growth rate is assumed and the mature root profile is scaled to fit intermediate growth stages.
3. The surface flux rate is checked. If E does not equal Ep, T may be increased.
4. Root extraction is governed by the water potential gradient, soil water conductivity, and plant flow resistance.
5. Salt is treated as a single bulk constituent. Movement is accomplished through mass flow, diffusion, and hydrodynamic dispersion.
6. T and Tp are cumulated for the calculation of relative yield.
7. Hourly E and T rates are calculated from the assumed sinusoidal daily distribution of ET.

Figure 29. A summary flow chart for model with important assumptions.

combinations of:

1. Amount of Irrigation and rain applied: 5.6, 10.3, 15.0, 24.4, 43.2, 56.4, 66.7 cm.

2. Quality of Irrigation Water: 6.35, 63.5, 100 meq/l.

3. Initial Soil Salinity: 20, 50, 200 meq/l.

4. Crop Type: corn, alfalfa, oats with deep, medium, and shallow roots respectively.

The effect of each of the four factors above was assessed by comparing the results for the incremental changes in their values. Quantitative presentations are shown in the previous figures. Generally, though, the effects of individual factors are as follows:

1. Irrigation and rain: Increased irrigation gave higher yield. At the highest irrigation levels, drainage occurred. Soil salinity decreased with increasing irrigation.

2. Irrigation Water quality: Water quality has relatively unimportant effects on yield and drainage. It does, however, increase soil salinity and, therefore, has significant impact on a long term basis.

3. Initial soil salinity: As initial salinity increases, yield and drainage decrease slowly while final soil salinity increases.

4. Crop Type: The effects of crop type show trends which vary with rooting depth. Although other differences are present among crops and were modelled, root zone depth is of primary importance. As root zone depth increases, yield and upward flow also increase. At the same time, soil salinity decreases or remains constant.

While the above trends can be separated and identified, the true value of this predictive model is in the combination of these effects.

Many combinations of levels of the factors outlined above were tested in order to learn more about the interactions involved. Table 7 presents a summary of these findings.

Extensions of the basic output

The predictions of the model were used as a basis for two other kinds of calculations. First, calculations were made over a ten-year period by using output from one year as input for the following year. This technique quantified the effect of soil salt buildup on yield. The resultant data show that management should not be dictated by considerations of yield alone. Over a 10-year period, the management of soil salinity can be an important factor. Predictions of the model provide a convenient quantitative means to assess management schemes. Another result of these long term calculations is information regarding drainage and salt flow to the watertable (Figure 28). As environmental quality increases in importance for land management, these factors will become a necessary consideration. A valuable result of the 10-year predictions presented here is the demonstration that careful management can provide maximum yield over a period of time without excessive environmental damage.

The second extension of the basic calculations was the consideration of irrigation uniformity and its effect on the basic calculations. A scheme was devised to combine the basic calculations to simulate the zones of different irrigation which are present when irrigation application is nonuniform. This technique allowed comparison of various irrigation systems for the factors of crop yield, soil salinity, and drainage. The result was an additional capability of the model. A comparison of irrigation systems can be made for given field situations in

Table 7. Effects on yield of various factors: irrigation amount, irrigation water quality, initial soil salinity, upward flow, and crop type.

Yield of	Effect of irrigation amount	Effect of water quality	Effect of initial salinity	Effect of upward flow	Yield of
Corn	No effect until low: 0.4 * ET	No effect on yield but does increase soil salinity.	Large effect but relative yields are still larger than other crops.	Large(up to 15 cm). Can satisfy crop demands at low irrigations. Decreases markedly under saline conditions.	Deep roots
Alfalfa	Limits yield below 0.9 * ET	Heightens effects of soil salinity and affects quality of drainage water.	Less important than for deep roots. A change of an order of magnitude can decrease yield as much as 10%.	Moderate importance Up to 9 cm.	Medium roots
Oats	Strongly affects yield below 1.2 * ET	Has most effect at high soil salinities. A 10-fold increase in irrigation water salinity can decrease yield 5%.	An order of magnitude change in salinity changes yield by only 5%.	The shallow root system relies primarily on surface irrigation although some upward flow is present (4 cm).	Shallow roots

order to assess long term gains and management costs. The example presented in this project was a comparison between a nonuniform flood irrigation system and a good quality sprinkler system both operating on a shallow rooted crop of oats. As expected, the sprinkler system afforded better yield than the flood system. This effect was, however, compounded over time. It was also shown that the sprinkler system provided much more control of drainage waters.

Conclusions

A model has been developed which treats the complex soil-plant system in sufficient detail to provide good predictions regarding yield under various conditions of practical management. The predictions of the model have been used in order to assess the importance of salt, water, and crop management. On a more practical level, the predictions have been used to simulate various land managment techniques. These simulations suggest possible schemes which will meet given standards of crop yield, irrigation amount, water quality, and drainage. The model can be considered a reliable tool which can be of use in land management planning. If the assumptions and basic requirements of data for the model can be satisfied, it can be used to quantitatively compare management alternatives with regard to:

1. Type and quality of irrigation system.
2. Irrigation amount and schedule.
3. Irrigation water quality.
4. Initial soil salinity.
5. Crop type.
6. Restrictions on drainage to or upward flow from a watertable.

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APPENDIX

Table 8. Comparison of irrigation water applied and initial salt concentration on relative transpiration of corn T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 63.5 meq/l.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l	Final salt concentration average meq/l
5.6	36.1	.86	-16.6	-	20	59
5.6	35.0	.83	-16.5	-	50	125
5.6	22.1	.53	-13.1	-	200	332
10.3	36.1	.93	-16.3	-	20	66
10.3	34.9	.90	-16.3	-	50	130
10.3	22.3	.58	-13.0	-	200	326
15.0	37.2	.99	-16.1	-	20	68
15.0	36.1	.97	-16.0	-	50	131
15.0	23.4	.63	-12.9	-	200	316
24.4	34.8	1.00	-15.3	-	20	64
24.4	34.7	1.00	-15.2	-	50	115
24.4	29.4	.85	-12.8	-	200	319
43.2	34.2	1.00	-10.8	-	20	63
43.2	34.2	1.00	- 9.6	-	50	98
43.2	34.2	1.00	- 7.5	-	200	271
56.4	35.1	1.00	- 1.7	-	20	73
56.4	35.8	1.00	- 1.3	-	50	103
56.4	35.5	1.00	- .5	-	200	245
63.5	36.2	1.00	8.1	.65	20	80
63.5	35.8	1.00	8.8	1.70	50	104

Table 9. Comparison of irrigation water applied and initial salt concentration on relative transpiration of corn T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 100 meq/l.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l	Final salt concentration average meq/l
5.6	36.1	.86	-16.6	-	20	62
5.6	34.8	.83	-16.5	-	50	130
5.6	22.0	.53	-13.1	-	200	232
10.3	35.9	.93	-16.3	-	20	74
10.3	34.7	.90	-16.2	-	50	139
10.3	22.2	.58	-13.0	-	200	333
15.0	36.4	.99	-16.1	-	20	78
15.0	35.3	.96	-16.0	-	50	140
15.0	22.7	.62	-12.9	-	200	320
24.4	34.4	1.00	-15.4	-	20	79
24.4	34.4	1.00	-15.2	-	50	131
24.4	28.1	.81	-13.2	-	200	324
43.2	34.2	1.00	-11.3	-	20	85
43.2	34.1	1.00	-10.5	-	50	121
43.2	34.2	1.00	-10.1	-	200	296
56.4	35.1	1.00	- 2.3	-	20	102
56.4	35.7	1.00	- 2.0	-	50	134
56.4	35.4	1.00	- .73	-	200	277
63.5	35.7	1.00	8.5	.70	20	117
63.5	35.5	1.00	8.7	1.70	50	140

Table 10. Comparison of irrigation water applied and initial salt concentration on relative transpiration of alfalfa T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 6.35 meq/1.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/1.	Final salt concentration average meq/1
5.6	25.0	.51	- 9.4	-	20	44
5.6	24.0	.49	- 9.1	-	50	102
5.6	15.8	.33	- 7.5	-	200	278
10.3	28.2	.59	- 9.1	-	20	42
10.3	27.2	.57	- 9.0	-	50	94
10.3	19.1	.40	- 7.4	-	200	269
15.0	32.4	.68	- 8.9	-	20	42
15.0	31.4	.65	- 8.8	-	50	93
15.0	23.1	.49	- 7.3	-	200	268
24.4	40.5	.87	- 8.5	-	20	42
24.4	39.6	.86	- 8.3	-	50	91
24.4	32.3	.70	- 6.9	-	200	263
43.2	46.3	1.00	- 5.2	-	20	27
43.2	46.3	1.00	- 4.9	-	50	62
43.2	44.6	.96	- 4.1	-	200	225
56.4	47.9	1.00	.56	.04	20	24
56.4	47.9	1.00	.56	.11	50	52
56.4	47.9	1.00	.43	.33	200	195
63.5	47.9	1.00	9.30	.72	20	21
63.5	47.9	1.00	9.40	1.80	50	44

Table 11. Comparison of irrigation water applied and initial salt concentration on relative transpiration of alfalfa T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 63.5 meq/1.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/1.	Final salt concentration average meq/1
5.6	25.1	.51	- 9.5	-	20	52
5.6	24.3	.50	- 9.2	-	50	110
5.6	15.4	.32	- 7.5	-	200	280
10.3	28.0	.58	- 9.3	-	20	58
10.3	27.0	.56	- 9.1	-	50	110
10.3	18.4	.38	- 7.4	-	200	275
15.0	32.1	.67	- 9.2	-	20	65
15.0	31.0	.65	- 9.0	-	50	116
15.0	22.5	.47	- 7.3	-	200	276
24.4	40.1	.87	- 8.9	-	20	79
24.4	39.1	.84	- 8.7	-	50	126
24.4	30.5	.66	- 6.8	-	200	279
43.2	46.3	1.00	- 6.4	-	20	72
43.2	46.3	1.00	- 5.9	-	50	108
43.2	42.4	.92	- 4.0	-	200	259
56.4	47.9	1.00	.13	.01	20	77
56.4	48.0	1.00	.23	.04	50	105
56.4	46.4	.97	1.20	.95	200	241
66.7	47.9	1.00	9.30	.72	20	81

Table 12. Comparison of irrigation water applied and initial salt concentration on relative transpiration of alfalfa T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 100 meq/l.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l.	Final salt concentration average meq/l
5.6	25.2	.52	- 9.5	-	20	56
5.6	24.3	.50	- 9.2	-	50	114
5.6	15.2	.32	- 7.5	-	200	280
10.3	27.8	.58	- 9.3	-	20	69
10.3	26.8	.56	- 9.2	-	50	118
10.3	17.9	.37	- 7.4	-	200	277
15.0	31.7	.66	- 9.2	-	20	77
15.0	30.7	.64	- 9.1	-	50	127
15.0	21.7	.45	- 7.3	-	200	279
24.4	39.4	.85	- 9.0	-	20	98
24.4	38.3	.83	- 8.9	-	50	143
24.4	28.8	.62	- 6.7	-	200	282
43.2	46.3	1.00	- 6.6	-	20	99
43.2	46.3	1.00	- 6.2	-	50	136
43.2	39.9	.86	- 3.2	-	200	274
56.4	48.0	1.00	- .08	-	20	110
56.4	48.0	1.00	- .05	-	50	138
56.4	44.1	.92	3.00	2.40	200	265
63.5	47.9	1.00	9.30	.73	20	119
63.5	47.9	1.00	9.30	1.80	50	142

Table 13. Comparison of irrigation water applied and initial salt concentration on relative transpiration of oats T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 63.5 meq/l.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l	Final salt concentration average meq/l
5.6	12.0	.26	- 4.0	-	20	33
5.6	11.6	.26	- 4.1	-	50	78
5.6	7.7	.17	- 3.8	-	200	262
10.3	14.2	.33	- 4.1	-	20	33
10.3	13.5	.32	- 4.1	-	50	77
10.3	8.4	.20	- 3.7	-	200	245
15.0	17.3	.41	- 4.1	-	20	33
15.0	16.3	.39	- 4.1	-	50	77
15.0	11.5	.28	-3.7	-	200	242
24.4	24.3	.63	- 3.9	-	20	34
24.4	24.0	.62	- 3.9	-	50	76
24.4	79.1	.50	- 3.4	-	200	241
43.2	34.9	.94	- 2.5	-	20	27
43.2	34.8	.94	- 2.4	-	50	60
43.2	31.7	.85	- 1.6	-	200	212
56.4	37.9	.99	1.2	.09	20	24
56.4	37.7	.98	1.3	.25	50	52
56.4	35.5	.92	2.2	1.70	200	187
63.5	37.6	.99	9.6	.74	20	21

Table 14. Comparison of irrigation water applied and initial salt concentration on relative transpiration of oats T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 63.5 meq/l.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l	Final salt concentration average meq/l
5.6	11.5	.26	- 4.0	-	20	38
5.6	11.1	.25	- 4.1	-	50	83
5.6	7.5	.17	- 3.8	-	200	267
10.3	13.7	.32	- 4.1	-	20	48
10.3	12.8	.30	- 4.1	-	50	90
10.3	7.9	.19	- 3.7	-	200	254
15.0	16.1	.39	- 4.1	-	20	53
15.0	15.3	.38	- 4.0	-	50	95
15.0	9.3	.23	- 3.6	-	200	246
24.4	22.7	.60	- 3.9	-	20	71
24.4	21.9	.58	- 3.9	-	50	108
24.4	15.4	.41	- 3.1	-	200	247
43.2	33.7	.91	- 2.4	-	20	74
43.2	32.9	.89	- 2.2	-	50	104
43.2	26.9	.73	.13	-	200	237
56.4	35.4	.93	1.9	.15	20	77
56.4	34.9	.92	2.1	.41	50	104
56.4	31.8	.83	4.3	3.30	200	298
63.5	36.3	.96	10.5	.81	20	80
63.5	36.1	.95	10.6	2.10	50	102

Table 15. Comparison of irrigation water applied and initial salt concentration on relative transpiration of oats T/Tp, total water used, drainage, salt flow to the groundwater, and average final salt concentration. Irrigation quality: 100 meq/l.

Irrig. and rain cm	T	T/Tp	Drainage cm	Salt flow to groundwater T/ac	Initial salt concentration meq/l	Final salt concentration average meq/l
5.6	11.2	.25	- 4.0	-	20	42
5.6	11.1	.25	- 4.1	-	50	89
5.6	7.4	.17	- 3.8	-	200	270
10.3	13.1	.31	- 4.1	-	20	56
10.3	12.4	.30	- 4.1	-	50	97
10.3	7.7	.19	- 3.7	-	200	261
15.0	15.5	.38	- 4.1	-	20	63
15.0	14.6	.36	- 4.0	-	50	102
15.0	8.5	.21	- 3.5	-	200	249
24.4	21.3	.57	- 3.9	-	20	88
24.4	20.5	.55	- 3.9	-	50	120
24.4	13.1	.35	- 2.7	-	200	249

VITA

Stuart W. Childs

Candidate for the Degree of

Master of Science

Thesis: A Model to Predict the Effects of Salinity on Crop Growth

Major Field: Soil Physics

Biographical Information:

Personal Data: Born at Rochester, Minnesota, August 11, 1949, son of Ann W. and Donald S. Childs, Jr.; U.S. Citizen; Single.

Education:

1974	M.S. Soil Science, Utah State University
1971	B.S. Geology, Stanford University
1967	Graduated from high school, Lawrenceville, New Jersey

Acquired Skills:

1972-Present	Research in Soil Physics and Crop Science. Computer Science knowledge: Fortran IV programming on Burroughs 6700 and Univac 1108
1971-1972	Laboratory and fieldwork in Botany
1970	Laboratory and fieldwork in Invertebrate Paleontology
1970	Geological field mapping

Thesis and Publication Titles:

M.S. Thesis 1974. A Model to Predict the Effects of Salinity on Crop Growth.

Hanks, R.J. et al. 1974 An Evaluation of Farm Irrigation Practices as a Means to Control the Water Quality of Return Flow. Utah Ag. Expt. Sta. Research Report 19.

Childs, S.W. and D. W. Goodall 1973 Seed Reserves of Desert Soils US/IBP Desert Biome Research Memorandum 73-5.

Griffin, R., R. J. Hanks, and S. W. Childs 1973 A Model for Estimating Water, Salt, and Temperature Distributions in the Soil Profile. US/IBP Desert Biome Research Memorandum.