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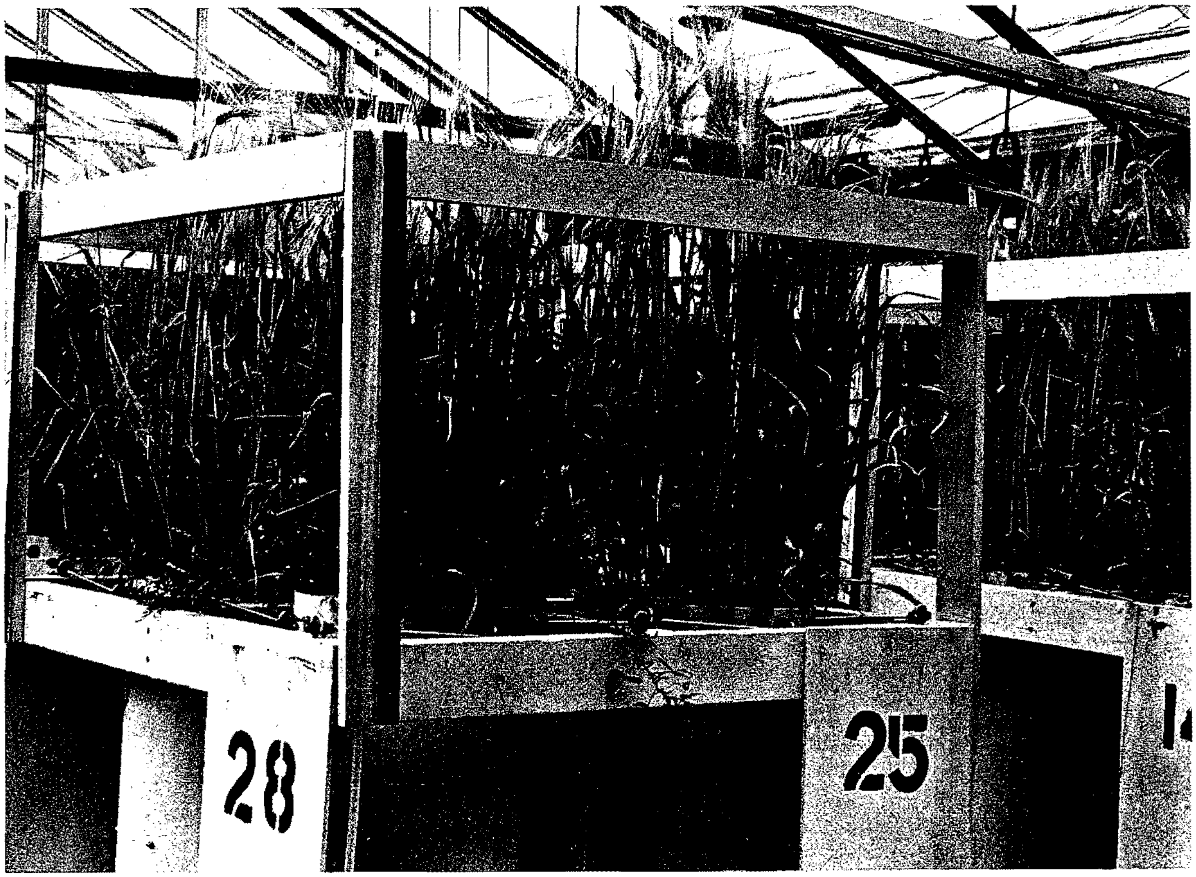

Utah Water Research Laboratory
Utah State University
Logan, Utah 84322

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IMPACT OF WATER AND SOILS HAVING HIGH SOURCE-SINK POTENTIALS ON WATER AND SALINITY MANAGEMENT UNDER IRRIGATION IN THE UPPER COLORADO RIVER BASIN

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ABSTRACT

Water management in irrigation projects is one potential method for reducing downstream salinity in the Colorado River. An important contribution can be made to developing more effective irrigation water management practices for water conservation and salinity control through identification and better understanding of the soil and water interactions that result in soils behaving as salt sources or as salt sinks. The interactions identified in this study were examined to determine the effects of various management alternatives on the quality and quantity of salt in subsurface return flow from irrigation projects.

A soil solution chemistry model was developed to describe the soil-irrigation water interactions. The model includes the effect of cation exchange capacity. The model was calibrated and checked with data obtained from lysimeters. A water management model that contained a soil solution chemistry component was calibrated for the Ashley Valley of Utah and was used to determine the sensitivity of stream flows and salinity to irrigation water management alternatives.

The source-sink behavior of soils was found to depend on water quality, residual soil salinity, and water management practices. The key relationships are described. In applying these relationships, site specific conditions must be examined to determine the effectiveness of proposed irrigation management changes that are expected to affect downstream salinity.

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Donna Falkenborg, editor for the Utah Water Research Laboratory oversaw the details of completion and printing of the report.

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LIST OF TEXT AND COMPUTER PROGRAM SYMBOLS

Text Symbol	Fortran Equivalent	Use
	AN	Sum of anions (equiv/l) or a general term for an anion
	ACCA,ACMG,... etc.	Apparent activity coefficients of Ca, Mg, ... etc.
	ACT1, ACT2	Activity coefficients for mono- and divalent ions
(Cl),(SO_4),... etc.	ACL,ASO_4,... etc.	Anion activities in solution (moles/l)
(Ca),(Mg),... etc.	ACA, AMG,... etc.	Cation activities in solution (moles/l)
Bd	BD	Soil bulk density (g/cm^3)
	CAT	Sum of cations (equiv/l) or a general term for cation
($CaCO_3^o$),($CaSO_4^o$)		Neutral ion pair activities in solution (moles/l)
$CaCO_3$	CACO or CACOIN	Lime (units vary)
	CASO	Gypsum (units vary)
CEC	CEC	Cation exchange capacity (me/100 g)
	CHARGE	Sum of cations minus sum of anions (CAT-AN)
CO_2		Carbon dioxide gas (atmospheres)
EC	EC or ECOLD	Electrical conductivity (mmhos/cm)
	ESP	Exchangeable sodium percentage
(H)	H	Hydrogen ion activity (mole/l)
I	IS	Ionic strength (moles/l)
	I	Square root of ionic strength $(moles/l)^{\frac{1}{2}}$
K		General selectivity coefficient term
$K_1,K_2,K_3...$	K1,K2,K3,...	Selectivity coefficients used in XCHANG subroutine
K_{a1}	KA1	First carbonic acid dissociation constant
K_{a2}	KA2	Second carbonic acid dissociation constant
K_{d1}	KD1	$CACO_3^o$ stability constant
K_{d2}	KD2	$CAHCO_3^+$ stability constant
K_{d3}	KD3	$CaOH^+$ stability constant
K_{d4}	KD4	$CaSO_4^o$ stability constant
K_{d5}	KD5	$MgCO_3^o$ stability constant
K_{d6}	KD6	$MgHCO_3^+$ stability constant
K_{d7}	KD7	$MgOH^+$ stability constant
K_{d8}	KD8	$MgSO_4^o$ stability constant
K_{d9}	KD9	$NaSO_4^-$ stability constant
K_{d10}	KD10	$NaCO_3^-$ stability constant
K_H	KH	Henry's law constant for CO_2 solubility
K_W	KW	Dissociation constant for water
(OH)		Hydroxide ion activity (moles/l)
P_{CO_2}	PCO2	Partial pressure of CO_2
pH	PH	Negative log of hydrogen ion activity
	SCA,SMG,... etc.	Soluble plus exchangeable cations (SCA=TCA+XCA, SMG=TMG+XMg.....etc.)
Ca,Mg,...etc.	TCA,TMG,... etc.	Cation concentrations (me/l or moles/l)
Cl,SO_4,... etc.	TCL,TSO4,... etc.	Anion concentrations (me/l or moles/l)
SAR	SAR	Sodium adsorption ratio
Θ	VH20	Volumetric water content (cm^3/cm^3)

Text Symbol	Fortran Equivalent	Use
	X1,X2	Starting values for Newton method iteration
K_{sp}	SP	General term for solubility product
K_{sp_1}	SP1	Solubility product for $CaSO_4 \cdot 2H_2O$
K_{sp_2}	SP2	Solubility product for $CaCO_3$
X_{Ca}, X_{Mg}.. etc.	XCA,XMG,.. etc.	Exchangeable cations (me/100 g)
	ZCA,ZMG	Square root of ACA, AMG
Z	Z	Ionic charge

I. INTRODUCTION

The conventional approach to salinity control in irrigated agriculture is to apply additional water beyond that needed for plant growth for the purpose of leaching or washing salt below the root zone. The salt to be leached is calculated to be that brought to the soil in the irrigation water. The simplest expression (USDA Handbook 60, 1954) of this concept is the salt balance equation:

$$EC_{iw} \times D_{iw} = EC_{dw} \times D_{dw} \quad . \quad . \quad . \quad . \qquad (1)$$

where EC_{iw} and EC_{dw} are the electrical conductivities, i.e., the salt concentrations, of the irrigation water and subsurface drainage water respectively and D_{iw} and D_{dw} are the depths, i.e., the total volumes, of the irrigation water infiltrated into the soil and the subsurface drainage water removed, respectively. A salt balance is achieved when the volume of salt removed equals the volume of salt added.

When the soils to be irrigated initially contain excess salts, extra water is added for leaching to reduce the salt content of the soil to a normal level. The excess salt is carried away in the subsurface drainage water.

In a river system, such as the Colorado, the river is both the primary source of water and the sink for the drainage or salt removal system. In the Upper Colorado River Basin where the irrigation water is obtained from mountain streams, relatively low salinity water is diverted and the subsurface return flows may pass through soils containing considerable salts. Where this occurs, the subsurface drainage water may carry more salt into the river than would be expected from a simple salt balance computation. In these circumstances, the soil acts as a salt source.

Unexpectedly, field studies of water management to control quality and quantity of return flow have shown circumstances under which the soil can also act as a sink for salt (Willardson and Hanks, 1976). In these circumstances, less salt is removed from the soil than is added; but the soluble salt concentration in the soil does not appear to increase proportionally.

After the source-sink behavior of soil and water was documented by field research (Willardson and Hanks, 1976), the present project was prepared to investigate the problem in detail. The objectives of the study were:

1. To determine the areal extent of soils that exhibit source-sink potential in the Upper Colorado River Basin and perfect procedures for evaluating the source-sink potential of these soils.

2. To identify the physical and chemical properties of soil important in the source-sink phenomenon.

3. To develop a method to predict the effects of long term irrigation management options on the quality of irrigation return flow for soils with various source-sink potentials.

4. To develop water management guidelines for these soils that will be effective in controlling return flow quality.

The previous field studies (Willardson and Hanks, 1976) showed that certain soils in the Upper Colorado River Basin do not require high levels of leaching to maintain a relatively low salt concentration in the water in the root zone. In effect, these soils behave as salt sinks. Increasing the leaching amount does not appreciably reduce the salt concentration in the soil solution; and in this situation, the soil behaves as a salt source. Thus the same soil acts as a salt source or a salt sink depending on the management practices followed.

This research was therefore directed toward identification of the soil and water interactions that result in salt source or sink behavior of soils and the effect of various management alternatives on the quality and quantity of return flow from irrigation projects.

II. METHODS

Both laboratory studies and computer modeling were used to pursue better understanding of soil behavior as a salt source or sink required to establish irrigation management practices effective for salinity control. Four specific studies used were:

1. A laboratory study of chemical precipitation during cycles of evaporation and water additions in a prepared solution salinized to represent irrigation water.

2. Greenhouse studies to determine how interactions between soil salts and nutrients affect fertility as evidenced in the growth of barley.

3. Application of the theory of soil solution chemistry reactions through computer modeling of salt movement downward through the root zone.

4. Hydrologic modeling of water and salinity movement in a large irrigated area in order to apply the results of the other three studies to determine how various water management practices affect soil and drainage water salinity. This modeling was based on the Ashley Valley in the Uintah Basin of northeastern Utah.

This section presents the methods used in each of these studies in the above order. The next section follows the same order in presenting and discussing the results.

Precipitation in Solution

A laboratory study was made to evaluate salt sink behavior in a simple solution. Salts were mixed to give an irrigation water of a relatively high salt content. The artificially salinized water had the following ion proportions:

Ca^{2+}	12 meq/l
Mg^{2+}	12 meq/l
Na^{+}	12 meq/l
SO_4^{2-}	34 meq/l
Cl^{-}	2 meq/l

The electrical conductivity of this irrigation water was 2.90 mmhos/cm. The sodium adsorption ratio (SAR) was 3.46. The sodium percentage was 33.3.

This solution was placed in a beaker and was subjected to wetting (water additions) and drying (evaporation) cycles simulating those which occur in an irrigated soil profile. The electrical conductivity of the solution was the only parameter monitored in the experiment.

An initial volume of 1000 ml was put in a beaker. The solution was evaporated to a volume of 800 ml by boiling gently. The solution was cooled to a temperature of 25 C and a 50 ml sample of the solution was removed for determination of electrical conductivity. The remaining 750 ml of solution were evaporated to a volume of 500 ml, again by gentle boiling; then 500 ml of the original irrigation solution were added to the beaker to bring the total volume of the solution back to the original 1000 ml. The procedure was repeated for 16 cycles. Addition of 500 ml of water simulates an irrigation, and the removal of the 50 ml sample for testing in each cycle is equivalent to a 10 percent leaching fraction. Removal of the 50 ml sample when the total volume was reduced to 800 ml in each cycle simulates extraction of a sample of the soil solution when the soil is near field capacity.

Salinity-Nutrient Interactions

Salinity management by control of water application may reduce root zone salinity. Even if it does not, some experimental work suggests that an interaction between soil fertility and salinity may reduce the effects of increased salt concentration in the root zone.

To determine whether fertility management could be a possible adjunct to salinity control, a greenhouse experiment was conducted using a nongypsiferous soil in small pots to determine the interaction effects of water quality, irrigation management, and fertilization upon the nutrition of barley. Four levels of nitrogen fertilizer (0, 100, 200, and 400 lb-N/ac), three levels of phosphorus fertilizer (0, 40, and 80 lb-P/ac), four levels of salty irrigation water (EC = 0.5, 1.5, 4.5, and 13.5 mmho/cm) and three frequencies of irrigation (2, 4, and 8-day intervals) were used. The number of treatments was (4 nitrogen) x (3 phosphorus) x (4 salinity water) x (3 irrigation management) x (4 replications) = 576. Barley (Hordeum vulgaris L.) was used as an indicator crop. To assure a good stand of plants, six to eight seeds were planted in each container (described below), irrigated with tap water until the seedlings were established,and then thinned at the two-leaf stage to two plants per pot. Salinity and water management treatments commenced after thinning.

Two types of pots were used in the experiment. Two of the replications and one-third of the other two replications were grown in plastic tubes 10 cm in diameter and 35 cm in length. These were closed at the bottom with a perforated plastic plate so that leachate passing the 30 cm soil depth could be collected. Two thirds of the other two replications were grown in hard paper pots containing the same weight of soil as was used in the leaching tubes. These pots, when filled, had a soil surface diameter of 21 cm. The combined total of both pot types provided four replications for the yield data and two replications of leachate and soil salinity data for the experiment.

The pots and plastic tubes were all filled with soil at a bulk density of 1.5 g/cm^3 obtained by packing the pots with 3.5325 kg of soil that had passed a 4-mm sieve.

The fertilizer treatments were all mixed into the upper 3 cm of the soil. The treatments form a complete 4 x 3 factorial for nitrogen and phosphorus. The nitrogen was applied as urea ($(NH_2)_2CO$ = 46%N) and the phosphorus as calcium superphosphate ($(Ca(H_2PO_4)_2 \cdot H_2O$ = 25.2%P).

The four irrigation waters were artificially mixed using a base of distilled water for the first 8 weeks and tap water for the rest of the growing period. The tap water electrical conductivity was 0.3 mmho/cm @ 25°C and contained less than 0.5 me/l sodium. Calcium and sodium chlorides were added in predetermined proportions to establish the four levels of water salinity (EC = 0.5, 1.5, 4.5, and 13.5 mmho/cm) while maintaining in all cases a sodium adsorption ratio (SAR) of 3.5 $(mM/L)^{1/2}$. The relation 1 mmho/cm = 10 me/L (1) was used for calculating the quantity of added salts.

Irrigation intervals of 2, 4, and 8 days were used between irrigation water applications. Field capacity for the soil was assumed to correspond to 25 percent water by volume. Therefore, prior to planting, 600 ml of tap water were added to each container. For the first 8 weeks, the volume of irrigation water applied was 300 ml per pot at each treatment irrigation. After 8 weeks the volume of applied water was doubled to 600 ml per irrigation. This increased irrigation quantity was required to meet the increased evapotranspiration demand resulting from plant growth and greenhouse temperature changes. During the course of the experiment, a relative difference was maintained between water application treatments of approximately 4:2:1 on a volume basis since a uniform amount of water was applied at 2, 4, and 8 day intervals to the different irrigation treatments.

Six weeks after sowing, the total number of tillers and the average height of the plants in the leaching cylinders were recorded. The average height was determined as the mean of the heights of the longest leaf of each plant. Selected treatments were photographed 3, 7, and 14 weeks after planting to record visual comparisons.

On June 4, 1978, one week after the last irrigation water application, the crop was harvested from all pots. The total growing season was 138 days. Main heads and tiller heads were harvested separately. The remainder of the plant upper parts were retained in paper bags for dry matter determinations. Gravimetric measurements of yield were made 4 weeks later in order to give the harvested material sufficient time to be air dried inside paper bags. Measurements made were of dry weight of the straw, number of main and tiller heads, and number of seeds and dry florets from main and tiller heads per each container. The weight of seeds from main and tiller heads was also determined.

The volume and electrical conductivity (EC) of the leachate samples were measured after every second irrigation. For water application frequencies (4 and 8 days), samples were taken after each irrigation in the last month of the growing season. Volume measurement was accomplished in the greenhouse immediately after collection.

Two composite soil samples were taken from each of the leaching cylinders at the end of the experiment. These samples represented the 0-15 cm and 15-30 cm depths, and were analyzed to determine the average EC_e at the 7.5 cm and 22.5 cm depths.

Electrical conductivities of the leachate samples and of the 1:1 soil extracts were measured in the laboratory. The electrical conductivity of the soil saturation extract was obtained by converting the $EC_{1:1}$ to EC_e, knowing the saturation percentage of the soil. The pH of the 1:1 extract was determined.

Eight yield parameters were obtained. These included 1) dry weight of straw, 2) grain weight from main heads, 3) number of main heads, 4) number of tiller heads, 5) number of seeds from main heads, 6) number of infertile florets from main heads, 7) number of seeds from tiller heads, and 8) number of infertile florets from tiller heads. Only two of these parameters, dry weight straw and grain weight from main heads, are discussed herein. A complete presentation of the data may be found in Bamatraf (1979).

Soil Chemistry Model

Movement of salt in the soil profile is a complex process. The salt moves primarily with the water; but while movement is taking place, the salt is reacting with the soil and other salts present in solution. In an agricultural situation, plants are extracting water from the soil solution by absorbtion through their roots. The nature of the root membranes is such that the plants can absorb the water without absorbing proportional amounts of salt. As the volume of water in the soil is decreased, the salt concentration increases and chemical precipitation may occur. If there is residual salt already in the soil, application of relatively high quality irrigation water may dissolve the salts, thereby increasing the salt concentration of the soil solution. These same salts may reprecipitate lower in the root zone as the plants remove water from the soil.

To portray the complex dynamic system described above, a computer model was developed that incorporated procedures developed earlier by others for examining parts of the system. A new model designed for calcareous soils was developed to better describe soil solution chemistry reactions.

Theory

The transport model of Childs and Hanks (1975), which has proven effective for simulating water flow and nonreactive salt transport, was modified to transport Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and SO_4^{2-} ions. The original model moved all salts as a group represented as me/l. After the transport model has executed a predetermined number of salt and water movement calculations, the user can specify through the input data whether to 1) print out the salt profile without considering chemical reactions, 2) call a chemical equilibrium subroutine to bring the solution salts into equilibrium with the lime and gypsum content of the soil, or 3) call in addition a cation exchange subroutine to include cation exchange equilibrium in the calculations.

Chemical equilibrium subroutine (CHEM). The chemistry model assumes that 1) the soil contains lime ($CaCO_3$), 2) that the soil is sufficiently buffered that the pH of each depth increment is constant, and 3) each soil depth increment is an open system with respect to carbon dioxide (CO_2) exchange with the soil atmosphere. Henrys law constant for CO_2 was also assumed to be independent of temperature and salt concentration.

The soil solution electrical conductivity (EC, mmhos/cm) was calculated from individual ion concentrations using the exponential method of McNeal et al. (1970). Solution ionic strength (I, moles/l) was calculated (Griffin and Jurinak, 1973) from:

$$I = 0.0127\ EC \quad \ldots\ldots\ldots \quad (2)$$

The mono- and divalent ion activity coefficient (γ_1 and γ_2) were calculated from the Davies relationship (Stumm and Morgan, 1970):

$$\log \gamma_i = -0.509\, Z_i^2 \left(\frac{I^{1/2}}{1.0 + I^{1/2}} - 0.3\, I\right) \quad \ldots\ldots\ldots \quad (3)$$

where Z_i is the ionic charge.

The partial pressure of CO_2 (P_{CO_2}) was calculated from pH and (Ca^{2+}) data using the equation developed as follows:

$$CO_2 + H_2O = H_2CO_3$$

$$\frac{H_2CO_3}{P_{CO_2}} = K_H$$

rewritten in terms of P_{CO_2} as:

$$P_{CO_2} = \frac{H_2CO_3}{K_H} \quad \ldots\ldots\ldots \quad (4)$$

then:

$$H_2CO_3 = H^+ + HCO_3^-$$

$$\frac{(H^+)\,(HCO_3^-)}{(H_2CO_3)} = K_{a1}$$

is rewritten in terms of H_2CO_3 and substituted into Equation 4, giving:

$$P_{CO_2} = \frac{(H^+)\,(HCO_3^-)}{K_H\, K_{a1}} \quad \ldots\ldots \quad (5)$$

where K_{a1} is the first dissociation constant for H_2CO_3. Next:

$$HCO_3 = H^+ + CO_3^{2-}$$

$$\frac{(H^+)\,(CO_3^{2-})}{(HCO_3)} = K_{a2}$$

is rewritten in terms of HCO_3^- and substituted into Equation 5 gives

$$P_{CO_2} = \frac{(H^+)^2\,(CO_3^{2-})}{K_H\, K_{a1}\, K_{a2}} \quad \ldots\ldots \quad (6)$$

where K_{a2} is the second dissociation constant for HCO_3^-. Then:

$$CaCO_3 = Ca^{2+} + CO_3^{2-}$$

$$(Ca^{2+})\ (CO_3^{2-}) = K_{SP2}$$

is rewritten in terms of (CO_3^{2-}) and substituted into Equation 6 gives

$$P_{CO_2} = \frac{(H^+)^2\ K_{SP2}}{K_H\, K_{a1}\, K_{a2}\ (Ca^{2+})} \quad . \quad . \quad . \quad . \quad (7)$$

Values for CO_3^{2-}) were calculated from Equation 6, rewritten in terms of (CO_3^{2-}), and (HCO_3^-) was calculated using Equation 5, rewritten in terms of HCO^-). Using activity coefficients and the appropriate equations and stability constants, the ion activities were corrected for ion pairing for (Ca), (Mg), (Na), and (SO_4). The ion pairs considered significant in the soil systems studied were $CaCO_3^0$, $CaHCO_3^+$, $CaOH^+$, $CaSO_4^0$, $MgCO_3^0$, $MgHCO_3^+$, $MgOH^+$, $MgSO_4^0$, $NaSO_4^-$ and $NaCO_3^-$.

The equation to calculate calcium activity, corrected for ionic strength and ion pairing is developed from the initial equations:

$$Ca = \frac{(Ca^{2+})}{\gamma_{Ca}} + \frac{(CaHCO_3^+)}{\gamma_{CaHCO_3^+}} + \frac{(CaOH^+)}{\gamma_{CaOH^+}} + \frac{(CaCO_3^0)}{\gamma_{CaCO_3^0}} + \frac{(CaSO_4^0)}{\gamma_{CaSO_4^0}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where Ca is the total calcium concentration in solutions (moles/l), (Ca^{2+}) is the activity of free calcium ion in solution, and the other terms in parentheses are the respective ion pair activities. Since $CaCO_3^0$ and $CaSO_4^0$ are uncharged, their activity coefficients are assumed to equal 1. The activity coefficients of $CaHCO_3^+$ and $CaOH^+$ are assumed to be equal and were designated as γ_1. The activity coefficient for calcium is designated as γ_2. The activity of each ion pair can be written in terms of its stability constant and component ions as follows:

$$(CaHCO_3^+) = \frac{(Ca^{2+})\ (HCO_3^-)}{K_{d2}}$$

$$(CaOH^+) = \frac{(Ca^{2+})\ (OH^-)}{K_{d3}}$$

$$(CaCO_3^0) = \frac{(Ca^{2+})\ (CO_3^{2-})}{K_{d1}}$$

$$(CaSO_4^0) = \frac{(Ca^{2+})\ (SO_4^{2-})}{K_{d4}}$$

where K_{d1}, K_{d2}, ... etc., are the respective stability constants. These expressions are then substituted into (8) and (Ca^{2+}) is factored from the right side to give

$$Ca = (Ca^{2+}) \left[\frac{1}{\gamma_2} + \frac{(HCO_3)}{K_{d2}\gamma_1} + \frac{(OH)}{K_{d3}\gamma_1} + \frac{(CO_3)}{K_{d1}} + \frac{(SO_4)}{K_{d4}} \right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Values for (HCO_3^-), (OH^-) and (CO_3^{2-}) can be obtained in terms of the H_2CO_3 dissociation constants, (H^+), K_H and P_{CO_2}. Equation 5 is rewritten in terms of (CO_3^{2-}) and these are substituted into Equation 9. The dissociation of water

$$H_2O = H^+ + OH^-$$

expressed as

$$(H^+)\ (OH^-) = K_W$$

is written in terms of (OH^-) and substituted into Equation 9. The value for (SO_4^{2-}) is obtained from a previous calculation similar to Equation 10. With these substitutions Equation 9 can be rewritten as

$$(Ca^{2+}) = Ca \div \left[\frac{1}{\gamma_2} + \frac{K_{A1}\, K_H\, P_{CO_2}}{(H)\ K_{d2}\ \gamma_1} + \frac{K_W}{(H)\ K_{d3}\ \gamma_1} + \frac{K_{A1}\, K_{A2}\, K_H\, P_{CO_2}}{(H)^2\ K_{d1}} + \frac{(SO_4^{2-})}{K_{d4}} \right] \quad . \quad . \quad . \quad . \quad (10)$$

The same approach is used to develop the equations for (Mg^{2+}), (Na^+), (K^+), (SO_4^{2-}) and (HCO_3^-) calculation.

Using the corrected (Ca^{2+}) and (CO_3^{2-}) or (SO_4^{2-}) values and the appropriate solubility product (K_{SP}) the amount of slightly soluble salt that must be added or removed from solution to bring the system into equilibrium can then be calculated by solving

$$(CAT-X)(AN-X) = K_{SP} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

for X where CAT is the solution cation activity and AN is the solution anion activity for the precipitation or dissolution reaction being considered.

The above cation activity calculations also provide corrected cation activity values for the cation exchange calculations.

Cation exchange subroutine (XCHANG). The cation exchange subroutine assumes that CEC is a constant for a given soil, independent of pH, ion type and concentration, that the soil solution is a true solution and that cation exchange is a reversible process. The subroutine did not consider anion exchange and further assumed that the sum of exchangeable Ca, Mg, Na, and K equals the CEC. That is:

$$\mathrm{CEC} = X_{Ca} + X_{Mg} + X_{Na} + X_K \quad . \; . \; . \; . \; . \quad (12)$$

where CEC is in me/100 g of soil and X_{Ca}, X_{Mg}, X_{Na}, and X_K are the exchangeable cations (me/100 g).

The selectivity coefficients K_1 through K_6 for the equilibrium between the cations in solution and the exchangeable cations are defined as:

$$\frac{(Ca^{2+})\ X_{Mg}}{(Mg^{2+})\ X_{Ca}} = K_1 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (13)$$

$$\frac{(Na^{+})\ X_{Ca}}{(Ca^{2+})^{\frac{1}{2}} X_{Na}} = K_2 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (14)$$

$$\frac{(K^{+})\ X_{Ca}}{(Ca^{2+})^{\frac{1}{2}}\ X_K} = K_3 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (15)$$

$$\frac{(K^{+})\ X_{Mg}}{(Mg^{2+})^{\frac{1}{2}}\ X_K} = K_4 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

$$\frac{(Na^{+})\ X_{Mg}}{(Mg^{2+})^{\frac{1}{2}}\ X_{Na}} = K_5 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (17)$$

$$\frac{(Na^{+})\ X_K}{(K^{+})\ X_{Na}} = K_6 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (18)$$

and the cation activities used in the above equations were corrected for ionic strength effect and ion pairing in the CHEM subroutine.

The equation for calculating X_{Ca} was developed by first rewriting Equations 13, 14, and 15 as follows:

$$X_{Mg} = \frac{(Mg^{2+})\ X_{Ca}\ K_1}{(Ca^{2+})} \quad . \; . \; . \; . \; . \; . \; . \quad (19)$$

$$X_{Na} = \frac{(Na^{+})\ K_{Ca}}{(Ca^{2+})^{\frac{1}{2}}\ K_2} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (20)$$

$$X_K = \frac{(K^{+})\ X_{Ca}}{(Ca^{2+})^{\frac{1}{2}}\ K_3} \quad . \; . \; . \; . \; . \; . \; . \quad (21)$$

These were then substituted into Equation 12 and X_{Ca} was factored from each right hand term to give:

$$\mathrm{CEC} = X_{Ca}\left[\frac{(Mg^{2+})K_1}{(Ca^{2+})} + \frac{(Na)}{(Ca^{2+})^{\frac{1}{2}}K_2} + \frac{(K)}{(Ca^{2+})^{\frac{1}{2}}K_3} + 1\right] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (22)$$

Dividing both sides of Equation 22 by the form in brackets gives:

$$X_{Ca} = \mathrm{CEC} \div \left[\frac{(Mg^{2+})K_1}{(Ca^{2+})} + \frac{(Na^{+})}{(Ca^{2+})^{\frac{1}{2}}K_2} + \frac{(K)}{(Ca^{2+})^{\frac{1}{2}}K_3} + 1\right] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (23)$$

Following this same procedure for Mg^{2+}, Na^{+}, and K^{+} gives Equations 24 through 26:

$$X_{Mg} = \mathrm{CEC} \div \left[\frac{(Ca^{2+})}{(Mg^{2+})K_1} + \frac{(Na^{+})}{(Mg^{2+})^{\frac{1}{2}}K_5} + \frac{(K)}{(Mg^{2+})^{\frac{1}{2}}K_4} + 1\right] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (24)$$

$$X_{Na} = \mathrm{CEC} \div \left[\frac{(Ca^{2+})^{\frac{1}{2}}K_2}{(Na^{+})} + \frac{(Mg^{2+})^{\frac{1}{2}}K_5}{(Na^{+})} + \frac{(K^{+})K_6}{(Na^{+})} + 1\right] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (25)$$

$$X_K = \mathrm{CEC} \div \left[\frac{(Ca^{2+})^{\frac{1}{2}}K_3}{(K^{+})} + \frac{(Mg^{2+})^{\frac{1}{2}}K_4}{(K^{+})} + \frac{(Na^{+})}{(K^{+})K_6} + 1\right] \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (26)$$

Equations 23 through 26 are the basis for the XCHANG subroutine which equilibrates solution and exchangeable cation concentrations during water and salt movement. The input required to define the initial exchangeable cation concentration are the soil CEC, the solution cation activities, and the selectivity coefficients for the appropriate exchange reactions. In subsequent exchangeable cation-solution cation adjustments, the solution cation concentrations and the parameters θ (water content) and Bd (bulk density) are also needed for each soil depth increment.

The above described approach can be expanded to any number of cations, provided the selectivity coefficients can be approximated for all possible cation pair, exchange reactions.

Modeling Procedure

The water movement-salt transport model of Childs and Hanks (1975) was modified so that it could be interfaced with the new subroutines (CHEM and XCHANG) presented above to describe the precipitation and dissolution of gypsum and lime in soils. Because the objectives of this study were primarily the development and testing of the chemical subroutine, the options to run more than one set of data at a time and to print out extra testing data that were part of the original model were omitted. The yield prediction calculations were also removed since the validation data were obtained from small lysimeters under artificial cropping conditions and the yields did not correspond to field conditions.

Only that part of the transport model that has been changed to allow interfacing with the CHEM subroutine is described (Appendix A). For a detailed transport model description see Wolf (1977).

In the described model format, the input data can be read from card, disk, or tape files (Appendix B). The first file contains the irrigation, rain, and evapotranspiration rates and durations, and the transported ion concentrations (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and $SO_4{}^{2-}$) for each irrigation water application. The second file contains the plant growth data, CEC, soil depth increments, root distribution with depth, initial water content, initial lime and gypsum profiles, pH, bulk density (Bd) and the initial soil solution concentrations of the transported ions. The third file contains the moisture release curve data and the corresponding hydraulic conductivity data.

Several options are available. If KIL1=0, the input data are printed out, if 1, the data are not printed out. When KILKEM=1, the CHEM subroutine is not called and the transported salts are moved in the profile without chemical or physical interaction with the soil. If KILEXC=1 the XCHANG subroutine is not called by the CHEM subroutine and cation exchange is not considered. The input values given to NWATER, INSOIL and MATRIX are the calling numbers for the data files described above which will be called, and are read in at program execution time. KALKEM is the number of moisture and salt movement calculations between each soil chemistry calculation and/or printout and is also read in at program execution time.

The SF array in the transport model, which originally contained the me/l of total salts in each irrigation water application has been changed to a two dimensional array containing the concentration of each transported ion (me/l) in each irrigation water application. For rain water application the concentration values cannot be zero since they are used in the denominator of some calculations. The value of 0.01 me/l is suggested.

The SE array in the transport model, that originally contained the me/l total dissolved salts in each soil depth increment, was changed to a 25x21 array that gives a complete physical and chemical soil profile description that is a function of time. A detailed description of the array is given in the CHEM subroutine development.

When the CHEM subroutine is used, the initial soil solution is equilibrated with lime and gypsum, if present, and if the XCHANG subroutine is called, initial X_{Ca}, X_{Mg}, X_{Na}, and X_K values are calculated from soil solution cation activities before any water or salt movement is calculated. These data are then printed.

The salt component term of the root sink function is calculated as the sum of Ca, Mg, Na, and K, expressed as the me/l total salts.

The salt transport loop was altered to move Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and $SO_4{}^{2-}$ independently as individual ion concentrations, whereas the original model (Childs and Hanks, 1975) moved salts as me/l total salts.

After each salt and water movement calculation the water balance is printed out. After KALKEM number of water calculations, either the soil profile data are printed or the CHEM subroutine is called with or without the XCHANG subroutine for each depth increment and the resulting soil profile description is printed. If CHEM is not called, $HCO_3{}^-$ is calculated as the cations minus the anions with $CO_3{}^-$ assumed to be zero. Soil solution EC and the SAR are calculated and both values are included in the print out.

The soil profile data calculated according to the option chosen is also printed after the final salt and water movement calculation (at TIME=CUMT).

Chemical equilibrium subroutine (CHEM). The required inputs for the CHEM subroutine are gypsum, lime (decimal fraction of soil on weight basis), pH, bulk density (g/cm^3), Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, and $SO_4{}^{2-}$ concentrations (me/l) and the volumetric water content (θ, cm^3/cm^3). If cation exchange is calculated, the soil CEC (me/100 g) is required and X_{Ca}, X_{Mg}, X_{Na}, and X_K (me/100 g) values are required for all but the initial calculation of exchange equilibrium. The CHEM subroutine returns new values for gypsum, lime, the transported ions, and exchangeable cations if exchange was calculated. Values are also calculated for $HCO_3{}^-$ and $CO_3{}^{2-}$ (me/l) concentration, EC (mmhos/cm) and SAR. Values of pH, Bd, θ, and CEC are assumed constant during execution of the subroutine. Flow charts for CHEM and the subroutines it calls are given in Appendix C.

The constants, K_{a1} and K_{a2}, K_H, gypsum and lime solubility products, and the various ion pair stability constants needed are listed in a DATA statement at the beginning of the subroutine. All constants were taken from Adams (1971) except, the solubility product of lime (Suarez, 1977).

The CHEM subroutine first converts the solution ion concentrations to moles/l and approximates values for HCO_3^- and CO_3^{2-}. If the Ca concentration is less than 0.0005 molar (1.0 me/l) the pH of that soil increment is changed to 8.4, the pH of a lime solution in contact with atmospheric CO_2. This is necessary when more than 10 to 15 cm of rain water is applied in one application without being interrupted by evaporation of water from the soil surface. Otherwise the leaching of lime from the surface soil depth increments is too rapid. The (H^+) value is next calculated from the pH value read in and the gypsum and lime contents are converted to moles/l units for later calculations.

The ECII subroutine is next called to calculate EC from ion concentrations and then the ACT function calculates the mono- and divalent ion activity coefficients (γ_1 and γ_2) using Equations 2 and 3.

Partial correction for ion pairing and ionic strength corrections are calculated for (SO_4^{2-}), (K^+), (Na^+), (Ca^{2+}), and (Mg^{2+}) before entering the chemical equilibrium loop. An example of how these equations were developed is shown for (Ca^{2+}) in the theory section (Equations 8 through 10).

The chemical equilibrium loop equilibrates the soil solution with lime and gypsum, if present at the predetermined pH.

Within the iteration loop, γ_1 and γ_2 are recalculated from the current EC value. Next P_{CO_2} is calculated from (H^+) and (Ca^{2+}) using Equation 5.

New corrected values are next calculated for (Ca^{2+}), (Mg^{2+}), (Na^+), and (SO_4^{2-}) from updated values of these calculations from previous iterations. A new (CO_3^{2-}) value is next calculated using Equation 6 rewritten in terms of (CO_3^{2-}).

An "apparent" activity coefficient for Ca is calculated by dividing (Ca^{2+}) by Ca. This value was used to convert the lime and gypsum to units equivalent to those of (Ca^{2+}). Using the values calculated for (Ca^{2+}), (CO_3^{2-}), (SO_4^{2-}), lime, gypsum and the appropriate solubility products, the PRECIP subroutine is called to bring the solution into equilibrium with lime and then with gypsum. The lime and gypsum are then converted back to moles/l and a new P_{CO_2} value is calculated using the new (Ca^{2+}) value. New (HCO_3^-) and (CO_3^{2-}) values are calculated from the new P_{CO_2} value. New solution concentrations are next calculated for Ca^{2+}, CO_3^{2-}, HCO_3^-, and SO_4^{2-}.

The original EC value is then compared with the EC calculated from the new ion concentration values and if the EC change exceeds 1 percent of the new EC value the equilibrium loop is repeated, otherwise the loop is exited.

If the net charge balance between cations and anions is less than 1 percent of the total cation charge, the ionic charge balance loop is stepped over. Otherwise a correction factor, F, is calculated for use in the charge balance loop. If the net charge is positive, Ca^{+2} is divided by F and HCO_3^-, CO_3^{2-}, and SO_4^{2-} (if gypsum is present) are multiplied by F. Lime is increased by adding the product $CO_3(F-1.0)$ to it and if gypsum is present it is decreased by subtracting the product $SO_4(F-1.0)$ from it. This series of calculations assumes the system is open to CO_2. As CO_2 is added to the solution at constant pH, HCO_3^- and CO_3^{2-} are formed. This requires that lime precipitate to maintain equilibrium conditions. The precipitation of lime decreases Ca^{2+} concentration which in turn increases gypsum solubility, if gypsum is present and maintains the solution saturated with respect to gypsum. It is assumed that the $HCO_3:CO_3$ ratio remains constant. The net effect is that the anion concentration increases and the cation concentration decreases. At this point the charge balance is again compared with the net cation charge and if the net difference still exceeds 1 percent of the total cation charge, the above calculations are repeated until electrical neutrality is approached, at which time the loop is exited.

If the initial net solution charge is negative, the procedure is reversed with CO_2 going out of solution, with Ca^{2-} increasing and HCO_3^-, CO_3^{2-}, and SO_4^{2-} (if gypsum is present) decreasing. Under these conditions lime is dissolved and gypsum is precipitated.

If cation exchange is to be simulated, the XCHANG subroutine is called at this point in the calculations, and the soil solution is equilibrated with the exchange phase. The ion concentrations are converted back to me/l and lime and gypsum are converted to decimal fractions. SAR is also calculated at this point and the subroutine returns to the main program (transport model) with the new values calculated.

The values passed back from the CHEM subroutine go into the two dimensional SE array. This array, when printed, gives a 21 column table. The rows represent soil depth increments (Appendix D). The columns are values for gypsum, lime (percent of soil by weight), pH, Bd (g/cm^3), Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} (me/l), θ (cm^3/cm^3), EC (mmhos/cm), SAR, exchangeable Ca, Mg, Na, and K (me/100 g) and soil depth increment boundaries (Robbins, 1979).

The ACT function called by CHEM calculates ionic strength (I) from EC using Equation 2 and then calculates mono- and divalent ion activity coefficients (γ_1 and γ_2) from I and Z_i, the ionic charge, using Equation 3.

The subroutine PRECIP uses a cation and an anion activity and the appropriate solubility product to determine whether solid precipitate should be dissolved or whether solution ions need to be precipitated to bring the solution into equilibrium with the precipitate. The SINK subroutine is then called to calculate the quantity of material that needs to change phase. When dissolving the chemical precipitate, the amount dissolved is not allowed to exceed the amount present. The cation and anion activities and the precipitate content are then corrected by this value and these corrected values are returned to the CHEM subroutine.

Using the cation and anion concentration, the solubility product and a starting value pass from the PRECIP subroutine, the SINK subroutine calculates the amount of solid phase material that must be dissolved or the moles/l of cation and anion that must be precipitated to bring the solution concentration into equilibrium with the solid phase material. This was accomplished by rewritting Equation 11 as:

$$X^2 - X * CAT - X * AN + CAT * AN - SP = 0 \quad . \ . \ . \ . \ . \ . \ . \ (27)$$

and then finding the appropriate root by the Newton method (Carnahan et al., 1969). A starting value near the solubility product value is used. The new value of X is then passed back to the PRECIP subroutine as the value to which the cation and anion concentrations must be increased or decreased and correspondingly, the amount of solid phase material that must be decreased or increased.

Electrical conductivity is calculated from solution ion concentration by the ECII subroutine. The concentrations may be in moles/l or me/l as long as the proper value is given for M, a flag to indicate which units are used. If mole/l units were read in, they are first converted to me/l. Next the maximum amount of calcium and magnesium sulfate is separated out and designated as gypsum, which has different coefficients than calcium, magnesium, or sulfate ions. The EC is then calculated using the exponential method and coefficients of McNeal et al. (1970). The calculated EC (mmhos/cm) value is then returned to the calling subroutine.

Cation exchange subroutine (XCHANG). Saturation extract concentrations of Ca, Mg, Na, K, Cl, SO_4, and HCO3, and EC for six samples of each of the two soils were determined (Table 1), as were the ammonium acetate extractable Mg, Na, and K. The CEC was also determined for these samples. The exchangeable Mg, Na, and K were calculated as the difference between the extractable and ammonium acetate extractable values. Because these soils contain lime and gypsum, exchangeable Ca was calculated as the CEC minus the sum of the other three cations. The soil samples were selected to give as wide a variety of exchangeable cation ratios as possible under the study conditions.

Table 1. Analytical data used to calculate the selectivity coefficients for the XCHANG subroutine.

Sample	Solution Ion Concentrations							EC	Exchangeable Ions			
	Ca	Mg	Na	K	Cl	SO_4	HCO_3	mmho	X_{Ca}	X_{Mg}	X_{Na}	X_K
Penoyer loam				me/l				mmho/cm		me/100 g		
1	33.40	9.70	1.47	2.63	1.70	39.50	5.80	3.0	4.46	1.87	0.01	0.56
2	24.50	17.33	35.05	3.33	42.40	36.05	1.90	5.6	3.78	2.37	0.31	0.44
3	25.35	17.67	37.33	3.67	53.80	27.50	1.90	6.2	3.89	2.23	0.26	0.52
4	17.10	11.10	14.33	4.00	14.90	30.80	1.60	3.4	4.17	2.01	0.12	0.60
5	30.01	28.33	5.67	3.67	34.30	30.60	2.50	5.7	3.46	2.93	0.04	0.47
6	11.20	4.67	7.72	1.67	1.60	21.00	2.00	1.8	4.55	1.81	0.11	0.43
7	16.30	10.00	5.67	4.33	3.90	31.20	1.70	2.7	4.00	2.12	0.05	0.73
8	15.00	11.67	22.84	3.53	4.20	45.10	2.70	3.8	3.53	2.41	0.16	0.80
Hunting silty clay loam												
9	18.00	8.96	6.04	1.67	8.21	17.30	8.90	2.7	10.16	4.02	0.13	0.59
10	56.25	25.62	15.21	2.08	17.47	70.50	8.10	7.5	9.89	4.24	0.23	0.54
11	38.25	19.37	17.92	2.71	39.70	31.10	7.70	7.0	9.41	4.41	0.32	0.76
12	52.31	26.46	25.21	2.92	69.08	27.60	8.10	9.5	9.67	4.25	0.30	0.68
13	34.31	18.75	8.33	3.33	16.88	38.60	7.40	6.0	9.44	4.44	0.20	0.80
14	42.75	20.41	26.87	1.84	40.85	41.40	8.10	7.5	10.03	3.94	0.35	0.58
15	28.13	12.06	11.87	1.87	10.92	35.50	7.90	4.4	10.05	3.87	0.28	0.70
16	38.25	15.21	5.00	2.08	2.25	49.40	8.00	4.5	10.63	3.56	0.14	0.57

Using the above data in a short version of the CHEM subroutine, activities were calculated for the four cations, correcting each for ionic strength and ion pairing. Equations 13 through 18 were then used to calculate the selectivity coefficients for each soil sample (Table 2). Only the K_5 value was significantly different for the two soils.

X-ray diffraction analysis showed that the two soils contained illite and kaolinite type clay minerals in about equal quantities. These were the only clay minerals detected.

The values obtained for K_1, K_2, and K_3 were compared with values found in the literature for other soils and clays (Table 3). The values reported for K_1 were generally between 0.5 and 1.1 for soils and clays with the exception of two tropical soils and a peat. All K_2 values listed were between 5.6 and 7.1. The K_3 values obtained by Udo (1978) for a kaolonite were considerably higher than the values found for the soils used in this study.

The XCHANG subroutine is divided into two segments (Appendices A and C). If NN in the subroutine calling statement equals 1, the first segment calculates X_{Ca}, X_{Mg}, X_{Na}, and X_K from the cation activities calculated by the CHEM subroutine, for initial soil profile conditions using Equations 23 through 26. The sum of exchangeable cations is then adjusted by a common factor to equal the CEC in me/100 g of soil. This is necessary to eliminate machine round off error in a few cases. Values for the exchangeable ions are then returned to the calling program.

Table 3. Selectivity coefficient values used for this study compared with values found in the literature.

		K_1	K_2	K_3
This study				
Penoyer loam		0.84	6.6	0.38
Hunting silty clay loam		0.83	5.8	0.37
Clark (1966)				
Wyoming bentonite		1.06		
Hunsaker and Pratt (1971)				
Brazilian loam		6.52		
Aiken soils		5.46		
Krishnamoorthy and Overstreet (1950)				
Utah bentonite		0.92		
Yolo clay		0.70		
Paul, Tanji, and Anderson (1966)				
Oakley soil		0.64	5.5	
Hanford soil		0.54	7.0	
Arbuckle soil		0.59	5.6	
Yolo soil		0.67	7.1	
Sacramento soil		0.66	6.8	
Salmon (1964)				
Wyoming bentonite		0.82		
Blisworth illite		0.82		
Peat		0.20		
Udo (1978)			X_R=0.1	X_R=0.2[a]
Kaolinite	10°C	0.52	54.5	28.0
	30°C	0.64	43.2	3.7

[a] X_R is the ratio of potassium to CEC at which these values are measured.

Table 2. Cation activities and selectivity coefficients calculated from data in Table 1.

Sample	Treatment	Sample Depth	Cation Activities Ca^{2+}	Mg^{2+}	Na^+	K^-	K_1	K_2	K_3	K_4	K_5	K_6
Penoyer loam		cm	mmoles/l									
1			5.0	1.6	1.1	3.1	0.90	7.7	0.45	0.23	3.9	17.0
2	5	0-12	3.5	2.6	27.5	2.7	0.84	5.7	0.39	0.28	4.1	15.0
3	5	12-25	3.9	2.8	29.2	2.9	0.79	6.3	0.33	0.24	4.0	17.9
4	5	25-50	2.7	1.9	11.7	3.3	0.70	7.7	0.44	0.26	4.5	17.6
5	13	0-25	4.6	4.6	4.5	2.9	0.86	5.7	0.32	0.27	4.8	17.9
6	14	25-37	2.0	0.9	6.5	1.4	0.98	6.0	0.37	0.21	3.7	17.7
7	14	37-62	2.6	1.7	4.7	3.7	0.82	7.3	0.39	0.26	4.8	18.7
8	14	62-87	1.8	1.5	18.0	2.9	0.83	6.2	0.34	0.26	4.7	18.1
		Selectivity coefficient means and standard deviations					0.84 ±0.08	6.6 ±0.8	0.38 ±0.05	0.25 ±0.02	4.3 ±0.4	17.5 ±1.1
Hunting silty clay loam												
9			3.4	1.8	5.0	1.4	0.76	6.7	0.41	0.23	3.7	17.1
10	7	10-25	6.5	3.2	11.5	1.6	0.88	6.2	0.37	0.23	3.8	16.6
11	9	0-10	5.7	3.0	13.9	2.1	0.89	5.4	0.35	0.23	3.5	15.5
12	9	10-25	7.6	4.0	19.2	2.3	0.84	5.6	0.37	0.22	3.5	15.7
13	9	25-50	4.8	2.8	6.5	2.7	0.82	4.9	0.39	0.24	3.1	13.0
14	11	0-25	5.8	2.9	20.7	1.4	0.78	6.5	0.33	0.18	3.6	19.8
15	11	37-62	4.2	1.9	9.6	1.5	0.85	5.2	0.34	0.19	3.0	15.6
16	13	0-15	5.2	2.2	4.0	1.7	0.79	5.8	0.41	0.23	3.0	13.4
		Selectivity coefficient means and standard deviations					0.83 ±0.05	5.8 ±0.6	0.37 ±0.03	0.22 ±0.02	3.4 ±0.3	15.8 ±2.1

When NN does not equal 1, the second program segment converts previously calculated exchangeable cations to moles/l units for calculation purposes. Apparent activity coefficients are calculated by dividing each cation activity by solution cation concentration. Each cation sum is then calculated as the exchangeable cation plus the soluble cation.

The subroutine then enters a loop which calculates new exchangeable cation values from the cation activities and these are then converted to moles/l in solution values. New soluble cation values are then calculated as a function of the old soluble cation values, the old exchangeable cation values and the new exchangeable cation values. Each exchangeable value is then recalculated as the difference between the cation sum and the soluble cation value. The exchangeable cations are then adjusted by a constant such that their sum is equal to the CEC. New cation activities are calculated for the next time through the loop by dividing each soluble cation value by its apparent activity coefficient.

After exiting the loop, new exchangeable cation values are converted back to me/100 g soil and the subroutine returns new soluble and exchangeable cation values to the calling subroutine.

Computer Model Validation

The chemical and water movement data to be used for model validation were obtained by irrigating two soils with waters containing three different $CaSO_4$ concentrations and using 10 and 25 percent leaching fractions. These 12 treatments (defined on Table 5) were randomly replicated three times in continuous weighing hydraulic lysimeters.

The lysimeter tanks were 0.30 m in diameter and 1.18 m deep. Each contained a 1.0 m depth of soil. Porous ceramic cups (1.0 bar) attached to sampling tubes in the sides of the lysimeters were inserted 0.25, 0.50, and 0.75 m below the soil surface (Robbins and Willardson, 1979). Drains were also provided in the bottom of the tanks. This system allowed for periodic nondestructive sampling of the soil solution and for continuous monitoring of water movement into and out of the soil.

The two soils used in the lysimeters came from Emery County, Utah. Penoyer loam is a coarse-silty, mixed, calcareous, mesic, Typic Tarrifluvent. Hunting silty clay loam is a fine-silty, mixed, calcareous, mesic, Aquic Ustifluvent. The Penoyer loam soil was chosen because it contained gypsum, and the Hunting silty clay loam soil was chosen because it contained no gypsum. Sample 1 in Table 1 is the chemical data for a field sample of the Penoyer soil. Sample 9 is the initial Hunting soil data. The sample of Penoyer loam had a CEC of 6.9 me/100 g, and the Hunting silty clay loam had a CEC of 14.9 me/100 g. The soils were passed through a 0.63 mm sieve and added dry to the lysimeter. The lysimeter tanks were gently pounded until 1.0 m height of each soil was reached. The final bulk densities were 1.42 g/cm^3 for the Penoyer soil and 1.20 g/cm^3 for the Hunting soil.

The lysimeters were planted to alfalfa (Medicago sativa L. 'Ranger'). On July 29, 1977, they were irrigated with 4.1 cm of distilled water. The lysimeters were moved outside on July 31, when the plants were 20 to 30 mm tall. Since some of the plants started to damp off due to Rhizoatonia solani 'Kuhn,' barley (Hardeum vulgare L. 'Steptoe') was planted in each lysimeter on August 6, 1977, to insure a growing crop. Each lysimeter received 1.4 cm of distilled water on August 2, 4, 7, and 10. Distilled water was used initially to establish the plants to prevent salt injury to the young plants during the hot August weather. On August 16 each lysimeter was irrigated with 3.4 cm of the prepared saline water to be used throughout the study. The lysimeters received 9.0 cm of rain on August 18 and 2.6 cm on August 25. They were irrigated with 5.5 cm of their respective salt water treatments on September 2, 7, and 12. Before the September 12 irrigation the lysimeters were moved into a greenhouse. After this date, all lysimeters were irrigated according to their respective water use and leaching fraction requirements.

The lysimeters were irrigated on September 16, 21, 26, 30; October 4, 8, 12, 17, 21, 25, 28, 31; November 4, 9, 14, 21, 28; December 9; January 4, 13, 23; February 1, 10, 20; March 1, 11, 21; and April 2.

The lysimeters were moved from the greenhouse into a large room on December 20 where artificial lighting was installed.

The barley was harvested on December 15 and the alfalfa was cut on February 1, March 11, and April 12.

No attempt was made to predict crop yield because of the unnatural growing conditions. The crops were grown primarily to extract soil moisture thus concentrating the soil solution and promoting chemical precipitation.

The irrigation water chemical compositions are shown in Table 4. The high, medium, and low designation refers to the relative $CaSO_4$ concentration in the water. Table 5 gives the treatments and the lysimeter numbers containing each treatment.

Soil solution samples were taken on September 8, December 15, February 2, March 12, and April 2. On the day following irrigation, sample bottles were attached to the sampling tubes and the bottles were evacuated with a small hand vacuum pump (see

Table 4. Irrigation water compositions.

Gypsum Content	Ca	Mg	Na	K	Cl	SO_4	HCO_3	Total	EC mmhos/cm
					me/l				
High	12.0	1.0	1.5	0.5	1.5	12.0	1.5	15.0	1.10
Medium	7.0	2.0	5.5	0.5	6.5	7.0	1.5	15.0	1.33
Low	5.0	3.5	6.0	0.5	13.0	0.5	1.5	15.0	1.46

Table 5. Treatments and lysimeter numbers containing each treatment.

Treatment number	1	2	3	4	5	6	7	8	9	10	11	12
Irrigation water	High	Med	Low	High	Med	Low	High	Med	Low	High	Med	Low
Leaching factor	10 percent			25 percent			10 percent			25 percent		
Soil	Penoyer loam						Hunting silty clay loam					
Lysimeter numbers	9	18	8	6	0	24	2	1	12	7	4	23
	20	33	11	13	14	27	3	26	17	19	25	31
	21	35	16	15	29	30	5	28	36	22	34	32

Robbins and Willardson, 1979). For most depths it was necessary to re-evacuate the bottles a second time 4 to 6 hours later to obtain a 50 to 100 ml sample.

The samples were taken to the laboratory and pH, EC and Cl, and HCO_3 were measured immediately (Richards et al., 1954). The samples were diluted with an equal volume of 0.1 N HCl. This prevented the lime from precipitating from solution due to the reduced P_{CO_2}. The acid also served to retard biological growth in the samples during storage. Na and K were later determined by flame emission, and Ca and Mg were determined by atomic absorption spectrophotometry. The SO_4 was determined turbidimetrically on a spectrophotometer.

To verify the model, the irrigation water chemical composition, the soil physical and chemical properties, and the irrigation frequency and durations were then read into the computer program. The potential evapotranspiration rate data were adjusted so that the computed evapotranspiration, water storage, and drainage agreed with the values measured with the lysimeters for a particular treatment. The soil profile pH values used in the model were also adjusted so that the predicted HCO_3 concentrations agreed with the measured data since neither in situ pH nor P_{CO_2} data were taken. The computed ion values were compared with the measured values for Ca, Mg, Na, K, Cl, SO_4, EC, and SAR. Calculations were made using 1) salt movement only, 2) salt movement plus chemical precipitation, and 3) salt movement together with chemical precipitation plus cation exchange all combined.

Hydrologic Modeling

Since the movement of water and the salts it carries through the soil profile is only one of numerous processes that occur concurrently in the hydrologic cycle in an agricultural watershed, evaluation of the effectiveness of on-farm water management options requires that this process be examined as part of the total hydrologic cycle. This can best be done by selecting a suitable hydrologic model and calibrating it for a watershed having considerable area in irrigated agriculture and a known salinity problem. For this study, a model previously developed by Shaffer (1977) was modified to do a better job of identifying the effects of changes in water management on salinity and applied to the Ashley Valley of northeastern Utah.

Model Structure

Thomas (1971), Hyatt (1970), Hill (1973), and Shaffer (1977) have developed models that can be used to describe the effect of irrigation water management practices on soil solution salinity. The model by Shaffer (1977) is the most comprehensive of these and was used as the basis for this work. The model is a relatively simple deterministic model that performs a sufficiently rigorous analysis to enable it to be applied, with only minor modifications, to any defined and bounded area. The model uses time increments of one month and thus cannot predict short term phenomena such as flood hydrographs. The model will determine the effects of irrigation water management changes, evapotranspiration rate changes, and surface and subsurface inflows on the monthly volume and salinity of basin outflows. The model is best adapted to analyzing problems over time periods of several years length. A flow chart for the water management model is shown in Figure 1. A flow chart for the companion hydrology model is shown in Figure 2.

Precipitation (rainfall) and temperatures used in the input data supplied the model were taken as the arithmetic mean of all data in the Ashley Valley. Most irrigated lands within the valley are relatively flat, and neither the temperature nor the precipitation varies greatly over the area.

Potential evapotranspiration measurements were available for the years of record included in this study. It was found, however, that the difference between potential evapotranspiration calculated by the modified Blaney-Criddle method (Blaney-Criddle, 1950) did not vary greatly from measured pan evaporation multiplied by a constant recommended by Hargreaves (1977). The modified Blaney-Criddle method was therefore incorporated into the model to facilitate application at other locations.

It was assumed in development of the model that a fixed proportion of potential evapotranspiration was potential evaporation. When the ground lay fallow, potential evaporation was assumed to equal potential evapotranspiration. Evaporation was assumed to vary with respect to potential evaporation as the square root of the number of days since the last irrigation. Both evaporation and transpiration from the soil were taken on a daily basis by the model.

The model accepts data on both surface and subsurface basin inflow. The flows can be further subdivided into groundwater inflow, stream inflow, tributary inflow, reservoir inflow, and ungaged inflow such as local springs. Records of surface flows from the four major streams and tributaries in Ashley Valley were obtained from the U.S. Geological Survey and the U.S. Bureau of Reclamation. Groundwater flow records are practically nonexistent, and flows were estimated by an option within the model. The basin is divided into several nodes or component parts, the groundwater outflow from one part becomes the groundwater inflow to the next part. Reservoir releases were obtained from local water commissioner reports.

Canal diversions are required input data. The volume of the monthly diversions does not normally exceed the water available for diversion. The water available is the sum of surface and subsurface inflows plus recycled irrigation water. Recycled irrigation water is that which was accounted for as canal seepage or as irrigation tailwater from irrigation that reappears for re-use within the basin.

Canal flows can be augmented by subsurface and overland flows from outside the basin, however, these were not measured inputs. Canal diversion records were obtained from the Utah State Water Commissioner and the Ashley Valley Water Users Association.

Canal water losses considered by the model included seepage losses, evaporative losses, and spillage losses that become overland flow. Both seepage and spillage were considered to be recycleable. Losses were taken being proportional to total canal flow. The constants of proportionality were established during calibration. Salt was routed with the lost water. Seepage from the canals was placed in a computational linear reservoir that released part of the water into the main groundwater reservoir.

Deep percolation from agriculture was also handled by a computational linear reservoir. Water from this reservoir was also discharged into the main groundwater reservoir. During the calibration process it was found that in the Ashley Valley the agriculture linear reservoir and the canal seepage linear reservoir could be combined with the main groundwater reservoir. This combination was achieved by manipulating the routing constants for both reservoirs.

Overland flow was derived from canal spills, runoff water from irrigation, and runoff from undeveloped lands. Runoff from undeveloped lands was ignored because of the low rainfall in the area.

Irrigation water movement is also shown in Figure 2 which is a flow diagram for the routing of water and salt in the model. Salt is carried with the water except when the water is moved as evaporation, rain, or snowmelt. Irrigation water quantity and quality can be either increased or decreased before it arrives at the point of use. The changes are caused by canal losses, surface runoff, return flow, phreatophyte losses and mineral weathering. Not all of these factors are significant in every system.

Soil profile water movement was represented by adaptation of a simple plate model reported by Hanks (1974). The model was

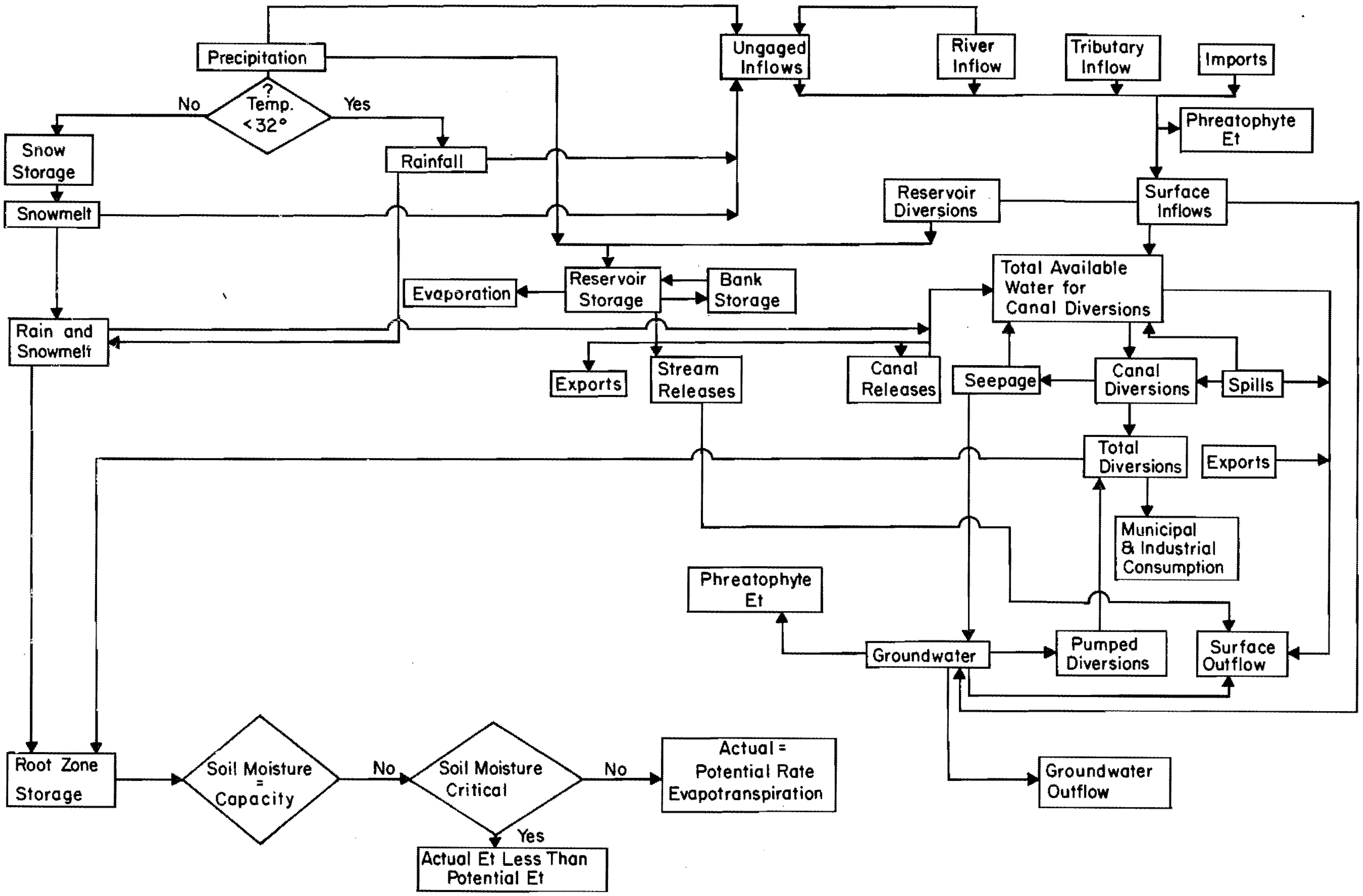

Figure 1. Water management model flow chart.

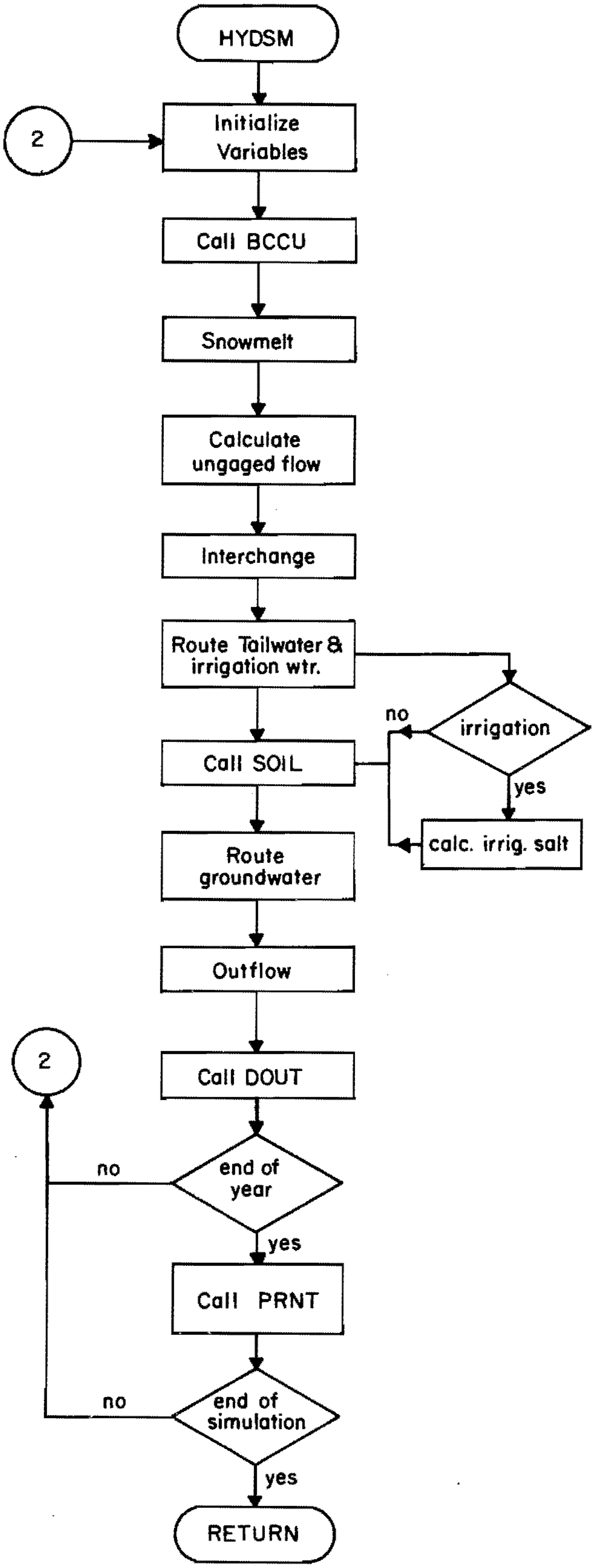

Figure 2. Hydrology model flow chart.

adapted to handle both water and salt. The method used for salt transport was developed by Terkeltoub and Babcock (1971) and divided the soil profile into 10 plates. Salt in each layer is brought into chemical equilibrium before the water carrying salt moves into the next layer. Figure 3 is a flow chart for the water flow model. The salt was handled by separate a subroutine named CHEM. The transport of salt is calculated separately from the extraction of water from the soil profile. Water was not taken from the profile layers in definite proportions but was taken from the layer having the most available water. All the transpiration for a single day was taken from a single layer. If there was insufficient water, it was extracted from two layers.

In the model, the soils of the basin being studied can be classified according to need. For the Ashley Valley, soils were classified according to the amount of solid phase gypsum in the soil profile. The proportion of the valley composed of each soil type was input data to the model.

Details of the data collection process used in the Ashley Valley model study are reported by Miller (1979).

Model Calibration

The model was calibrated to match runoff and salt movement in the Ashley Valley, a valley of about 30 square miles located in the Uintah Basin in northeastern Utah. The valley includes the city of Vernal and has a mean elevation of 5,700 feet. Irrigation water for the valley is supplied by the Vernal Unit of the Central Utah Project wherein Steinaker Reservoir was constructed by the Bureau of Reclamation. The principal crops are related to the livestock industry and include alfalfa, pasture, barley, corn silage, wheat, and oats.

The calibration was a three-stage process. First, the model was run using initially estimated parameter values and varying these to test sensitivity. These trial runs showed the concentration of deep percolation from agricultural lands to remain fairly constant over a wide range of many variables. It was therefore possible to use the initial concentrations of deep percolation throughout the remainder of the preliminary calibration process. By initially bypassing the chemistry subroutine, costs of calibration are reduced considerably.

The second stage of calibration applied the optimization routine to refine model parameter values to obtain least error predictions for either salt or streamflow. To further reduce costs, a simple soil model can be substituted that predicts deep percolation and actual transpiration with less

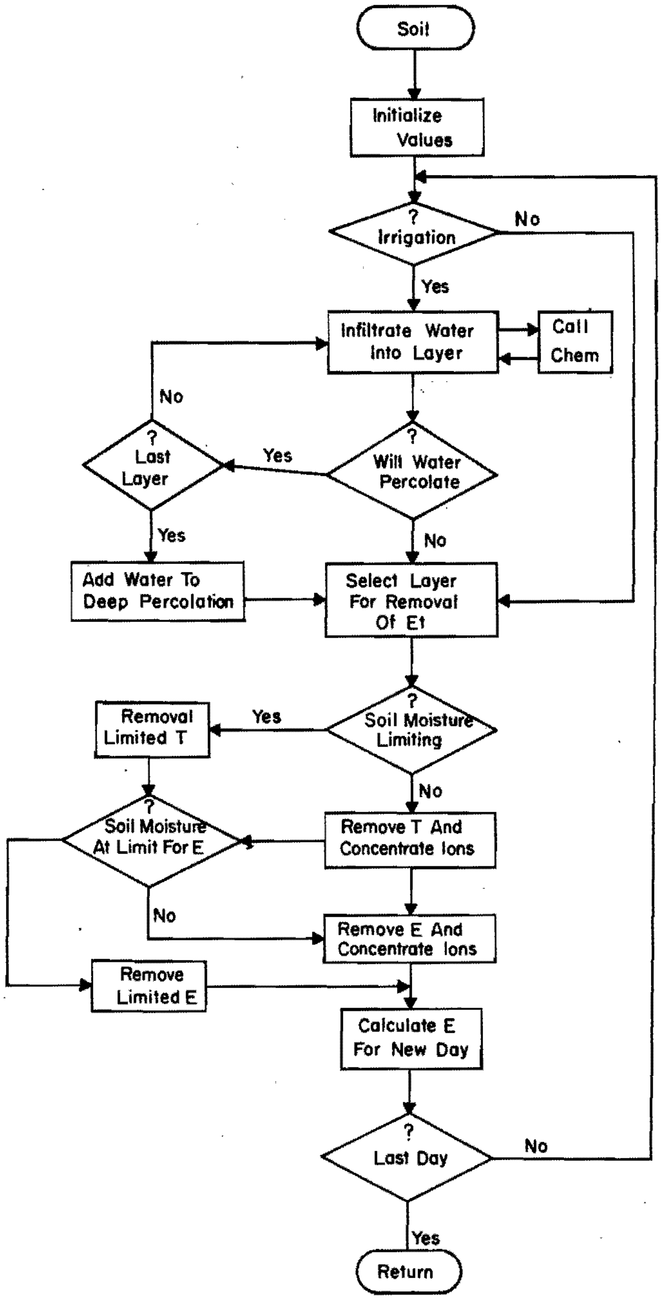

Figure 3. Flow chart for soil profile water movement.

cost than the plate soil model. By shunting both the chemistry subroutine and the soil subroutine, the costs of calibration were reduced by more than one order of magnitude. A single run of the model with one pass through a HYDSM routine, two years per pass, costs about 20 cents with the simplifications. A single run without the simplifications costs about two dollars. The difference becomes more dramatic with more passes through the subroutine HYDSM, which, with the simplifications, becomes the least expensive portion of the entire model. The third stage of calibration consisted of replacing the simplifications with the detailed models in order to finalize the parameter optimization.

In summary, the calibration process is the estimation of reasonable parameter values to fit the measured responses of the basin. A pattern search routine facilities the fitting process but is of little help without accurate data. If data are lacking, knowledgeable estimates can still be made of reasonable parameter values. Some understanding of the hydrologic processes is important since more than one solution for the parameter vector may produce an equally good fit, and a calibration which disregards real world processes may be misleading.

The model contains 40 parameters that provide a great deal of power to represent variations in waterflow processes in a basin. Obviously, if all these parameters are used in a two-year calibration with monthly data, more degrees of freedom would be used in calibrating the program than the data justify. Since many of these variables are highly interdependent, the calibration of two variables does not necessarily reduce two degrees of freedom. Nevertheless, significance is lost if all variables are used for calibration. The least significant variables should be ignored and some parameters must be set to values other than zero to be insignificant. For instance, the routing constants are all significant when their values are zero. They become insignificant when their value is 100 or greater because of the exponential nature of the functions in which they are used. An easy solution to calibration may be possible, but some idea of the significance and meaning of the results must be maintained.

A flow chart showing the logic of the calibration routine is shown in Figure 4. The program and the procedures followed in its calibration are detailed by Miller (1979). Appendix E is an outline of the input data preparation required for the model.

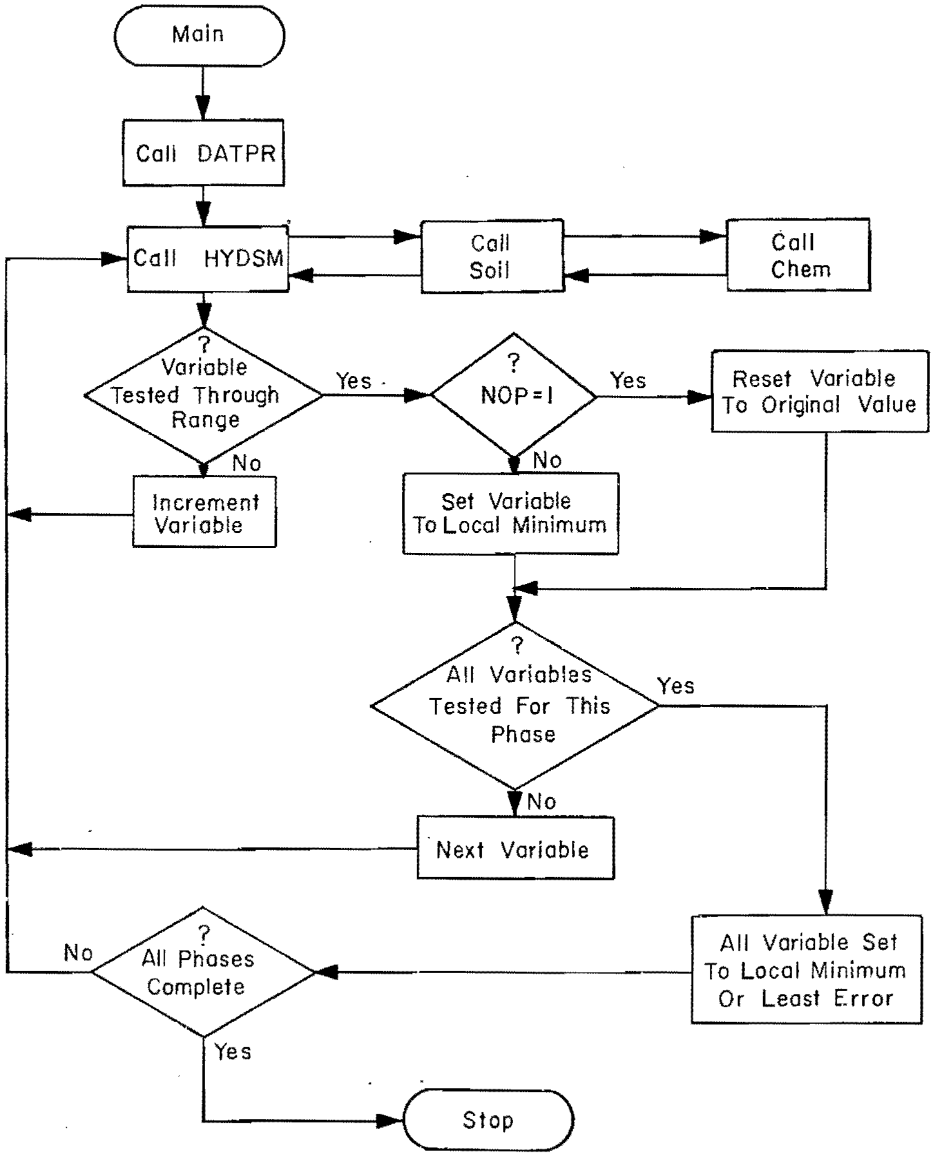

Figure 4. Flow diagram of main program calibration.

III. RESULTS AND DISCUSSION

Precipitation in Solution

In the solution precipitation experiment, calcium sulfate crystals began to precipitate in the beaker after the second drying cycle. This indicated that the concentration had exceeded the solubility of calcium sulfate and salts were being removed from solution. The precipitated crystals were inert with respect to the salts remaining in solution. As the number of drying cycles increased, an increasing amount of gypsum precipitated. The measured electrical conductivity of the solution was less than would be expected from adding the same amounts of salt to a solution in which precipitation was not occurring.

The measured electrical conductivity of the 50 ml sample extracted was plotted against the number of the drying cycle. The theoretical electrical conductivity of similar solutions but without precipitation were also plotted. The curves are shown in Figure 5 for the experimental data and for a zero, a 10 percent, a 15 percent, and a 20 percent leaching fraction in a solution where zero precipitation was assumed. Without precipitation, a 22 percent leaching fraction would be required to obtain a solution salinity equal to that measured. The straight line in Figure 5 shows the expected salinity of the solution with no precipitation and a zero leaching fraction. The lowest curve is the measured electrical conductivity of the artificial water. On the right hand side of Figure 5 are the ultimate equilibrium salinities of solutions without precipitation and having the indicated leaching fractions.

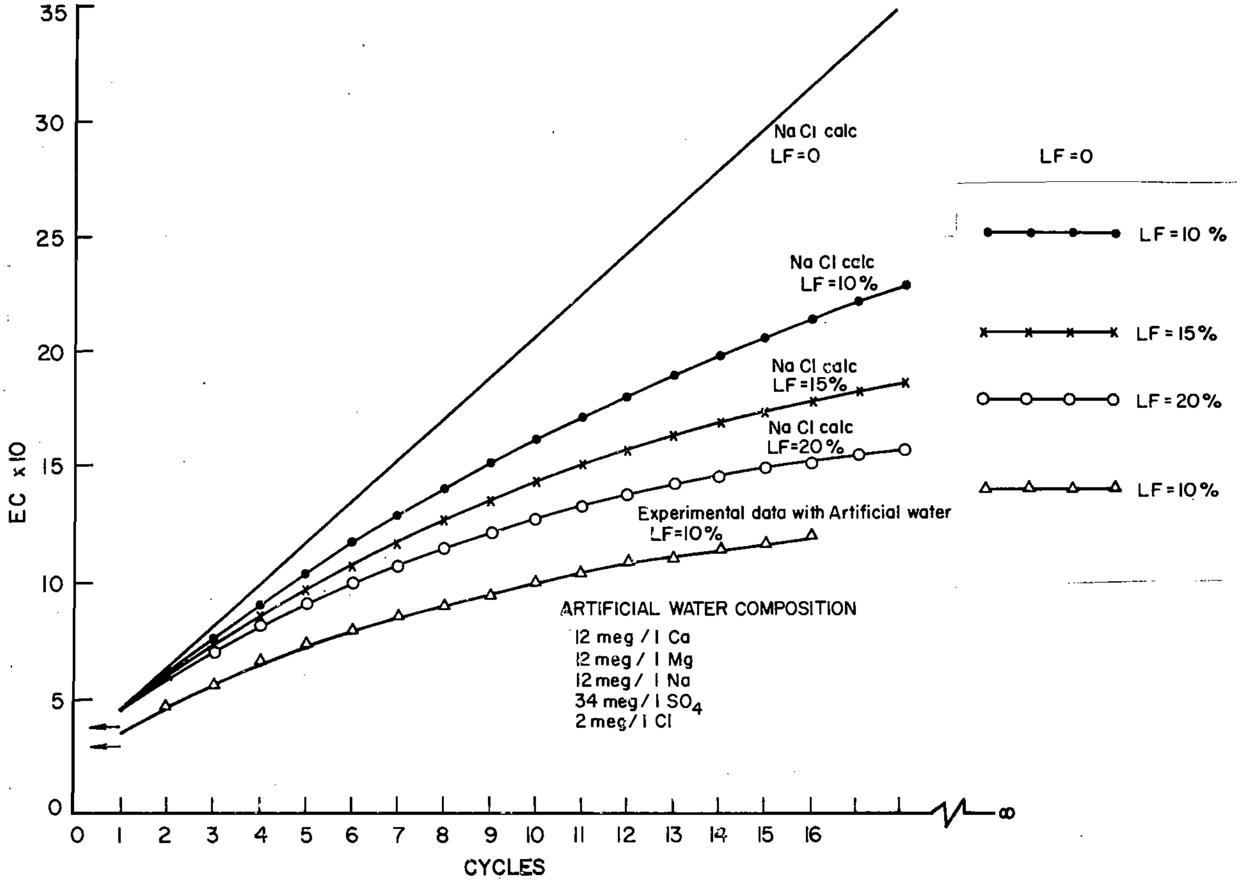

Figure 5. Electrical conductivity curves for precipitating and nonprecipitating solutions subjected to drying cycles.

The results of this simple experiment show that the leaching fraction required to obtain a given soil solution salinity can be lower than that theoretically required if precipitation is occurring and if the soil is acting as a salt sink.

Salinity-Nutrient Interactions

The yield comparisons of principal interest in a salinity-nutrient interaction study are the forage dry matter and the grain yields. The treatment using 0.5 mmho/cm irrigation water at a 4-day irrigation interval was selected as the reference "control" treatment. This treatment maximized yield for most of the study combinations. Yields expressed as percentages of this control yield at each fertility level are presented in Table 6 for straw dry weight. Direct comparisons are possible within any fertility block by using the percentage values in Table 6, and comparisons may be made between blocks by using the measured absolute yield values given in parentheses.

Table 6. Percent dry matter yield deviation from the control treatment.[a] (Absolute values of greatest yields given in parentheses.) (mtons/ha)

Fertility Combination	Salinity Level	Water Application Interval (days)		
		2	4	8
N0P0	1	60.0	100.00	84.6
	2	58.8	85.1	92.3
(16.01)	3	56.2	74.4	88.9
	4	41.4	65.7	67.1
N1P0	1	73.3	100.0	74.9
	2	78.0	145.0	90.7
(16.1)	3	75.2	84.4	98.7
	4	34.2	85.8	88.1
N2P0	1	81.4	100.00	67.1
	2	96.3	114.66	88.1
(16.99)	3	62.2	112.2	95.9
	4	53.9	62.1	82.7
N3P0	1	72.1	100.00	46.4
	2	67.4	113.22	59.2
(24.21)	3	117.8	88.9	73.9
	4	57.3	65.1	64.5
N0P1	1	64.7	100.00	91.2
	2	77.2	127.4	111.7
(11.43)	3	72.4	105.2	109.8
	4	54.9	106.5	103.9
N1P1	1	58.7	100.00	59.7
	2	50.0	84.10	70.2
(21.23)	3	50.4	88.60	56.3
	4	39.6	64.3	62.8
N2P1	1	55.4	100.00	57.0
	2	61.6	76.1	61.0
(22.55)	3	66.7	102.9	67.0
	4	32.8	72.63	59.3
N3P1	1	75.6	100.00	58.2
	2	89.8	89.9	51.0
(29.78)	3	72.1	86.6	51.1
	4	58.7	52.2	37.1
N0P2	1	76.2	100.00	107.9
	2	79.8	115.5	106.4
(12.70)	3	70.5	87.9	119.8
	4	52.1	62.4	112.4
N1P2	1	53.1	100.00	72.0
	2	48.9	83.7	78.1
(20.66)	3	58.6	89.9	71.3
	4	38.7	60.8	56.5
N2P2	1	49.8	100.00	54.2
	2	45.9	79.7	57.0
(27.03)	3	48.2	58.0	69.5
	4	32.0	66.1	20.8
N3P2	1	85.2	100.00	54.6
	2	61.7	113.02	54.2
(25.65)	3	81.1	89.8	69.1
	4	49.0	62.0	49.1

[a] N1 = 0 lb-N/ac
N2 = 100
N3 = 200
N4 = 400

P1 = 0 lb-P/ac
P2 = 40
P3 = 80

Salinity 1:EC = 0.5 mmho/cm
2:EC = 1.5
3:EC = 4.5
4:EC = 13.5

Generally at any constant level of phosphorus fertilization, salt tolerance, as indicated by high dry weight straw yield, is increased by fertilizing with more nitrogen. These trends were less evident as the interval between irrigations was increased. As salinity of the irrigation water was increased at any frequency of irrigation, yield decreased.

The analysis of variance results (Table 7) show that phosphorus and most of the two and three way interactions are not significant with respect to most of the yield parameters.

ET vs Dry Matter Yield

Figures 6 and 7 show dry matter yield in metric tons per hectare extrapolated from the data pots (3.5 kg soil) as a function of the evapotranspiration. Dry matter yield increased to a maximum when the water consumption was approximately 11 liters per pot, then declined with increasing ET. Increasing the water in the soil apparently resulted in increased evapotranspiration but caused some aeration and nutritional problems that gave lower yields. These results suggest that excessive soil moisture may not only reduce yield directly through leaching nutrients but also indirectly through loss of stand (DM) caused by poor aeration and plant diseases which tend to increase under

Table 7. F-test results of treatment interactions.

S_v #	Source of Variation	Error Term #	DF-Ratio V_1/V_2	Required F-Value		Dependent Vairables F-Value							
				5%	1%	1	2	3	4	5	6	7	8
2	W	6	2/9	4.26	8.02	3.08	6.73[b]	3.76	8.90[a]	.30	9.62[a]	2.12	10.36[a]
3	S	13	3/27	2.96	4.60	10.09[a]	5.60[a]	7.99[a]	3.69[b]	2.31	8.05[a]	6.40[a]	5.21[a]
4	N	14	3/27	2.96	4.60	14.16[a]	1.82	7.83[a]	4.14[b]	.10	8.45[a]	5.72[a]	6.31[a]
5	P	15	2/18	3.55	6.01	0.42	0.51	.025	0.16	0.92	1.43	0.22	0.13
7	WxS	13	6/27	2.46	3.56	2.52[b]	7.75[a]	3.87[a]	4.09[a]	5.35[a]	6.52[a]	3.09[b]	5.21[a]
8	WxN	14	6/27	2.46	3.56	3.05[b]	3.07[b]	3.68[a]	1.83	0.83	19.32[a]	2.36	2.57[b]
9	SxN	20	9/81	1.99	2.64	0.90	1.97	0.52	0.46	1.07	2.23[b]	1.38	0.58
10	WxP	15	4/18	2.93	4.58	0.26	.31	1.14	1.31	0.39	2.15	0.72	1.03
11	SxP	21	6/54	2.27	3.15	1.53	2.06	0.44	1.46	2.93[b]	1.28	1.23	1.42
12	NxP	22	6/54	2.27	3.15	0.86	0.64	0.32	0.91	0.83	0.13	0.33	0.51
16	WxSxN	20	18/81	1.74	2.18	1.15	1.91[b]	1.09	0.61	2.03[b]	1.12	1.48	0.58
17	WxSxP	21	12/54	1.93	2.53	0.79	1.09	1.54	2.51[b]	0.94	1.02	1.51	2.25[b]
18	WxNxP	22	12/54	1.93	2.53	0.73	0.73	0.68	1.02	0.57	0.56	0.27	1.08
19	SxNxP	24	18/162	1.68	2.06	1.22	0.93	0.81	0.46	1.02	0.61	1.63	0.41
23	WxSxNxP	24	36/162	1.51	1.78	0.98	0.78	1.13	0.69	0.83	0.89	1.21	0.79

[a] Significant at the 1% level.
[b] Significant at the 5% level.

Dependent Variable:

1. Dry matter yield (g/pot)
2. Number of main heads.
3. Number of tiller heads.
4. Number of seeds from main heads.
5. Number of dry florets from main heads.
6. Number of seeds from tiller heads.
7. Number of dry florets from tiller heads.
8. Weight of seeds from main heads (g).

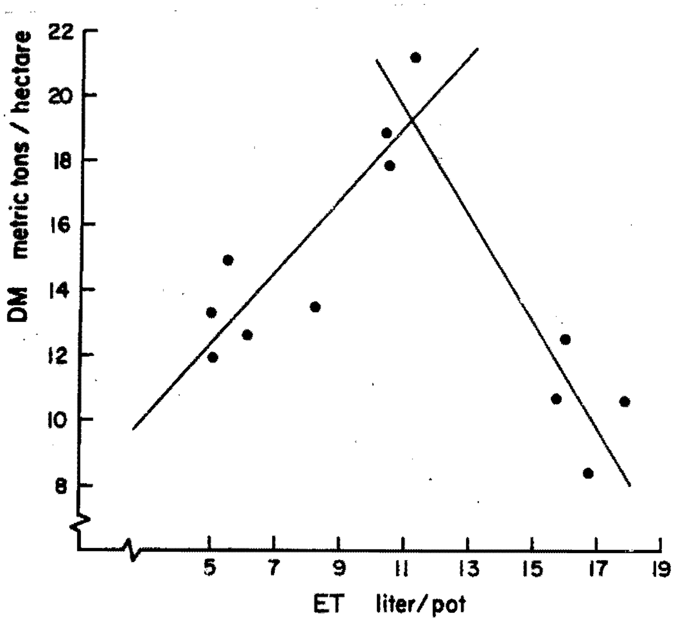

Figure 6. Dry matter yield as a function of evapotranspiration from greenhouse pots for the medium nitrogen and medium phosphorus treatments.

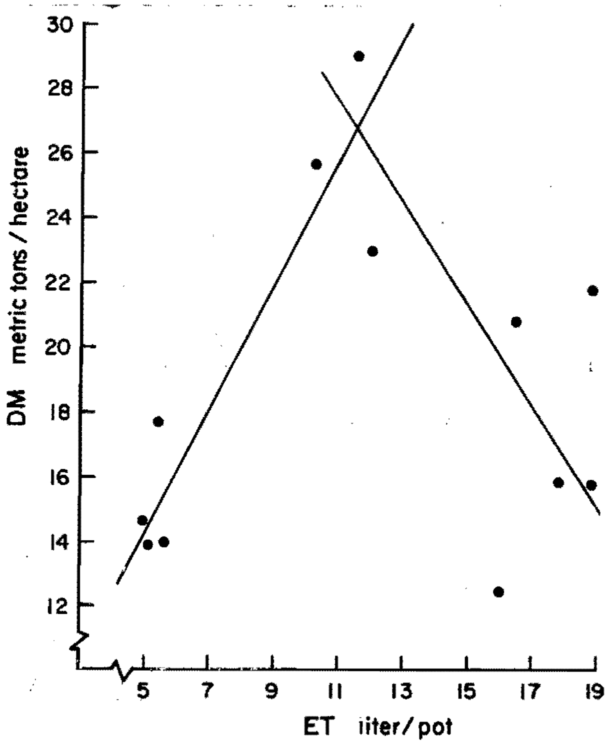

Figure 7. Dry matter yield as a function of evapotranspiration from greenhouse pots for the high nitrogen and high phosphorus treatments.

high moisture conditions. Increasing the nitrogen and phosphorus levels increased dry matter yields by about 30 percent but did not change the tendency for yield to maximize and then reduce at higher levels of evapotranspiration.

The relationship between dry matter production and leaching fraction is presented for one treatment (N_4P_2) in Figure 9. The 2-day frequency of irrigation produced higher leaching fractions than the 4 and 8-day frequencies since the total water applied was the same regardless of the interval. The 4 and 8-day irrigation intervals had similar leaching fractions. Dry matter yield was greatest at the 4-day frequency. These trends were similar to those obtained in most other fertility-irrigation combinations, indicating that with the salinities of the water and growing conditions of the experiment conducted here, the highest leaching fraction did not produce the highest yield. Greater water applications apparently have adverse effects that exceed the beneficial effects produced by keeping the soil wet in saline situations in a pot culture.

Two different shaped pots were used in this experiment. The statistical analysis presented here combines all pots without regard to shape. From visual inspection of the data, however, it appears that pot geometry influenced yield. The statistical analysis was redone to separate these effects as reported in detail by Bamatraf (1979).

Leachate and Leaching Fraction

The leaching fraction (LF) in the pot experiment showed a clear relationship with both irrigation interval and salinity. Leaching fraction increased with increasing irrigation water quantity (shorter irrigation interval) and with salinity of the irrigation water (Figure 8). The increased leaching fraction with the shorter irrigation interval is due to the greater amounts of water added. Since the leaching fraction is defined as the fraction of applied water that appears as drainage water (Bower et al., 1970), these findings suggest that there were no drainage problems during the growing season. Dry matter and grain yields reached a maximum at a medium leaching fraction and then declined.

The first yield decrement caused by an increased LF could be due to nutritional problems and a higher water content as a consequence of nutrient leaching and increased irrigation quantity. Where the amount of water leached through the root zone was near that required to balance soil nutritional and osmotic conditions for the crop, yields were greatest. Sometimes yield decreased because of insufficient water supply.

There was a positive relation between the seed formation ratio (SFR), an indicator of grain yield, and the leaching fraction. The SFR was calculated as:

$$SFR = [\#TS / (\#TF + \#TS)]$$

where

SFR = seed formation ratio
#TS = total number of seeds per pot
#TF = total number of dry florets per pot

Figure 8 shows the variation of the leaching fraction, grain yield, and the SFR with the water application interval. The responses can be interpreted in at least two different ways. On the one hand, all three have been affected by the changes in leaching fraction at the higher irrigation quantities (short irrigation intervals), showing an inverse relation with LF under different irrigation salinity levels. On the other hand, the differences in both the grain yield and the SFR are not well correlated with different levels of irrigation water salinity at the longer irrigation intervals because of the dominant influence of the amount of water applied on yield.

A positive relation was obtained between water salinity and leaching fraction at the shortest irrigation interval. The higher the salinity of irrigation water, the higher the LF. Bower et al. (1969) obtained similar results. They observed that as the salinity of irrigation water increased from 2 to 4 mmhos/cm, the LF was increased from 0.13 to 0.29, respectively, under similar irrigation regimes. In this study the increases in LF range from 35 to 43 percent as the salinity increased from 1.5 to 13.5 mmhos/cm.

At the longest irrigation interval, the leaching fraction was lowest for the highest salinity irrigation water (Figure 8). The seed formation ratio (SFR) and the grain yield was highest for the saltiest water. A relatively low leaching fraction of a given irrigation interval was caused by a higher total evapotranspiration since the amount of water applied was the same between treatments at that irrigation interval. For the 8-day irrigation interval, yields were directly related to ET as reflected by the differences in leaching fraction. At the shortest irrigation interval, leaching fraction was directly related to salinity of the water but grain yield and SFR responses were variable.

Soil Salinity

A noticeable increase in the electrical conductivity of saturated soil extract (EC_e) was evident for the 8-day irrigation interval. The greatest increase in EC_e was found in the longest irrigation interval at any level of irrigation water salinity at both 0-15 and 15-30 cm depth increments.

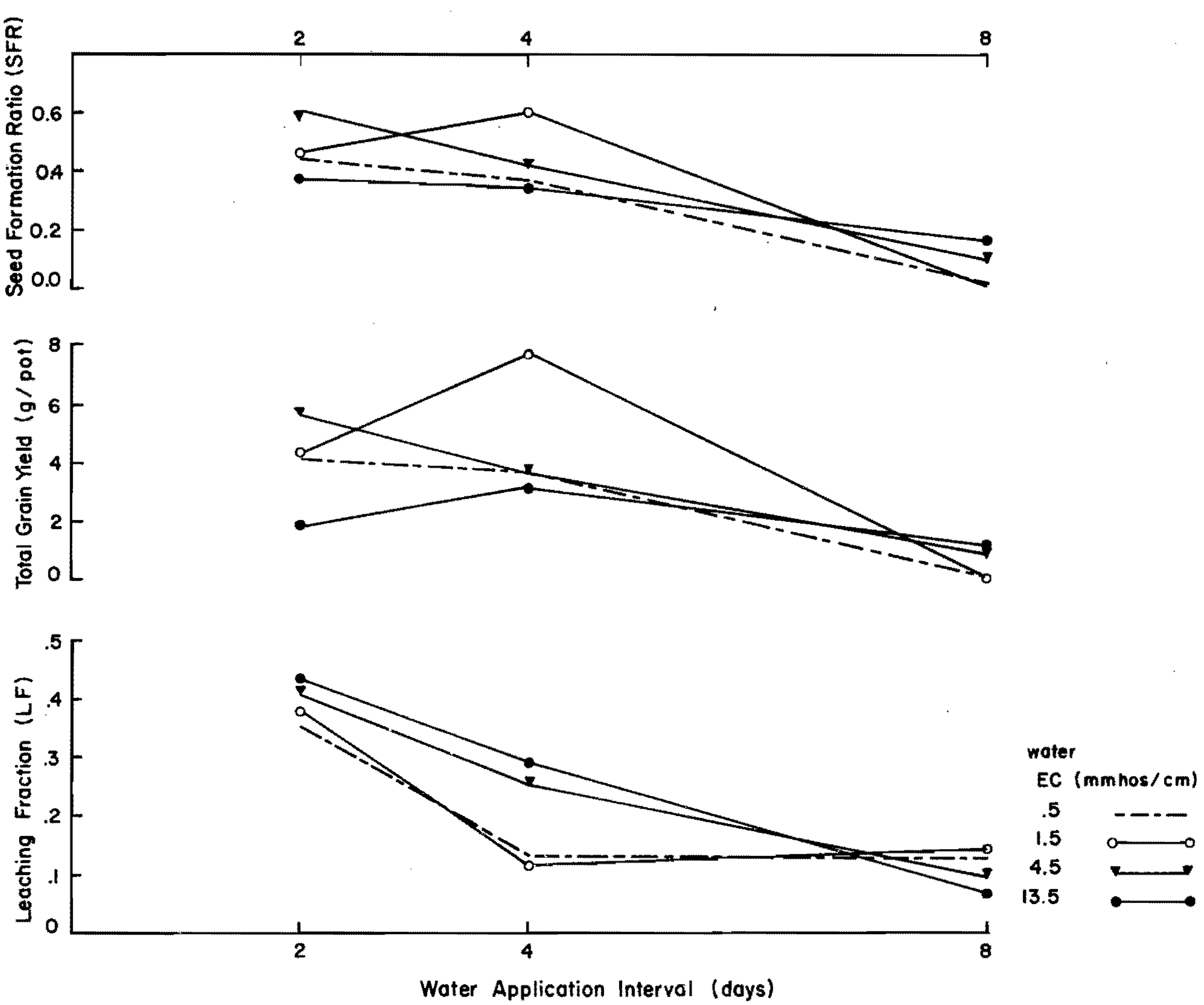

Figure 8. Water application interval effects on leaching fraction and plant response.

The final salinity of the soil was increased for all irrigation intervals as the salinity of irrigation water was increased. Increasing irrigation water quantity did not completely control soil salinity when saline irrigation water was used. This study shows that use of saline water under these specific experimental conditions would respond to proper management of water if the water has a salinity of 4.5 mmhos/cm or less.

The distribution of salts in the soil profile in the pots followed to a certain extent the common experience that soil profile salinization and desalinization is correlated to the amount of irrigation water applied. As the amount of irrigation water is increased, desalinization through leaching occurs. For the highest water application (a 2-day irrigation interval) salinity increased with depth in the pots (Figure 7). The difference in salinity between the top and bottom half of the pots was greater as the salinity of the applied irrigation water increased. For the longest irrigation interval (8 days) and the lowest leaching fraction (Figure 8) the highest salinity is found in the top of the pots (Figure 10). Soil in the saline pots tends to be better aggregated so that applied irrigation water would quickly penetrate to the bottom of the pot. In the period between irrigations, the water would migrate to the upper root zone where the salt would be deposited. The shallow pots and the long irrigation interval create a soil-water system that is similar to a high-water table condition.

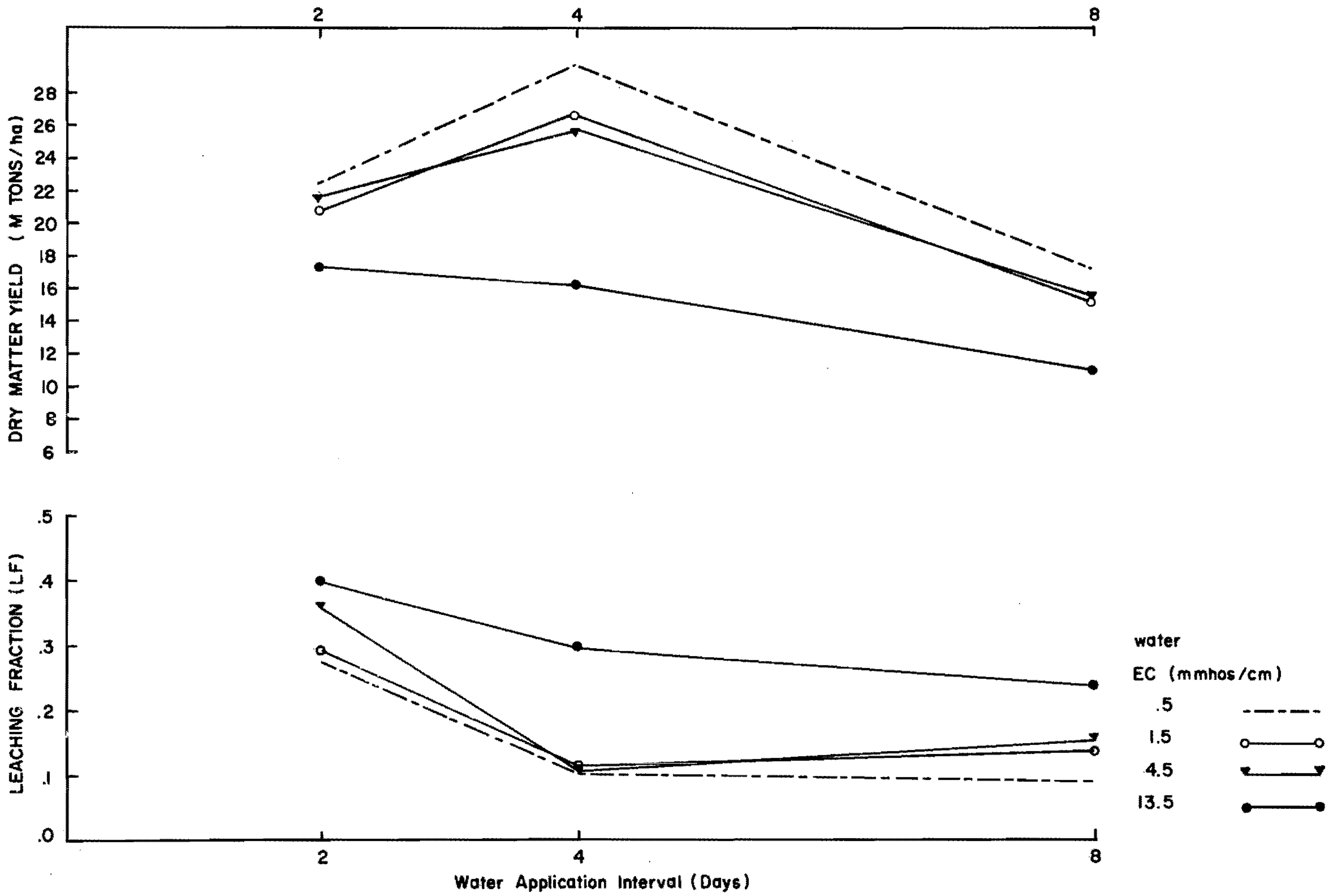

Figure 9. Relationship between dry matter production and leaching fraction.

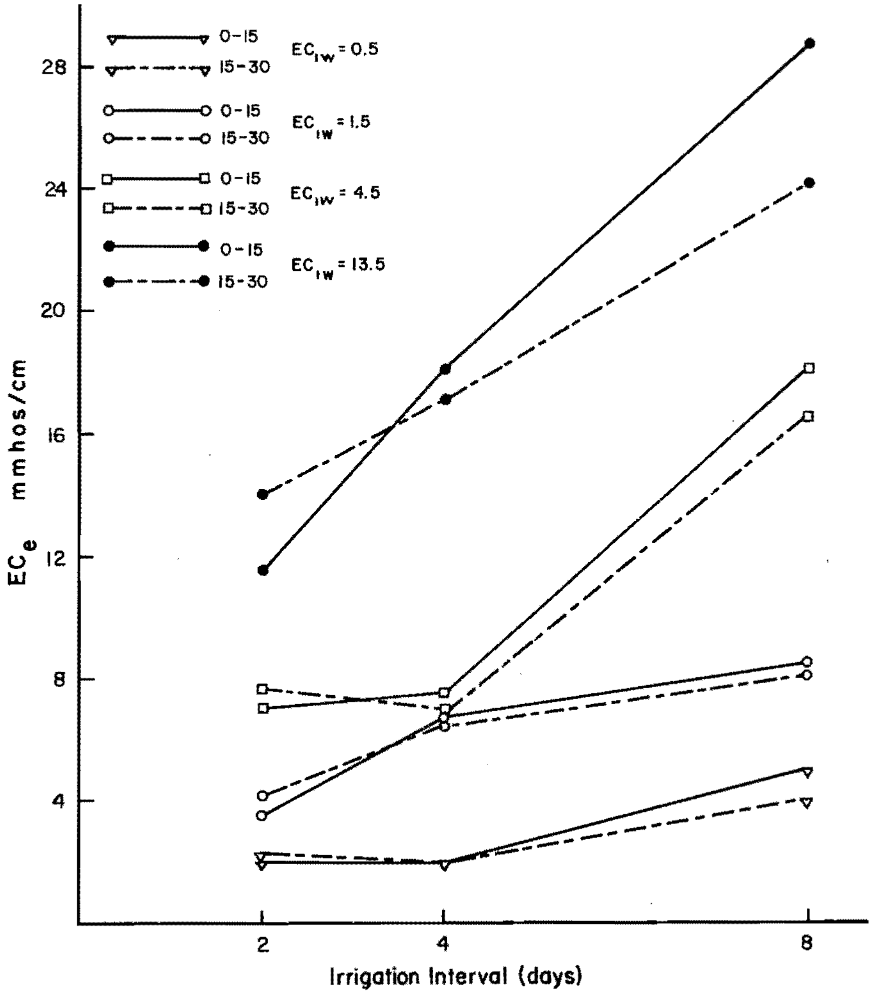

Figure 10. Salt distribution through soil profile as influenced by irrigation interval and salinity at constant selected fertility combination (No P_1) = (ε).

Soil Chemistry Model

The combined transport-chemistry-exchange model was designed so that the user could choose from among three calculation method options. Salt can be moved through the soil profile without chemical reaction with the soil. Salt can be moved in combination with chemical precipitation and dissolution. Finally, salt can be moved with chemical precipitation and dissolution combined with cation exchange equilibrium reactions. These options will be referred to as 1) SALTFLOWI, 2) SALTFLOWII, and 3) SALTFLOWIII, respectively.

In all 12 treatments (defined on Table 5) SALTFLOWIII gave the best prediction of all measured parameters; however, in some cases one of the other calculation options also gave satisfactory predictions for a particular parameter. Satisfactory SAR prediction for all treatments was possible only with SALTFLOWIII after the February 2 (189 days after planting, or day 189) sample date.

Only treatments 6 and 7 of the 12 treatments modeled will be discussed in detail. Treatment 6 was irrigation of Penoyer loam with water containing 6.0 me/l Ca and 0.5 me/l SO_4 at a 25 percent leaching fraction. This soil initially contained 0.7 percent gypsum by weight. This treatment produced the greatest gypsum dissolution rate of the 12. Treatment 7 consisted of irrigating Hunting silty clay loam with water containing 12 me/l Ca and 12 me/l SO_4 at a 10 percent leaching fraction. This soil initially did not contain gypsum, but this treatment produced the greatest amount of gypsum precipitation of all the treatments applied to this soil. The two soils also differ in that the Penoyer loam has a CEC of 6.9 me/100 g and Hunting silty clay loam has a CEC of 14.9 me/100 g.

Electrical conductivity predictions for treatment 6 were satisfactory by all three methods for the December 15, 1977, (day 140) sampling date (Figure 11a), however by April 2, 1978, (day 278) SALTFLOWI was starting to over estimate EC (Figure 11b). Only SALTFLOWIII satisfactorily calculated EC for treatment 7 (Figures 12a and 12b). The other two methods overestimated EC on both sample dates shown. Electrical conductivity predictions were too high by the last sample date for all 12 treatments when SALTFLOWI was used.

Predicted SAR values using SALTFLOWI were too high at the 25 cm depth on day 140 and at the 25 and 50 cm depths on day 278 for treatment 6 (Figures 13a and 13b). SALTFLOWII also predicted too high values of SAR at 50 and 75 cm on day 278. This trend was observed for all treatments when gypsum was being dissolved from the soil profile. Calculated SAR values for treatment 7 by all three methods were similar on the day 140 sampling (Figure 14a). By day 278 the SALTFLOWI calculation underestimated SAR at the 25 and 50 cm depths while SALTFLOWII overestimated the SAR for those depths but under estimated SAR at 75 cm (Figure 14b). This trend was observed for those treatments where gypsum was being precipitated from soil solution.

To explain the differences in the ability of the three model options to predict EC and SAR, it was necessary to look at the prediction of the individual ions since they are each handled differently by the SALTFLOWIII model due to differences in chemical behavior.

The chloride ions were considered to move independent of chemical reactions and cation exchange. Prediction of Cl^- was satisfactory for all treatments when the calculated water movement into and out of the soil profiles agreed with the measured water movement in the lysimeters (Figures 15a and 15b). This would suggest that the original salt transport model was working properly.

SALTFLOWIII underestimated the Ca^{2+} ion concentration in about one-half of the cases while satisfactorily estimating Ca^{2+} in the rest (Figure 16a, 16b, and 17a). The under estimation varied from slight to as much as 35 percent. This may be ascribed to the soil solution being supersaturated

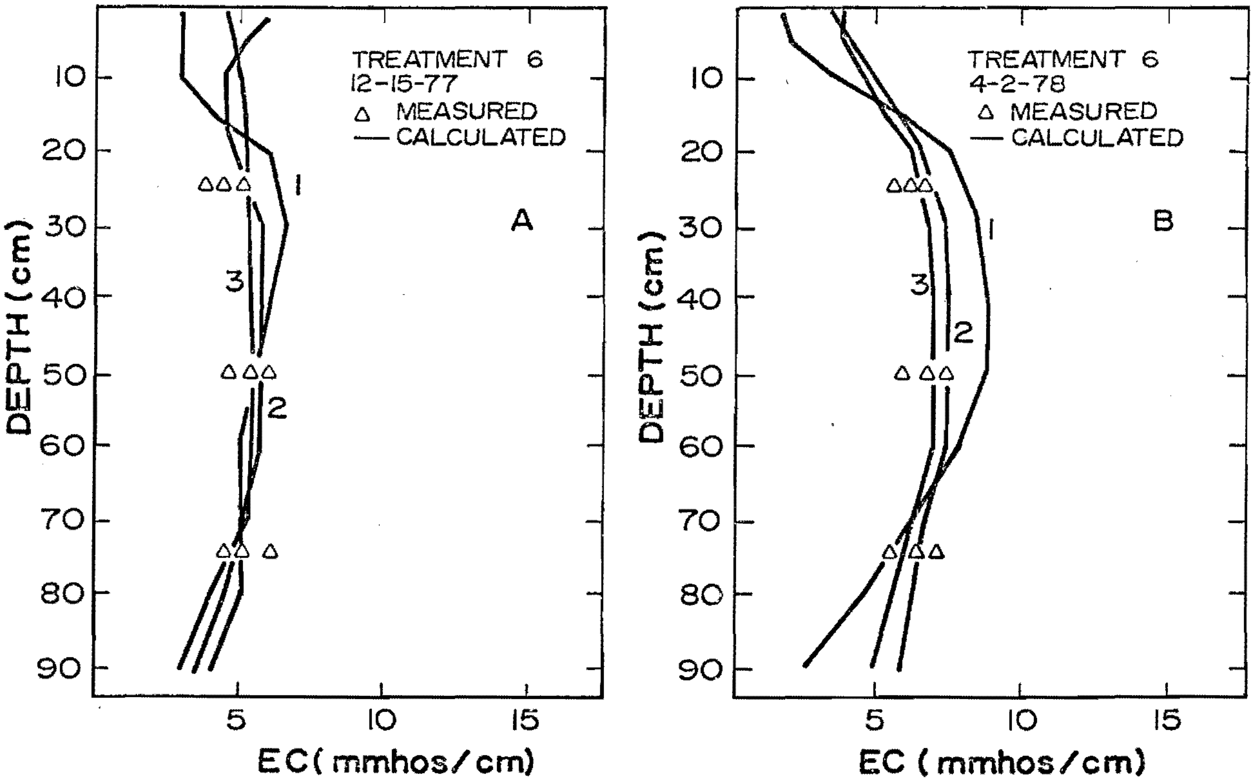

Figure 11a,b. Measured EC values and values calculated by (1) SALTFLOWI, (2) SALTFLOWII and (3) SALTFLOWIII for treatment 6 on 12-15-77 and 4-2-78 (day 140 and 278).

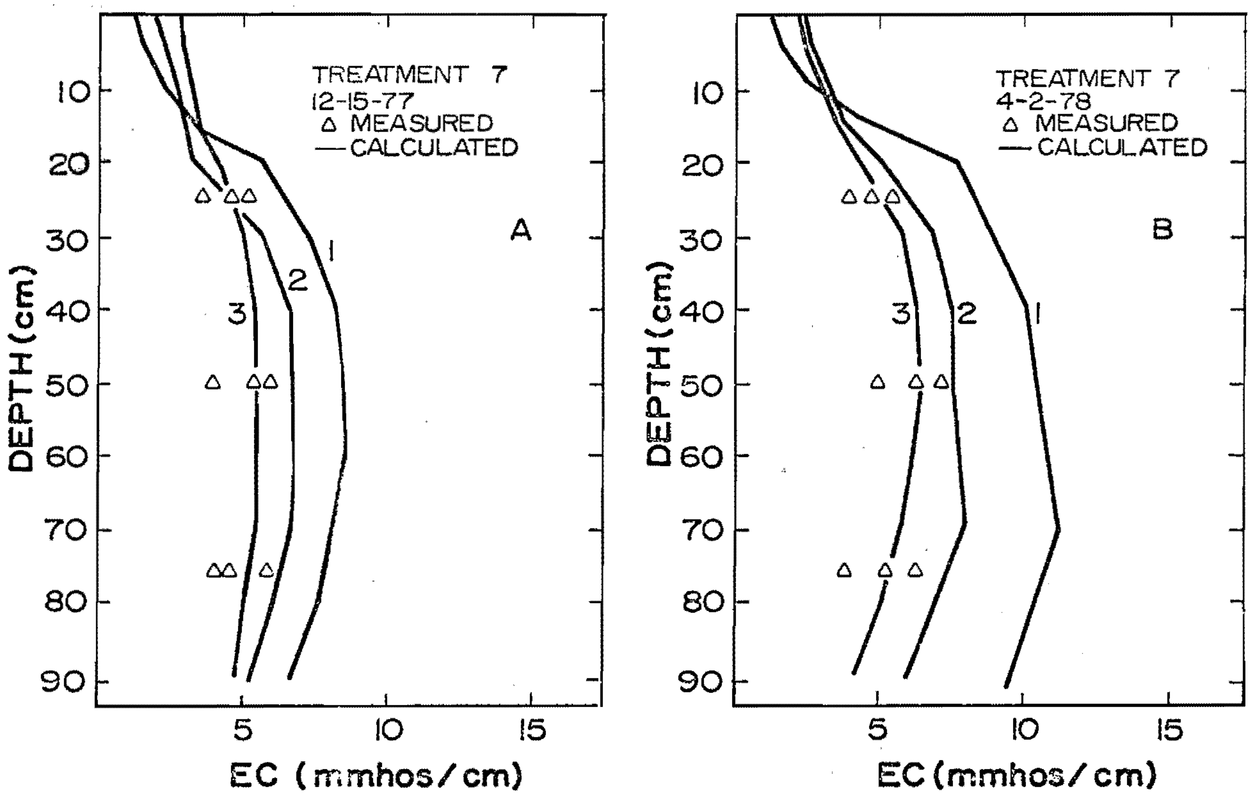

Figure 12a,b. Measured EC values and values calculated by (1) SALTFLOWI, (2) SALTFLOWII and (3) SALTFLOWIII for treatment 7 on 12-15-77 and 4-2-78 (day 140 and 278).

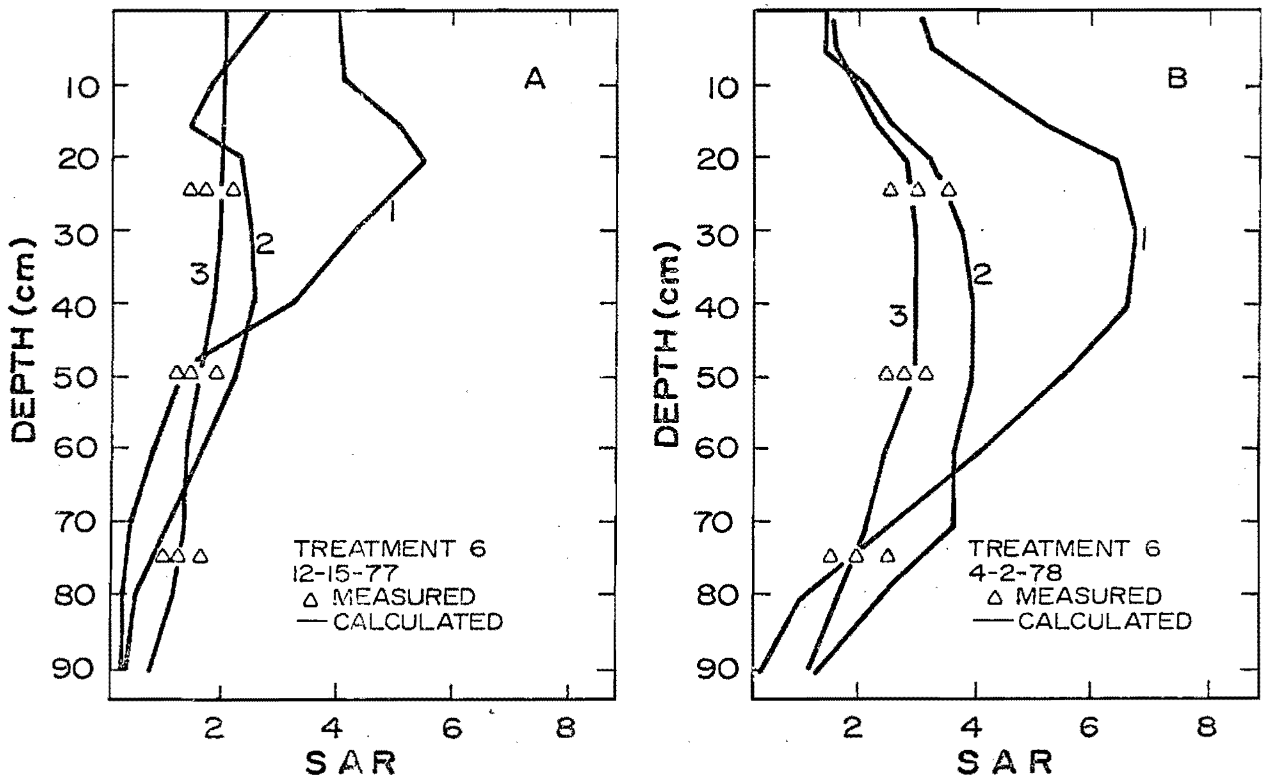

Figure 13a,b. Measured SAR values and values calculated by (1) SALTFLOWI, (2) SALTFLOWII and (3) SALTFLOWIII for treatment 6 on 12-15-77 and 4-2-78 (day 140 and 278).

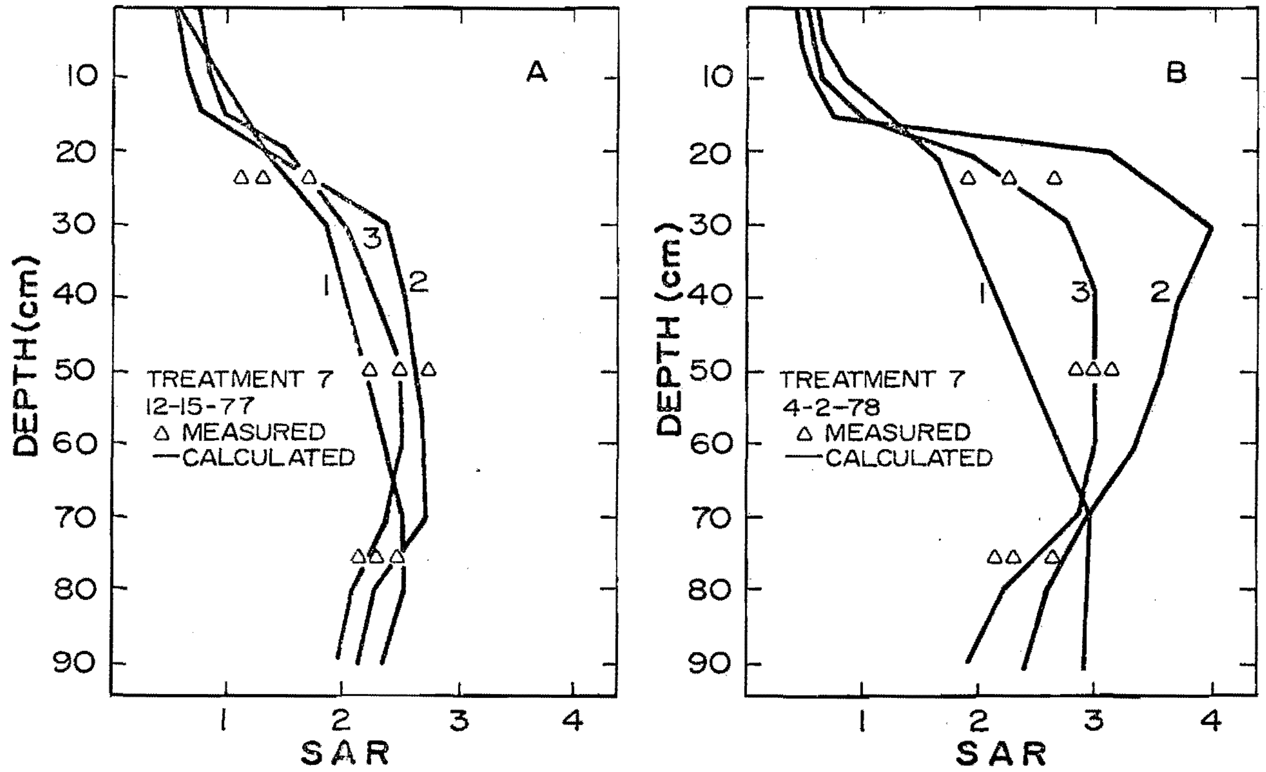

Figure 14a,b. Measured SAR values and values calculated by (1) SALTFLOWI, (2) SALTFLOWII and (3) SALTFLOWIII for treatment 7 on 12-15-77 and 4-2-78 (day 140 and 278).

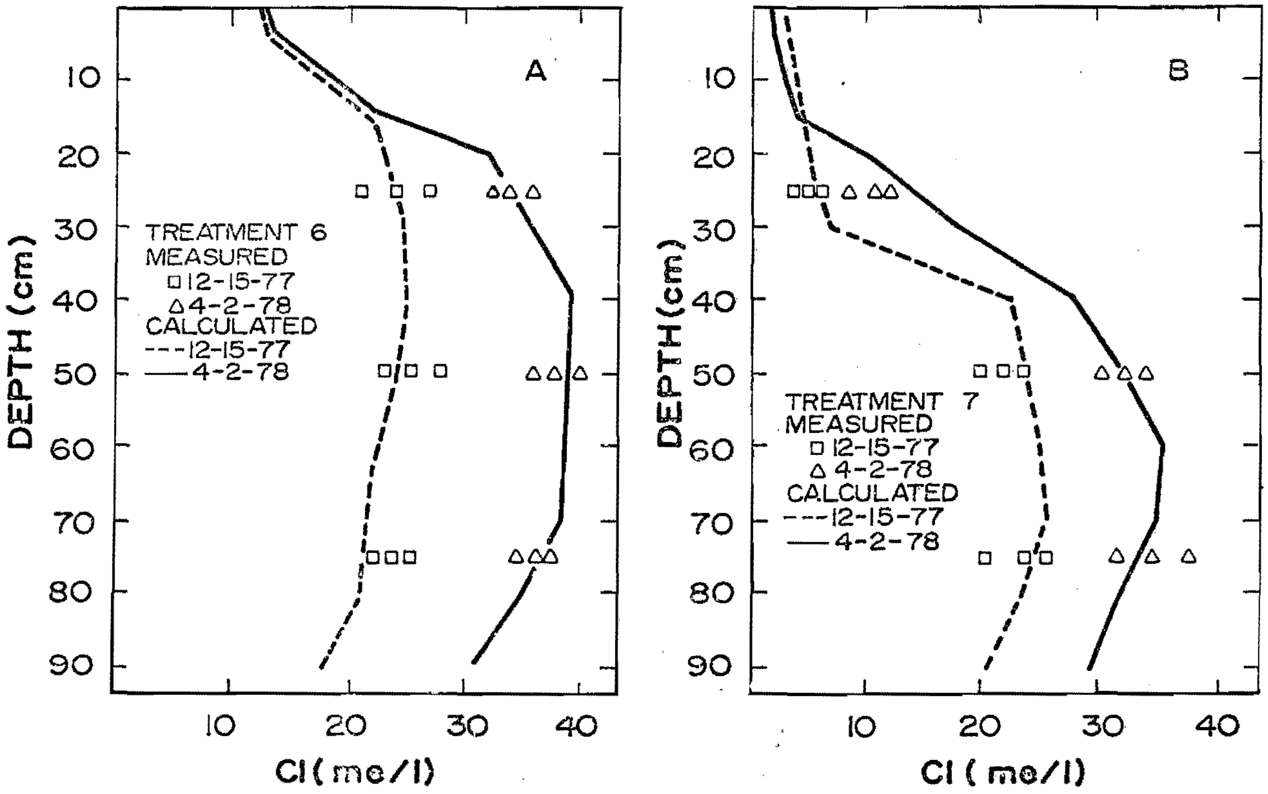

Figure 15a,b. Measured Cl concentrations and concentrations calculated for treatments 6 and 7 on 12-15-77 and 4-2-78 (day 140 and 278) by all three options.

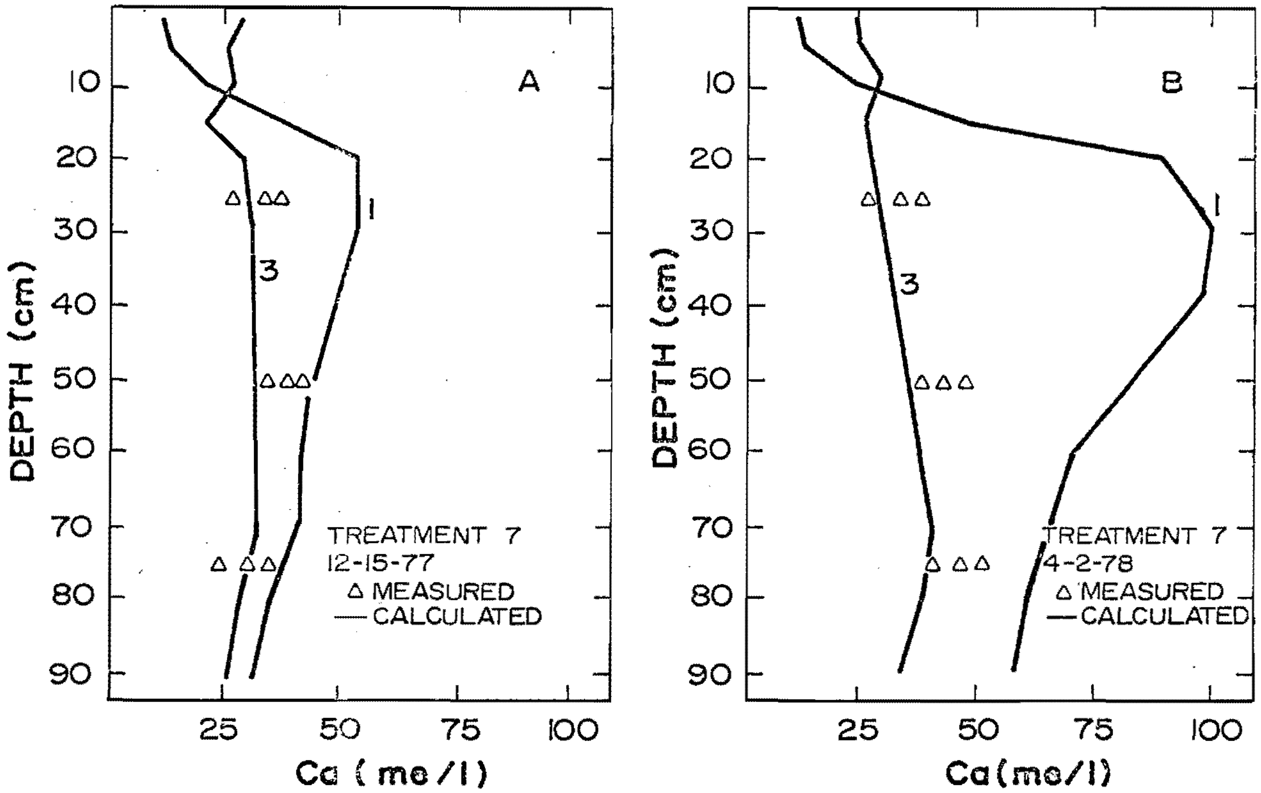

Figure 16a,b. Measured Ca concentrations and concentrations calculated by (1) SALTFLOWI, and (3) SALTFLOWIII for treatment 7 on 12-15-77 and 4-2-78 (day 140 and 278).

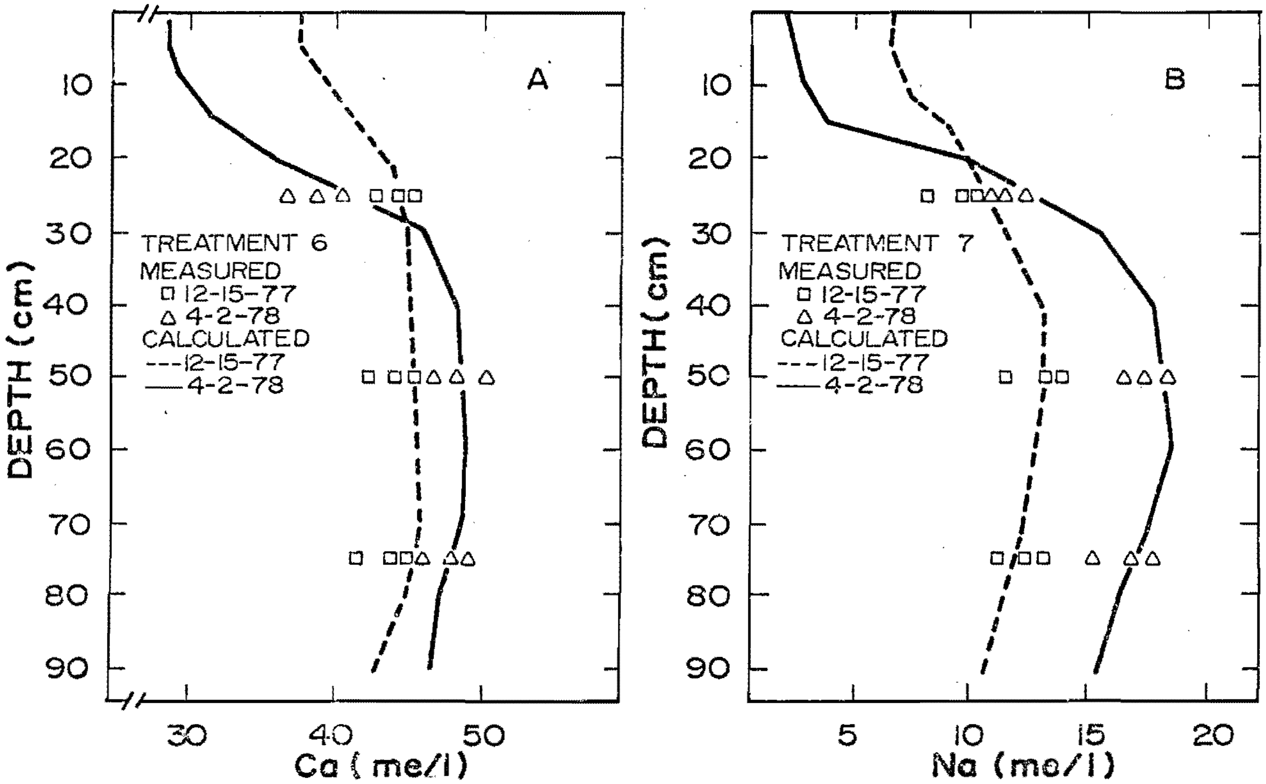

Figure 17a,b. Measured Ca concentrations and concentrations calculated for treatment 6 on 12-15-77 and 4-2-78 (day 140 and 278) measured Na concentrations and concentrations calculated for treatment 7 on 12-15-77 and 4-2-78 (day 140 and 278) by SALTFLOWIII.

with lime and or CO_2, since lime would tend to precipitate from solution in some of the closed sample bottles if allowed to sit without acid treatment for more than 3 to 5 days before analysis. Treatment 6 shows that leaching of Ca^{2+} from the surface layers of a gypsiferous soil occurs when the soil is irrigated with a low SO_4 water (Figure 17a). When dissolution of gypsum was not considered in this and other treatments, SAR predictions were higher than when SALTFLOWIII was used (Figures 13a and 13b). When chemical precipitation was not considered in treatment 7 (Figures 16a and 16b), Ca^{2+} concentration predictions were extremely high. The same thing was observed for the SO_4 and HCO_3^- concentrations (not shown). This explains in part, the overestimation of EC (Figure 12b) and underestimation of SAR (Figure 14b) for treatments where gypsum was precipitating when only salt transport (SALTFLOWI) was simulated.

Sodium concentration in soil solution was satisfactorily predicted by SALTFLOWIII (Figures 17b, 18a, and 18b). However, when cation exchange was not considered (SALTFLOWII), the cation concentrations were not adequately predicted. In treatment 6 (Figures 18a and 18b), the soil originally contained 1.5 me/l Na^+ in the saturation extract and was irrigated with water containing 6 me/l Na^+. It will be shown later that some of the Na^+ applied was exchanged for other ions. This explains part of the overestimation of SAR when SALTFLOWII was used (Figure 13b).

Estimations of Mg^{2+} and K^+ concentrations were also satisfactory for all treatments when the SALTFLOWIII was used (Figures 19a, 19b, 20a, and 20b). When cation exchange was not considered (SALTFLOWI and SALTFLOWII), the predicted movement of these cations from the upper soil depth increments was too rapid because both soils were irrigated with water containing 0.5 me/l K^+ and treatment 6 irrigation water contained 1.0 me/l Mg^{2+} and treatment 7 received water containing 3.5 me/l Mg^{2+}. Both soils initially contained considerably higher concentrations of these two cations in their saturation extracts than were in the applied irrigation water.

Predicted exchangeable Na^+, K^+, and Mg^{2+} (Figure 21a) and exchangeable Ca^{2+} (Figure 21b) values are shown along with the measured values in the original Penoyer soil. The same data are also shown for the Hunting soil (Figures 22a and 22b). In both cases the predicted exchangeable Ca^{2+} increased in the upper depth increments and decreased lower in the profile. This was balanced by

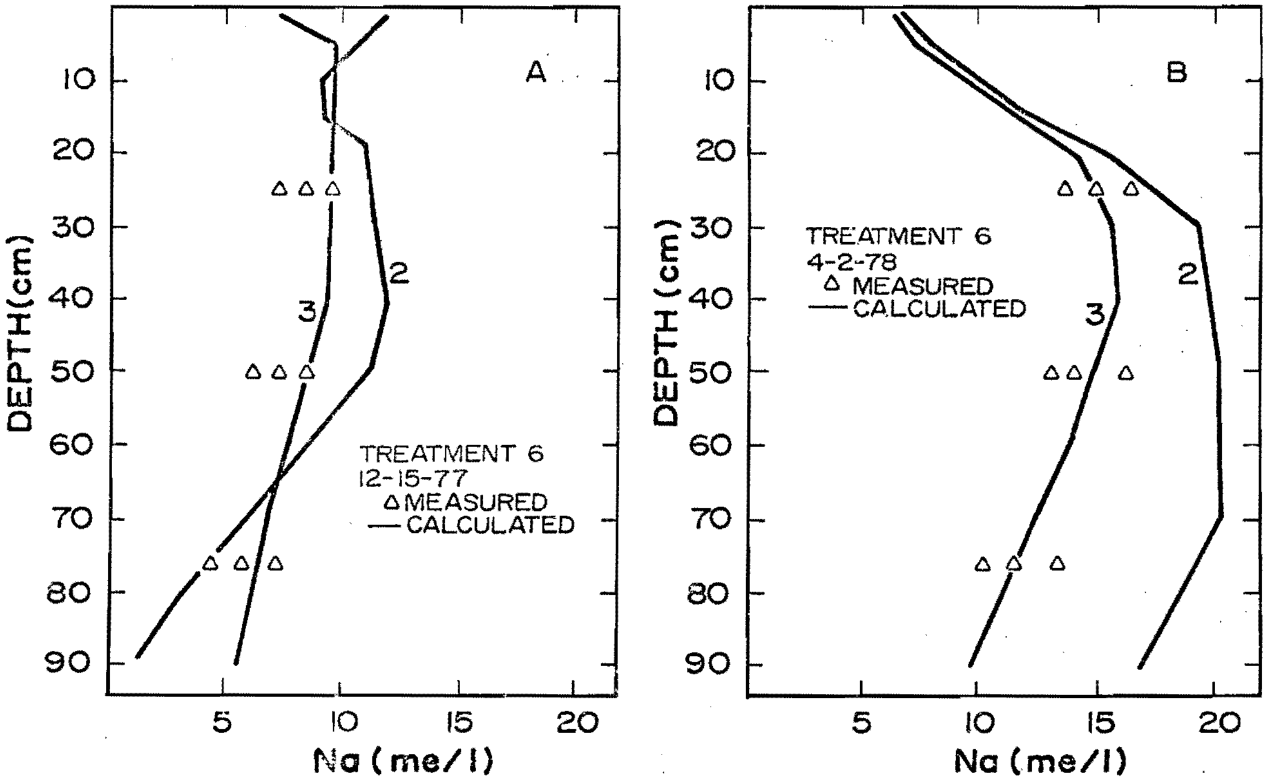

Figure 18a,b. Measured Na concentrations and concentrations calculated by the (2) SALTFLOWII and (3) SALTFLOWIII for treatment 6 on 12-15-77 and 4-2-78 (day 140 and 278).

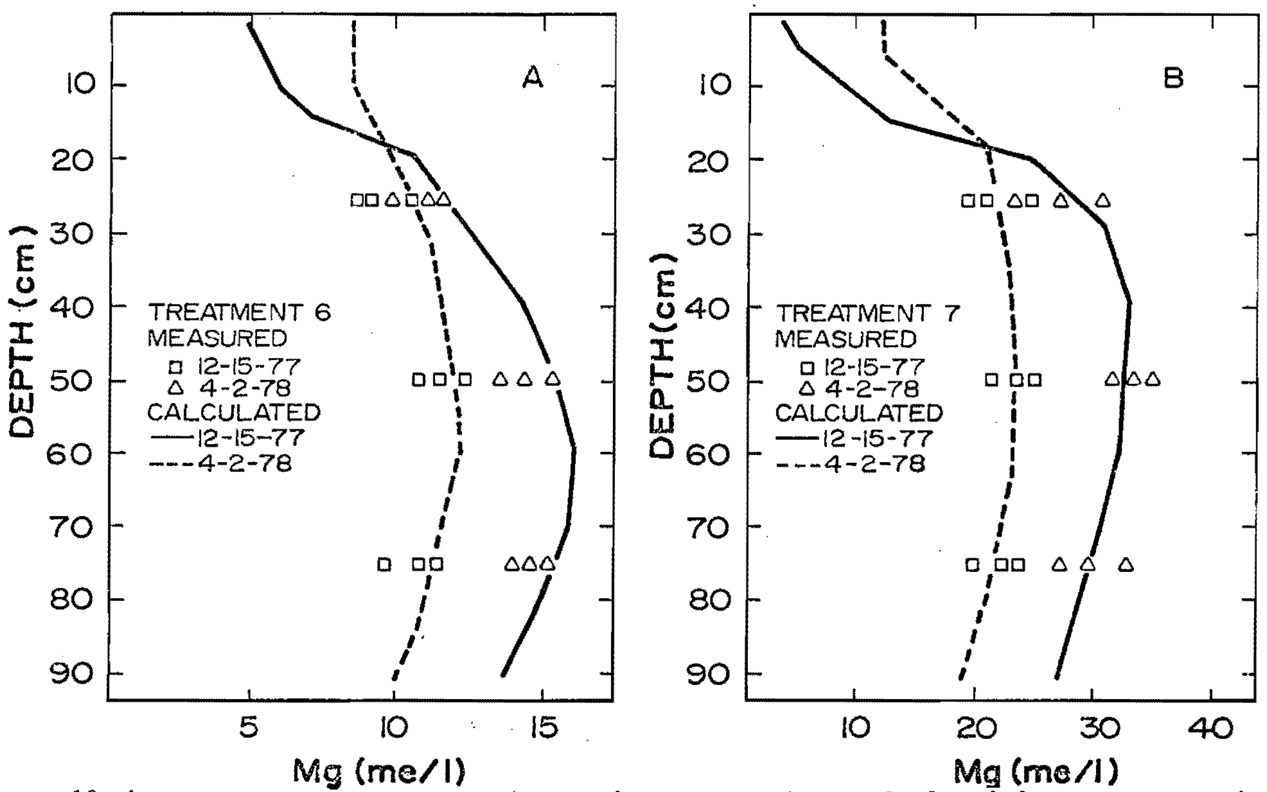

Figure 19a,b. Measured Mg concentrations and concentrations calculated for treatments 6 and 7 on 12-15-77 and 4-2-78 (day 140 and 278) by SALTFLOWIII.

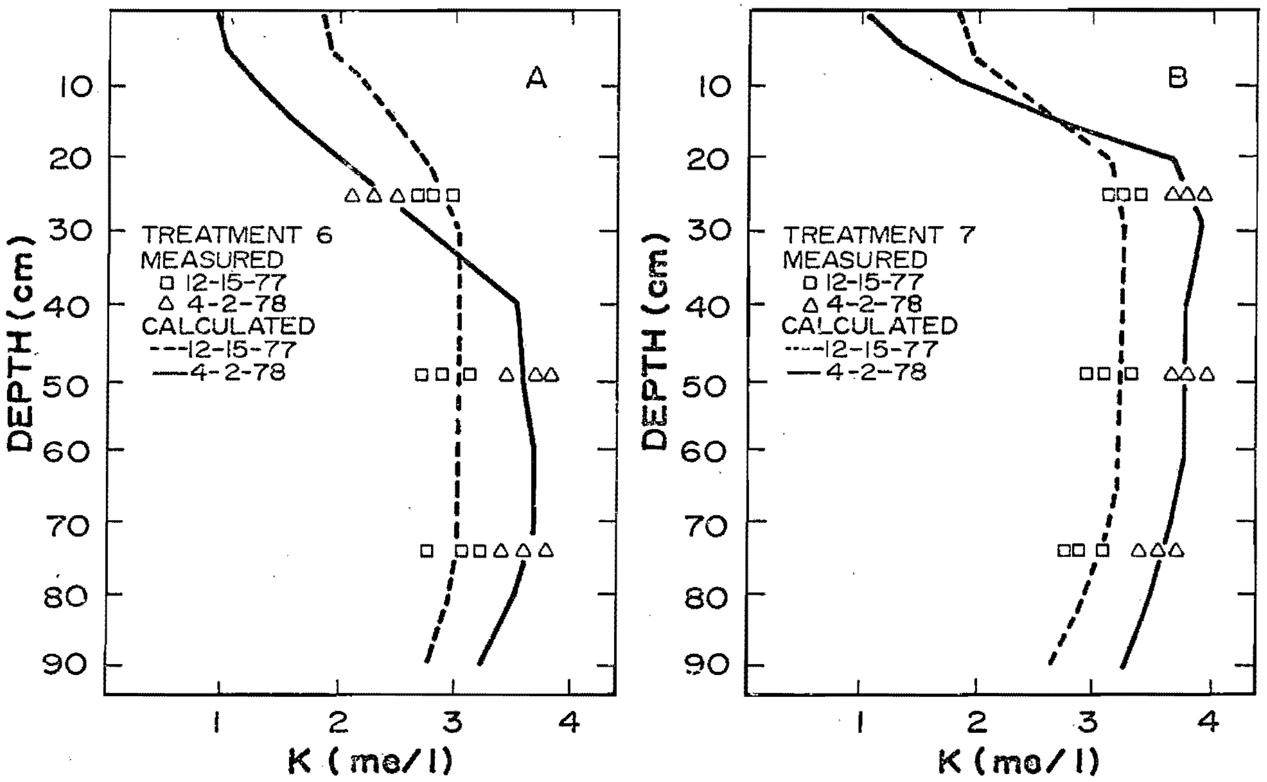

Figure 20a,b. Measured K concentrations and concentrations calculated for treatments 6 and 7 on 12-15-77 and 4-2-78 (day 140 and 278) by SALTFLOWIII.

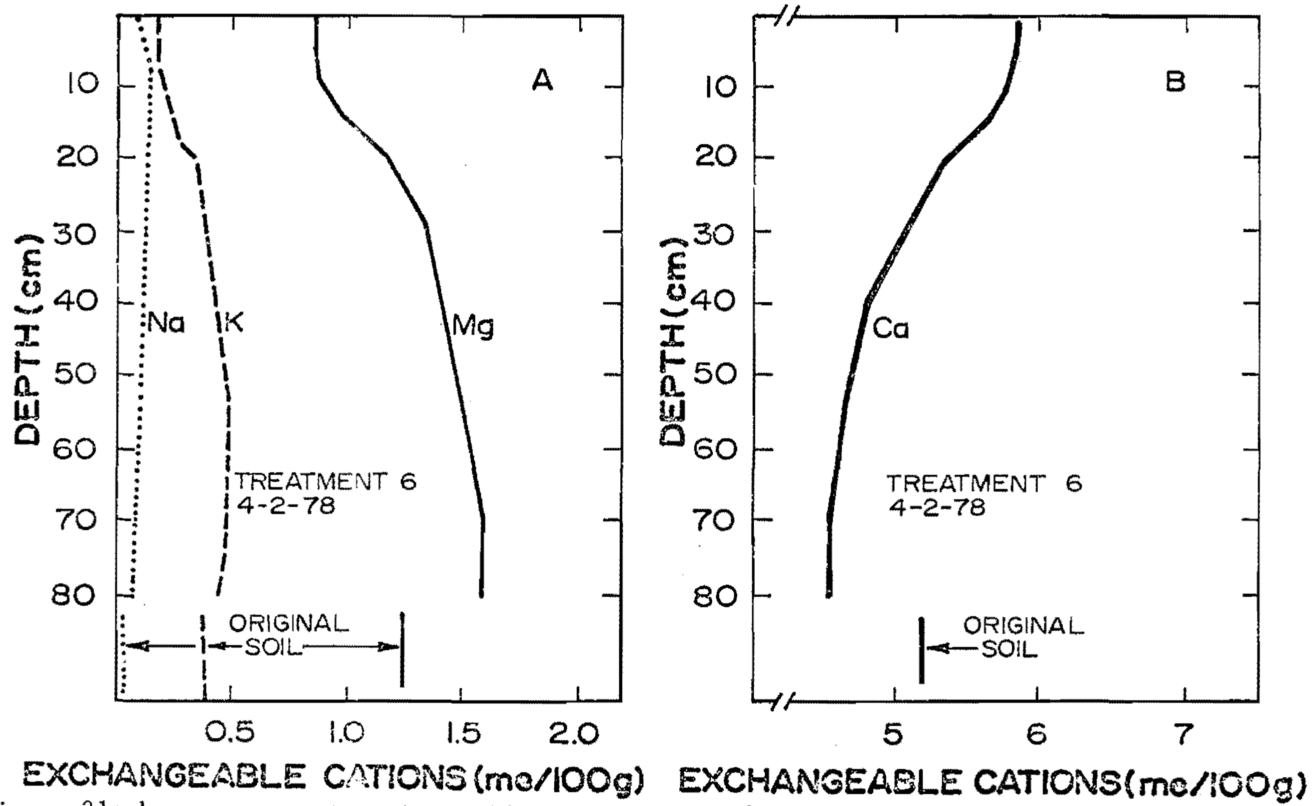

Figure 21a,b. Calculated exchangeable Na, K, Mg and Ca concentrations for treatment 6 on 4-2-78 (day 278) and the measured exchangeable cation concentrations for the original soil as it was added to the lysimeters (day 1).

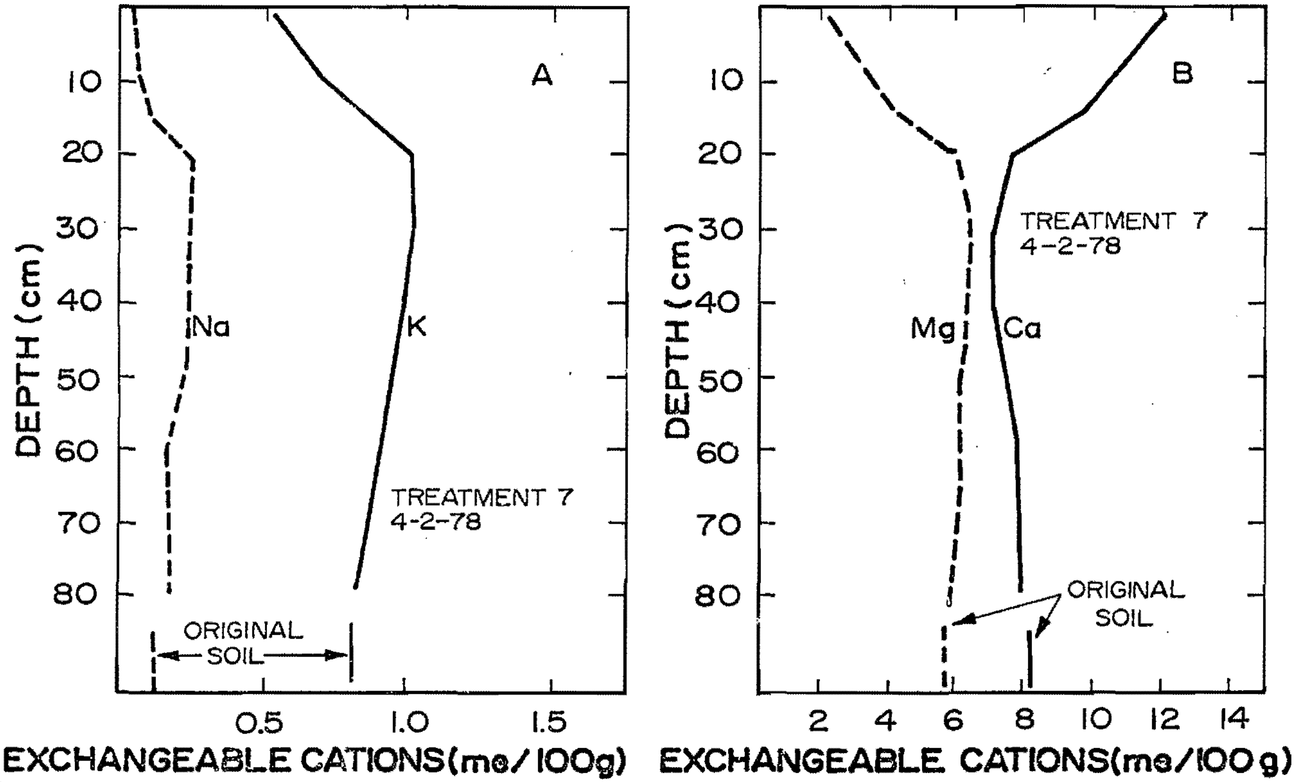

Figure 22a,b. Calculated exchangeable Na, K, Mg and Ca concentrations for treatment 7 on 4-2-78 (day 278) and the measured exchangeable cations for the original soil as it was added to the lysimeters (day 1).

exchangeable Mg and K decreases in the upper profile and increases in the lower part of the profile. Exchangeable Na increased throughout the profile in treatment 6. In treatment 7, Na^+ was desorbed near the surface and adsorbed in the lower depths. It should be noted that for the Penoyer soil (CEC = 6.9 me/100 g), the boundary between desorption and adsorption of Ca is not as abrupt as that for the Hunting soil (CEC = 14.9 me/100 g). This is considered to be due to the difference in CEC values for the two soils. Measured data are not available for comparison with the predicted exchangeable cation values.

Prediction of the SO_4^{2-} concentrations in the soil solution under both dissolution (Figure 23a) and precipitation conditions (Figure 23b) were satisfactory when SALTFLOWIII was used. The measured values for SO_4^{2-} were more variable than the other ions due to greater analytical problems in its measurement. When SALTFLOWII was used, SO_4^{2-} concentration prediction was in error inversely to the direction of Ca^{2+} error since, as the concentration of Ca^{2+} increases, SO_4^{2-} concentration must decrease or if Ca^{2+} concentration decreases, SO_4^{2-} concentration must increase. This is necessary to avoid violation of the solubility product of gypsum. When SO_4^{2-} was calculated with SALTFLOWI, SO_4^{2-} acted as an inert salt that was not affected by precipitation or dissolution of gypsum. This resulted in unsatisfactory SO_4^{2-} concentration predictions by this option.

Bicarbonate concentration simulation generally underestimated experimental data when SALTFLOWIII was used (Figures 24a and 24b). This result, like the Ca^{2+} concentration prediction, appeared to be due to the system being supersaturated with $CaCO_3$. Carbonate concentration data were calculated and printed for SALTFLOWII and SALTFLOWIII simulations but are not shown here since carbonate concentration was so small in these pH ranges that it cannot be measured or validated. For the calculations shown, a pH of 6.9 was used for the Penoyer soil and 6.8 was used for the Hunting soil because it was found by trial and error that these pH values gave the best overall results. The measured pH values of the saturation extracts for the Penoyer and Hunting soils were 7.3 and 7.5 respectively. It should be noted that a natural soil is in equilibrium with a much higher P_{CO_2} than is a laboratory prepared saturation extract, thus a lower pH should be expected in the soil (Oster and Rhoades, 1975).

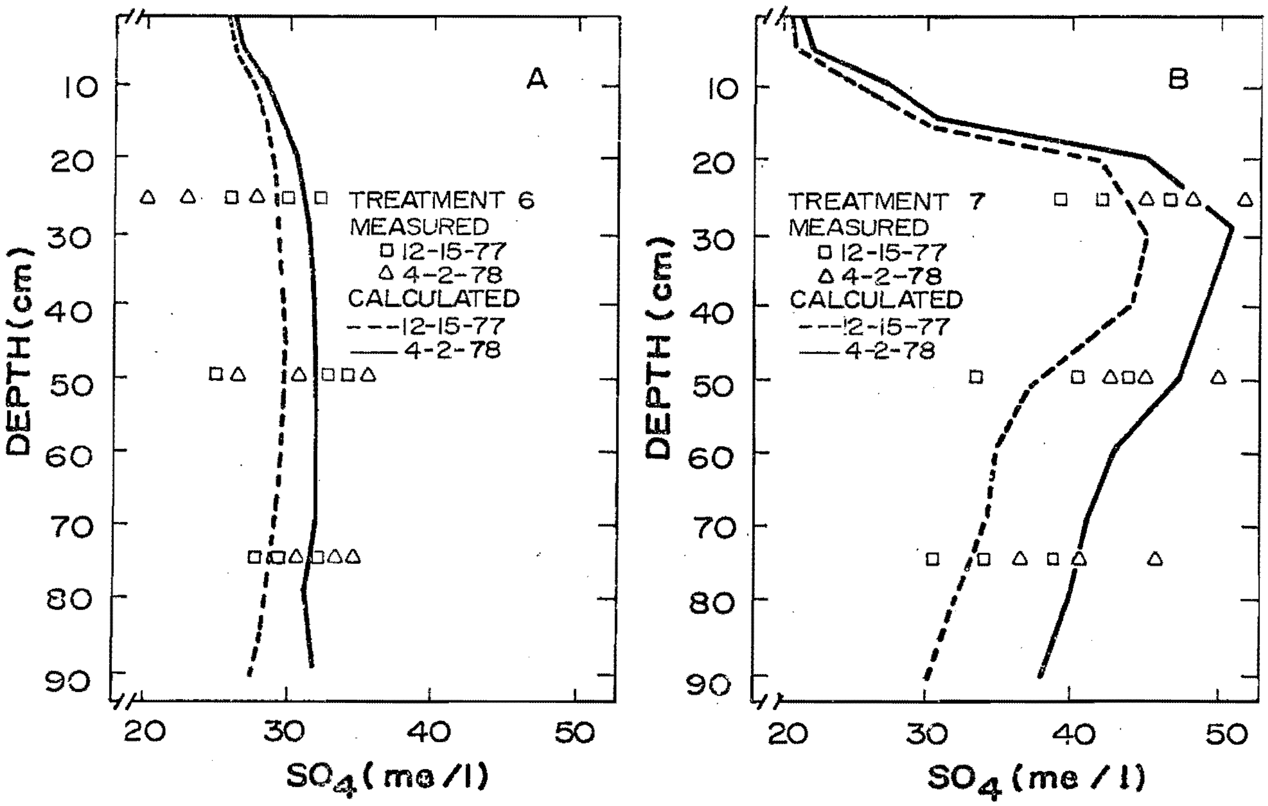

Figure 23a,b. Measured SO4 concentrations and concentrations calculated for treatments 6 and 7 on 12-15-77 and 4-2-78 (day 140 and 278) by SALTFLOWIII.

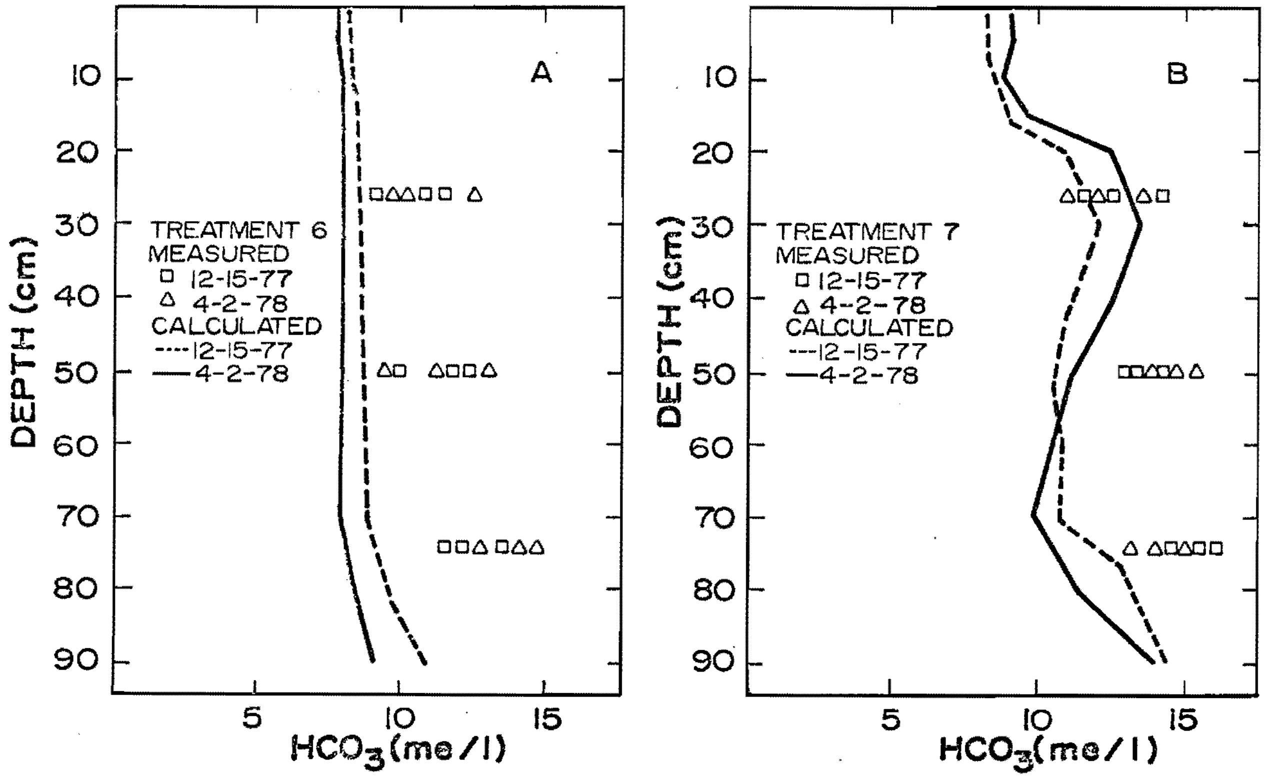

Figure 24a,b. Measured HCO_3 concentrations and concentrations calculated for treatments 6 and 7 on 12-15-77 and 4-2-78 (day 140 and 278) by SALTFLOWIII.

Irrigation Water Effects

The behavior of salt in the soil is a function of the ionic species present in the water, the salts present in the soil, and the leaching fraction. The chemistry models developed in this study can be used to examine the relation between leaching fraction and the electrical conductivity of the drainage water for waters with different combinations of ionic species. Table 8 shows the equilibrium salinity at the bottom of a soil profile for a nonreactive soil irrigated with waters of different concentrations and different proportions of high and low solubility salts. Theoretical waters having salts consisting of 100 percent NaCl, 50 percent NaCl and 50 percent $CaSO_4$, and 10 percent NaCl and 90 percent $CaSO_4$ are illustrated.

An irrigation water with an electrical conductivity of 1.0 mmhos/cm and containing salts in a proportion of 90 percent calcium sulfate and 10 percent sodium chloride would have an electrical conductivity of 3 mmhos/cm in the drainage water with a 10 percent leaching fraction. Water having the same initial electrical conductivity (1.0 mmhos/cm) but having only sodium chloride salts would have an electrical conductivity of 10 in the drainage water with a 10 percent leaching fraction. The calcium sulfate leaching fraction water carries less salt out

Table 8. Equilibrium concentration of the soil solution at the bottom of a root zone (EC_{dw}) for different water chemistries and different leaching fractions.

EC_{iw} mmhos/cm	Water comp[1]	Leaching Fraction 20%	10%	5%	1%
0.5	Na	2.5	5	10	50
	Na-Ca	2.0	4	7	30
	Ca-Na	1.7	3	3	4
1.0	Na	5	10	20	100
	Na-Ca	4	7	12	57
	Ca-Na	3	3	4	8
2.0	Na	10	20	40	200
	Na-Ca	7	12	24	110
	Ca-Na	3	4	7	25
4.0	Na	20	40	80	400
	Na-Ca	12	22	50	225
	Ca-Na	4	7	10	50

[1] Na water has only sodium chloride, Na - Ca water has 50 percent calcium sulphate and 50 percent sodium chloride, and Ca-Na water has 90 percent calcium sulphate and 10 percent sodium chloride combined to give the required electrical conductivity.

of the soil than was added because precipitation occurred in the soil profile. A water with 50 percent NaCl salts and 50 percent $CaSO_4$ would have some precipitation in the soil and an electrical conductivity of the drainage water (7 mmhos/cm) between the two extremes. Some of the values in Table 8 are extremely high and would be unrealistic in a natural situation. The results do however illustrate that precipitation of salts in a soil profile will cause the electrical conductivity of the soil solution in a soil profile to be lower than a simple leaching fraction calculation based on steady state conditions and conservation of salt would indicate. The salts precipitated are removed from the water, thus, less salt leaves the soil than was applied. As the proportion of highly soluble salts in the water increases, the precipitation of salts in the soil decreases and the electrical conductivity of the drainage water is more nearly that predicted by the common leaching fraction equation.

Leaching Fraction and Relative Salt Load

The amount of salt leaving a soil profile is proportional to the product of the volume of water leaving the profile times the electrical conductivity of the water. The amount of salt added to the profile is proportional to the volume of water added times the electrical conductivity of the irrigation water. For a salt balance to be obtained, the amount of salt entering with the irrigation water must be equaled by the amount of salt leaving in the drainage water. When the leaching fraction is increased, more water and consequently more salt is added to the soil. If salt balance is to be maintained, more salt must also be removed since more is added. The drainage water will be reduced in volume by the amount of evapotranspiration and the salt concentration in the drainage water will be enough higher to attain a salt balance. If the irrigation waters contain salts that precipitate such as calcium carbonate and calcium sulfate, less salt may be removed than is added. The precipitated salts remain in the soil.

Figure 25 shows a hypothetical example of the differences water management can make depending on the character of the salts in the water and soil. Two cases are shown. One case is for irrigation of a soil containing residual calcium sulfate with a water containing only calcium sulfate salt. The EC of the irrigation water is 1.0 mmhos/cm and the evapotranspiration is 1.0 unit of depth per unit area. The other case is for a soil containing no residual salts being irrigated with a water containing only soluble salts (no Ca, SO_4, CO_3, or HCO_3). The initial EC of the irrigation water is 1.0 mmhos/cm and the evapotranspiration is again 1.0. Figure 25 shows the EC of the drainage water and the relative salt load in the drainage water as a function of leaching fraction. Relative salt load is the total salt being removed with a constant evapotranspiration of 1.0 unit of depth per unit area. High values of relative salt load in the drainage water at high leaching fractions for the totally soluble salt case is a result of the high amounts added with the extra irrigation water used to obtain the high leaching fraction. The net salt added to or subtracted from the soil in the totally soluble salt system is equal to zero.

In Figure 25 the curves of EC_{dw} versus leaching fraction show that for the totally soluble salt system, the EC_{dw} is a function of leaching fraction alone. The curve for a soil containing residual calcium sulfate irrigated with a calcium sulfate water is horizontal with an electrical conductivity approximately equal to the saturation electrical conductivity of calcium sulfate. For a leaching fraction greater than approximately 50 percent, calcium sulfate is being dissolved from the residual amount in the soil, the electrical conductivity of the drainage water is constant, and "salt loading" of the drainage water occurs. At leaching fractions less than approximately 50 percent, precipitation of calcium sulfate occurs, and the electrical conductivity of the drainage water remains approximately at the saturation electrical conductivity of a calcium sulfate solution.

The curves for relative salt load in Figure 25 for the two irrigation waters show that "salt loading" of the drainage water occurs at leaching fractions greater than 50 percent for the calcium sulfate water, but that precipitation of salt in the soil occurs for leaching fractions less than 50 percent. The curve of relative salt load for the completely soluble salt water shows the salt load consistent with a salt balance. When the curve for the calcium water is above the curve for the completely soluble salt water, salt loading is occurring. When the calcium water curve is below the soluble salt water curve, salt unloading is occurring.

Upper Colorado River Basin Soils and Waters

Through cooperation of the U.S. Bureau of Reclamation in Salt Lake City, Utah, data were obtained on soil and water analyses for irrigated and potentially irrigable areas in the Upper Colorado River Basin. These soils and waters were analyzed using the appropriate soil chemistry model to determine the salt loading conditions for various leaching fractions. Some of the soils contained residual calcium sulfate salts, and some did not. Existing and potential irrigated lands contained both kinds of soils.

Table 9 shows water sampling locations having waters of very similar chemical characteristics. The corresponding soils, whether with or without residual salts, were also similar. The electrical conductivity of the waters were all approximately 0.4 to 0.5 mmhos/cm.

Figure 26 shows the effects on electrical conductivity of the drainage waters and relative salt load in the drainage water for the above listed waters applied to soils with and without residual calcium sulfate salts for various leaching fractions. For soils with and without indigenous residual calcium sulfate salts, the electrical conductivity of the drainage water is essentially constant for all leaching fractions greater than 30 percent. The relative salt load is high as expected for soils containing residual

Table 9. Water sampling locations.

Ashley Creek at "Sign of the Main" (Utah)
Cimmaron Creek at USGS Gage Cimmaron (Colorado)
East Fork at Smiths Fork 7 miles below China Meadows Dam (Wyoming)
Blacks Fork 2 miles below Meeks Cabin Dam (Wyoming)
Uintah River near Neola (Utah)
Yellowstone Creek near Altonah (Utah)
Lake Fork River near "C" Canal Diversion (Utah)
Lake Fork River at Lake Fork Dam Site (Utah)
Green River near Fontenelle Dam Site (Wyoming)
Green River at Big Island Bridge (Wyoming)

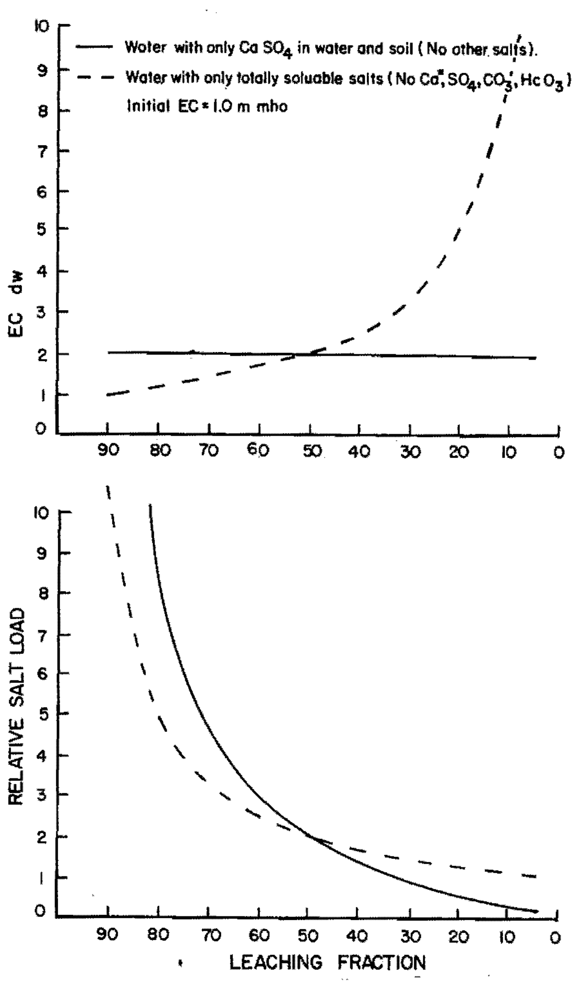

Figure 25. Electrical conductivity of drainage water EC_{dw} and relative salt loads for a soil water system containing only soluble salts or only calcium sulphate (precipitating) salts.

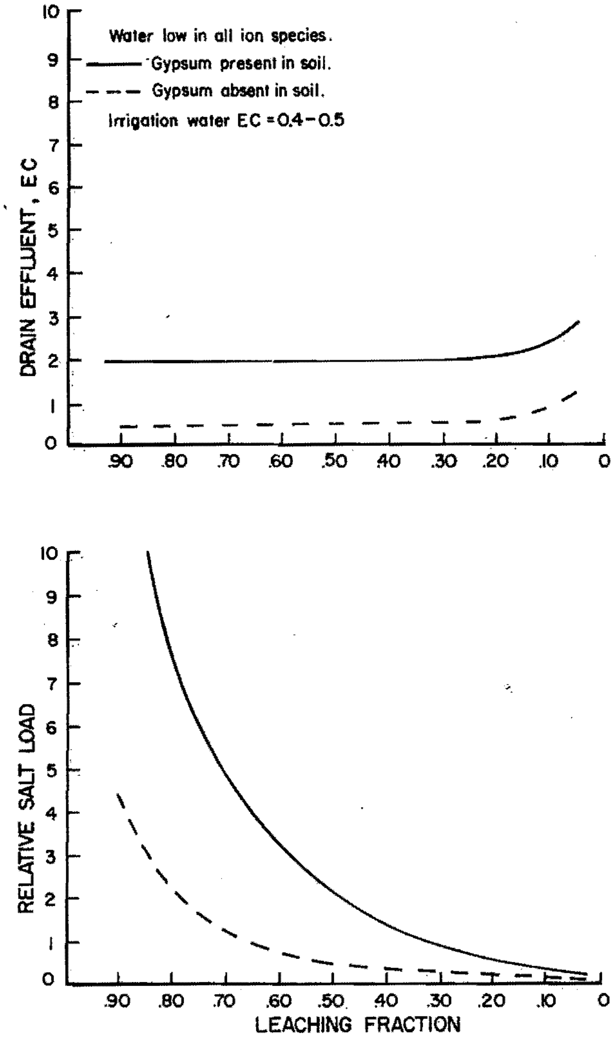

Figure 26. Typical curves of drainage water electrical conductivity and relative salt loading for specific Upper Colorado River locations for actual waters and corresponding soils with and without residual salts.

calcium sulfate salts. The relative salt load includes the salt applied with the irrigation as indicated in the previous section.

"Salt loading" becomes a problem when the leaching fraction is too high on soils containing residual calcium sulfate salts. The passage of water of relatively low concentration through the soil causes dissolution of the residual calcium sulfate salts. The drainage water carries away from the soil more salt than was added to the soil in the irrigation water. The opposite is true when the leaching fraction is low and precipitation occurs.

The effect of water management on return flow of salt to the groundwater system can be illustrated by a computed example. Assuming that 80 percent of the irrigation water is absorbed by the soil and that 70 percent of the water applied is stored in the root zone, the irrigation water storage efficiency will be 0.875 or 87.5 percent. If the evapotranspiration is assumed to be 1.0 foot (305 mm), the net amount of salt in the drainage water can be calculated. The data are shown in Table 10. The leaching fraction in the computation is the water applied for the purpose of leaching plus the average amount of water passing through the soil due to irrigation water distribution uniformity losses.

Whether the soil contains residual gypsum or not, leaching fractions less than 17 percent resulted in a net removal of salt from the irrigation water. For a soil containing gypsum and with a 25 percent leaching fraction and evapotranspiration equal to 1.0, the water passing through the soil would be ET(1/(1-LF) = 1.0(1/(1-0.25)) = 1.33. Multiplying the amount of water applied by the salt concentration of the irrigation water (0.40) would show approximately 0.53 tons of salt added. The water going to drainage would be 0.33 as calculated above. The salt concentration would be (0.33)(2.12) = 0.70 tons of salt removed. The difference would show a salt loading of 0.17 tons. If the leaching fraction is reduced to 13 percent by irrigation scheduling or more uniform water application, the salt removed in the drainage water would be 0.12 tons less than that applied in the irrigation water (Table 10).

For irrigation of soils containing no residual calcium sulfate with these waters, a net removal of salt from the water at all leaching fractions was calculated. Changing water management practices would not affect the salt load in the return flow.

Appendix F shows the detailed soil and water sample analyses for other locations in the Upper Colorado River Basin. The tables show the values of electrical conductivity and chemical ion distribution of the water at the bottom of the root zone for different leaching fractions. The column labeled T-SALT is the relative amount of salt carried by the subsurface return flow. The net amount of salt in the effluent can be calculated as:

$$\text{Net relative salt} = \left(\frac{ET}{1 - LF}\right)(LF\ EC_{dw} - EC_{iw})$$

$$\text{Net relative effluent salt} = (ET/(1 - LF))((LF)(EC_{dw}) - EC_{iw})$$

If the computed value is negative, less salt is leaving the soil profile than is entering the soil profile with the irrigation water.

Table 10. Leaching fraction effects on return flow salt loading for some Upper Colorado River Basin soils and waters.

	Residual Gypsum in Soil			No. Residual Salts		
Leaching Fraction	EC_{dw} mmhos/cm	Salt in effluent Tons/AF	Net salt in effluent Tons/AF	EC_{dw}	Salt in effluent tons/af	Net salt in effluent tons/af
0.91	1.97	19.74	15.47	0.43	4.35	-0.10
0.67	2.00	3.99	2.85	0.43	0.86	-0.34
0.50	2.02	2.02	1.22	0.44	0.44	-0.36
0.40	2.05	1.36	0.70	0.46	0.31	-0.36
0.33	2.06	1.03	0.42	0.49	0.24	-0.36
0.29	2.07	0.83	0.28	0.51	0.21	-0.36
0.25	2.12	0.71	0.17	0.54	0.18	-0.35
0.22	2.11	0.60	0.08	0.57	0.16	-0.35
0.20	2.16	0.54	0.04	0.59	0.15	-0.35
0.13	2.25	0.35	-0.12	0.71	0.11	-0.35
0.10	2.38	0.26	-0.18	0.84	0.09	-0.35
0.05	2.82	0.15	-0.27	1.25	0.07	-0.36

Estimating Subsurface Return Flow EC

For predicting equilibrium or steady state subsurface return flow electrical conductivities (EC), the possible soil-irrigation water combinations in the Upper Colorado River Basin can be divided into three general groups. Each group shows a unique relationship between the irrigation water quality and the subsurface return flow quality. The groups are:

1. When both the soil and irrigation water are low in calcium or sulfate, or one is low in calcium and the other is sufficiently low in sulfate so that the solubility of gypsum is not exceeded, then the EC of the drainage waters will be approximately equal to the EC of the irrigation waters divided by the leaching fraction (LF).

2. When the soil contains residual gypsum but the calcium and sulfate in the irrigation water are sufficiently low so that evapotranspiration (ET) effects do not concentrate the calcium and sulfate in the soil solution water sufficiently to cause precipitation of gypsum, then the subsurface return flow EC will be approximately 2.2 mmhos plus the estimated nongypsum salt EC of the irrigation water divided by the LF. Under these conditions gypsum will be dissolved from the soil profile until all the solid phase gypsum is removed at which time the conditions of soil-water group 1 will exist.

3. When the irrigation water contains sufficient calcium and sulfate that the concentration due to ET exceeds the gypsum solubility (30.5 meq/l), the EC of the subsurface return flow will be approximately 2.2 mmhos/cm plus the nongypsum salt EC divided by the LF. This will be the case regardless of the soil gypsum status since gypsum will be precipitated as long as this irrigation water-LF condition exists. For condition 3, the soil will always be acting as a salt sink.

Under field conditions where residual gypsum exists in the soil, a field may fluctuate between conditions 2 and 3, depending on the water management. A change from condition 2 to 1 could also happen if low calcium-low sulfate water is used over a long period of time. The length of time to go from condition 2 to 1 will depend on the LF, the leaching rate, the soil gypsum content, and the calcium and sulfate concentration of the irrigation water.

The 2.2 mmhos/cm value for EC is approximate, it will increase somewhat with the content of "nongypsum" salts and be reduced by calcium carbonate content. The former effect is due to the increased gypsum solubility at higher total salt concentrations and is referred to as the indifferent salt effect. Calcium carbonate precipitation will occur in most of the soils in the Upper Colorado River Basin when irrigated with available waters. For estimation purposes, however, both effects can be ignored.

Hydrologic Modeling

Quantity and Quality Simulations

The water management model was calibrated for the Ashley Valley by trying to match simulated against recorded flow measured by the U.S. Bureau of Reclamation at their gage on Ashley Creek at Jensen, Utah, for water years 1971 and 1972. Model variables were adjusted by a pattern search routine until model output most nearly matched the measured flow rate and salinity. Twelve variables were used to calibrate streamflows, and 19 other variables were used to calibrate salt flow for seven ions.

Despite the many processes simulated, the model very reliably predicted monthly runoff volumes from all periods of the year with an r^2 of 0.999 (Figure 27). During May and June, the large flows in Ashley Creek at Jensen are caused by spring snowmelt that is not diverted to Steinaker Reservoir or to the canal network. From July to October, the flows are surface irrigation return flows, groundwater effluent, and small undiverted flows from tributaries to Ashley Creek. In winter, streamflows are mostly irrigation return flow in the form of groundwater effluent. All winter streamflow from Ashley Creek is diverted into the Steinaker Reservoir.

The correlation of simulated with gaged salinity was also very good. For the seven ions (Ca^{2+}, Na^+, Mg^{2+}, K^+, SO_4^{2-}, HCO_3^-, Cl^-) which individually constitute most of the salt load of Ashley Creek, the r^2 for predicted versus measured salinities (measured in meq/liter) ranged from 0.945 for chloride to 0.990 for magnesium (Figures 28-30).

Salinities drop dramatically during peak runoff in June. The large flows which result from spring snowmelt cannot be entirely diverted to Steinaker Reservoir or to the irrigation canal system. The undiverted water runs downstream and dilutes the more saline return flows which predominate the rest of the year. This return flow is carrying salts picked up by the groundwater and carried into the stream through seepage. The fresh water-groundwater interchange effect is less noticeable with higher streamflows. The model predicted a higher percentage of groundwater interchange with smaller undiverted flows than with higher flowrates. This is borne out by comparing what actually happened in the months of May and June. Both May and June normally have a high percentage of undiverted flows, but in

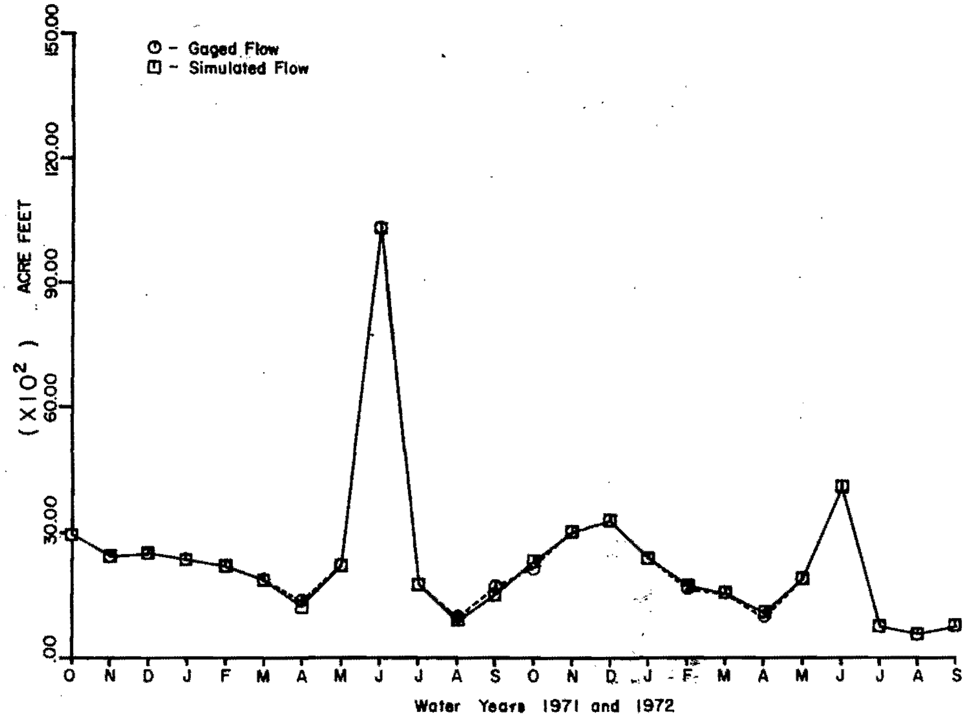

Figure 27. Gaged and simulated flow of Ashley Creek at Jensen, Utah.

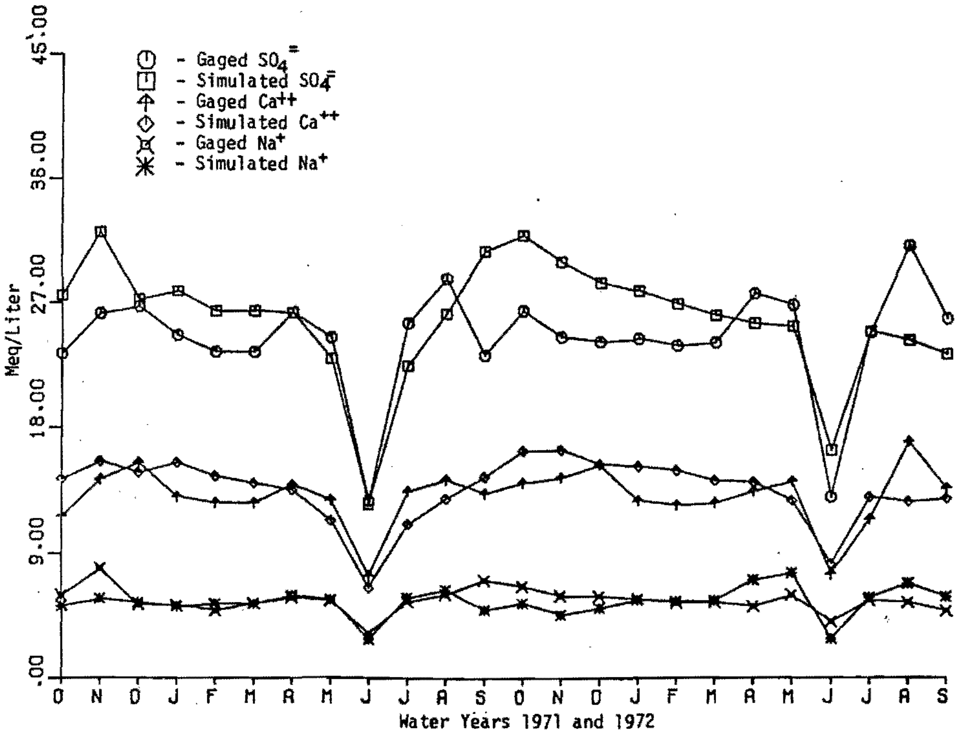

Figure 28. Gaged and simulated sulfate, calcium, and sodium salinity at Ashley Creek at Jensen, Utah.

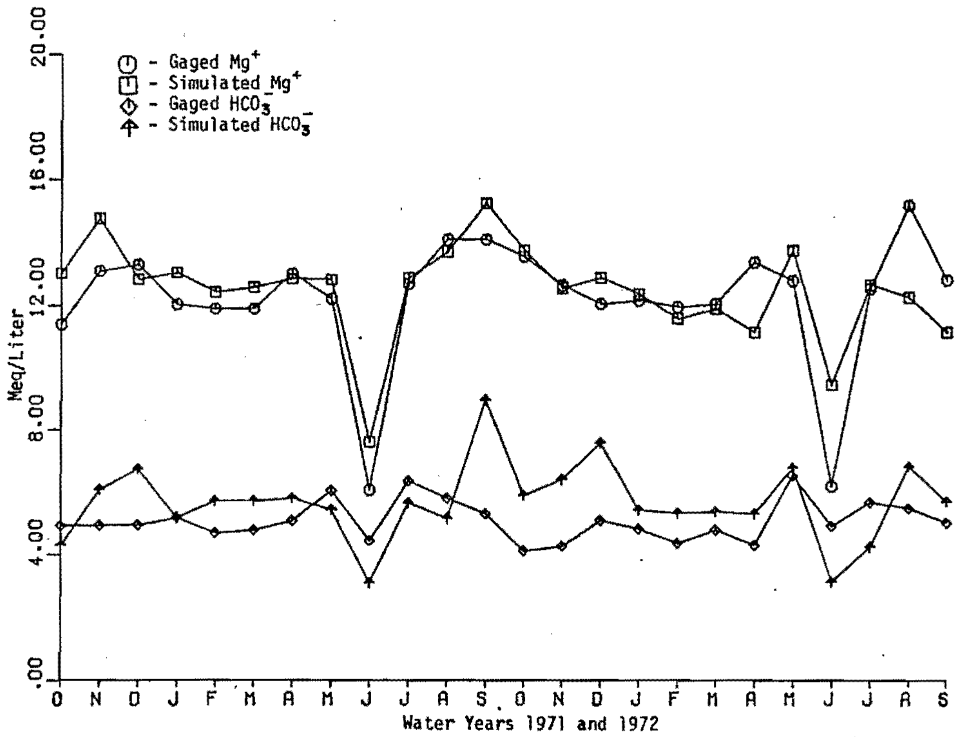

Figure 29. Gaged and simulated magnesium and bicarbonate salinity of Ashley Creek at Jensen, Utah.

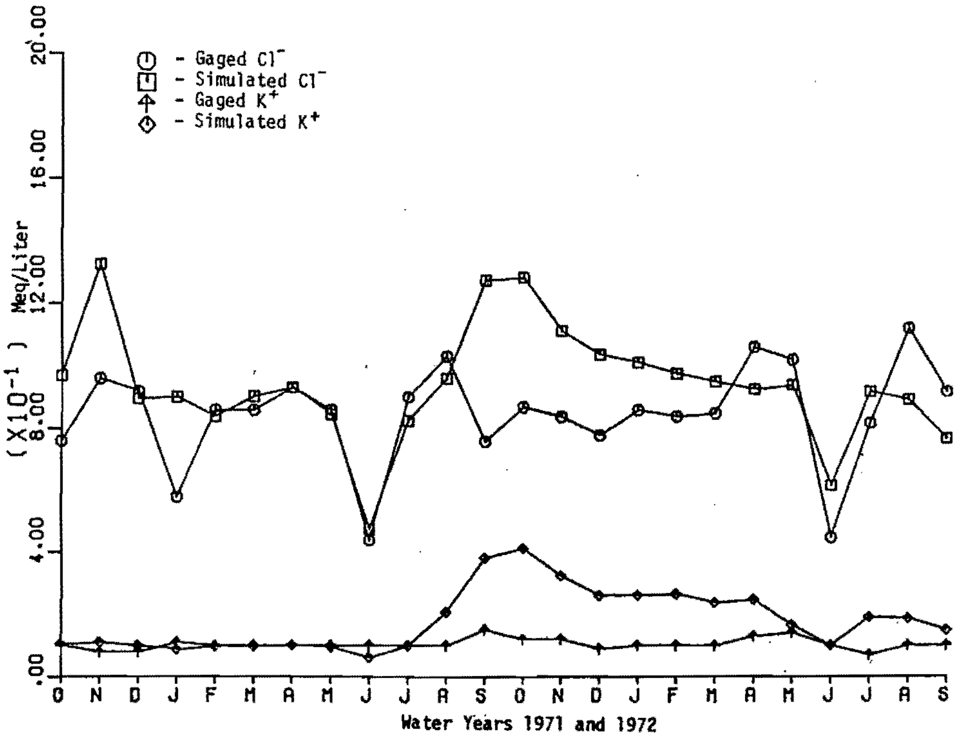

Figure 30. Gaged and simulated chloride and potassium salinity of Ashley Creek at Jensen, Utah.

May, the salinity of streamflow at Jensen was practically unchanged because the percentage of groundwater interchange was higher.

Sensitivity to Irrigation Efficiency

Figures 31 through 43 show the sensitivity of simulated streamflow and salinity to variation in irrigation application efficiency. The existing efficiency is estimated at 96 percent. The other efficiencies used in the sensitivity testing were 100 (Figures 31 through 34), 75 (Figures 35 through 38), and 50 (Figures 39 through 42) percent.

Very little irrigation tailwater actually returns to the stream as surface flow since any surface flows are diverted and rediverted through the canal network. High overall irrigation application efficiencies (determined by model calibration to be 96 percent for Ashley Valley) cause a high percentage of the water delivered to farms to enter the soil profile. In this case, the water that percolates through the soil into the groundwater system is delayed there for several months before reappearing downstream as return flow. Low application efficiencies return water to the stream relatively quickly in the form of irrigation tailwater. Since the model uses monthly time increments, the tailwater from surface irrigation is returned to the stream in the same time interval in which the irrigation occurs. The sensitivity comparisons showed that irrigation application efficiencies significantly affect flows in May and June when most irrigation occurs. Decreased irrigation application efficiencies also decrease winter flows because less water enters the groundwater system.

Streamflow salinities were also sensitive to changes in irrigation application efficiency. During months when snowmelt runoff was high and Ashley Creek water quality was relatively good, subsurface irrigation return flows decreased stream quality more significantly than did surface irrigation return flows. When groundwater effluent was mixed with surface flows, overall water quality of the surface flows decreased since groundwaters of the basin were very nearly saturated with gypsum and had higher overall salt content than did surface flows. In the month of June when snowmelt runoff was high, Ashley Creek water quality was also slightly decreased by surface irrigation return flows. During the months of August and July when groundwater return flows constitute the largest portion of the measureable flows past Jensen, Utah, increased surface irrigation return flows resulting from low application ef-

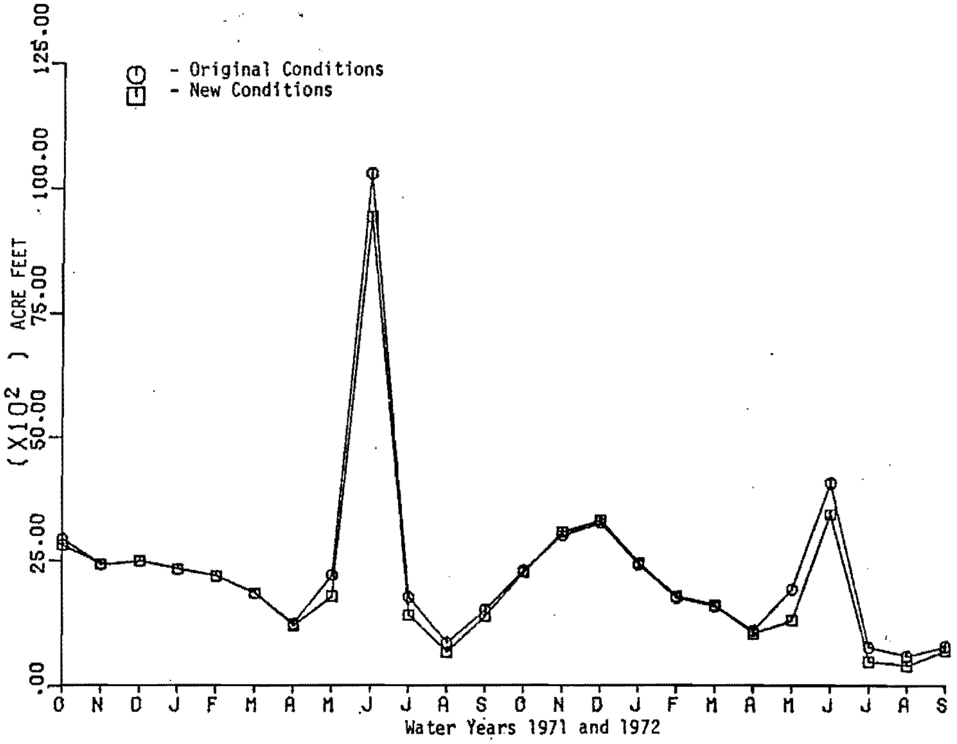

Figure 31. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with application efficiency increased from 96 percent to 100 percent.

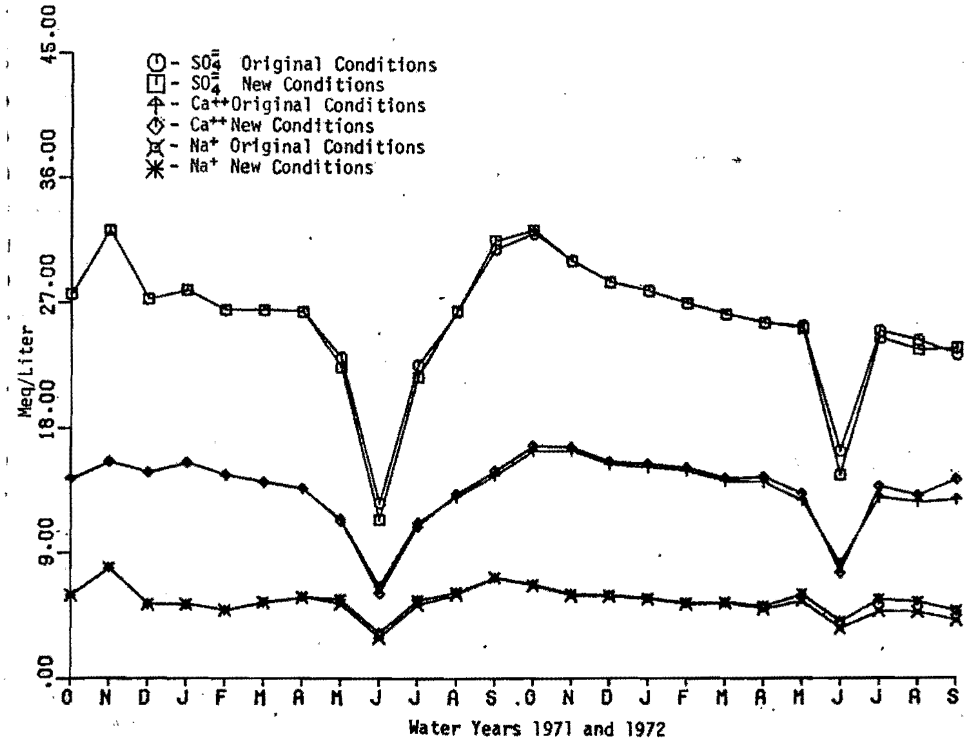

Figure 32. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency increased from 96 percent to 100 percent.

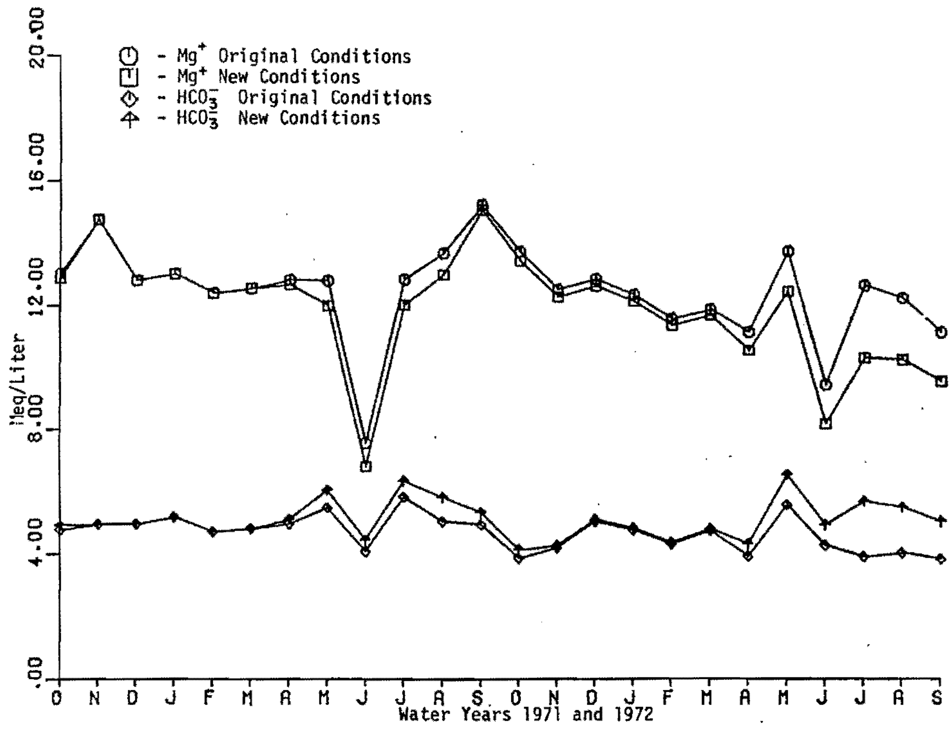

Figure 33. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency increased from 96 percent to 100 percent.

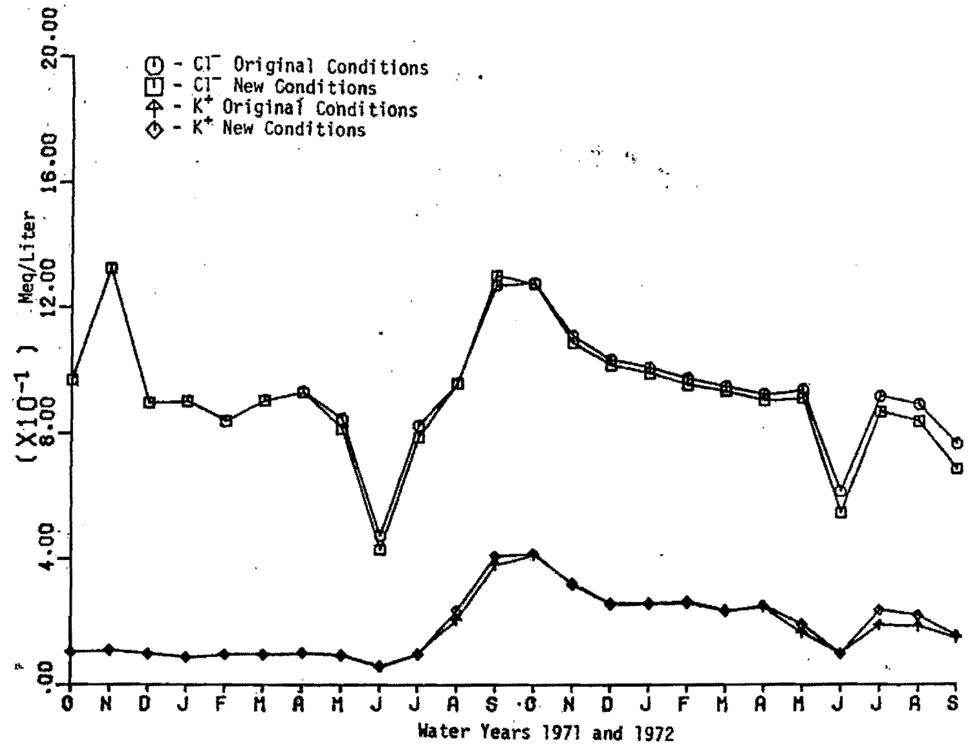

Figure 34. Simulation of salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency increased from 96 percent to 100 percent.

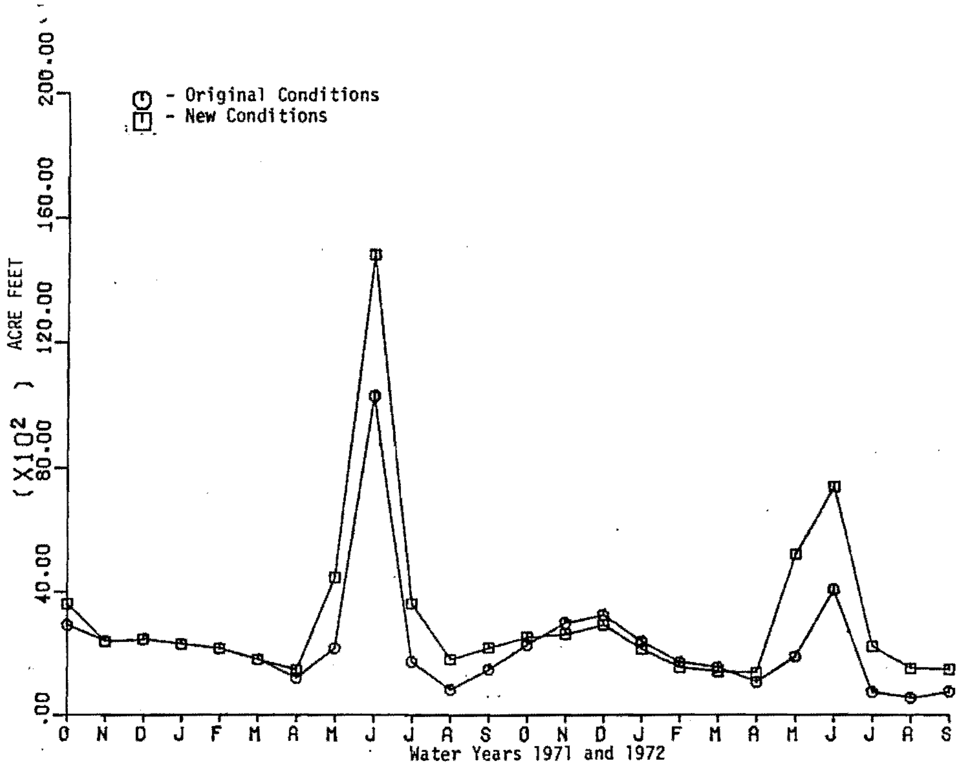

Figure 35. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 100 percent.

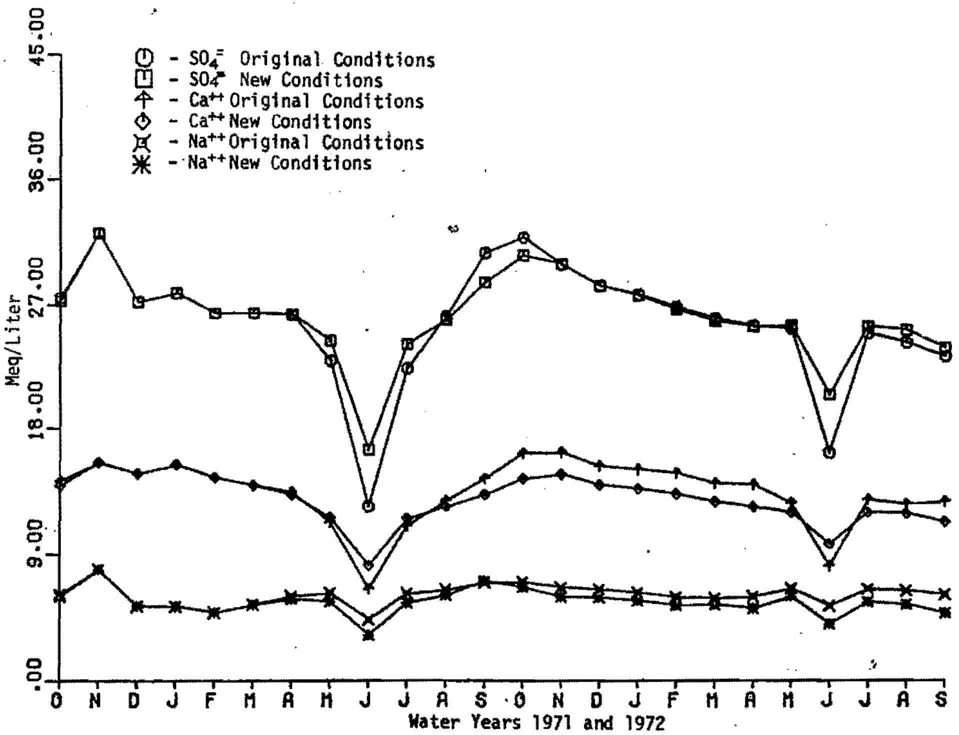

Figure 36. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 75 percent.

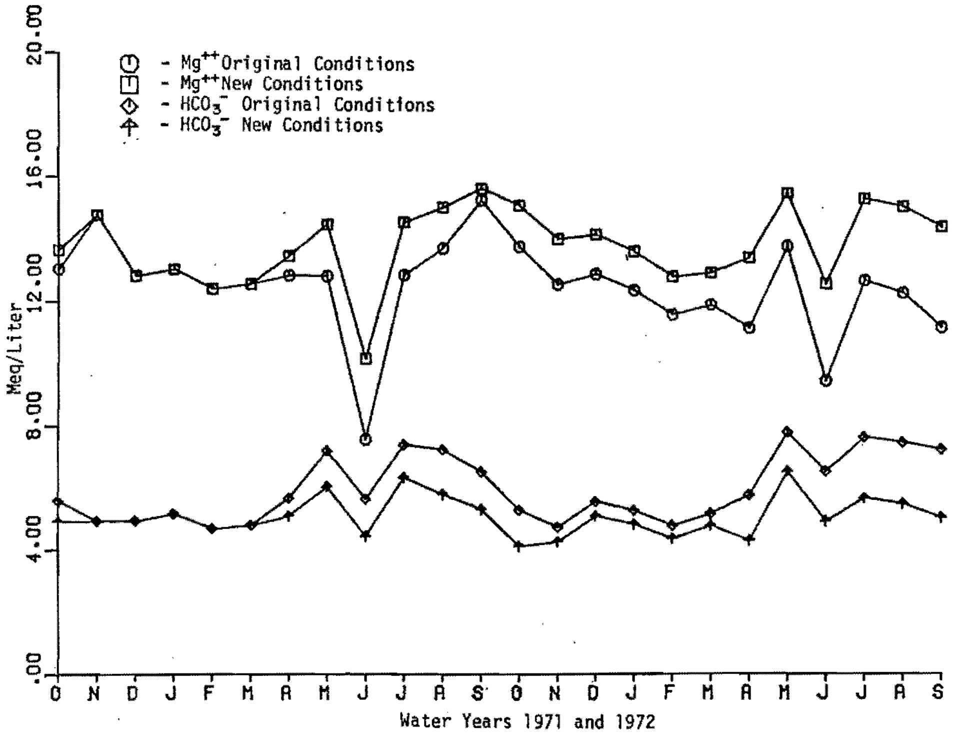

Figure 37. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 75 percent.

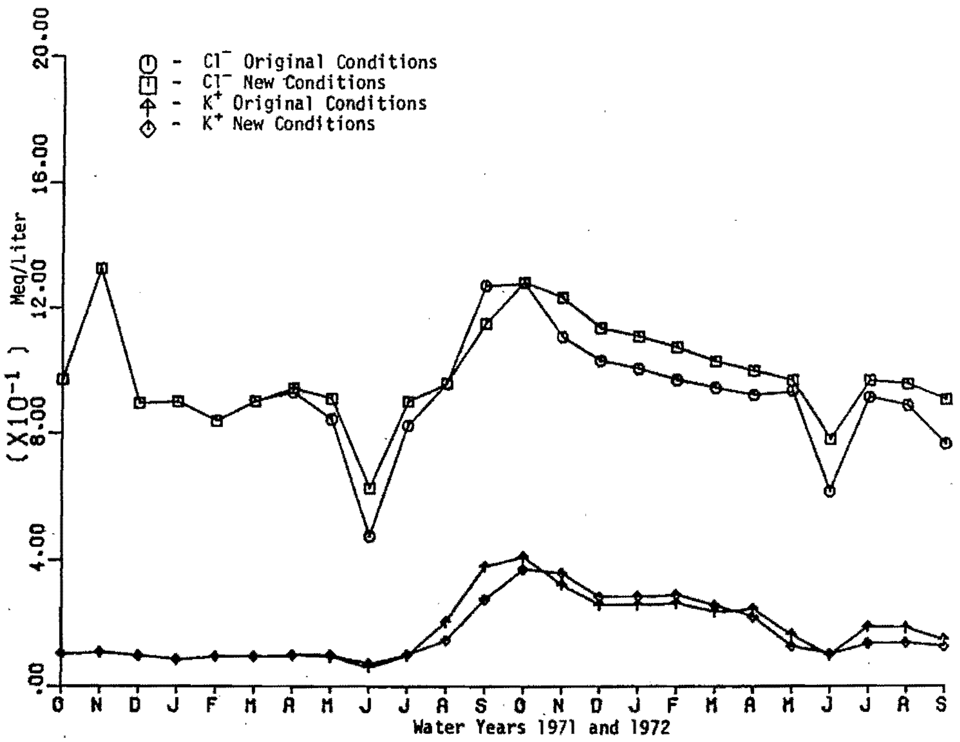

Figure 38. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 75 percent.

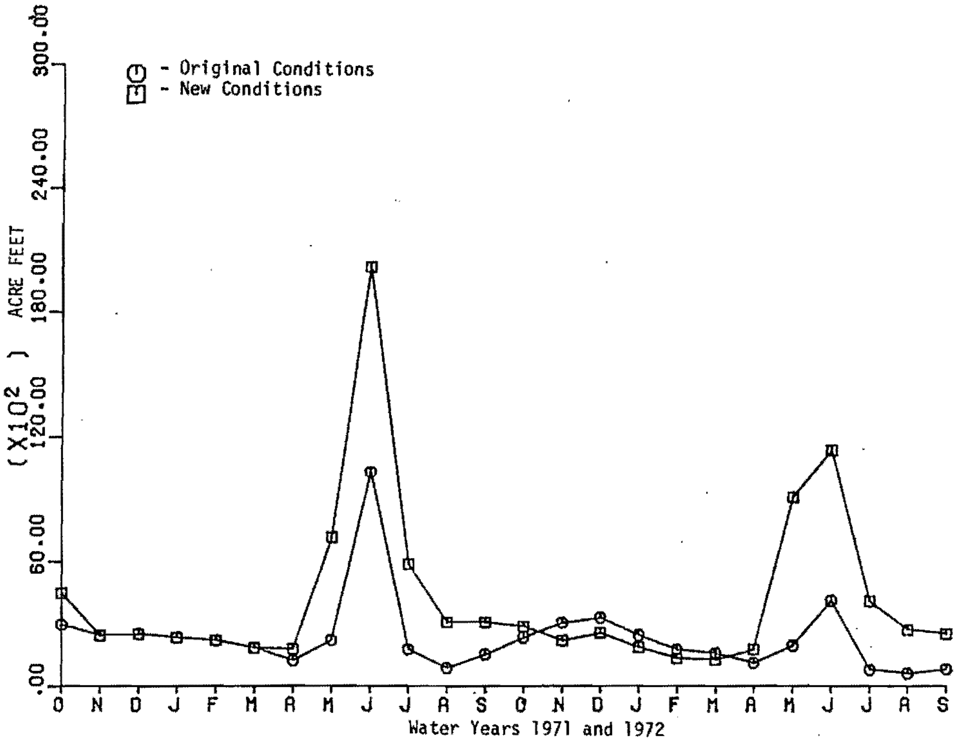

Figure 39. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 50 percent.

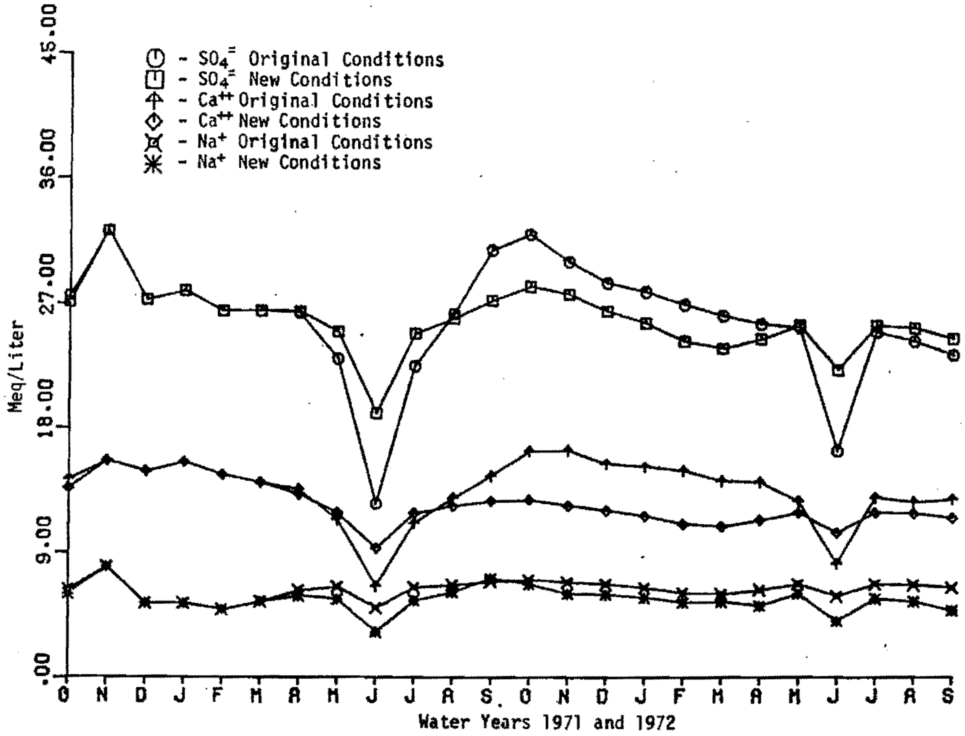

Figure 40. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 50 percent.

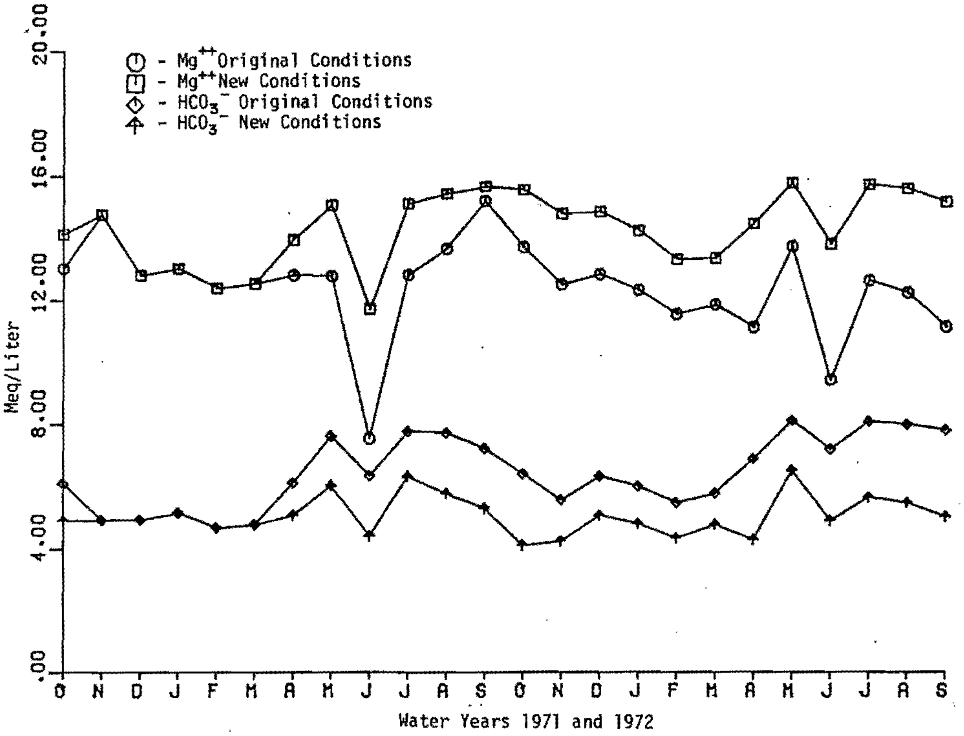

Figure 41. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 50 percent.

ficiency increased Ashley Creek water quality at Jensen, Utah. The overall effect of increasing irrigation application efficiency was to decrease streamflow quality.

Sensitivity to Canal Conveyance

Figures 44 through 55 show the sensitivity of simulated streamflow and salinity to variation in canal conveyance efficiency. Before reaching the farm, canal water can be diminished through canal spillage, subsurface seepage, or evapotranspiration. Canal spillage and evaporation losses were not considered significant in the Ashley Creek Basin, but canal seepage and transpiration from phreatophytes are important. Canal conveyance efficiency was defined as the proportion of the water diverted that is actually available for delivery. Efficiency can be improved by lining canals and making more water available for use. Conveyance efficiencies in the Ashley Creek Basin varied between 60 and 80 percent. The average canal conveyance efficiency of the basin was estimated to be 68 percent from the model. While canal seepage reappears and can be used downstream for irrigation in some basins, very little canal seepage returned to be used as irrigation water in the Ashley Creek Basin.

Varying canal conveyance efficiency affected Ashley Creek in two ways. With increased conveyance efficiencies, less water infiltrated to the groundwater system. Consequently, during winter months, streamflows were decreased. Winter streamflows originated mainly from groundwater return flow because nearly all surface flows coming into the basin are diverted to Steinaker Reservoir in the months of November to March. During the summer, increased canal conveyance efficiencies increased irrigation tailwater flows but caused streamflows to rise only slightly since the water saved would be applied to the farms.

Varying canal conveyance efficiency also greatly affected Ashley Creek water quality. When water seeps through the canal bottom, it picks up salts by dissolution and mixing with saline groundwaters. The more saline water gradually returns through the groundwater system to the stream. When canal conveyance efficiency was improved, more water was available for irrigating existing lands within the basin. Less water returned to the stream as deep percolation than would have returned as canal seepage because the added irrigation water increased evapotranspiration. When the existing acreage was irrigated with the recovered water, the salinity

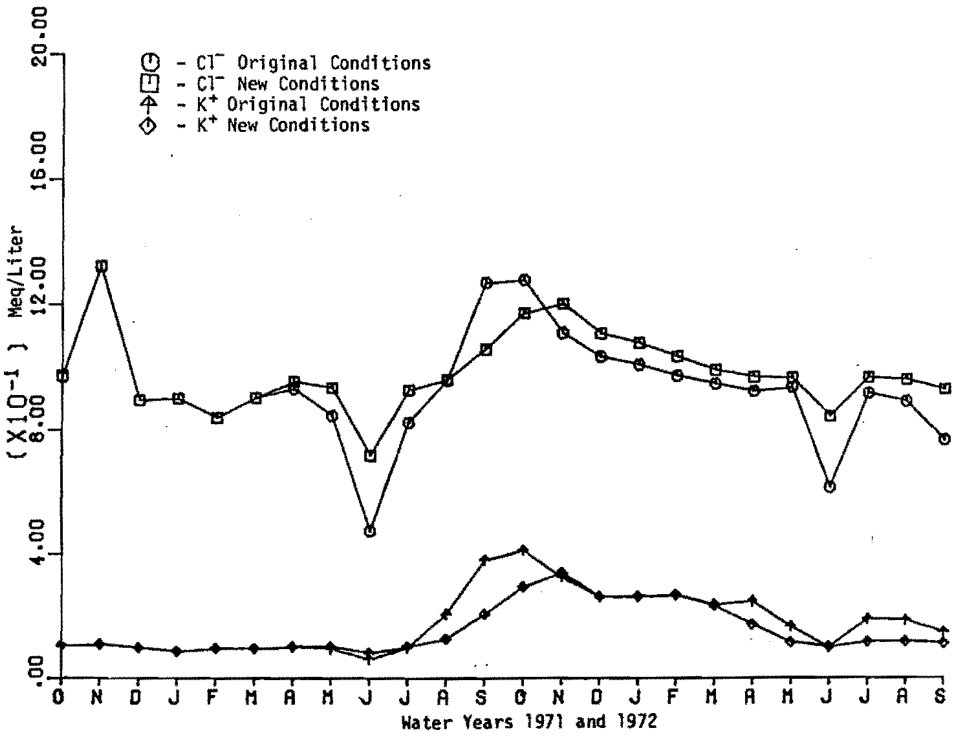

Figure 42. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with basin application efficiency decreased from 96 percent to 50 percent.

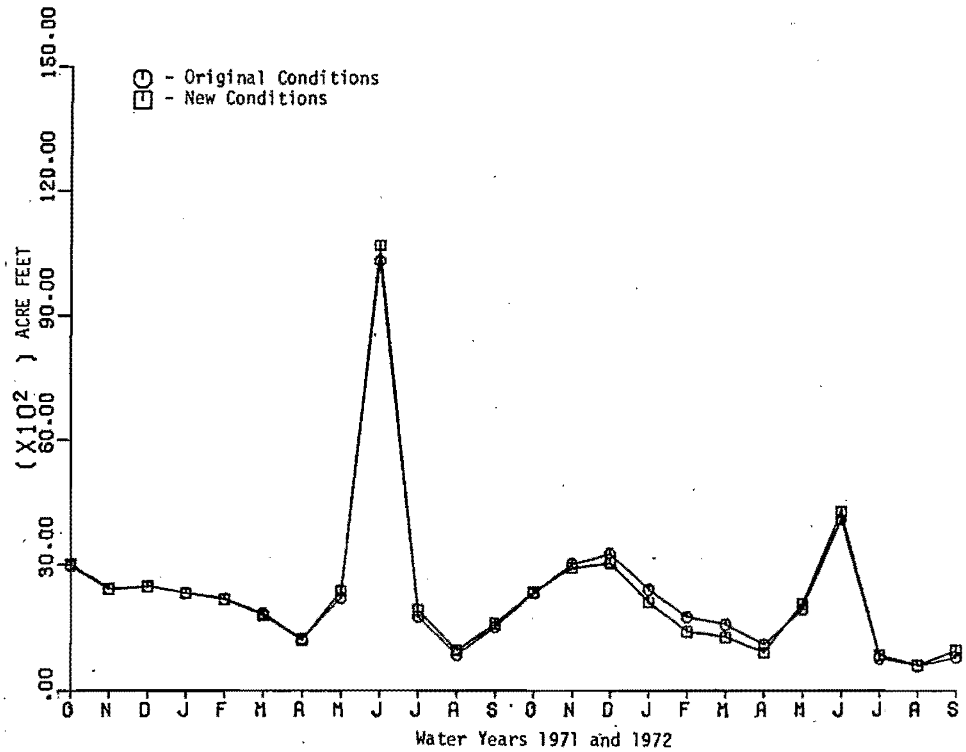

Figure 43. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent.

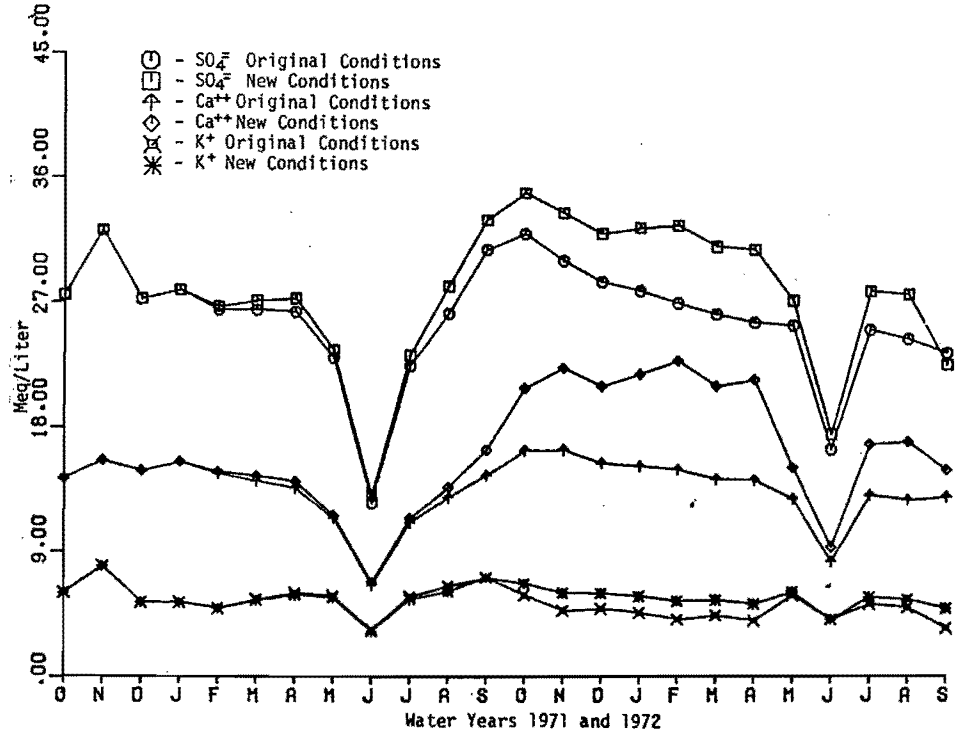

Figure 44. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent.

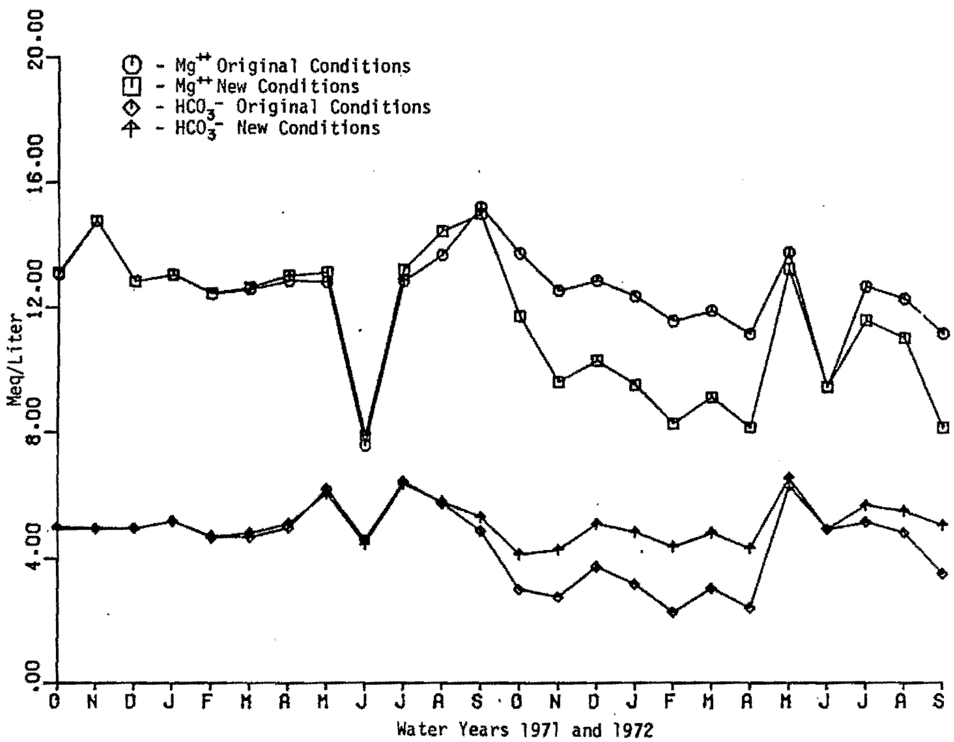

Figure 45. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent.

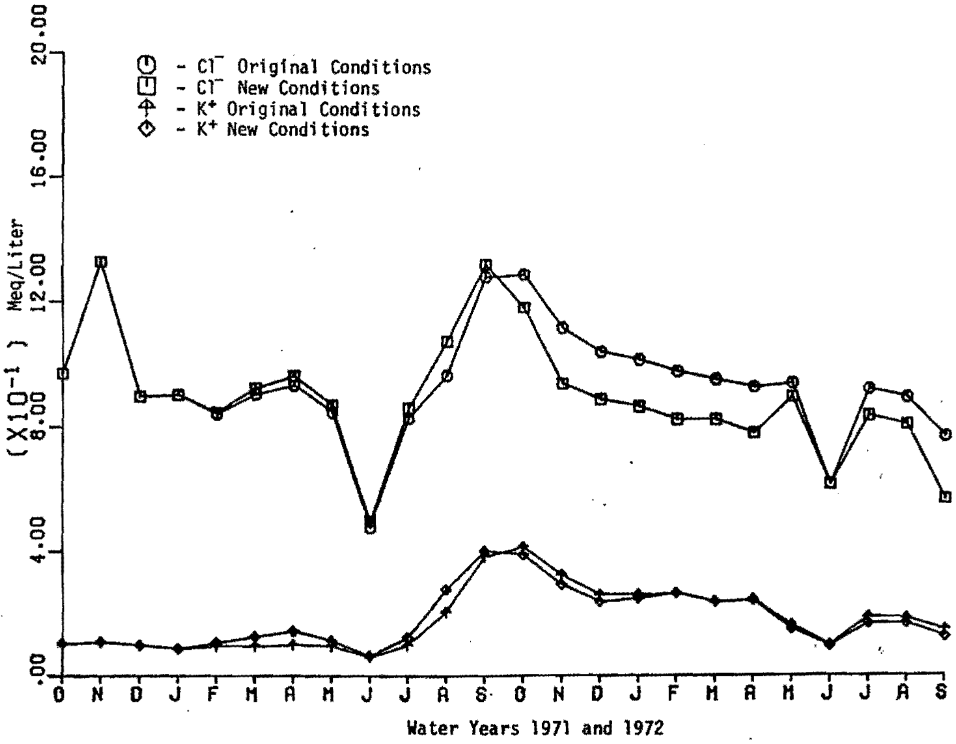

Figure 46. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent.

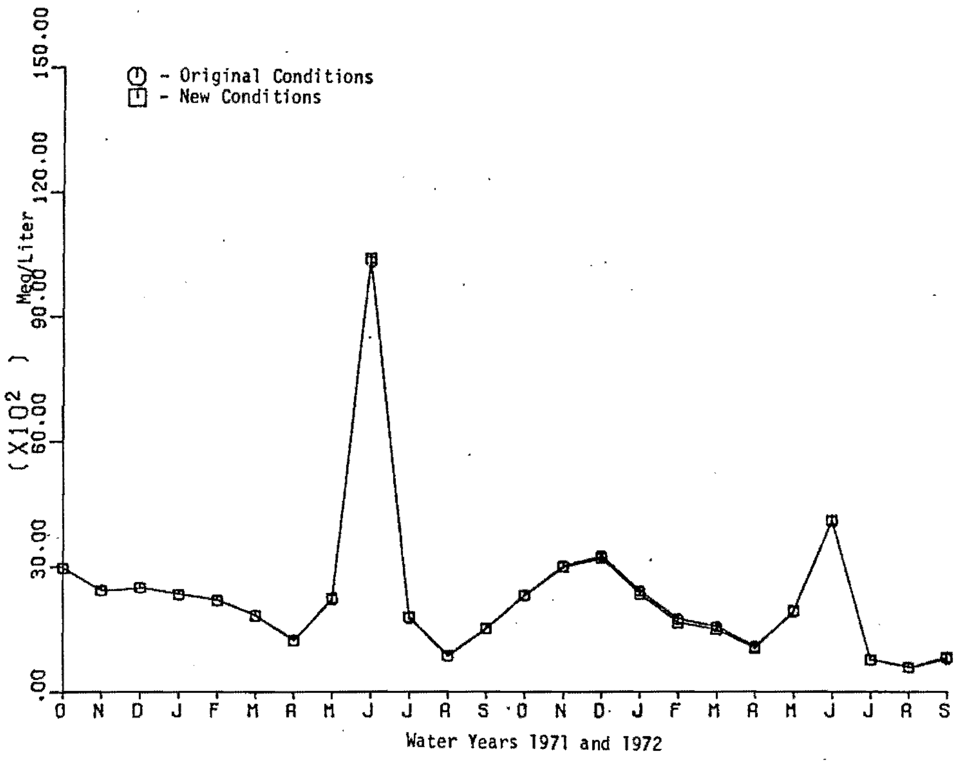

Figure 47. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 75 percent.

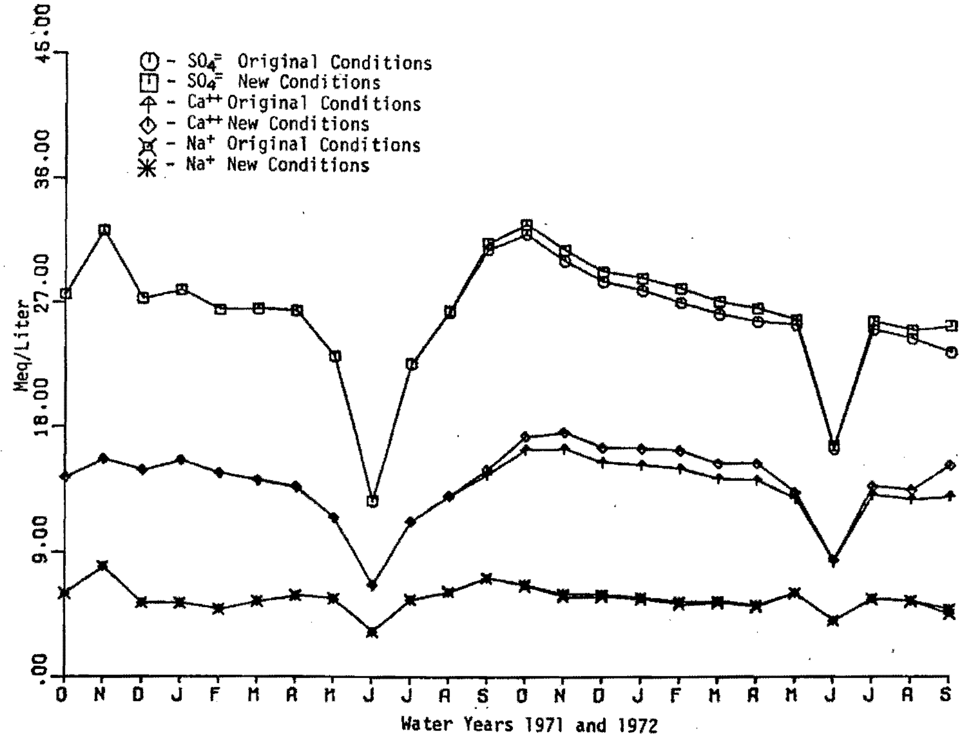

Figure 48. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 75 percent.

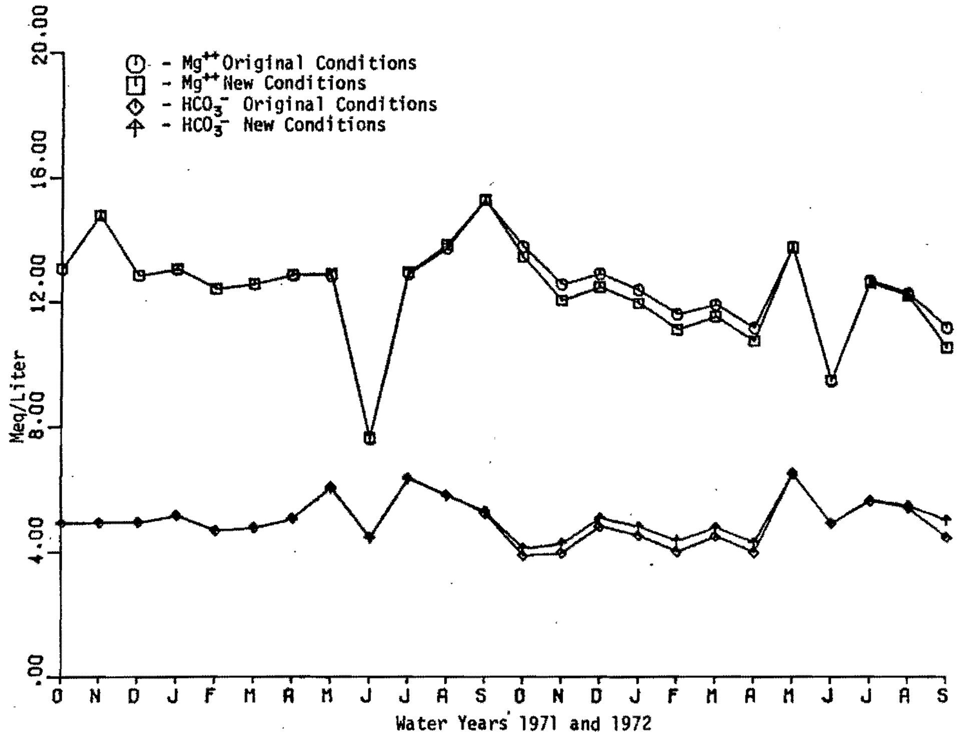

Figure 49. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 75 percent.

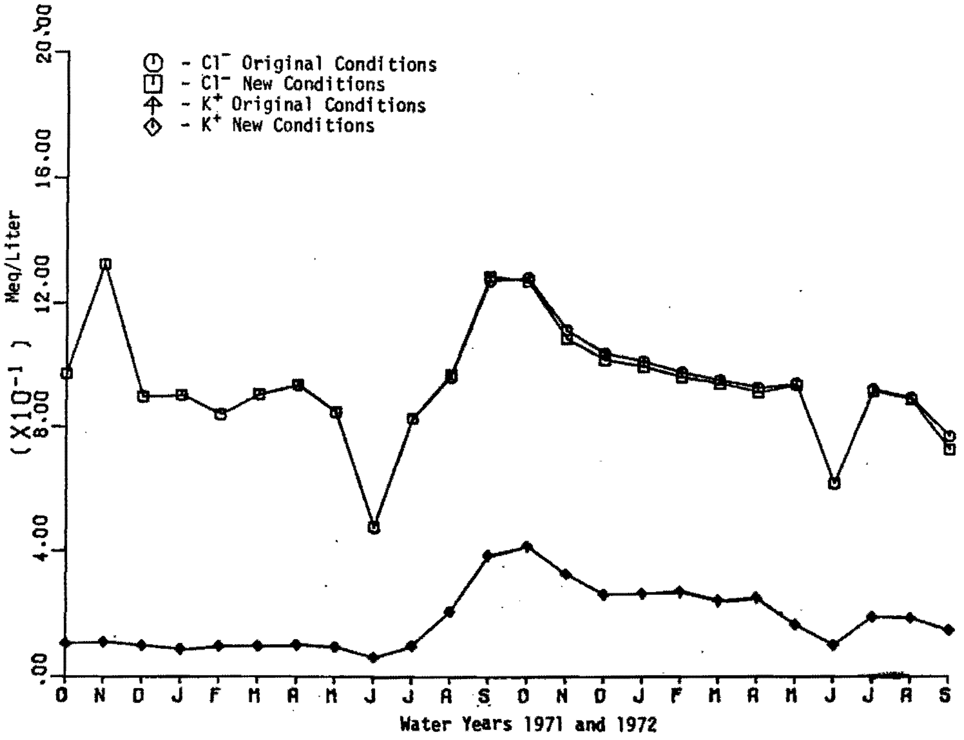

Figure 50. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 to 75 percent.

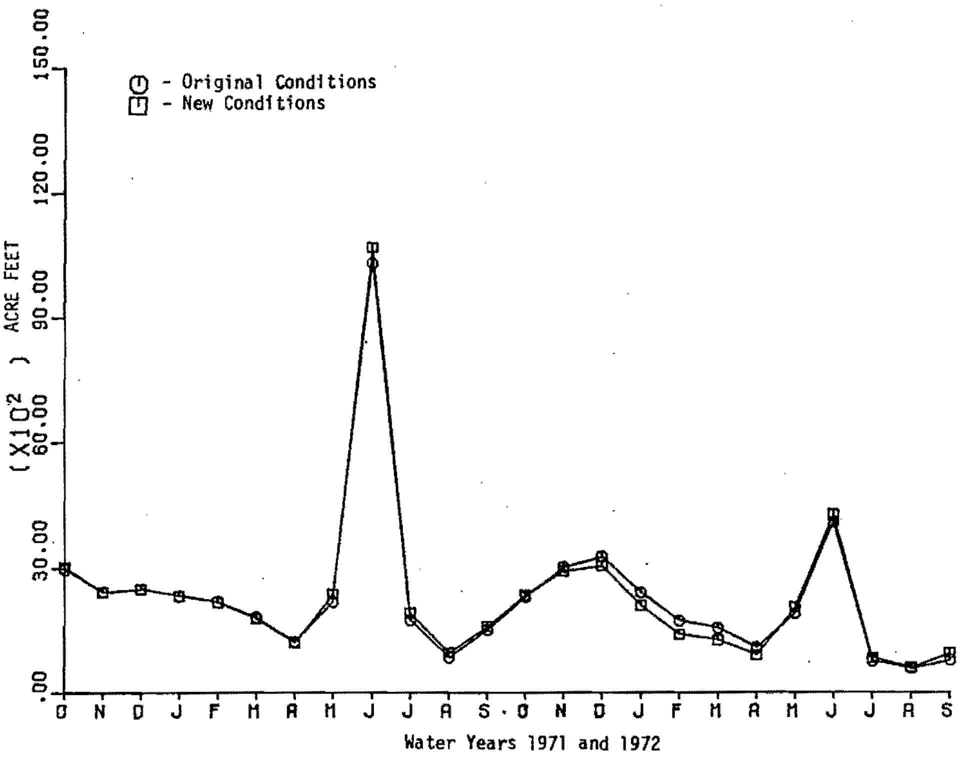

Figure 51. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency decreased from 68 percent to 50 percent.

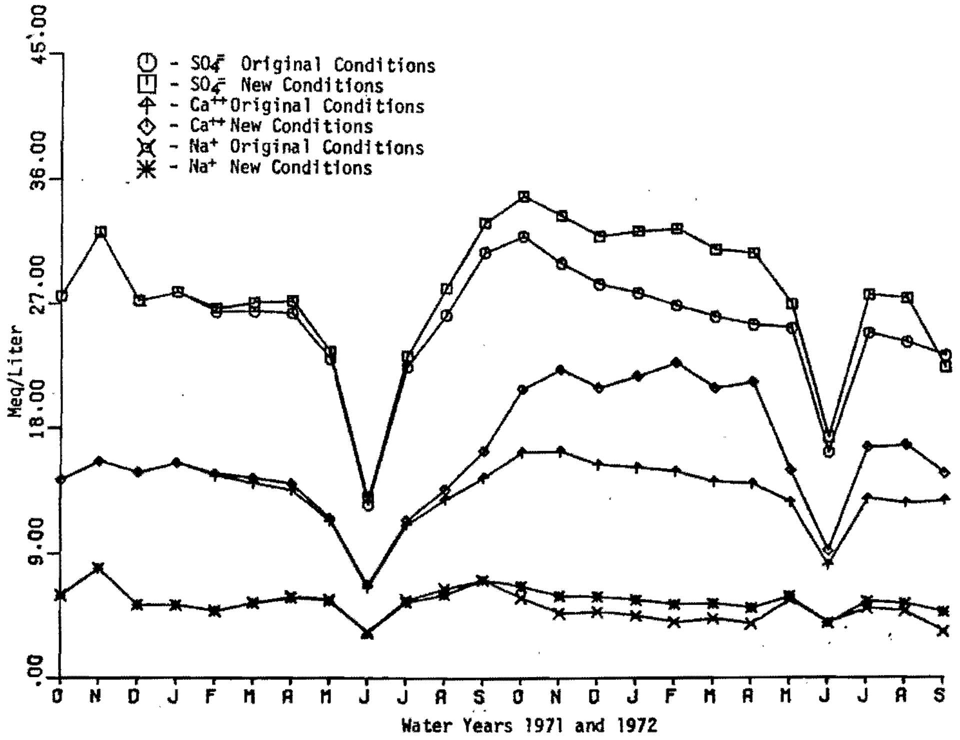

Figure 52. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency decreased from 68 percent to 50 percent.

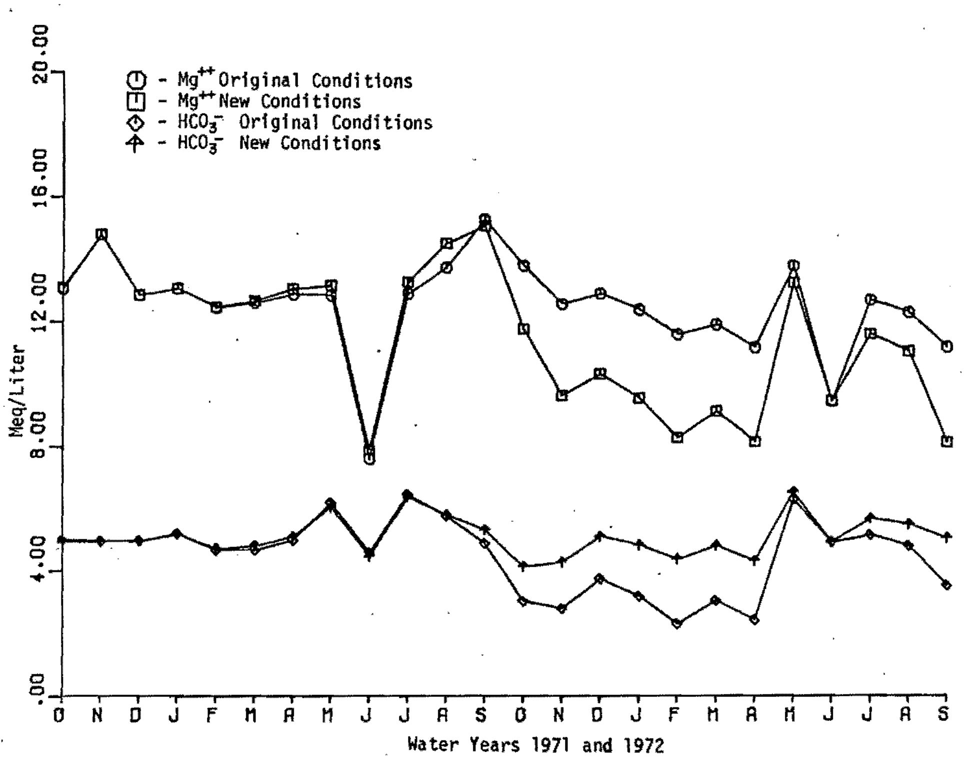

Figure 53. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency decreased from 68 percent to 50 percent.

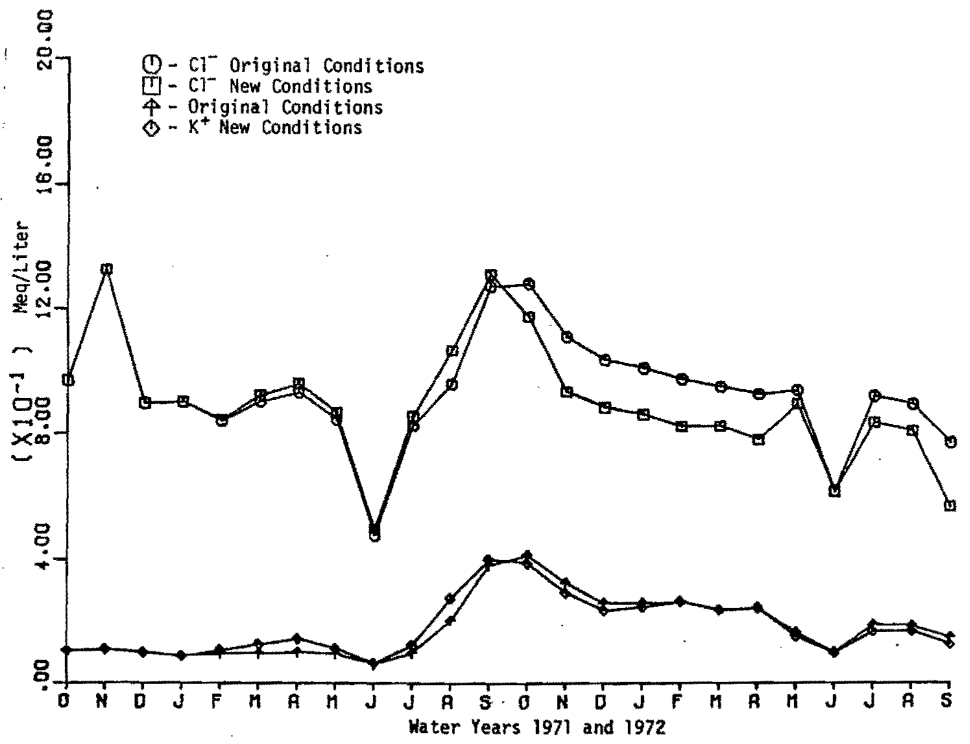

Figure 54. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency decreased from 68 percent to 50 percent.

of the deep percolation from the irrigated lands was even higher than the salinity of canal seepage. The model predicted that average salinity of Ashley Creek at Jensen, Utah, will increase if water recovered by canal lining is used on existing acreage.

Sensitivity to Irrigated Acreage

Figures 55 through 62 show the sensitivity of simulated streamflow and salinity to variation in the irrigated acreage in the Ashley Creek Basin. Figures 55 through 58 show the effect of an increase of 7700 irrigated acres, and Figures 59 through 62 show the effect of a decrease of 6300 acres. Increasing irrigated acreage decreased the valley leaching fraction. When irrigated acreage was increased, the salinity of deep percolation from irrigated farmland correspondingly increased. The increase was not great because some precipitation of semi-soluble salts occurred. Also, the net volume of deep percolation was less. The overall effect of increasing irrigated acreage was to decrease flows at Jensen, Utah.

Sensitivity to Combinations of Factors

Figures 63 to 66 show the effects of simultaneously improving canal conveyance efficiency to 100 percent and increasing the irrigated area by 8300 acres. The net effects were that winter flows were decreased and winter salinities were sharply increased. The reason was that deep percolation from agricultural lands was increased, but the increase in deep percolation was not as great as the amount of water which would enter the groundwater system if the canals had not been lined. Since the salinity contribution of deep percolation from agricultural lands is greater than that from canal conveyance loss, the resulting salinity of the groundwater return flow was also higher.

Figures 67 to 70 show the effects of simultaneously improving canal conveyance efficiency to 100 percent and routing the recovered water downstream through the stream channel. Since less water was diverted for irrigation, flowrates during the irrigation season were increased. During the winter, however, flows were decreased since

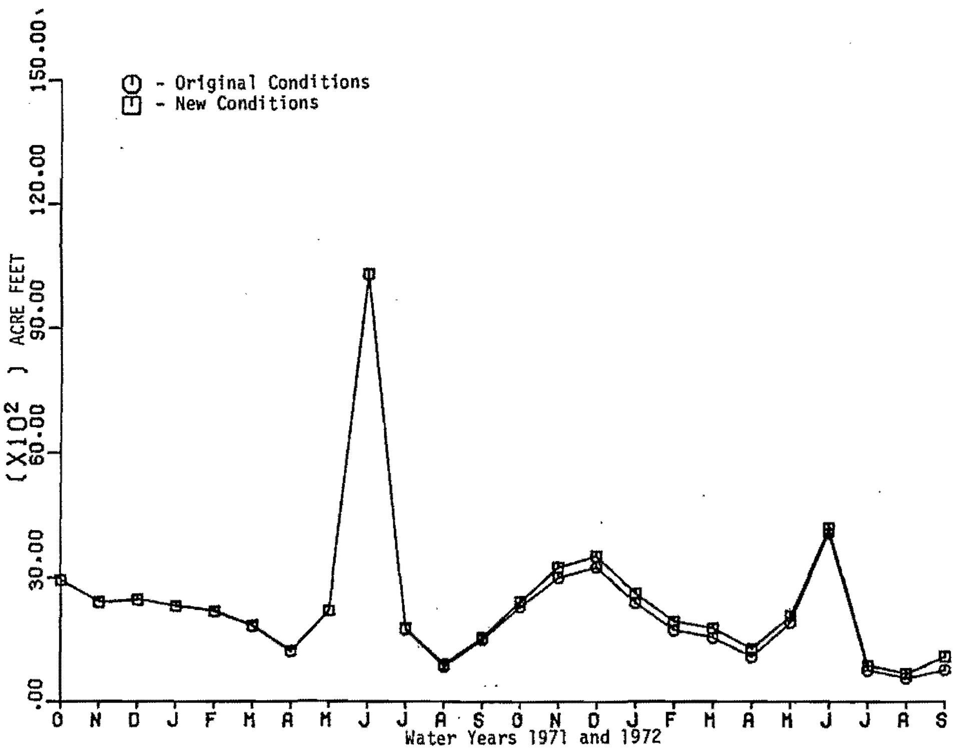

Figure 55. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage decreased 7,700 acres.

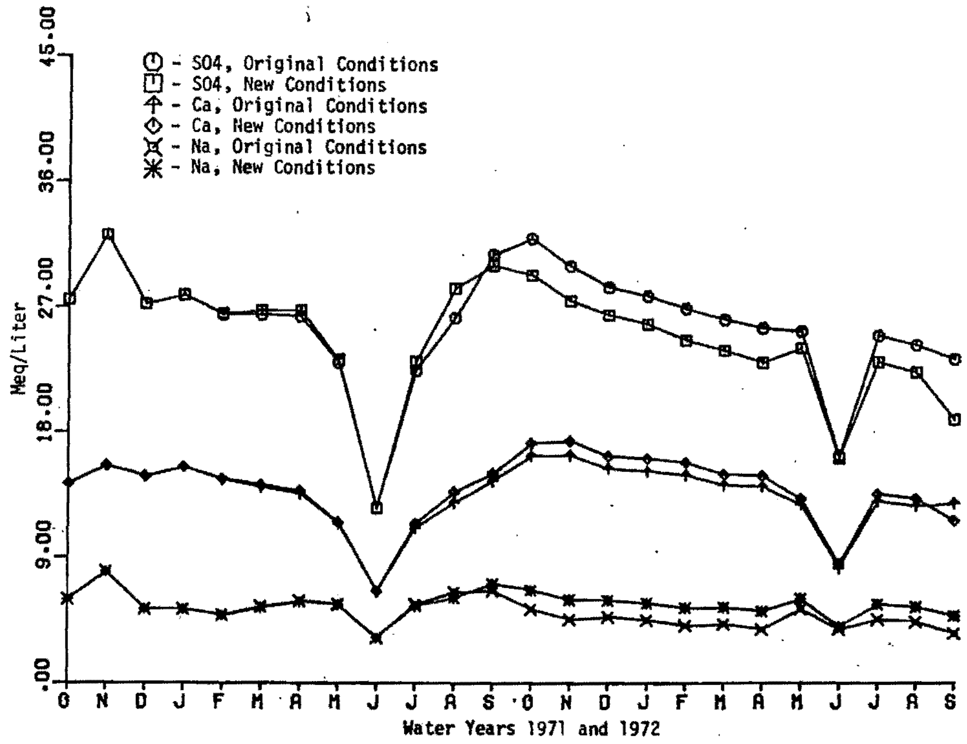

Figure 56. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage decreased 7,700 acres.

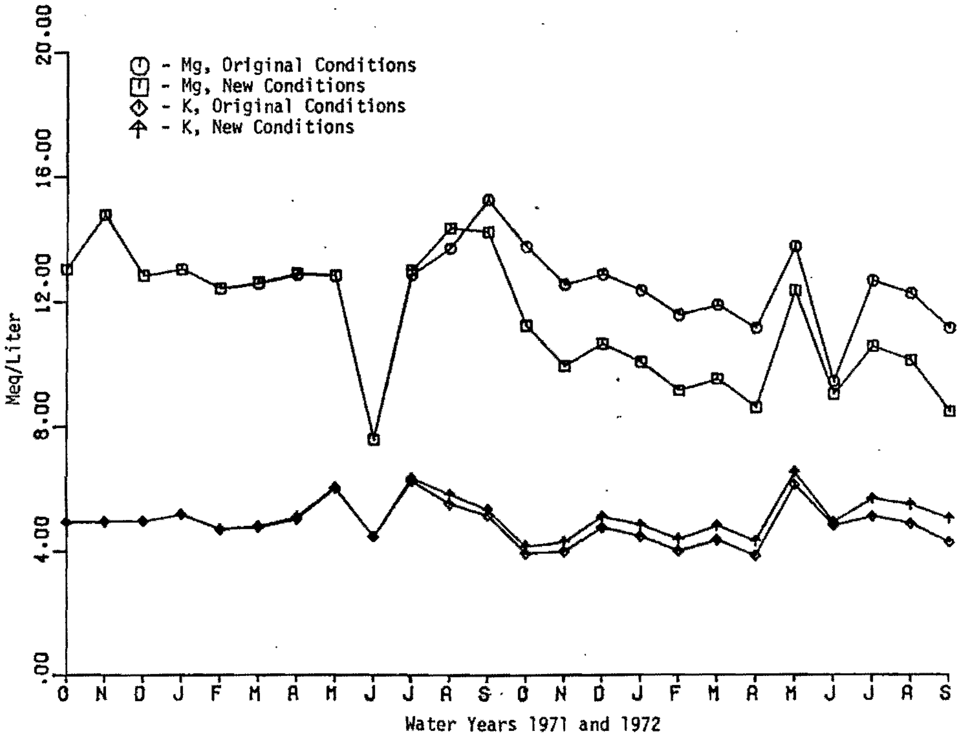

Figure 57. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage decreased 7,700 acres.

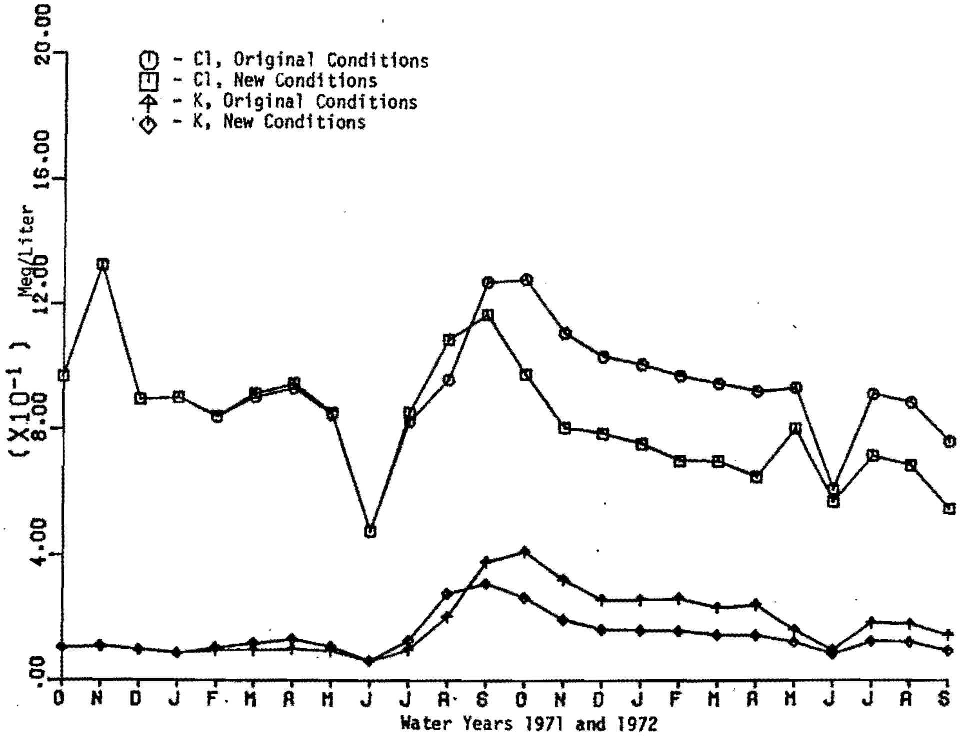

Figure 58. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage decreased 7,700 acres.

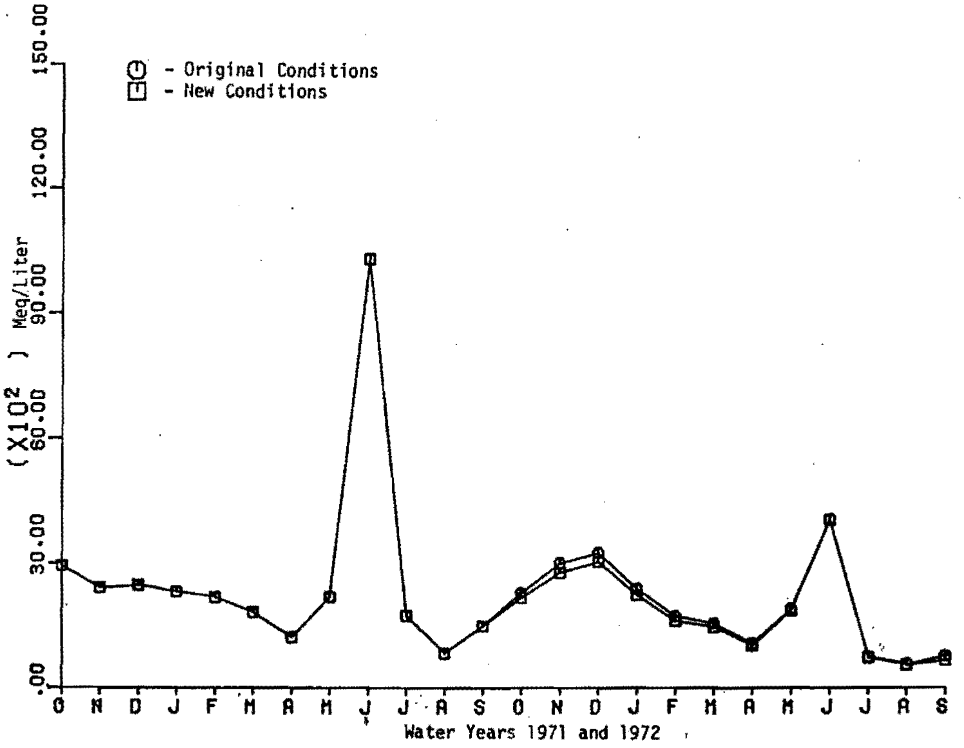

Figure 59. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage increased 6,300 acres.

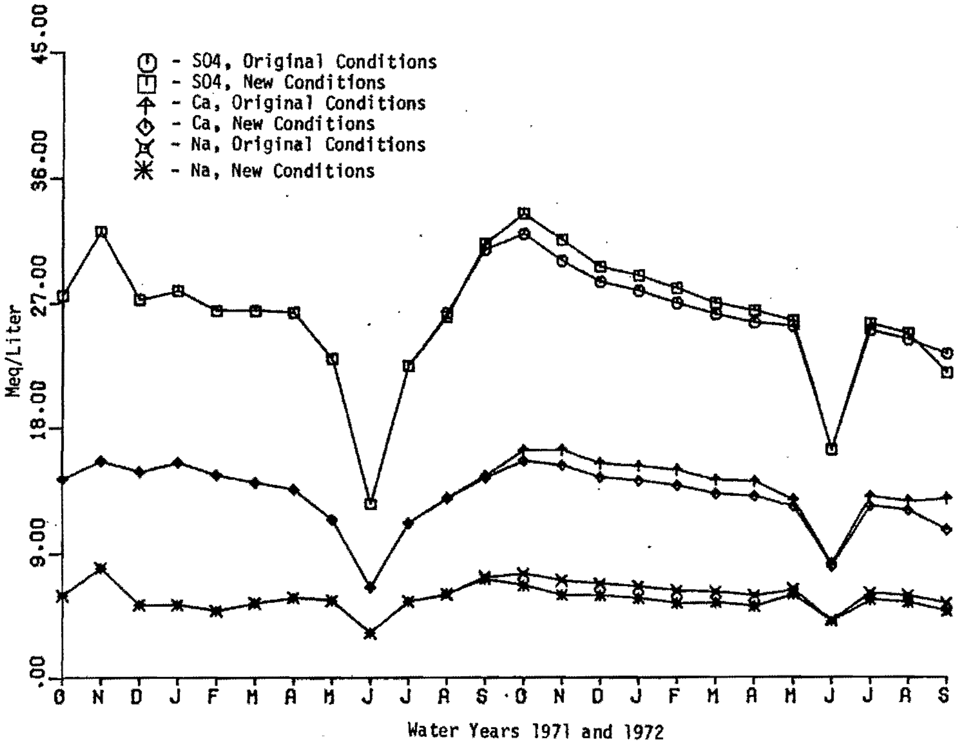

Figure 60. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage increased 6,300 acres.

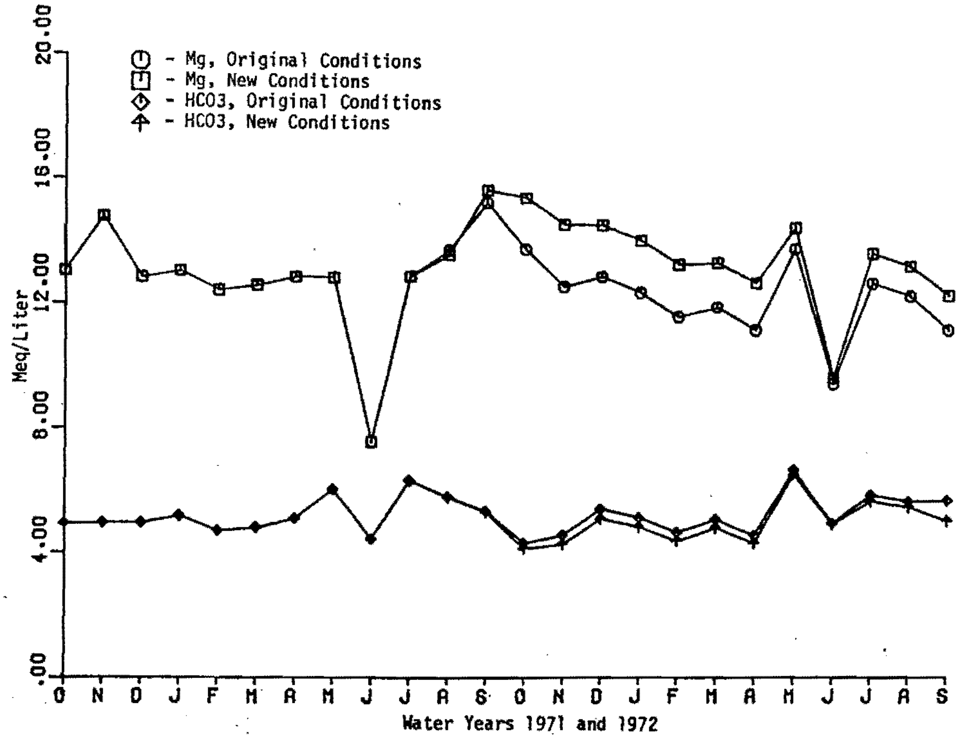

Figure 61. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage increased 6,300 acres.

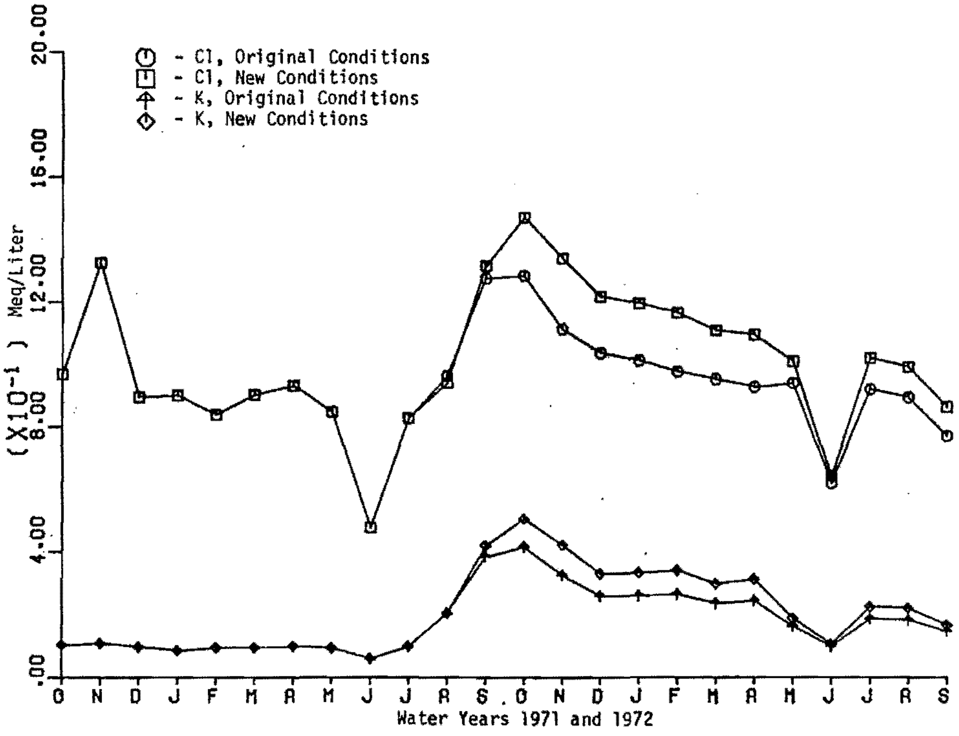

Figure 62. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with irrigated acreage increased 6,300 acres.

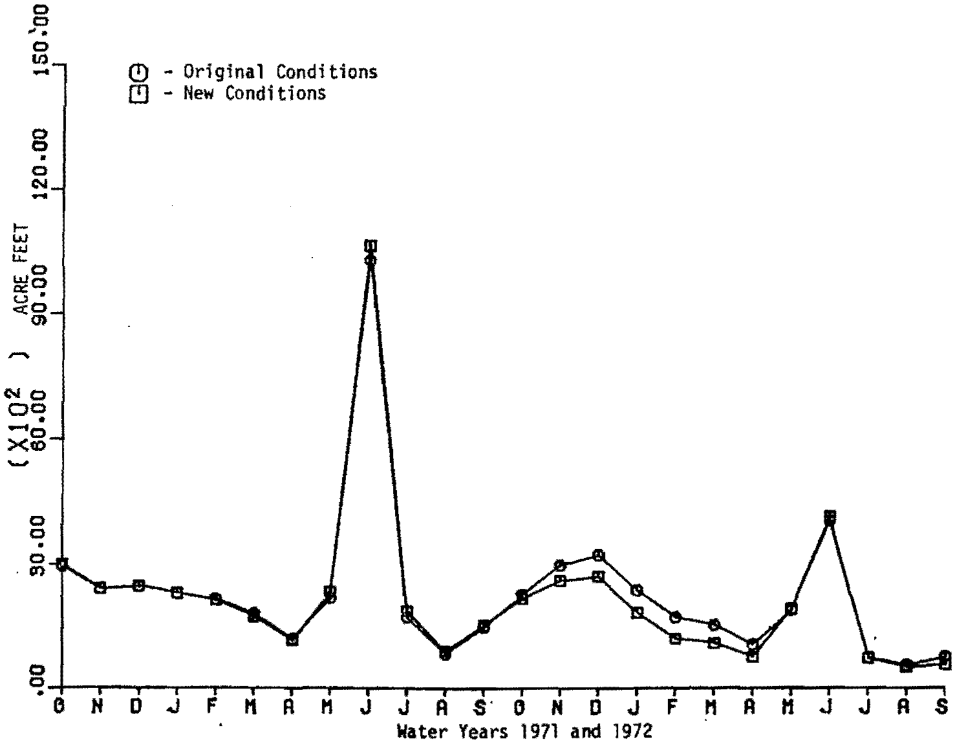

Figure 63. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent and irrigated acreage increased 8,300 acres.

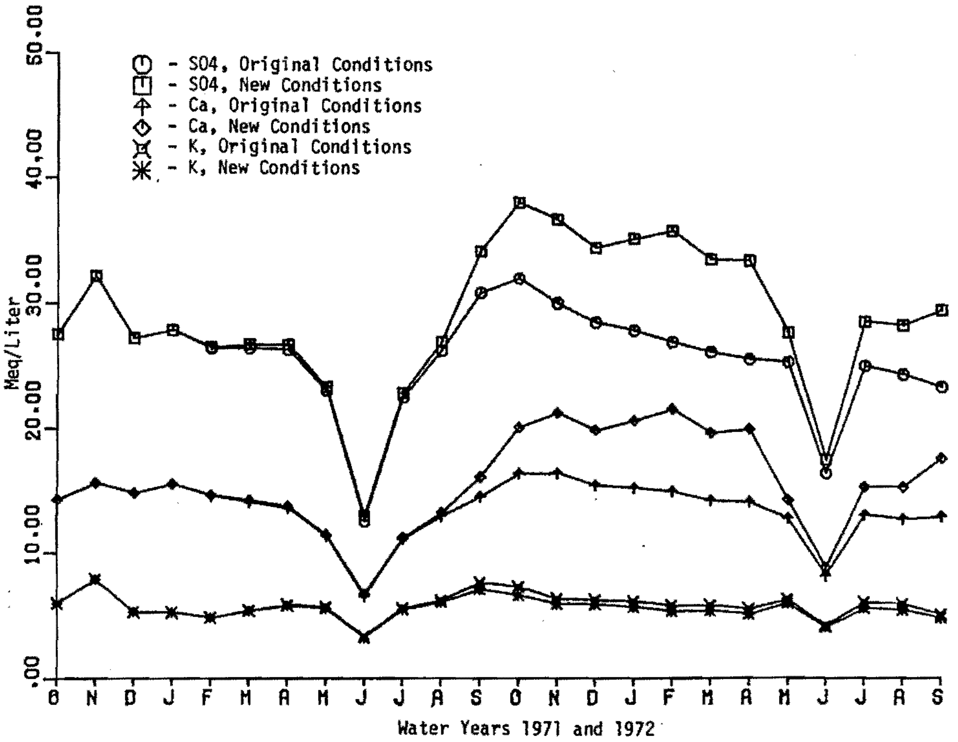

Figure 64. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent and irrigated acreage increased 8,300 acres.

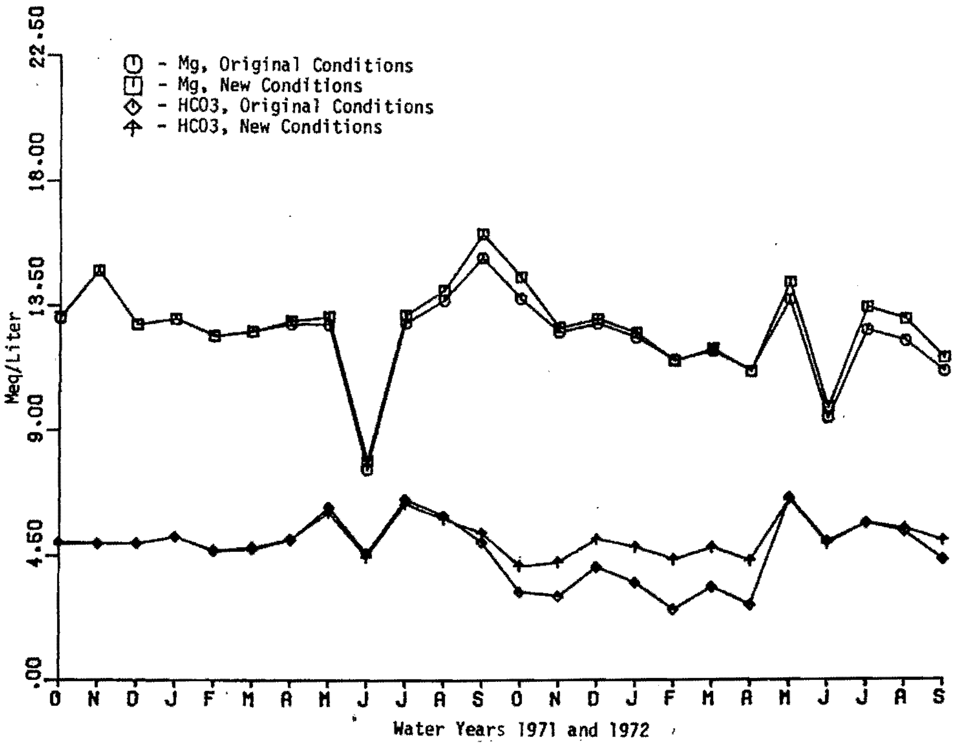

Figure 65. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent and irrigated acreage increased 8,300 acres.

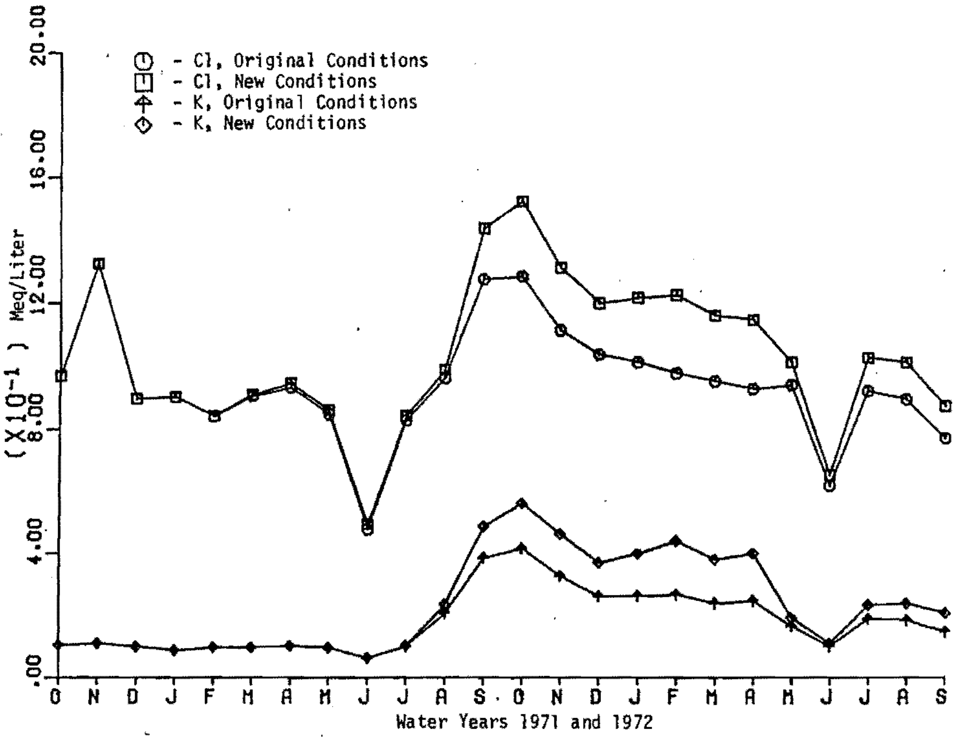

Figure 66. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent and irrigated acreage increased 8,300 acres.

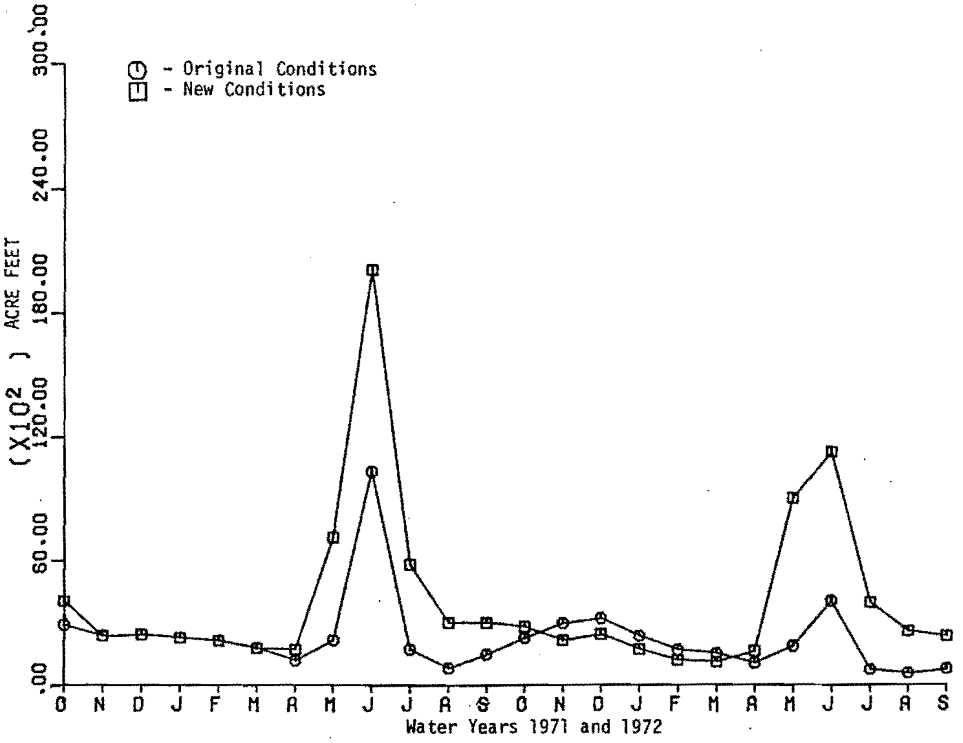

Figure 67. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while canal diversions are decreased so that the quantity of water delivered to farmlands remains unchanged.

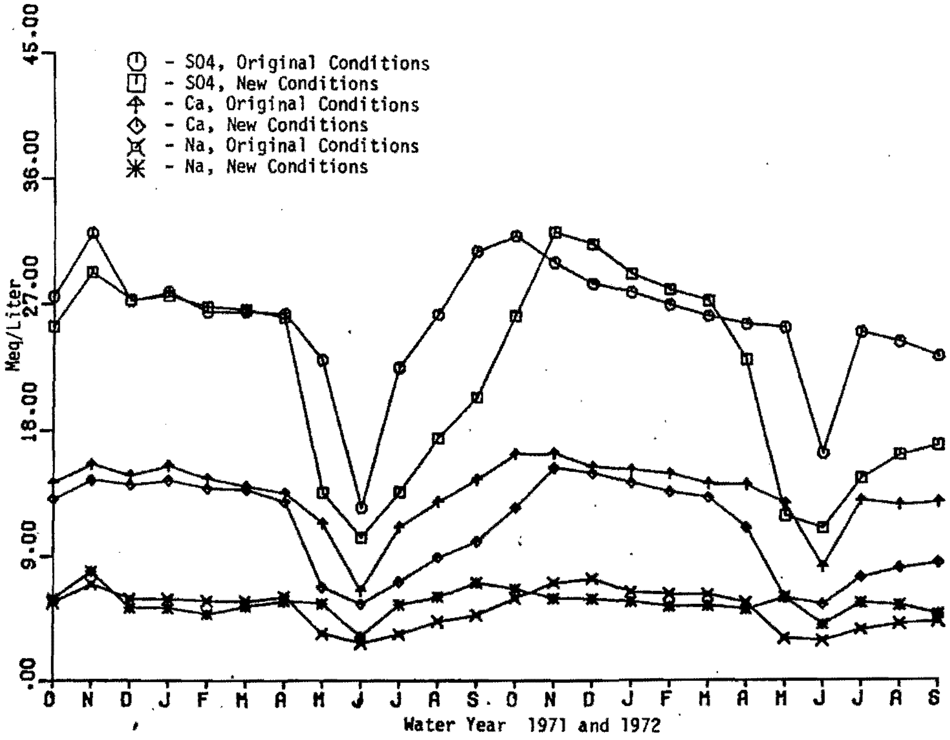

Figure 68. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while canal diversions are decreased so that the quantity of water delivered to farmlands remains unchanged.

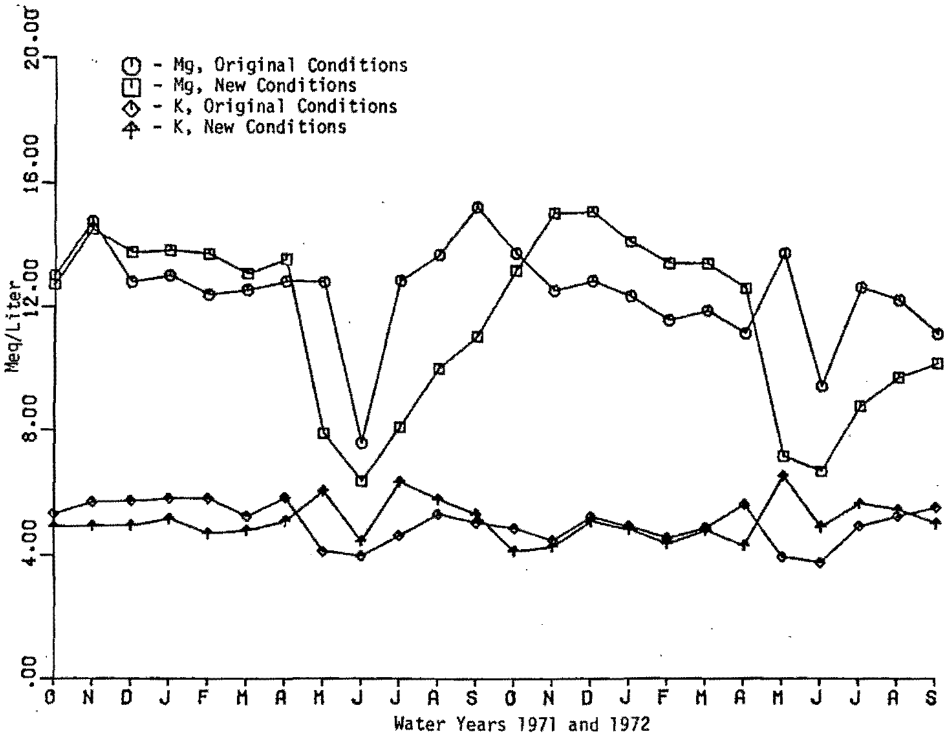

Figure 69. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while canal diversions are decreased so that the quantity of water delivered to farmlands remains unchanged.

the groundwater reservoir was not recharged with as much water from the canal conveyance losses. Instead of being recharged with relatively good quality canal water, the groundwater system was recharged with poor quality return flow from agricultural lands. Hence, the quality of Ashley Creek during the winter was also sharply decreased.

Figures 71 to 74 show the effect of routing the water recovered by lining irrigation canals directly out of the basin in a lined channel before diversion to the canal system. The advantage of diverting recovered canal water out of the basin is to increase the quality of the water which reaches the Green River by eliminating groundwater interchange. During the irrigation season both flowrate and salinity would be practically unchanged in Ashley Creek for 1971 conditions. However, during the winter months, the flowrate of the creek was considerably lower. The salinity of return flow during months other than May and June was also significantly increased. In the water year 1972, there is a marked decrease in both flowrate and quality of flow during the irrigation season. This would adversely affect water users who diverted their irrigation water from Ashley Creek near Jensen.

The model predicted that the salinity of recovered canal seepage was improved by 25 percent by transporting it to the river in a lined channel rather than allowing it to flow down the Ashley Creek channel. The increase would have been higher, but the groundwater-surface water interchange effect is more pronounced when flowrates in Ashley Creek are lower.

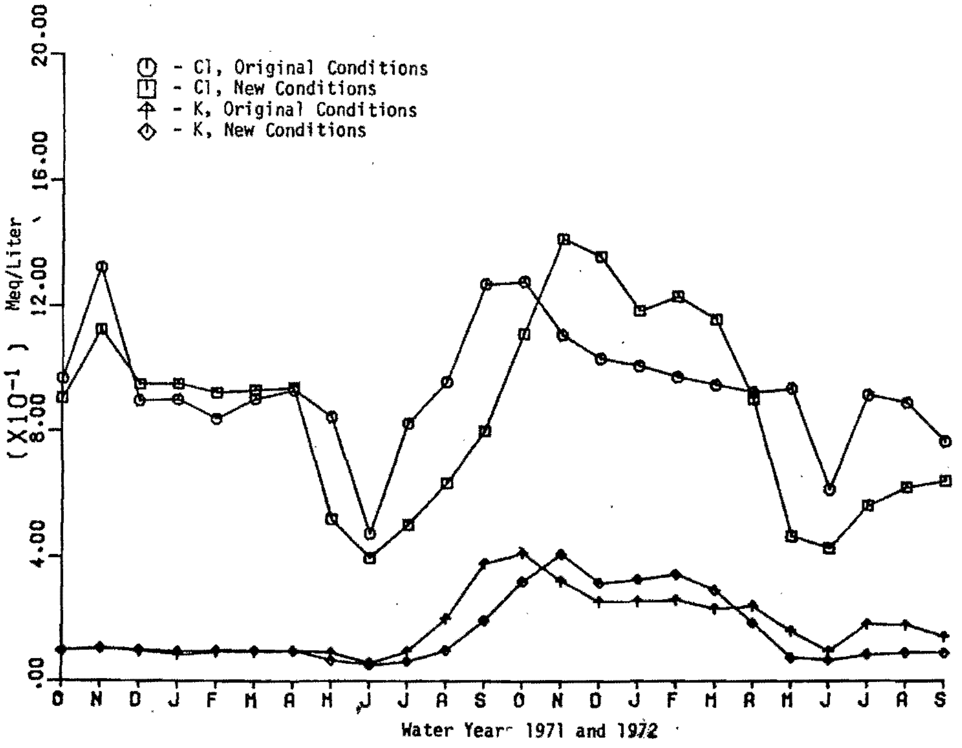

Figure 70. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while canal diversions are decreased so that the quantity of water delivered to the farmlands remains unchanged.

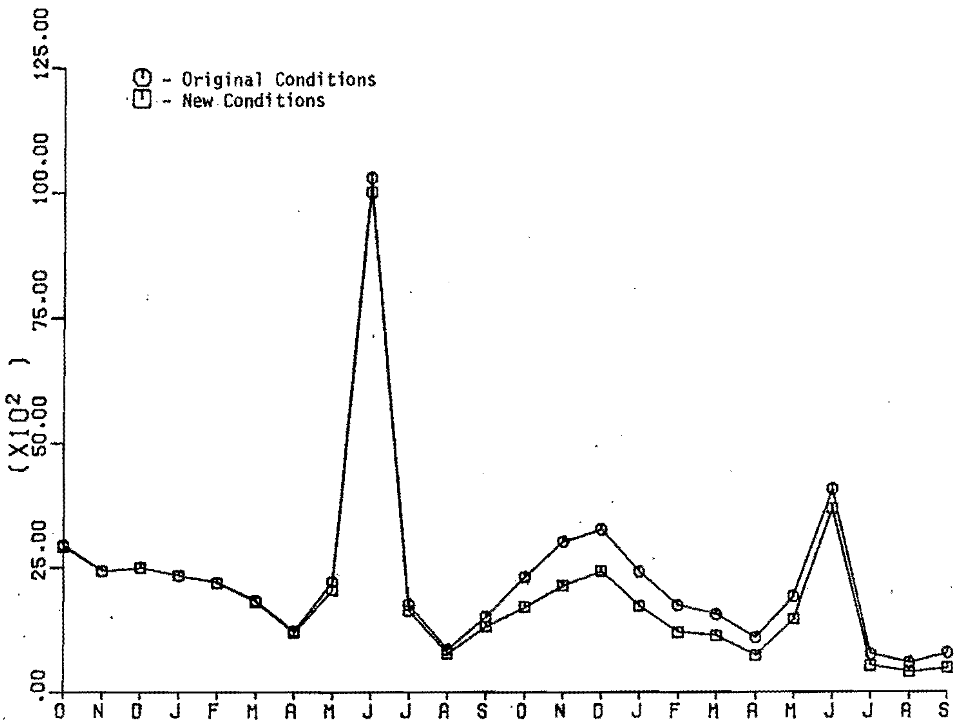

Figure 71. Simulated streamflow of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while water made available by increasing canal conveyance efficiency is exported from the basin in a lined channel.

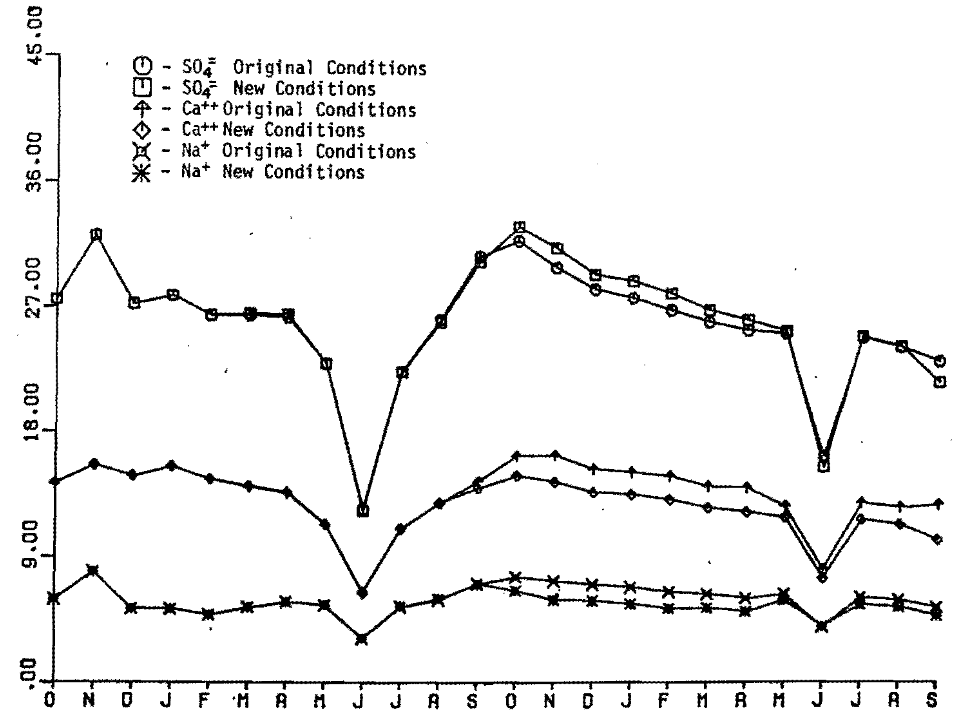

Figure 72. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while water made available by increasing canal conveyance efficiency is exported from the basin in a lined channel.

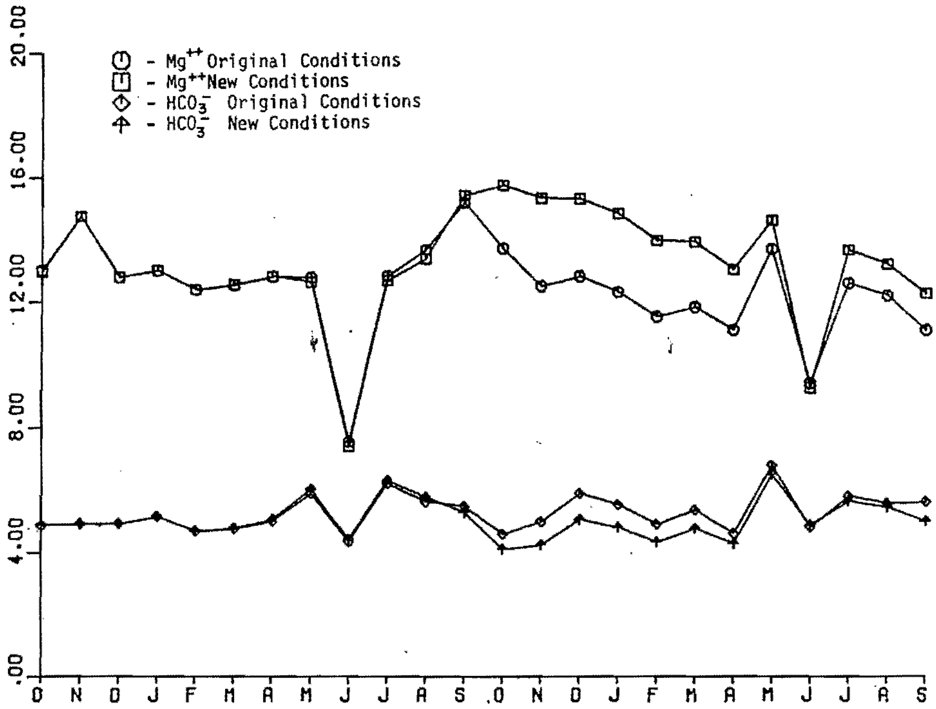

Figure 73. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while water made available by increasing canal conveyance efficiency is exported from the basin in a lined channel.

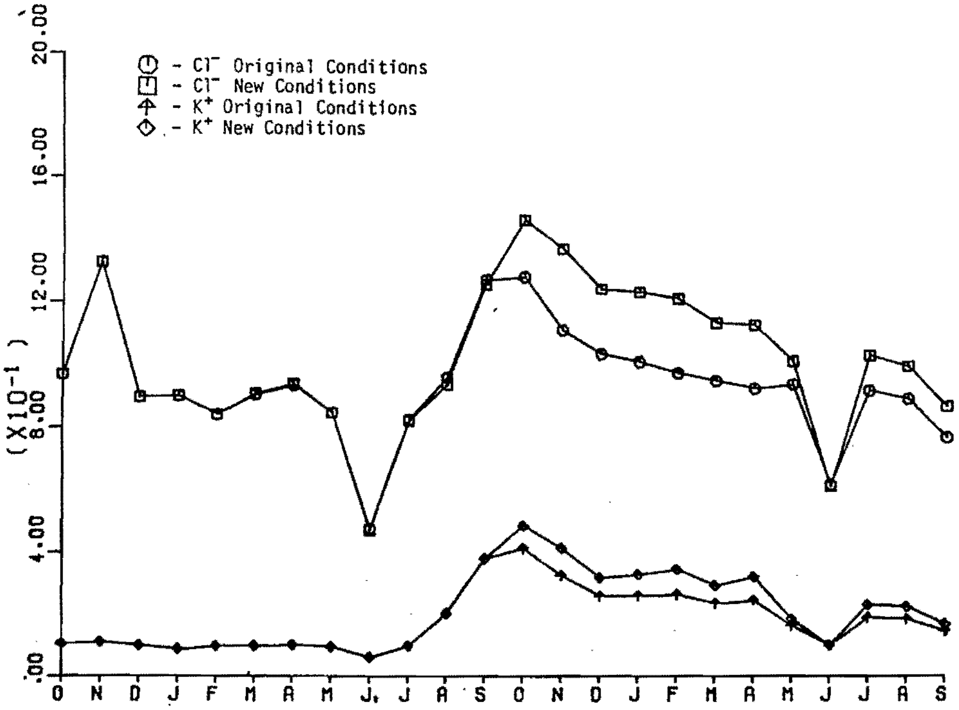

Figure 74. Simulated salinity of Ashley Creek at Jensen, Utah, with original conditions and with canal conveyance efficiency increased from 68 percent to 100 percent while water made available by increasing canal conveyance efficiency is exported from the basin in a lined channel.

IV. CONCLUSIONS

This study showed that chemical precipitation during cycles of evaporation and water additions reduce the salt content of the solution below values theoretically expected for a given leaching fraction. Greenhouse studies then showed that increasing irrigation water quantity is not effective in controlling soil salinity when saline irrigation water is used. Chemical modeling of water and salt movement through soil was then used to distinguish between the condition when the soil contributes to downstream salinity, and the conditions when the soil acts as a salt sink. Finally, a model of the Ashley Creek drainage basin above Jensen, Utah, was used to examine the effects of irrigation efficiency, canal conveyance efficiency, and irrigated acreage on streamflow and salinity in seven different ions by month of the year.

Irrigation water management practices will be used more effectively for water conservation and salinity control as studies such as these are continued so that the relevant processes can be better understood. Careful planning based on such an understanding can be used to promote productive management and reasonable use. Through careful management, the reductions of both quality and quantity associated with various uses can be held to practical values. Resources will not be wasted trying to obtain improved water quality when it is practically impossible to do so. The work reported here suggests that water quality can be conserved in irrigated farming by reducing the leaching fraction to take advantage of situations where the soil acts as a salt sink.

Greenhouse studies allow investigation of soil-water-plant interactions under closely controllable conditions. Such studies are useful in identification of possible field treatments. In a replicated greenhouse experiment both dry matter and grain yields were decreased by salinity. In the pot experiment, changes in nitrogen fertilization did not affect yields consistently. With a fixed water application schedule, increasing salinity of the irrigation water resulted in more return flow.

Interfacing a chemical precipitation-dissolution subroutine and a cation exchange subroutine with an existing water movement-salt transport model provided a computer program that satisfactorily predicts EC, SAR, and Mg^{2-}, Na^+, K^+, Cl^-, and SO_4^{2-} concentrations in the soil solution. The values predicted for Ca, HCO_3, and probably CO_3 concentrations were slightly low when compared to data from hydraulic weighing lysimeters. A chemistry subroutine was necessary for Ca^{2+}, SO_4^{2-}, HCO_3^-, and CO_3^{2-} predictions when precipitation or dissolution reactions were involved. A cation exchange subroutine was required for satisfactory Ca^{2+}, Mg^{2+}, Na^+, K^+, and SO_4^{2-} predictions when the cation ratios in the irrigation water differed from those of the soil solution. Both subroutines were required for reasonable EC and SAR calculation.

The combined transport-chemistry-exchange model was developed with options 1) to move salt through the soil profile without chemical reaction, 2) to move salt coupled with chemical precipitation and dissolution of lime and gypsum, or 3) for salt movement and chemical precipitation combined with cation exchange equilibrium. These options were given the respective acronyms of SALTFLOWI, SALTFLOWII, and SALTFLOWIII.

The P_{CO_2}-HCO_3-CO_3-pH interaction calculations are considered to be the most serious weakness of SALTFLOWII and SALTFLOWIII. A constant pH was assumed for each depth increment and P_{CO_2} was calculated from pH and calcium activity (Ca^{2+}) and then (HCO_3^-) and (CO_3^{2-}) were calculated from (Ca^{2+}), P_{CO_2}, and pH. This procedure requires a cyclic iteration type calculation. Under field conditions P_{CO_2} and pH are also related to other factors including the ratios between various cations, Cl^- and SO_4^{2-}. Even with this weakness SALTFLOWIII was quite satisfactory for predicting salt movement and root zone salt storage under the conditions tested.

The continuous weighing lysimeters used to obtain validation data for these models proved satisfactory and provided a convenient, economical means of obtaining soil solution samples and of controlling water movement and storage in the soil column (Robbins and Willardson, 1979). The lysimeters were filled with soil taken from the surface 20 cm of the area where the soils were obtained. This provided for an initially uniform profile in the lysimeters, thus the initial conditions were easily described. However, this method resulted in an abnormally high organic matter content in the lower part of the profile. This appeared to result in reducing conditions at the initial wetting front. The first water samples showed the highest difference between measured and calculated Ca and HCO_3 concentrations. After 3 to 5 liters of water had passed through the profile this abnormality was not observed. In future studies, surface soil probably should not be used in lysimeters below its natural depth.

Recommendations for followup work include:

1. Better theoretical or practical methods need to be developed to model the P_{CO_2}-HCO3-CO3-pH interaction in the soil chemistry subroutine.

2. The SALTFLOW model needs to be tested under conditions of reclaiming and development of saline-sodic and sodic soils.

3. The model needs to be tested for soils receiving high salt concentration waters (brines) to determine the upper limit of its effectiveness for extremely salty conditions.

4. Obtaining selectivity coefficients for a variety of soils by the method used here needs further consideration. Selectivity coefficients for adsorption as well as desorption for each cation used also need to be evaluated to determine the possibility of hysteresis effects and its consequences.

5. The XCHANG model needs to be directly validated by comparing measured and calculated exchangeable cation values.

The model developed to examine irrigation water management policies considers effects of water conveyance efficiency, average irrigation application efficiency, irrigation water quality, and varied irrigated or phreatophyte acreage. The sensitivity analysis revealed that the salinity of return flow in Ashley Creek in eastern Utah is most sensitive to changes in water conveyance efficiency. Although significant changes in Ashley Creek salinity were obtained by varying average basin irrigation application efficiency by 50 percent, in practice application efficiency can be varied much less. Since it was determined by model calibration and actual data that the net basin application efficiency is close to 96 percent, application efficiency could realistically not be varied more than 10 percent.

The model showed that lining canals in the Ashley Creek Basin would increase the amounts of water delivered to farmlands. However, the model raises doubts as to whether water quality changes derived from canal lining would produce economically justifiable results. What is done with water made available for use by canal lining has a significant effect on Ashley Creek water quality.

For instance, the model predicted that if the existing acreage were irrigated with the recovered water, the leaching fraction would be increased, and return flow quality from the area would decrease. If additional acreage in the basin is irrigated with the recovered water, the percentage of water going to deep percolation would be decreased. However, with this alternative, the quality of return flow would not be improved. Varying the amount of irrigated acreage does have some effect on the salinity of return flow, but the net effect is not great when even as many as 6,000 acres were taken out of production. Allowing water recovered by canal lining to flow undiverted through the Ashley Creek stream channel would improve water quality. However, since Ashley Creek loses fresh water to seepage in the upper reaches and gains saline water from the groundwater downstream, the improvement is not as great as with other alternatives. The maximum benefit would be obtained by exporting any water made available by lining canals directly into the Green River in a lined channel.

The major disadvantage of increasing water quality of the Green River by exporting Ashley Creek water in a lined channel is that no benefit accrues to the farmers of the Ashley Creek Basin. The model data suggests that water users near the Jensen area would find their water quality and quantity reduced significantly if water made available by lining channels in Ashley Creek Basin were exported to the Green River in a lined channel. The answer as to whether lining irrigation canals will significantly improve water quality of return flow in addition is tenuous.

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APPENDIX A

MAIN COMPUTER PROGRAM FOLLOWED BY SUBROUTINES

```
$ RESET FREE
FILE  6(KIND=PRINTER)
FILE  10(KIND=PACK,MAXRECSIZE=14,TITLE="(400035003)IRRWAT",
     *AREASIZE=450,BLOCKSIZE=420)
FILE  20(KIND=PACK,MAXRECSIZE=14,TITLE="(400035003)LOAM",
     *AREASIZE=450,BLOCKSIZE=420)
FILE  30(KIND=PACK,MAXRECSIZE=14,TITLE="(400035003)MATRIX",
     *AREASIZE=450,BLOCKSIZE=420)
C
C***THE WATER FLOW-SALT TRANSPORT MODEL OF CHILDS AND HANKS (1975)
C   IS MODIFIED HERE TO MOVE CALCIUM, MAGNESIUM, SODIUM, POTASIUM,
C   CHLORIDE AND SULFATE (MEQ/L) AS SEPERATE SPECIES WHEREAS, IN
C   THE ORIGINAL MODEL, SALTS WERE MOVED AS MEQ/L OF TOTAL SALTS.
C
C***ALAMBA, DIFO, DIFA, DIFB ARE SALT LOOP PARAMETERS.
C   DELW IS WATER CONTENT INCREMENTS IN WATER CONTENT TABLE
C   DETT IS INITIAL AND SMALLEST TIME INCREMENT USED.
C   CONQ IS LARGEST WATER CONTENT CHANGE ALLOWED.
C   HWET IS PRESSURE OF HIGHEST POSSIBLE WATER CONTENT ALLOWED.
C   WATL IS LOWEST POSSIBLE WATER CONTENT.
C   HLOW IS LOWEST ROOT POTENTIAL ALLOWED.
C   HHI IS HIGHEST ROOT POTENTIAL ALLOWED.
C   RRES IS ROOT RESISTANCE TERM.
C   TAA=1 FOR ZERO FLUX AT BOTTOM, TAA=0 FOR CONSTANT MATRIC POTENTIAL
C   AT BOTTOM OF PROFILE.
C   TT IS 1.0 FOR LASSONEN AND 0.5 FOR CRANK-NICHOLSON METHODS.
C   IF KILI=1, INPUT DATA IS NOT PRINTED ON OUTPUT.
C   IF KILKEM=1, CHEM SUBROUTINE IS NOT CALLED AND THE SALT MOVES
C   WITHOUT PRECIPATATION OR DISSOLUTION OF LIME OR GYPSUM.
C   IF KILEXC=1, THE CATION EXCHANGE SUBROUTINE IS NOT CALLED BY
C   THE CHEM SUBROUTINE.
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C   THE NWATER FILE CONTAINS IRRIGATION WATER AND ET DATA.
C   THE INSOIL FILE CONTAINS THE INITIAL SOIL SALT AND WATER DATA.
C   THE MATRIX FILE CONTAINS THE MOISTURE RELEASE CURVE DATA.
C   KALKEM IS THE NUMBER OF WATER AND SALT MOVEMENT CALCULATIONS BETWEEN
C   EACH CALLING OF THE CHEM SUBROUTINE.
C   DATA1, DATA2, AND DATA3 ARE FILE HEADINGS.
C   IER IS 2 TIMES THE NUMBER OF SURFACE FLUX CHANGES.
C   TIME IS CUMULATIVE TIME AT START OF CALCULATIONS.
C   CUMT IS THE TIME AT THE END OF CALCULATIONS.
C   V(I) IS THE SURFACE BOUNDRY ARRAY AS FLUX,TIME TO END, FLUX,TIME TO
C   END, ETC.  +FLUX=IRRIGATION OR RAIN  -FLUX IS ET POTENTIAL(CM/HR).
C   SF(I,JJ) IS THE SALT CONTENT OF THE IRRIGATION WATER WHERE JJ=1 IS
C   CA, JJ=2 IS MG, JJ=3 IS NA, JJ=4 IS K, JJ=5 IS CL, AND JJ=6 IS SO4.
C   ALL IN UNITS OF ME/L.  THESE VALUES CANNOT BE ZERO.  SUGGESTED THAT
C   VALUES OF 0.01 MEQ/L BE USED FOR EACH ION FOR RAIN WATER.
C   K IS THE NUMBER OF SOIL DEPTH INCREMENTS.
C   NB IS THE NUMBER OF DEPTH INCREMENT CALCULATIONS (USUALLY K)
C   RDFDAY IS NUMBER OF DAYS FOR DEVELOPMENT OF MATURE ROOT PROFILE.
C   RDFDEL IS NUMBER OF COMPUTATION INCREMENTS IN ROOT GROWTH LOOP.
C   ESTART IS DAYS FROM TIME=0 TO START OF COVER GROWTH.
C   ESTOP IS DAYS FROM TIME=0 TO MAXIMUM EFFECTIVE COVER GROWTH.
C   AK1 IS  TRANSPIRATION/EVAPOTRANSPIRATION.
C   AK2 IS  TRANSPIRATION/EVAPOTRANSPIRATION WHEN ET .NE. ET POTENTIAL.
C   CEC IS CATION EXCHANG CAPACITY (ME/100G).
C   DD(I) IS DEPTH INCREMENT ARRAY (FIRST VALUE IS 0).
C   RDFSAV(I) IS FINAL ROOT DENSITY ARRAY IN DECIMAL FRACTIONS.
C   W(I) IS THE INITIAL SOIL WATER PROFILE, STARTING AT TOP.
C   SE(I,JJ) CONTAIN THE INITIAL SOIL CHEMESTRY VALUES. (SEE THE CHEM
C   SUBROUTINE FOR EXPLANATION OF EACH TERM).
C   ND IS THE NUMBER OF ENTRIES IN THE WATER CONTENT-POTENTIAL TABLE
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C    (NOTE! ENTRIES ARE NEEDED FOR ZERO WATER CONTENT AND ONE ABOVE
C    WATH).
C    WATH IS HIGHEST POSSIBLE WATER CONTENT.
C    HDRY IS PRESSURE OF LOWEST POSSIBLE WATER CONTENT.
C    P(I) MATRIC POTENTIAL ARRAY.
C    E(I) IS THE HYDRAULIC CONDUCTIVITY ARRAY.
C
C***FOR EXPLAINATION OF OTHER TERMS IN THE MAIN PROGRAM SEE  WOLF,
C    JAMES A. (1977)  THE EVALUATION OF A COMPUTER MODEL TO PREDICT THE
C    EFFECTS OF SALINITY ON CROP GROWTH.  MS THESIS UTAH STATE UNIVER-
C    SITY, LOGAN, UTAH 84322.
C
      DIMENSION A(25),B(25),C(25),F(25),RDFSAV(25),ROOT(25),RDF(25)
      DIMENSION DD(25),H(25),G(25),Y(25),W(25),P(125),D(125),T(125)
      DIMENSION E(125),V(125),TET(65),DATA1(25),DATA2(25),DATA3(25)
      DIMENSION SE(25,21),SF(65,6),SS(25,10),SD(25)
      DATA ALAMBA/.4/,DIFD/.05/,DIFA/.001/,DIFB/10./,DELW/.01/,
     *DETT/.024/,CONQ/.03/,HWET/.0/,WATL/.03/,
     *HLOW/-15000./,HHI/.0/,RRES/1.05/,TT/1.0/
      READ/,KIL1,KILKEM,KILEXC
      READ/,NWATER,INSOIL,MATRIX,KALKEM
      READ(NWATER,2001)DATA1
      READ(INSOIL,2001)DATA2
      READ(MATRIX,2001)DATA3
      READ(NWATER,1180)IER
      READ(NWATER,2010)TIME,CUMT,TAA
      IR=IER/2
      READ(NWATER,2010)(V(I),I=1,IER)
      READ(NWATER,2010)((SF(I,JJ),JJ=1,6),I=1,IR)
      READ(INSOIL,1180)K,NB
      KK=K+1
      READ(INSDIL,2010)RDFDAY,RDFDEL,ESTART,ESTOP,AK1,AK2,CEC
      IF(KILEXC.EQ.1)CEC=0
      READ(INSOIL,2010)(DD(I),I=1,KK)
      READ(INSOIL,2010)(RDFSAV(I),I=1,KK)
      RFAD(INSOIL,2010)(W(I),I=1,KK)
      READ(INSOIL,2020)((SE(I,JJ),JJ=1,10),I=1,KK)
      READ(MATRIX,1180)ND
      READ(MATRIX,1220)WATH,HDRY
      READ(MATRIX,1190)(P(I),I=1,ND)
      READ(MATRIX,1190)(E(I),I=1,ND)
      WRITE(6,2025)DATA1,DATA2,DATA3
      IF(KIL1.EQ.1)GO TO 20
      WRITE(6,1280)
      WRITE(6,1180)K,IER,NB,ND
   20 T(1)=0.
      D(1)=(E(1)*(P(2)-P(1)))
      DO 30  I=2,ND
      D(I)=E(I)*(P(I)-P(I-1))+D(I-1)
   30 T(I)=DELW+T(I-1)
      IF(KIL1.EQ.1)GO TO 60
      WRITE(6,1240)
      NE=ND/2
      DO 40 I=1,NE
   40 WRITE(6,1250)T(I),P(I),E(I),D(I),T(NE+I),P(NE+I),E(NE+I),D(NE+I)
   60 KC=1
   65 AK4=0.5/RDFDAY
      DELDAY=RDFDAY*24./RDFDEL
      PDXDAY=DELDAY
      HROOT=HLOW
      LL=1
      DO 67 JJ=5,10
  67  SE(1,JJ)=SF(1,JJ-4)
      DO 68 I=2,KK
      SE(I,13)=W(I)
      SE(I,20)=DD(I-1)
  68  SE(I,21)=DD(I)
      CWFLX=0.0
      DELT=DETT
      TM=1.0-TT
      TBB=1.0-TAA
      YMAX=WATH
      RUNOF=0.0
      CUMS=0.
      MYTIME=0
      RPI=0.
      CUMB=0.0
      CUMM=0.0
      SUMA=0.0
      SCM=0.
      IROF=0
      EVAP=0.
      SIRR=0.
      CTRAN=0.0
      PIT=0.0
      J=(W(1)-T(1))/DELW+1.0
      H(1)=(P(J+1)-P(J))*(W(1)-T(J))/DELW+P(J)
      G(1)=H(1)
      C(1)=DELW/(P(J+1)-P(J))
      DO 70 I=2,K
   70 PIT=W(I)*(DD(I+1)-DD(I-1))/2.+PIT
      DO 80 I=2,KK
      J=(W(I)-T(1))/DELW+1.0
      H(I)=(P(J+1)-P(J))*(W(I)-T(J))/DELW+P(J)
      C(I)=DELW/(P(J+I)-P(J))
   80 G(I)=H(I)
      IF(KIL1.EQ.0)WRITE(6,1260)
      DO 90 I=1,KK
      IF(I.EQ.1) GO TO 90
      IF(KIL1.EQ.0)WRITE(6,1210)DD(I),C(I),W(I),H(I),RDFSAV(I)
   90 Y(I)=W(I)
      IF(KIL1.EQ.1)GOTD 95
      WRITE(6,2030)
      WRITE(6,2035)((SE(I,JJ),JJ=1,10),I=1,KK)
C
C***COVER GROWTH LOOP
C
  95  AK3=0.5/(ESTOP-ESTART)
      IF(KIL1.EQ.0)WRITE(6,1200)
      DO 110 I=2,IER,2
      IR=I/2
      IF(V(I-1).GE.0.0) GO TO 110
      TET(IR)=V(I-1)
      IF(V(I)/24..LT.ESTART) GO TO 100
      V(I-1)=TET(IR)-TET(IR)*AK1/(1.+EXP(6.-AK3*(V(I)-ESTART*24.)))
      GO TO 110
  100 V(I-1)=TET(IR)
  110 IF(KIL1.EQ.0)WRITE(6,1220)V(I),V(I-1),TET(IR),SF(IR,1),SF(IR,2),
     *SF(IR,3),SF(IR,4),SF(IR,5),SF(IR,6)
      WFDD=V(1)
      EOR=V(1)
      ET=TET(1)
      IF(KIL1.EQ.1)GO TO 120
      WRITE(6,1290)
      WRITE(6,1210) DETT,CONQ,TAA,TIME,TT,CUMT,RRES
      WRITE (6,1300)
      WRITE(6,1210)HDRY,HWET,WATL,WATH,HLOW,HHI,DELW
      WRITE(6,1310)
      WRITE(6,1210)ALAMBA,DIFO,DIFA,DIFB
      WRITE(6,1270)
      WRITE(6,1210)RDFDAY,RDFDEL,ESTART,ESTOP,AK1,AK2,CEC
  120 KCK=1
      HROOT=G(2)
      IF(KILKEM.EQ.1)GOTO 126
C
C***THE CHEM SUBROUTINE CALCULATES INITIAL LIME AND GYPSUM EQUILIBRIUM
C    WITH THE SOIL SOLUTION IF KILKEM IS NOT 1 AND CALCULATES INITIAL
C    EXCHANGABLE CATION VALUES IF CEC IS NONZERO.  THESE VALUES ARE THEN
C    PRINTED.
C
      WRITE(6,2040)
      DO 125 I=2,KK
      SE(I,13)=W(I)
      CALL CHEM(SE(I,1),SE(1,2),SE(I,3),SE(I,4),SE(I,5),SE(1,6),
     *SE(I,7),SE(I,8),SE(I,9),SE(I,10),SE(I,11),SE(I,12),SE(I,13),
     *SE(I,14),SE(I,15),SE(I,16),SE(I,17),SE(1,18),SE(I,19),CEC,1)
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```
      WRITE(6,2044)(SE(I,JJ),JJ=1,21)
  125 CONTINUE
  126 WRITE(6,1230)
  130 TOP=WATH
C
C***ROOT GROWTH LOOP
C
      IF(IRDF.EQ.1) GO TO 190
      IF(ABS(RDFDEL-0.).LT.1.0E-6) GO TO 170
      IF(TIME.LT.RDXDAY) GO TO 190
      IF(TIME.GT.DELDAY*RDFDEL) GO TO 170
      RDXDAY=DELDAY+RDXDAY
      DROOT=DD(KK)/(1.+EXP(6.-AK4*TIME))
      J=2
      DO 160 I=2,KK
      RDF(I)=0.
  140 IF(J.GE.KK) GO TO 160
      ROOT(J)=DROOT*DD(J)/DD(KK)
      IF(ROOT(J).GE.DD(I)) GO TO 150
      RDF(I)=RDFSAV(J)*(ROOT(J)-DD(I-1))/(ROOT(J)-ROOT(J-1))+RDF(I)
      IF(ROOT(J-1).GT.DD(I-1)) RDF(I)=RDFSAV(J)*(1.-((ROOT(J)-DD(I-1))/(
     1ROOT(J)-ROOT(J-1))))+RDF(I)
      J=J+1
      GO TO 140
  150 RDF(I)=(DD(I)-DD(I-1))/(ROOT(J)-ROOT(J-1))*RDFSAV(J)+RDF(I)
      IF(ROOT(J-1).GT.DD(I-1)) RDF(I)=RDF(I)-(ROOT(J-1)-DD(I-1))/(ROOT(J
     1)-ROOT(J-1))*RDFSAV(J)
      IF(ROOT(J).GT.DD(I)) GO TO  160
      J=J+1
  160 CONTINUE
      GO TO 190
  170 DO 180 I=1,KK
  180 RDF(I)=RDFSAV(I)
      IRDF=1
  190 BOT=WATL
C
C***COMPUTATION OF CONDUCTIVITY (B) AND WATER CAPACITY (C)
C
      HKP=H(1)
      WKP=W(1)
      IF (EOR-0.0) 200,220,210
  200 W(1)=WATL
      H(1)=HDRY
      GO TO 220
  210 W(1)=WATH
      H(1)=HWET
  220 TWW=(W(1)+Y(1))*0.5
      IF(TWW.GT.WATH) TWW=WATH
      J=(TWW-T(1))/DELW+1.0
      BB=(TWW-T(J))/DELW
      DIFFA=(D(J+1)-D(J))*BB+D(J)
      HI=(P(J+1)-P(J))*BB+P(J)
      DO 350 I=1,K
      TW=(W(I+1)+Y(I+1))*0.5
      J=(TW -T(1))/DELW+1.0
      BB=(TW-T(J))/DELW
      DIFFB=(D(J+1)-D(J))*BB+D(J)
      GI=(P(J+1)-P(J))*BB+P(J)
      IF(ABS(EOR).GT.1.0E-6) GO TO 230
      B(1)=0.
      GO TO 330
  230 IF(ABS(HI-GI).LT.0.0001) GO TO 320
      B(I)=(DIFFA-DIFFB)/(HI-GI)
      IF(I.GT.1) GO TO 330
  240 ER=(B(1)*(H(1)*TT-H(2)*TT-G(2)*TM+G(1)*TM+DD(2)))/DD(2)
      IF((ABS(1.1*EOR-ER)-ABS(0.1*EOR)).LE.0.0) GO TO 250
      IF(KCK.EQ.1) GO TO 260
      IF(KCK.LT.12) GO TO 270
  250 H(1)=(EOR*DD(2)/B(1)+H(2)*TT-G(1)*TM+G(2)*TM-DD(2))/TT
      IF(H(1).LT.HDRY) H(1)=HDRY
      IF (H(1).GT.HWET) H(1)=HWET
      GO TO 330
  260 H(1)=HKP
      W(1)=WKP
      KCK=KCK+1
      GO TO 220
  270 KCK=KCK+1
      IF (ER-EOR) 280,330,290
  280 IF((W(I)-WATH).GE.0.0) GO TO 330
      BOT=W(1)
      W(1)=(W(1)+TOP)*0.5
      GO TO 300
  290 IF((W(1)-WATL).LE.0.0) GO TO 330
      TOP=W(1)
      W(1)=(W(1)+BOT)*0.5
  300 J=(W(1)-T(1))/DELW+1.0
      BB=(W(1)-T(J))/DELW
      IF(ABS(EOR-0.).LT.1.0E-06) GO TO 330
      H(1)=(P(J+1)-P(J))*BB+P(J)
  310 TWW=(W(1)+Y(1))*0.5
      J=(TWW-T(1))/DELW+1.0
      BB=(TWW-T(J))/DELW
      DIFFA=(D(J+1)-D(J))*BB+D(J)
      HI=(P(J+1)-P(J))*BB+P(J)
      GO TO 230
  320 B(I)=(D(J+1)-D(J))/(P(J+1)-P(J))
      IF(I.EQ.1) GO TO 240
  330 TWW=TW
      HI=GI
      DIFFA=DIFFB
      TW=(W(I+1)+Y(I+1))*0.5
      J=(TW -T(1))/DELW+1.0
  340 C(I+1)=DELW/(P(J+1)-P(J))
  350 CONTINUE
      KCK=1
C
C***NEW T-POT WHEN E-ACTUAL IS LESS THAN E-POT
C
      ETPL=ET
      IF(ET.GE.0.) GO TO 470
      IF(EOR.GT.0.) GO TO 380
      IF(TIME/24..LT.ESTART) GO TO 370
      IF(ABS(WFDD).GT.ABS(EOR))WFDD=EOR
      IF(ABS(WFDD-EOR).LT.1.0E-3) GO TO 370
      ETALT=(ET-EOR)*(1.+(AK2/AK1-1.)*(EOR-WFDD)/EOR)
      IF(WFDD.LT.(ET-ETALT)) GO TO 360
      ETPL=ETALT
      GO TO 380
  360 ETPL=ET-WFDD
      GO TO 380
  370 ETPL=ET-EOR
      IF(ABS(ETPL-0.).LT.1.0E-4) GO TO 470
  380 HHOLD=HROOT
C
C***COMPUTATION OF ROOT SINK FUNCTION
C   OP=.36*(MEQ/L)/10*1000CM/ATM   MEQ/L=10MILLIMHOS/CM
C   MEQ/L TOTAL SALTS IS ASSUMED TO BE SUM OF CA, MG, NA, AND K
C   CONCENTRATION
C
      SINK=0.0
      DO 390 I=2,K
  390 E(I)=G(I)-36.*(SE(I,5)+SE(I,6)+SE(I,7)+SE(I,8))-DD(I)*RRES
      LCNT=0
  400 DSAVE=DSINK
      DSINK=0.
      SINK=ETPL
      DO 410 I=2,K
      IF(HROOT-E(I).GT.0.) GO TO 410
      SINK=SINK+B(I)*RDF(I)*E(I)
      DSINK=DSINK+B(I)*RDF(I)
  410 CONTINUE
      IF(DSINK.NE.0.) GO TO 420
      IF(HROOT.EQ.HLOW) GO TO 440
      HROOT=HLOW
```

```
      GO TO 400
  420 IF(DSINK.EQ.DSAVE) GO TO 440
      HROOT=SINK/DSINK
      IF(HRUOT.LT.HLOW) HROOT=HLOW
      LCNT=LCNT+1
      IF(LCNT.LE.20) GO TO 400
      WRITE(6,430)
  430 FORMAT('  LCNT.EQ.20')
  440 SINK=0.
      DO 460 I=2,K
      IF(HROOT-E(I).GT.0.)GO TO 450
      A(I)=B(I)*2.*RDF(I)*(HROOT-E(I))/(DD(I+1)-DD(I-1))
      SINK=SINK+RDF(I)*B(I)*(HROOT-E(I))
      GO TO 460
  450 A(I)=0.
  460 CONTINUE
      GO TO 490
  470 DO 480 I=2,K
      SINK=0.
  480 A(I)=0.
C
C***WATER FLOW TRIDIAGONAL MATRIX SOLUTION
C
  490 DO 530 I=2,K
      POT=(DD(I+1)-DD(I-1))/(2.0*DELT)
      DLXA=(DD(I)-DD(I-1))
      DLXB=(DD(I+1)-DD(I))
      BB=C(I)*POT/TT+B(I)/DLXB+B(I-1)/DLXA
      DA=(C(I)*POT*G(I)+(B(I)/DLXB)*(TM*(G(I+1)-G(I))-DLXB)+(B(I-1)/DLXA
     1)*(TM*(G(I-1)-G(I))+DLXA)+A(I)*(DD(I+1)-DD(I-1))*0.5)/TT
      IF(I.GT.2.0) GO TO 520
      IF(H(1).GE.HWET.OR.H(1).LE.HDRY) GO TO 500
      DA=DA-((B(I-1)/DLXA)*(TM*(G(I-1)-G(I))+DLXA))/TT+EOR/TT
      BB=BB-B(I-1)/DLXA
      GO TO 510
  500 DA=DA+H(I-1)*B(I-1)/DLXA
  510 F(I)=DA/BB
      E(I)=(B(I)/DLXB)/BB
      GO TO 530
  520 IF(I.GE.K) GO TO 540
      E(I)=(B(I)/DLXB)/(BB-(B(I-1)/DLXA)*E(I-1))
      F(I)=(DA+(B(I-1)/DLXA)*F(I-1))/(BB-(B(I-1)/DLXA)*E(I-1))
  530 CONTINUE
  540 BB=BB-TAA*B(I)/DLXB
      DA=DA+TAA*(B(I)/DLXB)*((G(I)-G(I+1))*TM+DLXB)/TT+TBB*B(I)/DLXB*H(
     1KK)
      H(I)=(DA+(B(I-1)/DLXA)*F(I-1))/(BB-(B(I-1)/DLXA)*E(I-1))
  550 I=I-1
      H(I)=E(I)*H(I+1)+F(I)
      IF(I.GT.2) GO TO 550
      IF(TAA.LT.1.0) GO TO 560
      IF(NFABU.LT.1) GO TO 560
      H(KK)=H(K)+DD(KK)-DD(K)
      G(KK)=G(K)+DD(KK)-DD(K)
      B(K)=0.0
  560 DO 580 I=2,K
  570 IF(H(I)-DD(I)-HWET.LE.0.)GO TO 580
      H(I)=HWET+DD(I)
  580 CONTINUE
C
C***COMPUTATION OF WATER CONTENTS AS A FUNCTION OF PRESSURES JUST COMP
C
      IF(H(1).GE.HWET.OR.H(1).LE.HDRY) GO TO 590
      WFDD=EOR
      IF(ABS(EOR).GT.1.0E-6) GO TO 620
      H(1)=H(2)
      GO TO 650
  590 WFDD=B(1)*((H(1)-H(2))*TT+(G(1)-G(2))*TM+DD(2))/DD(2)
      GOTO 650
  620 H(1)=(EOR*DD(2)/B(1)+H(2)*TT-G(1)*TM+G(2)*TM-DD(2))/TT
  640 IF(H(1).LT.HDRY) H(1)=HDRY
      IF (H(1).GT.HWET) H(1)=HWET
      GO TO 590
```

```
  650 I=1
  660 IF(ABS(H(I)-G(I)).LT.0.0001) GO TO 720
      NHI=ND
      NLO=1
      J=25
  670 IF (H(I)-P(J)) 680,710,690
  680 NHI=J
      GO TO 700
  690 NLO=J
  700 JT=J
      J=(NHI-NLO)/2+NLO
      IF(ABS(J-JT).GT.0.00) GOTO 670
      IF(H(I).GE.P(J)) GO TO 710
      J=J-1
  710 WAT=(H(I)-P(J))*DELW/(P(J+1)-P(J))+T(J)
      W(I)=WAT
      GO TO 730
  720 W(I)=Y(I)
  730 DO 740 I=2,KK
      W(I)=C(I)*(H(I)-G(I))+Y(I)
      IF(W(I).GT.WATH) W(I)=WATH
      IF(W(I).LT.WATL) W(I)=WATL
  740 CONTINUE
  750 SUM3=0.0
      SUM2=0.0
      SUM1=0.0
      DO 760 I=2,K
      SUM1=W(I)+SUM1
      SUM2=Y(I)+SUM2
      IF(ABS(SUM1-SUM2).LE.ABS(SUM3)) GO TO 760
      SUM3=SUM1-SUM2
  760 CONTINUE
      IF(ABS(SUM3).LE.ABS(CONQ)) GO TO 770
      IF(DELT.LE.DETT*0.1) GO TO  770
      DELT=0.5*DELT
      GO TO 490
  770 SUM1=0.0
      SUM2=0.0
      DO 780 I=2,K
      SUM1=W(I)*(DD(I+1)-DD(I-1))/2.+SUM1
  780 SUM2=Y(I)*(DD(I+1)-DD(I-1))/2.+SUM2
      CWF=SUM1-PIT
      WFRDD=(SUM1-SUM2)/DELT
      WFUU=B(NB)*((H(NB)-H(NB+1))*TT+(G(NB)-G(NB+1))*TM+DD(NB+1)-DD(NB))
     1/(DD(NB+1)-DD(NB))
      CUMS=WFDD*DELT+CUMS
      IF(WFDD. GT. 0.)STRR=WFDD*DELT+SIRR
      IF(WFDD. LT. 0.)EVAP=WFDD*DELT+EVAP
      CUMB=WFUU*DELT+CUMB
      SUMA=SUMA+SINK*DELT
      CTRAN=CTRAN+ETPL*DELT
      CWFLX=(SUM1-SUM2)
      KB=K-1
      IF(EOR.GE.0.)RPI=RPI+EOR*DELT
C
C***THE SALT LOOP CALCULATES THE MOVEMENT OF THE IONS CA, MG, NA, K
C    CL, AND SO4 INDEPENDENTLY OF EACH OTHER.
C
      DO 860 JJ=5,10
      WFRU=WFDD
      ALFA=0.0
      WATU=(Y(1)*TM+W(1)*TT+Y(2)*TM+W(2)*TT)/2.
      DO 785 I=1,KK
 785  SS(I,JJ)=SE(I,JJ)
      DO 810 I=2,K
      DLXA=(DD(I)-DD(I-1))
      DLXB=(DD(I+1)-DD(I))
      DLXC=(DD(I+1)-DD(I-1))*0.5
      WFRD=B(I)*((H(I)-H(I+1))*TT+(G(I)-G(I+1))*TM+DLXB)/DLXB
      IF(I .EQ.2.AND.EOR.LT.0.0) WFRU=0.
      WATD=(Y(I)*TM+W(I)*TT+Y(I+1)*TM+W(I+1)*TT)/2.0
      BETA=DIFO+DIFA*EXP(DIFB*WATD)+ALAMBA*ABS(WFRD/WATD)
      TW=DELT*(W(I)-Y(I))*(WFRD+WFRU)/(8.*(W(I)+Y(I)))
```

```
      AX=TW*WFRU/(DLXA*WATU)+ALFA/DLXA*WFRU/2.
      IF(I.EQ.2)AX=WFRU
      CX=TW*WFRD/(DLXB*WATD)+BETA/DLXB-WFRD/2.
  805 BB=W(I)*DLXC/(TT*DELT)+AX*WFRU+CX*WFRD
      DA=(Y(I)*SS(I,JJ)*DLXC/DELT+TW*(AX*(SS(I-1,JJ)-SS(I,JJ))*WFRU*
     2SS(I,JJ)-CX*(SS(I,JJ)-SS(I+1,JJ))-WFRD*SS(I,JJ))))/TT
      IF(I.GT.2)GO TO 790
      DA=DA+AX*SS(I-1,JJ)
      BB=BB-AX*WFRU
      F(I)=DA/BB
      E(I)=CX/BB
      GO TO 800
  790 IF(I.GE.K) GO TO 820
      E(I)=CX/(BB-AX*E(I-1))
      F(I)=(DA+AX*F(I-1))/(BB-AX*E(I-1))
  800 ALFA=BETA
      WATU=WATD
  810 WFRU=WFRD
  820 DA=DA +CX*SS(I+1,JJ)
      SE(I,JJ)=(DA+AX*F(I-1))/(BB-AX*E(I-1))
  830 I=I-1
      SE(I,JJ)=E(I)*SE(I+1,JJ)+F(I)
      IF(I.GT.2)GO TO 830
      IF(TAA.EQ.1.0.OR.WFRD.GT.0.0)SE(KK,JJ)=SE(K,JJ)
      DO 860 I=2,K
      IF(SE(I,JJ).GE.SE(I-1,JJ).OR.SE(I,JJ).GE.SE(I+1,JJ))GO TO 860
      IF(KS.EQ.1)GO TO 860
      IF(I.EQ.2) GO TO 850
      IF(I.EQ.K) GO TO 840
      IF (SE(I-1,JJ).LE.SE(I+1,JJ)) GO TO 850
  840 TW=(SE(I+1,JJ)-SE(I,JJ))*W(I)*(DD(I+1)-DD(I-1))*0.5
      SE(I-1,JJ)=SE(I-1,JJ)-TW/(W(I-1)*(DD(I)-DD(I-2))*0.5)
      SE(I,JJ)=SE(I+1,JJ)
      GO TO 860
  850 TW=(SE(I-1,JJ)-SE(I,JJ))*W(I)*(DD(I+1)-DD(I-1))*0.5
      SE(I+1,JJ)=SE(I+1,JJ)-TW/(W(I+1)*(DD(I+2)-DD(I))*0.5)
      SE(I,JJ)=SE(I-1,JJ)
  860 CONTINUE
      CHLBAL=0.0
      DO 889 I=2,K
  889 CHLBAL=CHLBAL+SE(I,9)*W(I)*(DD(I+1)-DD(I-1))*.5
      IF(EOR.LE.0) GO TO 880
      RUNOF=(EOR-WFD0)*DELT+RUNOF
  880 TIME=TIME+DELT
      IF(LL.LT.KALKEM)GOTO 890
      WRITE(6,2040)
      LAST=0
  881 DO 885 I=2,KK
      SE(I,13)=W(I)
      IF(KILKEM.EQ.1)GOTO 882
C
C***IF THE CHEM SUBROUTINE IS CALLED, THE SOIL SOLUTION IS EQUILIBRATED
C   WITH LIME AND GYPSUM AND IF CEC IN NONZERO THE SOIL SOLUTION IS
C   EQUILIBRATED WITH THE EXCHANGE PHASE.
C
      CALL CHEM(SE(I,1),SE(I,2),SE(I,3),SE(I,4),SE(I,5),SE(I,6),
     *SE(I,7),SE(I,8),SE(I,9),SE(I,10),SE(I,11),SE(I,12),SE(I,13),
     *SE(I,14),SE(I,15),SE(I,16),SE(I,17),SE(I,18),SE(I,19),CEC,0)
      GOTO 884
C
C***IF CHEM IS NOT CALLED, SAR IS CALCLUATED AND HCO3 IS CALCULATED AS
C   CATIONS-ANIONS.  CO3 IS ASSUMED ZERO.  THE SOLUTION EC IS CALCUL-
C   ATED BY THE ECII SUBROUTINE.  PROFILE DATA IS THEN PRINTED.
C
  882 SE(I,15)=SE(I,7)/SQRT((SE(I,5)+SE(I,6))/2.)
      SE(I,11)=ABS(SE(I,5)+SE(I,6)+SE(I,7)+SE(I,8)-SE(I,9)-SE(I,10))
      SE(I,12)=0.0
      CALL ECII(SE(I,5),SE(I,6),SE(I,7),SE(I,8),SE(I,9),SE(I,10),
     *SE(I,11),SE(I,12),SE(I,14),0)
  884 WRITE(6,2044)(SE(I,JJ),JJ=1,21)
  885 CONTINUE
      CUMH2O=0.0
      DO 887 I=2,K
  887 CUMH2O=CUMH2O+SE(I,13)*(SE(I,21)-SE(I,20))
      WRITE(6,2145)CUMH2O
      IF(LAST.EQ.1)GOTO 1150
      WRITE (6,1230)
      LL=0
  890 WRITE(6,1220)TIME,CWF,SIRR,CUMB,RUNOF,CUMS,EVAP,SUMA,CTRAN,HROOT
  900 IF(ABS(SUM3-0.).GT..0001) GO TO 920
  910 DELT=3.*DELT
      GO TO 960
  920 TW=ABS(CONQ*DELT/SUM3)
  930 IF(TW.GE.0.1*DETT) GO TO 940
      TW=0.1*DETT
      GO TO 950
  940 IF(TW.LE.1000.0*DETT) GO TO 950
      TW=1000.0*DETT
  950 IF(TW.GT.2.0*DELT) GO TO 910
      DELT=TW
C
C***TEST TO SEE IF EVAP OR RAIN INTENSITY (EOR) HAS CHANGED
C
  960 IF(IDELT.EQ.1) DELT=DELT1
      IDELT=0
      IF(DELT.LT.DETT)DELT=DETT
      IF(DELT.GT.6.) DELT=6.
      IF(TIME-V(KC+1).LT.0.0)GOTO 980
      EOR=V(KC+2)
      IR=(KC+2)/2
      DO 975 JJ=5,10
  975 SE(1,JJ)=SE(IR+1,JJ-4)
      ET=TET(IR+1)
      KC=KC+2
      MTIME=0
      DELT=DETT
      GO TO 990
  980 IF((TIME+DELT).LE.V(KC+1)) GO TO 990
      DELT=V(KC+1)-TIME
C
C***CALCULATION OF HOURLY ET DEMAND FROM LYSIMETER DATA
C
  990 LL=LL+1
      IF(V(KC).GT.0.) GO TO 1040
      LTIME=TIME/24
      TIMEL=LTIME
      TIMEA=TIME/24.-TIMEL
      LTIME=(TIME+DELT)/24
      TIMEL=LTIME
      TIMED=(TIME+DELT)/24.-TIMEL
      IF(TIMED.LT.TIMEA) GO TO 1020
      IF(0.5-TIMEA.LT.0.0001)GO TO 1020
      IF(TIMED.LE.0.5)GO TO 1000
      TIMED=0.5
      DELT1=DELT
      IDELT=1
      DELT=(0.5-TIMEA)*24.
 1000 IF(MTIME.EQ.1)GO TO 1010
      MTIME=1
      TIMEC=V(KC+1)-TIME
      IF(TIMEC+24.*TIMEA.GT.24.)TIMEC=24.*(1.-TIMEA)
      EORH2O=V(KC)*TIMEC
      IR=(KC+1)/2
      ETH2O=TET(IR)*TIMEC
      TIMEL=TIMEC
      IF(TIMEC.GE.12.)TIMEL=12.
      DENOM=COS(TIMEA*6.2832)-COS(TIMEL*6.2832/24.)
 1010 ETNEW=(COS(TIMEA*6.2832)-COS(TIMED*6.2832))/DENOM
      EOR=ETNEW*EORH2O/DELT
      ET=ETNEW*ETH2O/DELT
      GO TO 1040
 1020 IF(TIMED.GE.0.5)GO TO 1030
      DELT1=DELT
      IDELT=1
```

```
      DELT=(1.-TIMEA)*24.
 1030 ET=0.
      EOR=0.
      MTIME=0
 1040 IF(DELT.LT.DETT) DELT=DETT
      IF(TIME-CUMT.LT.0) GO TO 1090
C
C***THIS STEP INITIATES CHEMICAL EQUILIBRUM CALCULATION AND PRINT OUT
C   OF PROFILE WHEN TIME=CUMT.
C
      WRITE(6,2040)
      LAST=1
      GOTO 881
 1090 Y(1)=(W(1)+Y(1))*0.5
      J=(Y(1)-T(1))/DELW+1.0
      BB=(Y(1)-T(J))/DELW
      IF(ABS(EOR-0.0).LT.0.0001) GO TO 1100
      G(1)=(P(J+1)-P(J))*BB+P(J)
 1100 DO 1130 I=2,KK
      J=(W(I)-T(1))/DELW+1.0
      BB=(W(I)-T(J))/DELW
      G(I)=(P(J+1)-P(J))*BB+P(J)
      TW=(W(I)-Y(I))+W(I)
      IF(TW.GT.WATH) GO TO 1110
      IF(TW.GE.WATL) GO TO 1120
      TW=WATL
      GO TO 1120
 1110 TW=WATH
 1120 Y(I)=W(I)
      W(I)=TW
 1130 CONTINUE
      GO TU 130
 1140 CONTINUE
 1150 STOP
C
C***FORMAT STSTEMENTS
C
 1180 FORMAT (20I3)
 1190 FORMAT (7E10.4)
 1200 FORMAT('0  TIME END   SOIL FLUX    ET FLUX     CA          MG
     *      NA         K          CL          SO4')
 1210 FORMAT (11E12.5)
 1220 FORMAT(12E11.4)
 1230 FORMAT      ('0   TIME       CWF       IRR+RAIN     CUMB       RUN O
     *FF   CUMS        EVAP       TRANACT    TRANPOT   WROOT')
 1240 FORMAT('0   WATER     POTENTIAL CONDUCTIVITY DIFFUSIVITY
     *      WATER     POTENTIAL CONDUCTIVITY DIFFUSIVITY')
 1250 FORMAT(4E12.5,12X,4E12.5)
 1260 FORMAT('0   DEPTH          C(I)       W-DEPTH     H-DEPTH   RDF-DEPTH
     *')
 1270 FORMAT('    RDFDAY      RDFDEL    ESTART         ESTOP        AK1
     *     AK2        CEC')
 1280 FORMAT('OK IER NB ND')
 1290 FORMAT(80H   DETT         CONQ         TAA          TIME         TT
     *         CUMT         RRES)
 1300 FORMAT('   HDRY         HWET         WATL         WATH         HLOW
     *     HHI          DELW')
 1310 FORMAT('   ALAMBA       DIFO         DIFA         DIFB')
 2001 FORMAT(25A1)
 2010 FORMAT(12F5.2)
 2020 FORMAT(2F5.4,8F5.2)
 2025 FORMAT('  ',25A1,25A1,25A1)
 2030 FORMAT('     CASO   CACO     PH      BD      CA      MG      NA      K
     *    CL      SO4')
 2035 FORMAT('    ',2F7.4,8F7.2)
 2040 FORMAT('     CASO   CACO   PH    BD     CA     MG     NA    K      CL
     *TSO4  THCO3 TCO3  VH20    EC    SAR     XCA     XMG     XNA     XK
     *DEPTH')
 2044 FORMAT('  ',2F7.5,2F5.2,7F6.2,F6.3,3F6.2,4F7.4,2X,F4.0,'-',F4.0)
 2145 FORMAT('0  TOTAL WATER IN PROFILE=',F6.2,'CM')
      END
```

```
C
C***CHEM SUBROUTINE AND ITS DEPENDENT SUBROUTINES.
C
C   WRITTEN BY;
C                  CHARLES W. ROBBINS
C                  DEPT. SOILS AND BIOMETEOROLOGY
C                  UTAH STATE UNIVERSITY
C                  LOGAN, UTAH  84322
C
C***PERMENANT ADDRESS AFTER JAN 1, 1979
C
C                  SNAKE RIVER CONS. RES. CENTER
C                  USDA SEA AR
C                  ROUTE 1  BOX 186
C                  KIMBERLY, ID  84301
C
C***THE CHEM SUBROUTINE AND THE FIVE DEPENDENT SUBROUTINES ARE INTENDED
C   TO BE USED TOGETHER AND INTERFACED WITH EXISTING STEADY STATE
C   OR TRANSIENT WATER FLOW, SALT TRANSPORT MODELS.  WHEN USED WITH
C   STEADY STATE MODELS THE XCHANG SUBROUTINE SHOULD NOT BE USED.
C   THESE SUBROUTINES ARE INTENDED TO PROVIDE A MORE THERMODYNAMICALLY
C   RIGOROUS DISCRIPTION OF LIME AND GYPSUM PRECIPITATION AND DISSOL-
C   UTION AND CATION EXCHANGE EQUILIBRIUM IN MINERAL SOILS CONTAINING
C   LIME WITH MEDIUM TO HIGH SALT CONCENTRATIONS.  THE PROGRAM ALSO
C   ASSUMES THE PH OF EACH DEPTH INCREMENT IS CONSTANT.
C
C***INPUT DATA DEFINED IN ORDER OF USE IN THE CALLING STATMENT ARE;
C   CASO=GYPSUM  CACO=LIME  (DECIMAL FRACTION ON WT. BASIS)
C   PH= -LOG HYDROGEN ACTIVITY
C   BD=SOIL BULK DENSITY (G/CUBIC CM.)
C   TCA=CALCIUM      TMG=MAGNESIUM      TNA=SODIUM
C   TK=POTASSIUM     TCL=CHLORIDE       TSO4=SULFATE
C                (ME/L IN SOLUTTON)
C   VH2O=VOLUMETRIC WATER CONTENT FOR THE SOIL DEPTH INCREMENT BEING
C   CONSIDERED (CUBIC CM/CUBIC CM).
C   IF THE XCHANG SUBROUTINE IS CALLED AND NN=1 VALUES ARE NEEDED FOR
C   THE FALLOWING.
C   XCA, XMG, XNA AND XK ARE EXCHANGABLE CALCIUM, MAGNESIUM, SODIUM
C   AND POTASSIUM.  (MEQ/100 G SOIL)  IF NN=0, THESE VALUES ARE NOT USED
C   AFTER EXECUTION THE CHEM SUBROUTINE RETURNS NEW VALUES FOR CASO,
C   CACO, TCA, TMG, AND TSO4 AND IF XCHANGE WAS CALLED AND NN=1, NEW
C   VALUES ARE RETURNED FOR XCA, XMG, XNA, AND XK. VALUES ARE ALSO CAL-
C   CULATED FOR;
C   THCO3=BICARBUNATE   TCO3=CARBONATE  (ME/L IN SOLUTION)
C   EC=ELECTRICAL CONDUCTIVITY  (MMHOS/CM)
C   SAR=SODIUM ADSORPTION RATIO
C   IF XCHANG WAS CALLED AND NN=0 THEN INITIAL VALUES ARE CALCULATED FOR
C   XCA, XMG, XNA, AND XK.  THE VALUES OF PH, BD, VH2O, CEC AND NN DO
C   NOT CHANGE DURING EXECUTION OF CHEM.
C
C***OTHER FORTRAN SYMBOLS USED IN THE SUBROUTINE.
C   CHEMICAL CONSTANTS USED IN THE DATA STATEMENT;
C   KH  HENRYS LAW CONSTANT FOR CO2
C   KW  STABILITY CONSTANT OF WATER
C   KA1 FIRST DISSOCIATION CONSTANT OF H2CO3
C   KA2 SECOND DISSOCIATION CONSTANT OF H2CO3
C   KD1 STABILITY CONSTANT OF CACO3
C   KD2 STABILITY CONSTANT OF CAHCO3+
C   KD3 STABILITY CONSTANT OF CAOH+
C   KD4 STABILITY CONSTANT OF CASO4
C   KD5 STABILITY CONSTANT OF MGCO3
C   KD6 STABILITY CONSTANT OF MGHCO3+
C   KD7 STABILITY CONSTANT OF MGOH+
C   KD8 STABILITY CONSTAND OF MGSO4
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C    KD9 STABILITY CONSTANT OF NASO4-
C    KD10 STABILITY CONSTANT OF NACO3-
C    SP1 SOLUBILITY PRODUCT OF GYPSUM
C    SP2 SOLUBILITY PRODUCT OF LIME
C    H=HYDROGEN ION ACTIVITY (MOLES/L)
C    ADJGYP AND ADJLIM CONVERT GYPSUM AND LIME BETWEEN DECIMAL FRACTIONS
C    AND MOLES/L IN SOIL SOLUTION.
C    ACT1 AND ACT2 ARE THE ACTIVITY COEFFICIENTS FOR MONO- AND DIVALENT
C    IONS.
C    CHEMICAL SYMBOLS PRECEEDED BY A, REPRESENT ION ACTIVITIES (ACA=
C    CALCIUM ACTIVITY ETC.).
C    PCO2 IS THE PARTIAL PRESSURE OF CARBON DIOXIDE (ATMOS.)
C    ACCA IS THE "APPARENT" ACTIVITY COEFFICIENT OF CALCIUM.
C    CAT AND AN ARE THE SUM OF CATIONS AND ANIONS (EQUIV./L).
C
       SUBROUTINE CHEM(CASO,CACO,PH,BD,TCA,TMG,TNA,TK,TCL,TSO4,
      *THCO3,TCO3,VH2O,EC,SAR,XCA,XMG,XNA,XK,CEC,NN)
       REAL KH,KW,KA1,KA2,KD1,KD2,KD3,KD4,KD5,KD6,KD7,KD8,KD9
      *,KD10
       DATA KH/.0339/,KW/.1E-13/,KA1/.5E-6/,KA2/.5E-10/,KD1/.63E-3/,
      *KD2/.055/,KD3/.0425/,KD4/.49E-2/,KD5/.4E-3/,KD6/.069/,KD7/
      *.263E-2/,KD8/.0063/,KD9/.24/,KD10/.0535/,SP1/.24E-4/,
      *SP2/.113E-7/
C
C***WARNING STATMENTS ARE PRINTED FOR DATA DEFICIENCIES.
C
       IF(CACO.LE.0.OR.PH.LT.5.0)GOTO 50
       IF(TCA.EQ.0.OR.TMG.EQ.0.OR.TNA.EQ.0.OR.TK.EQ.0.OR.TCL.EQ.0)GOTO 52
       IF(BD.LE.0.7.OR.VH2O.LE.0)GOTO 54
C
C***CONCENTRATIONS ARE CONVERTED FROM MEQ/L TO MOLES/L AND APPROXIMATE
C    VALUES ARE GIVEN TO THCO3 AND TCO3.
C
       TCA=TCA/2000.
       TMG=TMG/2000.
       TNA=TNA/1000.
       TK=TK/1000.
       TCL=TCL/1000.
       TSO4=TSO4/2000.
       THCO3=2.*(TCA+TMG-TSO4)+TNA+TK-TCL
       THCO3=ABS(THCO3)
       TCO3=0.0
C
C***IF TCA IS LESS THAN 0.0005 MOLAR THE PH IS CHANGED TO 8.4, THE PH
C    OF A LIME SOLUTION IN CONTACT WITH ATMOSPHERIC CO2.
C
       IF(TCA.LT.0.0005)PH=8.4
       H=10.**(-PH)
C
C***LIME AND GYPSUM ARE CONVERTED FROM DECIMAL FRACTION ON A WEIGHT
C    BASIS TO MOLES/L SOIL SOLUTION.
C
       ADJGYP=BD*5.81/VH2O
       CASO=CASO*ADJGYP
       CASOIN=CASO
       ADJLIM=BD*10./VH2O
       CACO=CACD*ADJLIM
C
C***EC IS CALCULATED FROM IONIC CONCENTRATIONS AND USED TO CALCULATE
C    THE MONO- AND DIVALENT ION MEAN ACTIVITY COEFFICIENTS.
C
       CALL ECII(TCA,TMG,TNA,TK,TCL,TSO4,THCO3,TCO3,EC,1)
       ACT1=ACT(1.,EC)
       ACT2=ACT(2.,EC)
C
C***FIRST APPROXIMATIONS OF ION ACTIVITIES ARE MADE FROM ACTIVITY
C    COEFFICIENTS AND THE ION PAIRS THAT CAN BE CONSIOERED AT THIS POINT.
C
       ASO4=TSO4*ACT2
       AK=TK*ACT1
       ANA=TNA*ACT1/(1.0+ASO4/KD9)
       ACA=TCA/(1./\CT2+KW/(KD3*ACT1*H)+ASO4/KD4)
       AMG=TMG/(1./ACT2+KW/(KD7*ACT1*H)+ASO4/KD8)
```

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       ASO4=TSO4/(1./ACT2+ACA/KD4+AMG/KD8+ANA/(ACT1*KD9))
C
C***CHEMICAL EQUILIBRIUM LOOP
C
       DO 20 I=1,10
C
C***NEW ACTIVITY COEFFICIENTS ARE CALCULATED FROM THE EC VALUE FROM
C    THE PREVIOUS CYCLE AND A NEW PCO2 VALUE IS CALCULATED.
C
       ACT1=ACT(1.,EC)
       ACT2=ACT(2.,EC)
       PCO2=H*H*SP2/(ACA*KH*KA1*KA2)
C
C***ACTIVITIES FOR CA, MG, NA AND SO4,  ARE CORRECTED FOR IONIC
C    STRENGTH AND ION PAIRING, AND ACO3 IS CALCULATED.
C
       ACA=TCA/(1./ACT2+KA1*KH*PCO2/(KD2*ACT1*H)+KW/(KD3*ACT1*H)+
      *KA1*KA2*KH*PCO2/(KD1*H*H)+ASO4/KD4)
       AMG=TMG/(1./ACT2+KA1*KH*PCO2/(KD6*ACT1*H)+KW/(KD7*ACT1*H)+
      *KA1*KA2*KH*PCO2/(KD5*H*H)+ASO4/KD8)
       ANA=TNA/(1./ACT1+ASO4/(ACT1*KD9)+KA1*KA2*KH*PCO2/(KD10*ACT2*H*H))
       ASO4=TSO4/(1./ACT2+ACA/KD4+AMG/KD8+ANA/(ACT1*KD9))
       ACO3=KA1*KA2*KH*PCO2/(H*H)
C
C***GYPSUM AND LIME ARE CONVERTED TO "ACTIVITIES" SO THEY WILL BE IN
C    THE SAME UNITS AS CA, CO3, AND SO4 FOR THE PRECIP SUBROUTINE.
C
       ACCA=ACA/TCA
       CACO=CACO*ACCA
       CASO=CASO*ACCA
C
C***THE SOIL SOLUTION IS EQUILIBRATED WITH LIME AND GYPSUM AND THEN
C    LIME AND GYPSUM ARE CONVERTED BACK TO MOLES/L.
C
       X1=.1E-6
       CALL PRECIP(ACA,ACO3,SP2,X1,CACO)
       X2=.002
       CALL PRECIP(ACA,ASO4,SP1,X2,CASO)
       CACD=CACO/ACCA
       CASO=CASO/ACCA
C
C***PCO2 IS RECALCULATED AND VALUES ARE CALCULATED FOR AHCO3 AND ACO3
C    ACTIVITIES AND NEW TCA, TCO3, THCO3 AND TSO4 VALUES ARE CALCULATED.
C
       PCO2=H*H*SP2/(ACA*KH*KA1*KA2)
       AHCO3=KA1*KH*PCO2/H
       ACO3=KA2*AHCO3/H

       TCA=ACA*(1./ACT2+KA1*KH*PCO2/(KD2*ACT1*H)+KW/(KD3*ACT1*H)+
      *KA1*KA2*KH*PCO2/(KD1*H*H)+ASO4/KD4)
       TCO3=ACO3*(1./ACT2+ACA/KD1+AMG/KD5+ANA/(KD10*ACT1))
       THCO3=(AHCO3/ACT1)*(1.+ACA/KD2+AMG/KD6)
       IF(CASO.EQ.0.AND.CASOIN.EQ.0)GOTO 10
       TSO4=ASO4*(1./ACT2+ACA/KD4+AMG/KD8+ANA/(ACT1*KD9))
C
C***IF THE NEW EC VALUE IS MORE THAN 1% DIFFERENT THAN ECOLD THE EQUI-
C    LIBRIUM LOOP IS GONE THROUGH AGAIN, OTHERWISE THE LOOP IS EXITED.
C
 10    ECOLD=EC
       CALL ECII(TCA,TMG,TNA,TK,TCL,TSO4,THCO3,TCO3,EC,1)
       IF(ABS(EC-ECOLD).LT.EC*0.01)I=10
 20    CONTINUE
C
C***IONIC CHARGE BALANCE LOOP
C    IF THE DIFFERENCE BETWEEN THE ANION AND CATION TOTAL CHARGE IS MORE
C    THAN 1% OF THE TOTAL CATION CHARGE THE CATION AND ANION CHARGE IS
C    BALANCED BY CORRECTING TCA AND THCO3,TCO3 AND TSO4 (IF CASO IS
C    PRESENT) BY INCREASING OR DECREASING TCO3 (ASSUMING THE SYSTEM IS
C    OPEN WITH RESPECT TO CO2) AND ADJUSTING THE OTHER THREE IONIC
C    CONCENTRATION SUCH THAT THE  SOLUBILITY PRODUCTS ARE NOT VIOLATED.
C
       CAT=2.*(TCA+TMG)+TNA+TK
       AN=2.*(TSO4+TCO3)+TCL+THCO3
```

```
      CHARGE=CAT-AN
      IF(ABS(CHARGE).LE.0.01*CAT)GOTO 40
      F=1.+ABS(0.25*CHARGE/CAT)
      IF(F.LT.1.01)F=1.01
      IF(F.GT.1.2)F=1.2
      IF(CHARGE.LT.0.0)GOTO 35
      DO 34 I=1,10
      TCA=TCA/F
      THCO3=THCO3*F
      CACO=CACO+TCO3*(F-1.)
      TCO3=TCO3*F
      IF(CASO.LE.0.00001)GOTO 30
      CASO=CASO-TSO4*(F-1.)
      IF(CASO.LT.0.0)CASO=0.0
      TSO4=TSO4*F
 30   CAT=2.*(TCA+TMG)+TNA+TK
      AN=2.*(TSO4+TCO3)+TCL+THCO3
      CHARGE=CAT-AN
      IF(CHARGE.LT.0.01*CAT)I=20
 34   CONTINUE
      GOTO 40
 35   DO 38 I=1,10
      TCA=TCA*F
      THCO3=THCO3/F
      CACO=CACO-TCO3*(F-1.)
      TCO3=TCO3/F
      IF(CASO.LE.0.00001)GOTO 36
      CASO=CASO+TSO4*(F-1.)
      TSO4=TSO4/F
  36  CAT=2.*(TCA+TMG)+TNA+TK
      AN=2.*(TSO4+TCO3)+TCL+THCO3
      CHARGE=CAT-AN
      IF(CHARGE.GT.-0.01*CAT)I=20
 38   CONTINUE
C
C***IF CEC IS NONZERO THE EXCHANGE SUBROUTINE BRINGS THE SOLUTION INTO
C   EQUILIBRIUM WITH THE EXCHANGE PHASE.
C
 40   IF(CEC.EQ.0.)GOTO 45
      CALL XCHANG(TCA,TMG,TNA,TK,ACA,AMG,ANA,AK,XCA,XMG,XNA,XK,
     *BD,VH2O,CEC,NN)
C
C***MOLES/L IN SOLUTION ARE CONVERTED TO MEQ/L AND GYPSUM AND LIME ARE
C   CONVERTED BACK TO DECIMAL FRACTIONS.  SAR IS ALSO CALCULATED.
C
 45   TCA=TCA*2000.
      TMG=TMG*2000.
      TNA=TNA*1000.
      TK=TK*1000.
      TSO4=TSO4*2000.
      THCO3=THCO3*1000.
      TCO3=TCO3*2000.
      TCL=TCL*1000.
      CASO=CASO/ADJGYP
      CACO=CACO/ADJLIM
      SAR=TNA/SQRT((TCA+TMG)/2.)
      GOTO 60
C
C***PRINT STATEMENTS AND FORMAT STATEMENTS FOR MISSING DATA.
C
 50   WRITE(6,51)
 51   FORMAT(' VALUE NEEDED FOR PH OR CACO')
      GOTO 60
 52   WRITE(6,53)
 53   FORMAT(' VALUE NEEDED FOR ONE OR MORE IONS')
      GOTO 60
 54   WRITE(6,55)
 55   FORMAT(' VALUE NEEDED FOR BD OR VH2O')
 60   RETURN
      END
```

Function ACT

```
C
C***THE FUNCTION ACT CALCULATES IONIC STRENGTH (IS) USING THE APPROXIMA-
C   TION OF GRIFFIN AND JURINAK (1973).  THE SQUARE ROOT (I) OF (IS) IS
C   THEN USED IN THE DAVIES EQUATION TO CALCULATE THE MONO- (Z=1) AND
C   DIVALENT (Z=2) ION MEAN ACTIVITY COEFFICIENTS.
C
      FUNCTION ACT(Z,EC)
      REAL IS,I
      IS=0.0127*EC
      I=SQRT(IS)
      ACT=10.0**(-0.509*Z*Z*(I/(1.0+I)-0.3*IS))
      RETURN
      END
```

Subroutine PRECIP

```
C
C***THE SUBROUTINE PRECIP USES CATION (CAT) AND ANION (AN) ACTIVITIES
C   AND THE SOLUBILITY PRODUCT (SP) TO DETERMINE IF SOLID PHASE
C   MATERIAL (PPT) MUST DISOLVE OR PRECIPITATE TO BRING THE SYSTEM INTO
C   CHEMICAL EQUIBILIBRUIM.  IT THEN CALLS THE SINK SUBROUTINE TO DETER-
C   MINE THE QUANTITY OF PPT TO BE DISOLVED OR PRECIPITATED.  XX IS THE
C   SINK SUBROUTINE STARTING VALUE ON INPUT, AND COMES BACK FROM SINK AS
C   THE VALUE THAT CAT, AN AND PPT IS TO BE CHANGED.
C
      SUBROUTINE PRECIP(CAT,AN,SP,XX,PPT)
      IF(CAT*AN-SP)10,30,20
 10   IF(PPT.LE.0.0)GOTO 30
      CALL SINK(CAT,AN,SP,XX)
      IF(PPT.LT.XX)XX=PPT
      CAT=CAT+XX
      AN=AN+XX
      PPT=PPT-XX
      GOTO 30
 20   CALL SINK(CAT,AN,SP,XX)
      CAT=CAT-XX
      AN=AN-XX
      PPT=PPT+XX
 30   RETURN
      END
```

Subroutine SINK

```
C
C***THE SUBROUTINE SINK USES CATION (CAT) AND ANION (AN) ACTIVITIES,
C   SOLUBILITY PRODUCT (SP), AND A STARTING VALUE (X) TO CALCULATE THE
```

```
C   CATION AND ANION ACTIVITY CHANGE DUE TO SOLUTION OR PRECIPITA-
C   TION OF SOLID PHASE TO BRING THE SYSTEM INTO CHEMICAL EQUILIBRIUM
C   FOR A GIVEN SPECIES.  THE NEWTON METHOD IS USED TO FIND X.
C
      SUBROUTINE SINK(CAT,AN,SP,X)
      DO 5 N=1,10
C
C***THIS STATEMENT KEEPS THE NEXT FROM DIVIDING BY ZERO
C
      IF(CAT+AN.EQ.2.0*X)X=X*1.1
      XI=X-(X*X-X*CAT-X*AN+CAT*AN-SP)/(2.0*X-CAT-AN)
      IF(ABS(XI-X).LT.ABS(X*.01)) N=10
      X=XI
 5    CONTINUE
      X=ABS(X)
      RETURN
      END
```

Subroutine ECII

```
C
C***THE SUBROUTINE ECII USES THE EXPONENTIAL METHOD OF MCNEAL ET AL.
C   1970 (SOIL SCI. 110:405-414) TO CALCULATE ELECTRICAL CONDUCIVITY
C   (EC) FROM CALCIUM, MAGNESIUM, SODIUM, POTASIUM, CHLORIDE, SULFATE,
C   BICARBONATE, AND CARBONATE (TCA,TMG,TNA,TK,TCL,TSO4,THCO3,TCO3)
C   CONCENTRATION.  IF THE CONCENTRATIONS ARE IN MOLES/L M MUST EQUAL
C   1.  IF THE CONCENTRATIONS ARE IN ME/L, M MUST NOT EQUAL 1.
C
      SUBROUTINE ECII(TCA,TMG,TNA,TK,TCL,TSO4,THCO3,TCO3,EC,M)
      REAL MG
      IF(M.EQ.1)GOTO 1
      X=1.
      Y=1.
      GOTO 2
C
C***X AND Y ARE USED TO CONVERT MOLES/L TO ME/L
C
   1  X=1000.
      Y=2000.
   2  CA=TCA
      MG=TMG
      SO4=TSO4
C
C***THE MAXIMUM CALCIUM AND MAGNESIUM SULFATE CONCENTRATION IS SEPERATED
C   OUT AS GYPSUM (CASO) BEFOR CALCULATING EC.
C
      IF(SO4.GT.CA)GOTO 10
      CASO=SO4
      CA=CA-SO4
      SO4=0.0
      GOTO 30
 10   CASO=CA
      SO4=SO4-CA
      CA=0.0
      IF(SO4.GT.MG)GOTO 20
      CASO=CASO+SO4
      MG=MG-SO4
      SO4=0.0
      GOTO 30
 20   CASO=CASO+MG
      SO4=SO4-MG
      MG=0.0
C
C***EC IS CALCULATED USING THE COEFFICIENTS OBTAINED BY MCNEAL ET AL.
C
 30   EC=.05641*((CA*Y)**.9202)+.05099*((MG*Y)**.9102)+
     *.04748*((TNA*X)**.9495)+
     *.07263*((TK*X)**.9706)+.069*((SO4*Y)**.8973)+
     *.0733*((TCO3*Y)**.8719)+.04143*((THCO3*X)**.9501)+
     *.07206*((TCL*X)**.9671)+.1133*((CASO*Y)**.8463)
      RETURN
      END
```

Subroutine XCHANGE

```
C***THE SUBROUTINE XCHANG IS DIVIDED INTO TWO SEGMENTS. IF NN EQUALS 1,
C   INITIAL EXCHANGABLE CATION CONCENTRATIONS ARE CALCULATED FROM THE
C   CATION EXCHANGE CAPACITY(CEC), AND CATION ACTIVITIES SUPPLIED BY THE
C   CALLING PROGRAM.  IF NN IS NOT EQUAL TO 1, NEW EQUILIBRIUM IS CAL-
C   CULATED FOR SOLUTION AND EXCHANGABLE CATIONS USING EXCHANGABLE
C   CATION AND SOLUTION CATION CONCENTRATIONS AND CATION ACTIVITIES,
C   BULK DENSITY (BD), VOLUMETRIC WATER CONTENT (VH2O), AND CEC
C   VALUES SUPPLIED FROM THE CALLING PROGRAM.
C   TCA,TMG,..ETC ARE MOLES/L OF SOLUTION CATIONS.
C   ACA,AMG,..ETC ARE CATION ACTIVITIES.
C   XCA,XMG,..ETC ARE EXCHANGABLE CATIONS, INITALLY AND FINALLY IN
C   MEQ/100G OF SOIL AND WITHIN THE SUBROUTINE THEY ARE CONVERTED TO
C   AND FROM MOLES/L.
C   OTHER FORTRAN SYMBOLS ARE SELF EXPLANATORY.
C
      SUBROUTINE XCHANG(TCA,TMG,TNA,TK,ACA,AMG,ANA,AK,XCA,XMG,XNA,XK,
     *BD,VH2O,CEC,NN)
C
C   SOME OF THE SELECTIVITY COEFFICIENTS, K1,K2,K3, ETC MAY VARY FROM
C   SOIL TO SOIL.
C
      REAL K1,K2,K3,K4,K5,K6
      DATA K1/0.84/,K2/6.6/,K3/.38/,K4/.25/,K5/4.3/,K6/17./
      IF(NN.EQ.1)GOTO 10
      GOTO 20
C   STARTING POINT EXCHANGABLE CATION VALUES ARE CALCULATED FROM
C   INITIAL INPUT DATA
  10  ZCA=SQRT(ACA)
      ZMG=SQRT(AMG)
      XCA=CEC/(K1*AMG/ACA+ANA/(ZCA*K2)+AK/(ZCA*K3)+1.)
      XMG=CEC/(ACA/(AMG*K1)+ANA/(ZMG*K5)+AK/(ZMG*K4)+1.)
      XNA=CEC/(ZCA*K2/ANA+ZMG*K5/ANA+AK*K6/ANA+1.)
      XK=CEC/(ZCA*K3/AK+ZMG*K4/AK+ANA/(AK*K6)+1.)
C
C   THE EXCHANGABLE CATIONS ARE CORRECTED BY A COMMON FACTOR TO FORCE
C   THE SUM OF EXCHANGABLE CATIONS TO EQUAL THE CEC.  IN A FEW CASES
C   MACHINE ROUND-OFF ERROR MAKES THIS NECESSARY.
C
      C=CEC/(XCA+XMG+XNA+XK)
      XCA=XCA*C
      XMG=XMG*C
      XNA=XNA*C
      XK=XK*C
      GOTO 50
C
C   ADJUSTMENT FACTORS ARE CALCULATED TO CONVERT EXCHANGABLE CATION
C   UNITS BETWEEN MEQ/100G OF SOIL AND MOLES/L IN SOLUTION.
C
  20  ADJ2=0.005*BD/VH2O
      ADJ1=0.010*BD/VH2O
      XCA=XCA*ADJ2
      XMG=XMG*ADJ2
      XNA=XNA*ADJ1
      XK=XK*ADJ1
      EQU=2.*(TCA+TMG)+TNA+TK
C
C   "APPARENT ACTIVITY COEFFICIENTS" ARE CALCULATED FOR EACH CATION.
C
      ACCA=ACA/TCA
      ACMG=AMG/TMG
```

```
      ACNA=ANA/TNA
      ACK=AK/TK
C
C   THE SUM OF EACH SOLUTION PLUS EXCHANGABLE CATION IS CALCULATED.
C
      SCA=TCA+XCA
      SMG=TMG+XMG
      SNA=TNA+XNA
      SK=TK+XK
C
C   THIS LOOP BRINGS THE NEW EXCHANGABLE AND SOLUTION CATIONS INTO EQUI-
C   LIBRIUM WITH EACH OTHER, ASSUMING, (1)THAT THE APPARENT ACTIVITY
C   COEFFICIENTS ARE CONSTANT, (2) THAT THE CEC IS CONSTANT AND EQUAL
C   TO THE SUM OF THE EXCHANGABLE CATIONS, AND (3) THAT EACH EXCHANG-
C   ABLE PLUS SOLUTION CATION CONCENTRATION REMAINS CONSTANT.
C

      DO 30 I=1,4
      ZCA=SQRT(ACA)
      ZMG=SQRT(AMG)
      XCANU=CEC/(K1*AMG/ACA+ANA/(ZCA*K2)+AK/(ZCA*K3)+1.)
      XMGNU=CEC/(ACA/(AMG*K1)+ANA/(ZMG*K5)+AK/(ZMG*K4)+1.)
      XNANU=CEC/(ZCA*K2/ANA+ZMG*K5/ANA+AK*K6/ANA+1.)
      XKNU=CEC/(ZCA*K3/AK+ZMG*K4/AK+ANA/(AK*K6)+1.)
      XCANU=XCANU*ADJ2
      XMGNU=XMGNU*ADJ2
      XNANU=XNANU*ADJ1
      XKNU=XKNU*ADJ1
      TCA=TCA*XCA*2./(XCANU+XCA)
      TMG=TMG*XMG*2./(XMGNU+XMG)
      TNA=TNA*XNA*2./(XNANU+XNA)
      TK=TK*XK*2./(XKNU+XK)
      EQUNU=2.*(TCA+TMG)+TNA+TK
      CC=EQU/EQUNU
      TCA=TCA*CC
      TMG=TMG*CC
      TNA=TNA*CC
      TK=TK*CC
      XCA=SCA-TCA
      XMG=SMG-TMG
      XNA=SNA-TNA
      XK=SK-TK
      C=CEC/((XCA+XMG)/ADJ2+(XNA+XK)/ADJ1)
      XCA=XCA*C
      XMG=XMG*C
      XNA=XNA*C
      XK=XK*C
      ACA=TCA*ACCA
      AMG=TMG*ACMG
      ANA=TNA*ACNA
      AK=TK*ACK
30    CONTINUE
      XCA=XCA/ADJ2
      XMG=XMG/ADJ2
      XNA=XNA/ADJ1
      XK=XK/ADJ1
50    RETURN
      END
```

APPENDIX B

SAMPLE INPUT DATA FILES

```
 100     10% LF GYP WATER SI CLAY L
 200     48
 300        01440.
 400    -.050 108.     50 120.-.050 228.     50 240.-.050 348.     50 360.
 500    -.050 468.     50 480.-.050 588.     50 600.-.050 708.     50 720.
 600    -.050 828.     50 840.-.050 948.     50 960.-.0501068.     501080
 700    -.0501188.     501200.-.0501308.     501320.-.0501428.     501440.
 800          0      0      0      0      0      0 1200   100   150    50   100 1200
 900          0      0      0      0      0      0 1200   100   150    50   100 1200
1000          0      0      0      0      0      0 1200   100   150    50   100 1200
1100          0      0      0      0      0      0 1200   100   150    50   100 1200
1200          0      0      0      0      0      0 1200   100   150    50   100 1200
1300          0      0      0      0      0      0 1200   100   150    50   100 1200
1400          0      0      0      0      0      0 1200   100   150    50   100 1200
1500          0      0      0      0      0      0 1200   100   150    50   100 1200
1600          0      0      0      0      0      ^ 1200   100   150    50   100 1200
1700          0      0      0      0      0      0 1200   100   150    50   100 1200
1800          0      0      0      0      0      0 1200   100   150    50   100 1200
1900          0      0      0      0      0      0 1200   100   150    50   100 1200
```

INSOIL

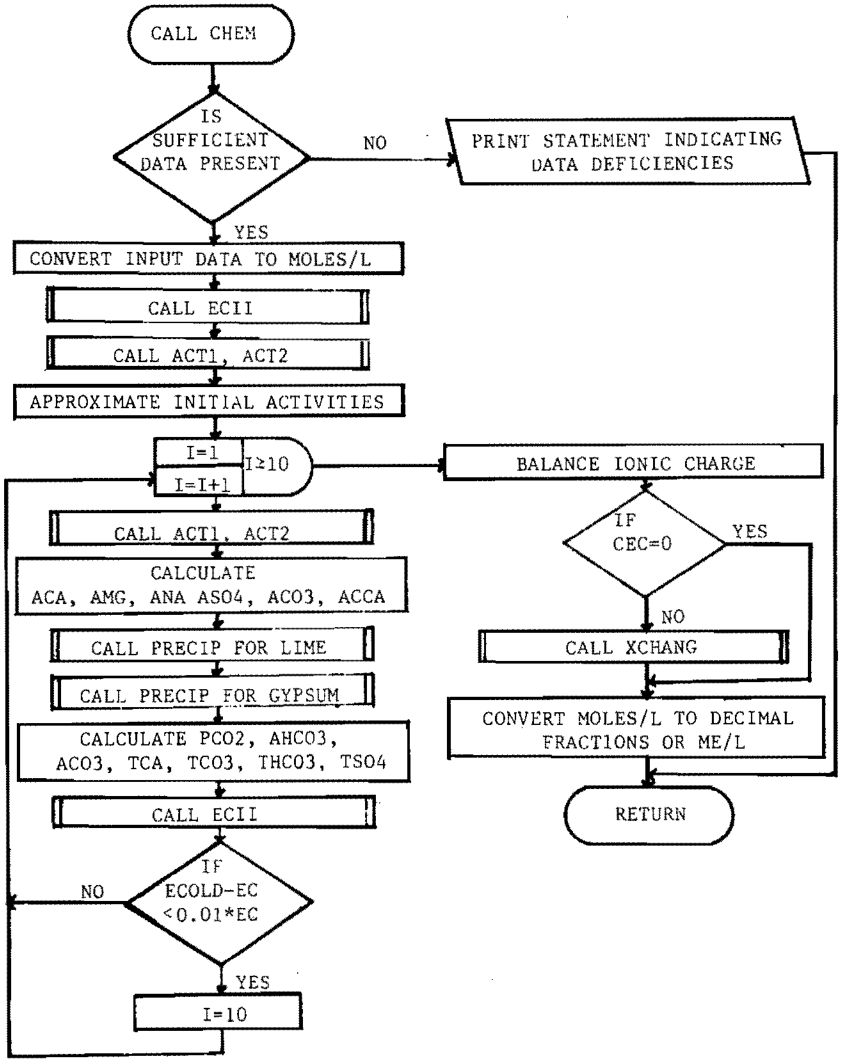
```
 100     SILTY CLAY LUAM NO GYPSUM
 200     13 13
 300      100  100  100  200   90   90 1490
 400        0  200  500 1000 1500 2000 3000 4000 5000 6000 7000 8000
 500     900015000
 600        0    2    5   10   15   18   20   20    5    3    2    0
 700        0    0
 800        0   30   30   30   30   30   30   30   30   30   30   30
 900       30   39
1000        0    0    0    0    0    0    0    0    0    0
1100        0   11  680  120 2200 1700  800  270 1800 1500
1200        0   11  680  120 2200 1700  800  270 1800 1500
1300        0   11  680  120 2200 1700  800  270 1800 1500
1400        0   11  680  120 2200 1700  800  270 1800 1500
1500        0   11  680  120 2200 1700  800  270 1800 1500
1600        0   11  680  120 2200 1700  800  270 1800 1500
1700        0   11  680  120 2200 1700  800  270 1800 1500
1800        0   11  680  120 2200 1700  800  270 1800 1500
1900        0   11  680  120 2200 1700  800  270 1800 1500
2000        0   11  680  120 2200 1700  800  270 1800 1500
2100        0   11  680  120 2200 1700  800  270 1800 1500
2200        0   11  680  120 2200 1700  800  270 1800 1500
2300        0   11  680  120 2200 1700  800  270 1800 1500
```

MATRIX

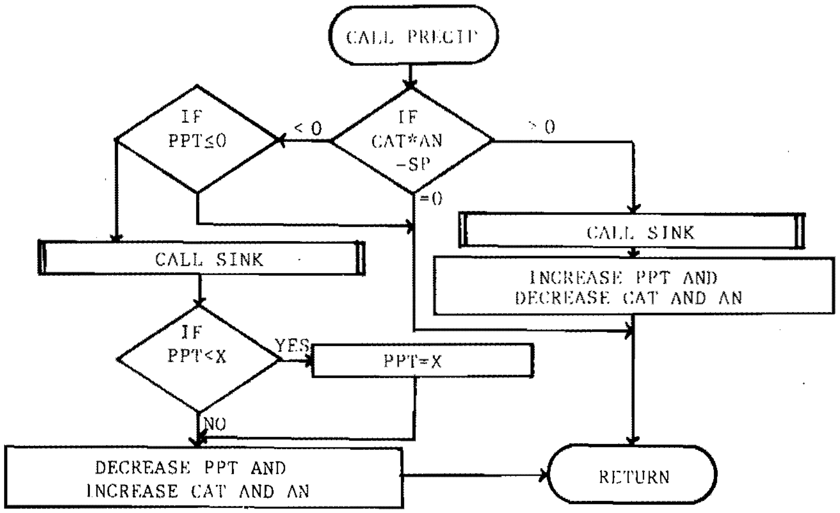
```
 100     SILTY CLAY LOAM MATRIX
 200     56
 300      .5400E+00 -.7420E+05
 400    -.2500E+06-.1219E+06-.9540E+05-.7420E+05-.5830E+05-.4770E+05-.3922E+05
 500    -.3180E+05-.2544E+05-.2014E+05-.1696E+05-.1325E+05-.9540E+04-.5830E+04
 600    -.4770E+04-.3710E+04-.2650E+04-.1590E+04-.7261E+03-.4982E+03-.4028E+03
 700    -.3498E+03-.3095E+03-.2786E+03-.2523E+03-.2311E+03-.2120E+03-.1950E+03
 800    -.1802E+03-.1666E+03-.1544E+03-.1431E+03-.1326E+03-.1230E+03-.1138E+03
 900    -.1053E+03-.9667E+02-.8966E+02-.8247E+02-.7558E+02-.6911E+02-.6286E+02
1000    -.5682E+02-.5109E+02-.4558E+02-.4028E+02-.3519E+02-.3032E+02-.2555E+02
1100    -.2068E+02-.1654E+02-.1219E+02-.7950E+01-.3922E+010,           .1000E+07
1200     .6000E-12 .4223E-10 .2314E-09 .7661E-09 .2012E-08 .4587E-08 .9475E-08
1300     .1829E-07 .3376E-07 .6066E-07 .1061E-06 .1822E-06 .3157E-06 .5879E-06
1400     .1131E-05 .2143E-05 .4060E-05 .8275E-05 .2233E-04 .6345E-04 .1551E-03
1500     .3239E-03 .6010E-03 .1024E-02 .1636E-02 .2492E-02 .3652E-02 .5192E-02
1600     .7199E-02 .9774E-02 .1304E-01 .1714E-01 .2225E-01 .2856E-01 .3632E-01
1700     .4581E-01 .5740E-01 .7150E-01 .8863E-01 .1094E+00 .1346E+00 .1652E+00
1800     .2026E+00 .2483E+00 .3045E+00 .3742E+00 .4616E+00 .5727E+00 .7166E+00
1900     .9086E+00 .1175E+01 .1572E+01 .2250E+01 .3926E+01 .4000E+01 .4000E+01
```

APPENDIX C

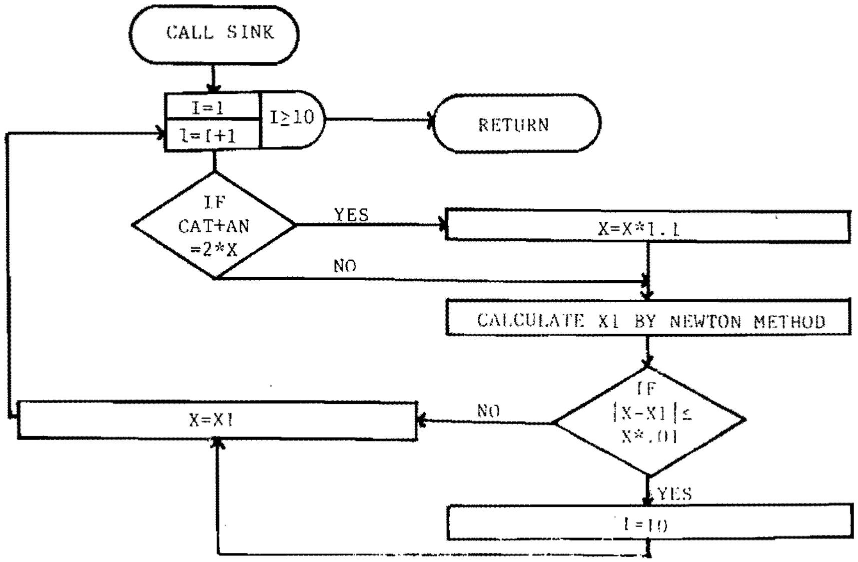
SUBROUTINE FLOW CHARTS

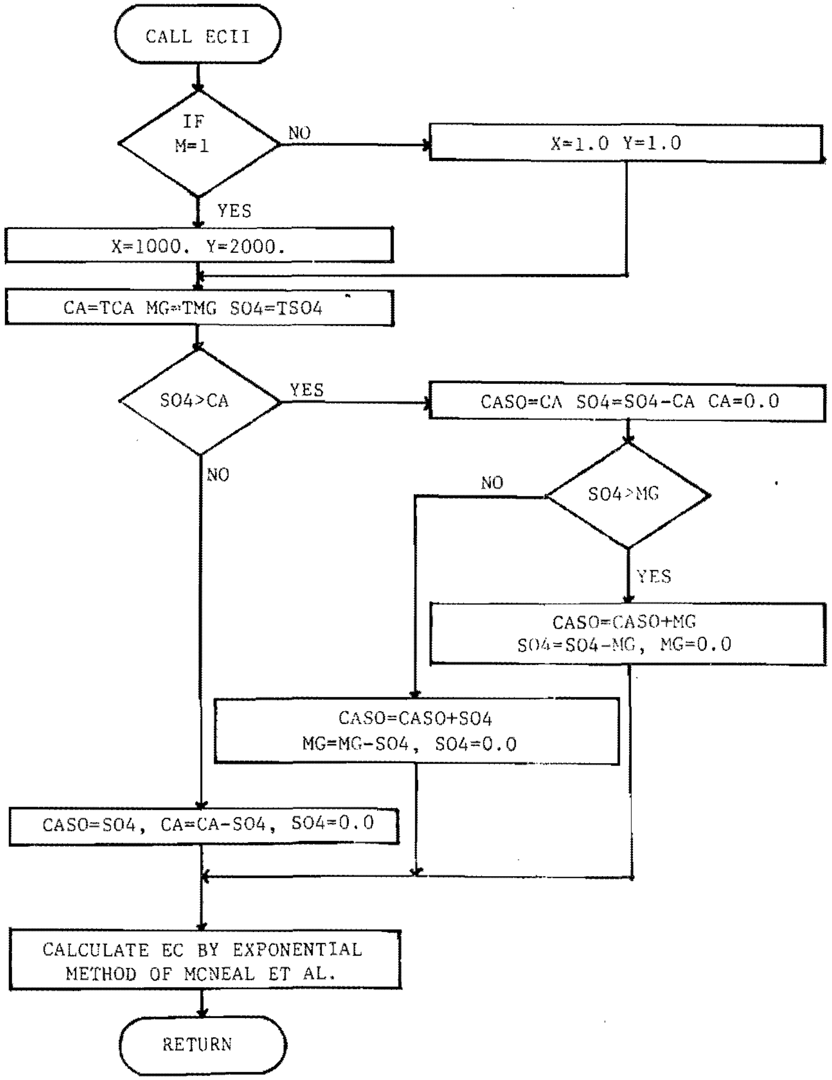


Subroutine PRECIP

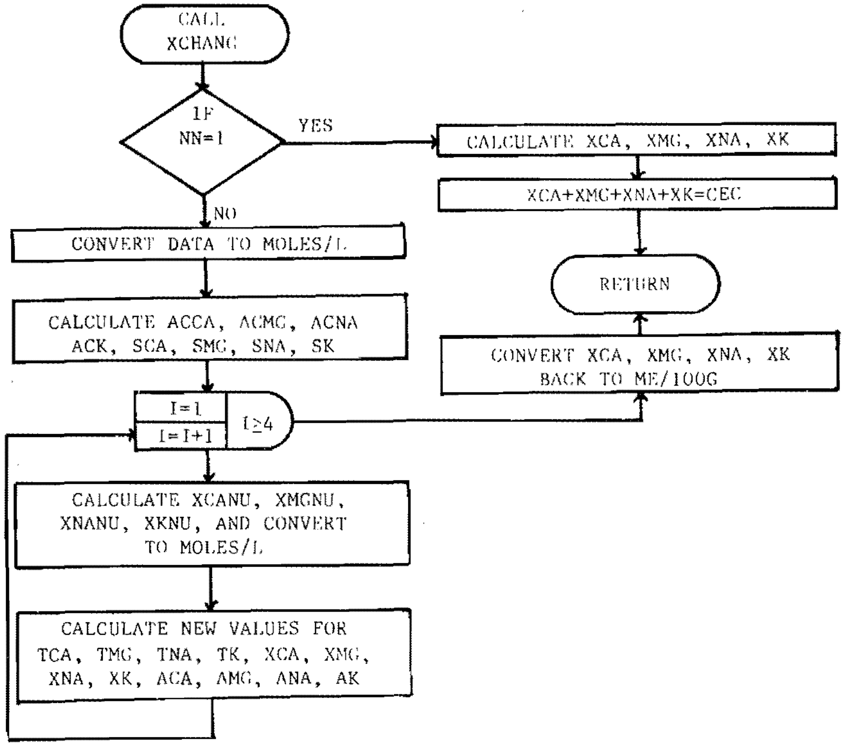


Subroutine SINK





Subroutine XCHANG



APPENDIX D

SAMPLE PRINTOUT OF SOIL PROFILE DATA

```
  CASO    CACU    PH    BD     CA     MG     NA     K      CL   TSO4  THCO3 TCO3   VH2O    EC    SAR    XCA    XMG    XNA     XK     DEPTH
0.000000.00110 6.80 1.20 20.05   4.61   1.96   1.38   1.50 12.00  9.33 0.029   0.43   1.89   0.56 9.2740 4.8328 0.0556 0.7377   0.-  2.
0.000000.00110 6.80 1.20 17.06   6.28   2.76   1.56   1.95 13.52 10.75 0.041   0.43   2.09   0.81 9.0119 5.0576 0.0727 0.7578   2.-  5.
0.000000.00110 6.80 1.20 19.27 10.80   4.48   2.06   2.82 21.64 11.96 0.064   0.42   2.79   1.16 8.6601 5.3353 0.0978 0.8068   5.- 10.
0.000000.00110 6.80 1.20 22.24 15.48   6.39   2.44   4.88 29.14 12.84 0.084   0.41   3.56   1.47 8.4031 5.5456 0.1221 0.6291  10.- 15.
0.000000.00110 6.80 1.20 26.42 20.80   9.17   2.88 16.90 29.34 12.66 0.099   0.39   4.85   1.89 8.2075 5.6919 0.1537 0.8469  15.- 20.
0.000000.00110 6.80 1.20 28.23 22.59 10.64   3.03 25.46 26.40 12.17 0.101   0.34   5.53   2.11 8.1726 5.7103 0.1697 0.8474  20.- 30.
0.000000.00110 6.80 1.20 29.19 23.44 11.20   3.10 29.19 25.44 11.88 0.101   0.27   5.85   2.18 8.1682 5.7104 0.1748 0.8466  30.- 40.
0.000000.00110 6.80 1.20 28.49 22.83 11.05   3.07 28.85 24.20 12.00 0.101   0.27   5.76   2.18 8.1775 5.7030 0.1740 0.8455  40.- 50.
0.000000.00110 6.80 1.20 28.43 22.79 11.04   3.07 28.85 24.08 12.01 0.101   0.28   5.75   2.18 8.1764 5.7034 0.1740 0.8462  50.- 60.
0.000000.00110 6.80 1.20 28.11 22.56 10.96   3.06 28.46 23.72 12.11 0.101   0.29   5.70   2.18 8.1737 5.7053 0.1735 0.8475  60.- 70.
0.000000.00110 6.80 1.20 20.86 16.25   7.98   2.62 18.37 15.31 13.63 0.097   0.30   4.29   1.85 8.2878 5.6431 0.1439 0.8253  70.- 80.
0.000000.00110 6.80 1.20 20.62 16.06   7.91   2.61 18.02 15.01 13.72 0.097   0.31   4.25   1.85 8.2887 5.6428 0.1432 0.8253  80.- 90.
0.000000.00110 6.80 1.20 20.58 16.06   7.90   2.61 18.00 15.00 13.75 0.098   0.39   4.24   1.85 8.2823 5.6486 0.1432 0.8259  90.-150.

 TOTAL WATER IN PROFILE= 28.83CM
```

APPENDIX E

INPUT DATA PREPARATION

A. Option Control Card in FORMAT (413)

Col.	Name	FORMAT	Description
1- 3	ITY	13	Program control option (1-6)
4- 6	IPL	13	Specification option subordinate to ITY (0-5)
4- 9	IPRT	13	Printing option subordinate to ITY, (0-2)
7-12	ICO	13	Line printer column width specification 1 = 80 column printer 1 = 132 column printer

B. Basic Data (Called with ITY = 1, IPL = 1)

Card	Col.	Name	FORMAT	Description
1	1- 3	NCROP	13	Number of crops
	4- 6	NPHRT	13	Number of phreatophytes
2	1-60	NDG$_j$	15A4	Headings for the column of the output tables
3- 8	1- 8	LABL$_i$	10A8	Sixty element vector of labels, each 8 characters long, for up to 60 lines of output from the model
9	3-10	DLAB	A8	Label for M & I consumptive use coefficients card
	11-15...	PKCMI$_i$	12F5.3	Twelve element vector of monthly M & I consumptive use coefficients
10	3-10	DLAB	A8	Label for proportion of daylight hours card
	11-15...	PDL$_1$	12F5.3	Twelve element vector of monthly proportion of daylight hours for the modified Blaney-Criddle Crop CU method
11	3-10	DLAB	A8	Label for B-C crop consumptive use coefficients
	11-15	CPKC$_{j,i}$	12F5.3	Twelve element vector of BC monthly CU coefficients for crop or phreatophyte$_j$

C. Subbasin Data Cards (Called with ITY = 1, IPL = 2 or 3)

Card	Col.	Name	FORMAT	Description
1	1- 2	ISB	12	Subbasin number (-9, 99)
	3- 7	IYRB	15	Beginning year of simulation
	8-12	NYR	15	Number of years of simulation
	21-80	BASID	15A4	Descriptive name of basin (less than 60 columns)
2	1- 4	KK	14	Number of soil layers for which there are data
	5- 8	NB	14	Number of soil layers considered in calculations
	9-12	NIONS	14	Number of ions to be considered
	13-16	NPOS	14	Number of soils to be considered
3	1-10	FREQ	E10.4	Days between irrigations
	11-20	APPL	E10.4	Maximum amount of water that can be applied to the soil before subroutine CHEM is called
	21-30	SAT	E10.4	Volumetric saturation water content of soil
	31-40	AIRDRY	E10.4	Airdry water content of soil
	41-50	FAC	E10.4	Fraction which represents water content at which ET becomes limiting
	51-60	DEPMAX	E10.4	Maximum rooting depth
4	1-30	PROP$_j$	E10.4	Portion of subbasin area which is soil type j
5	1-70	AK1$_i$	E10.4	Twelve element vector representing proportion of ET which is Transpiration
6	1-70	PTCA$_{j,i}$	(7E10.4)	Gypsum content of soil j in meq/l
7	1-70	RIONS$_{1,j,k}$	(7E10.4)	Ca++ concentration in jth soil type in meq/l
8	1-70	RIONS$_{2,j,i}$	(7E10.4)	Mg++ concentration in meq/l
9	1-70	RIONS$_{3,j,i}$	(7E10.4)	Na+ concentration in meq/l
10	1-70	RIONS$_{4,j,i}$	(7E10.4)	K+ concentration in meq/l
11	1-70	RIONS$_{5,j,i}$	(7E10.4)	CO3-- concentration in meq/l

C. Subbasin Data Cards (Continued)

Card	Col.	Name	FORMAT	Description
12	1-70	$RIONS_{6,j,i}$	(7E10.4)	HCO3- concentration in meq/l
13	1-70	$RIONS_{7,j,i}$	(7E10.4)	Cl- concentration in meq/l
14	1-70	$RIONS_{8,j,i}$	(7E10.4)	SO4-- concentration in meq/l
Repeat Cards 6-14 for NPOS soil types				
15...	1-70	Il_i DCA_i	(13F7.0)	Crop number and area for crop i. Can put up to 7 sets/card and requires a set for each crop and phreatophyte
16	11-20	URLND	F10.0	Urban land area
	21-30	UNDLND	F10.0	Undeveloped land area
		return if IPL = 5		
17	1-3	N_i	1513	Fifteen element vector of number of stations for each of 15 types of hydrologic data
18	1-40	FMT_1	10A4	Format for temperature data which follows
19	---	T	FMT_1	Monthly temperature data in °F (format specified by FMT_1)
20	1-40	FMT_2	10A4	Format for precipitation data in inches which follows
21	---	PPT	FMT_2	Monthly precipitation data
22	1-40	FMT_k	10A4	Format for kth data (k = 3 to 15)
23	1-40	FMT_{ks}	10A4	Format for salinity of water flows in meq/l (k = 3 to 10)
24	---	IX	FMT_k	Power of 10 by which all data on this card are multiplied
	---	DAT_k	FMT_k	Monthly values of kth hydrologic data in acre-feet. Do not include format or data card if N = 0
25	---	$AIO_{k,1,i}$	FMT_{ks}	Concentration of Ca++ in water of data k in meq/l for month i
26	---	$AIO_{k,2,i}$	FMT_{ks}	Concentration of Mg++ in water
27	---	$AIO_{k,3,i}$	FMT_{ks}	Concentration of Na+
28	---	$AIO_{k,4,i}$	FMT_{ks}	Concentration of K+
29	---	$AIO_{k,5,i}$	FMT_{ks}	Concentration of CO3--
30	---	$AIO_{k,6,i}$	FMT_{ks}	Concentration of HCO3-
31	---	$AIO_{k,7,k}$	FMT_{ks}	Concentration of Cl-
32	---	$AIO_{i,8,1}$	FMT_{ks}	Concentration of SO4--

Continue with format and data pairs for all data necessary. The data specified by k as follows: If N_k = 0, that format and data pair should not be included.

k = 3 is River inflow, RIV
= 4 is Tributary inflow, TRB
= 5 is Ungaged correlation inflow, QCOR
= 6 is Groundwater inflow, QGI
= 7 is Gaged outflow, GAG
= 8 is Pumped water from shallow aquifer, OPUM
= 9 is Reservoir release, REL
= 10 is Inbasin release, ARD
= 11 is Canal division, CNL
= 12 is M & I diversion, MIDIV
= 13 is Reservoir inflow, RIN
= 14 is Reservoir exports from the basin, REXP
= 15 is Basin export from the stream channel, BEXP

D. Reservoir Parameter Cards (Called with ITY = 1, IPL = 3 or 4). These Cards Are Not Included If IRES = 0, Which Indicates That There Is No Reservoir In the Subbasin.

Card	Col.	Name	FORMAT	Description
1- 2	11-20	RES_i	(10x7F10.0)	Fourteen element vector of reservoir parameters

Reservoir parameters are indexed as follows:

i = 1 STI initial storage in acre-feet
= 2 CSTI not used
= 3 STMN minimum usable storage
= 4 STMX maximum allowable storage
= 5 A_1 reservoir area at zero storage
= 6 C_1 coefficient in area vs. storage equation
= 7 C_2 exponent in area vs. storage equation
= 8 BPS break point storage value between equation defined by A_1, C_1 and C_2 and the one defined by A_2, C_3 and C_4

D. Reservoir Parameter Cards (Continued)

Card	Col.	Name	FORMAT	Description
				i = 9 A_2 reservoir area at zero storage for equation above BPS = 10 C_3 coefficient in area vs. storage equation = 11 C_4 exponent in area vs. storage equation = 12 DSPD change in gaged storage for the calibration period = 13-14 Not used

E. Parameter Specification Cards (Called when ITY = 2*)

Card	Col.	Name	FORMAT	Description
1	1- 3	NPR	13	Number of parameters (60)
	4- 6	MANG	13	Management option specification for canal diversions MANG = -1 Calibration mode - Use QCNL recorded but limit to water available for diversion, WAD = 0 Calibration mode - Use QCNL as recorded = 1 Management mode - Calculate QCNL and use without limit to satisfy PET = 2 Management mode - Calculate QCNL but limit to WAD = 3 Management mode - Calculate QCN but put leaching water to zero and limit QCNL to WAD
	7- 9	IRES	13	Reservoir option specification MANG = 0 No reservoir = 1 Tributary or upstream reservoir and requires reservoir inflow, RIN, to be read as input data = 2 Downstream reservoir - sets the reservoir inflow to the computed simulated surface runoff
	10-12	IQGO	13	Groundwater outflow limiting option: IQGO = 0 Limit routed groundwater outflow, QGO, to be nonnegative 1 Allow QGO to take on any value
	13-15	ITMX	13	Integration limit for calculating canal seepage
	16-25	TOLF	E10.3	Error criteria for indicating convergence in calculating canal seepage
	26-35	WH	E10.3	Multiplier for weighting the objective function calculations
2	3-10	$DLAB_1$	A8	Label for canal diversion option vector
	11-34	$IDTM_i$	1212	Vector of diversion option controls - one for each month If IDTM = 0 Do not allow diversion = 1 Allow diversion
3	3-10	$DLAB_2$	A8	Label for allowable soil moisture storage card
	11-70	CMS_i	12F5.3	Vector of soil moisture level. CMS, that must be maintained in calculating QCNL when in the management mode
4- 9	1-80	PR_i	(10F8.3)	The 60 element vector of model parameters (see Table 2)

If ITY = 5, enter here and read only the 6 parameter cards

F. Pattern Search Specification Cards (Called when ITY = 6)

Card	Col.	Name	FORMAT	Description
1	1- 3	NPS	13	Number of parameters to be searched or if NPS = 300 print the entire output table
	4- 6	NPH	13	Number of phases for pattern search (1-5)
	7-21	NOP_i	513	Vector of options for resetting the initial parameter vector at the completion of each phase If NOP_i = 0 Reset to the original initial parameter vector = 1 Reset to the best local minimized objective function parameter vector

F. Pattern Search Specification Cards (Continued)

Card	Col.	Name	FORMAT	Description
2	1- 4	L	14	Parameter number to be searched
(NPS+1)	4- 8	NLL	14	Number of steps in the search
	9-18	PLL	E10.5	Lower boundary for parameter L
	19-28	PHL	E10.5	Upper boundary for parameter L

Note: If NPS = 1 then will only read one type 2 card and return to read another type 1 card. If NPH is outside the range of (1-5), then will return to read a program option control card.

GLOSSARY OF PARAMETERS USED IN CALIBRATION

Par	Name	Description	Units
1	SNI	Initial snow storage	Inches
2	SNK	Snowmelt rate coefficient	
3	TSM	Threshold temperature at which snow melts	Deg F
4	TPR	Threshold temperature above which precipitation is rain	Deg F
5	COR	Ungaged flow correlation with correlating stream	Ac-ft/ac-ft
6	CSN	Ungaged flow correlation with snow melt	Ac-ft/in
7	CRN	Ungaged flow correlation with precipitation as rain	Ac-ft/in
8	RTH	Runoff threshold for ungaged flow from rain	Inches
9	CTP	Ungaged flow correlation with total precipitation	Ac-ft/inch
10	PTH	Runoff threshold for ungaged flow from total precipitation	Inches
11	SMI	Initial soil moisture level	Inches
12	CSM	Critical soil moisture to limit evapotranspiration	Inches
13	SMC	Soil moisture holding capacity	Inches
14	DTA	Delay time for routing DP	Months
15	SMSTRC	Factor limiting ET when soil moisture is critical	
16	CONCL	Percent salt contribution from natural sources to canal DP	
17	CDP	Proportion of soil moisture above CSM that goes to DP	
18	PSP	Proportion of spills from canal diversions	
19	ECV	Canal conveyance efficiency	
20	EAP	Irrigation application efficiency	
21	CNI	Initial rate for routing canal seepage to GW	Ac-ft/month
22	CNK	Canal seepage rate routing coefficient	
23	CRT	Proportion of canal seepage that returns to stream	
24	C1	Influent flow coefficient for QRIV = 1	Ac-ft/month
25	C2	Influent flow coefficient	
26	C3	Influent flow limiting value of C1 - C2 Log_{10} (QRIV)	
27	GWI	Initial rate of groundwater outflow	Ac-ft/month
28	DLY	Groundwater routing rate coefficient	
29	CGO	Proportion of GW outflow from basin	
30	TAJ	Adjusting coefficient on temperature	
31	PAJ	Adjusting coefficient on precipitation	
32	CNA	Adjusting coefficient on canal diversions	
33	GWA	Adjusting coefficient on groundwater inflow	
34	DMIA	Adjusting coefficient for M & I diversions	
35	CUMI	Adjusting coefficient for M & I CU	
36	CUA	Adjusting coefficient for irrigated land CU	
37	BSF	Adjusting coefficient for phreatophyte ET	
38	CUPGW	Proportion of CU for phreatophytes from GW	
39	CUUR	Coefficient for CU on urban land	
40	CUUN	Coefficient for CU on undeveloped land	
41	PURGW	Proportion of urban undeveloped land runoff to GW	
42	SCNR	Ration of actual inbasin reservoir releases to canals	
43	STH	Snowmelt threshold for ungaged flow from snowmelt	Inches
44	PBST	Proportion of bank storage for reservoir operation	
45	CUT	Interchange coefficient for RIV	Ac-ft/month
46	QSN	Coefficient for salt contribution from natural sources to DP	
47	QRN	Coefficient for salt contribution from natural rain	QGJ
48	QUR Q	Coefficient for salt contribution from natural sources to urban DP and runoff	
49-60	AGW	Values of delayed GM - one for each month of delay up to 12	Ac-ft/month
61	ROV	Coefficient for salt to tailwater and spills	
62	RINT	Interchange coefficient for RIV	
63	EXIN	Interchange coefficient for RIV	
64	CNBC	Proportion of canal spills that are recycled	
65-72		Initial salinity of groundwater outflow	
73-80	QGC	Initial salinity of canal groundwater outflow	

APPENDIX F

LEACHING FRACTION EFFECTS FOR TYPICAL SOILS AND WATERS IN THE COLORADO RIVER BASIN

The following waters were low in all ions and are represented by a single graph in Figure 26. Typical water analyses for different leaching fractions are shown in the tables.

Ashley Creek at "Sign of the Main" (Utah)
Cammoron Creek at USGS gage, Cammoron (Colorado)
East Fork Smiths Fork 7 miles below China Meadows Dam (Wyoming)
Blacks Fork 2 miles below Meeks Cabin Dam (Wyoming)
Uinta River near Neola, Utah
Yellowstone Creek near Altonah, Utah
Lake Fork River near "C" canal diversion (Utah)
Lake Fork River at Lake Fork Dam Site (Utah)
Green River near Fontenelle Dam Site (Wyoming)
Green River at Big Island Bridge (Wyoming)

WATER OF LOW CONCENTRATION OF ALL IONS IN MEQ/L GYPSUM PRESENT IN SOIL

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
DIS	PPT	7.80	0.04	0.93	27.89	0.66	0.16	0.03	27.95	0.02	0.045	1.97	0.91
PPT	PPT	7.80	0.06	0.94	27.94	0.90	0.22	0.04	28.15	0.03	0.046	2.00	0.67
PPT	PPT	7.80	0.08	0.95	27.68	1.20	0.30	0.06	28.60	0.04	0.047	2.02	0.50
PPT	PPT	7.80	0.10	0.95	27.93	1.50	0.37	0.07	28.57	0.05	0.047	2.05	0.40
PPT	PPT	7.80	0.12	0.96	27.66	1.80	0.45	0.09	28.99	0.06	0.049	2.06	0.33
PPT	PPT	7.80	0.14	0.97	27.36	2.10	0.52	0.10	29.46	0.07	0.050	2.07	0.29
PPT	PPT	7.80	0.15	0.98	27.68	2.40	0.60	0.12	29.52	0.08	0.050	2.12	0.25
PPT	PPT	7.80	0.17	0.98	27.33	2.70	0.67	0.13	29.94	0.09	0.051	2.11	0.22
PPT	PPT	7.80	0.19	0.99	27.33	3.00	0.75	0.15	30.22	0.10	0.052	2.16	0.20
PPT	PPT	7.80	0.28	1.03	26.81	4.50	1.12	0.22	31.71	0.15	0.056	2.25	0.13
PPT	PPT	7.80	0.37	1.08	26.36	6.00	1.50	0.30	33.36	0.20	0.060	2.38	0.10
PPT	PPT	7.80	0.70	1.23	25.20	12.00	3.00	0.60	39.36	0.40	0.078	2.82	0.05
IRR	WTR	--	--	1.56	1.00	0.60	0.15	0.03	0.20	0.02	0.00	0.40	

WATER OF LOW CONCENTRATION OF ALL IONS NO GYPSUM IN SOIL

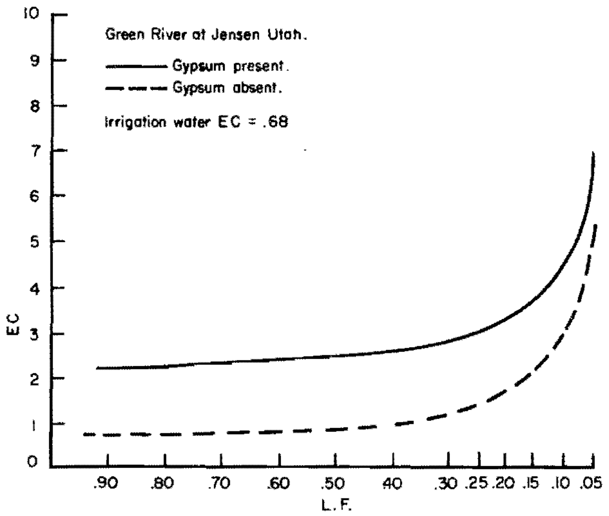
CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.11	3.89	3.47	0.66	0.16	0.03	0.22	0.02	0.055	0.43	0.91
EQU	PPT	7.80	0.16	3.98	2.91	0.90	0.22	0.04	0.30	0.03	0.107	0.43	0.67
EQU	PPT	7.80	0.21	4.22	2.77	1.20	0.30	0.06	0.40	0.04	0.108	0.44	0.50
EQU	PPT	7.80	0.26	4.37	2.73	1.50	0.37	0.07	0.50	0.05	0.111	0.46	0.40
EQU	PPT	7.80	0.30	4.53	2.68	1.80	0.45	0.09	0.60	0.06	0.118	0.49	0.33
EQU	PPT	7.80	0.34	4.69	2.63	2.10	0.52	0.10	0.70	0.07	0.126	0.51	0.29
EQU	PPT	7.80	0.38	4.86	2.58	2.40	0.60	0.12	0.80	0.08	0.134	0.54	0.25
EQU	PPT	7.80	0.42	5.04	2.52	2.70	0.67	0.13	0.90	0.09	0.143	0.57	0.22
EQU	PPT	7.80	0.45	5.23	2.47	3.00	0.75	0.15	1.00	0.10	0.153	0.59	0.20
EQU	PPT	7.80	0.62	6.75	2.01	4.50	1.12	0.22	1.50	0.15	0.250	0.71	0.13
EQU	PPT	7.80	0.75	7.35	1.97	6.00	1.50	0.30	2.00	0.20	0.286	0.84	0.10
EQU	PPT	7.80	1.17	13.32	1.24	12.00	3.00	0.60	4.00	0.40	0.790	1.25	0.05
IRR	WTR	--	--	1.56	1.00	0.60	0.15	0.03	0.20	0.02	0.00	0.00	

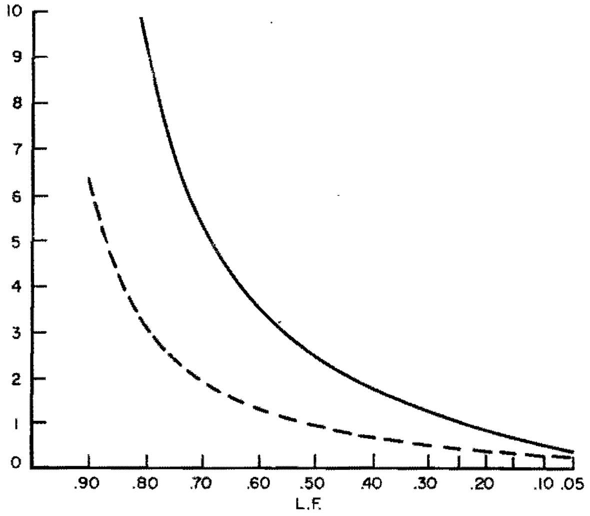
WATER FROM GREENRIVER AT JENSEN NO GYPSUM

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	1.28	4.13	3.42	1.94	2.09	0.06	2.50	0.50	0.095	0.70	0.90
EQU	PPT	7.80	1.43	4.43	3.18	2.18	2.34	0.06	2.80	0.56	0.121	0.74	0.80
EQU	PPT	7.80	1.59	4.54	3.19	2.49	2.67	0.07	3.20	0.64	0.125	0.78	0.70
EQU	PPT	7.80	1.79	4.68	3.20	2.92	3.13	0.08	3.75	0.75	0.136	0.85	0.60
EQU	PPT	7.80	2.07	5.02	3.11	3.50	3.76	0.10	4.50	0.90	0.155	0.95	0.50
EQU	PPT	7.80	2.43	5.30	3.13	4.39	4.72	0.13	5.65	1.13	0.176	1.09	0.40
EQU	PPT	7.80	2.99	6.14	2.93	5.83	6.27	0.17	7.50	1.50	0.227	1.31	0.30
EQU	PPT	7.80	3.38	6.62	2.91	7.00	7.52	0.20	9.00	1.80	0.251	1.49	0.25
EQU	PPT	7.80	3.91	7.41	2.80	8.75	9.40	0.25	11.25	2.25	0.308	1.75	0.20
EQU	PPT	7.80	4.68	8.60	2.69	11.67	12.53	0.33	15.00	3.00	0.403	2.16	0.15
EQU	PPT	7.80	5.96	11.41	2.39	17.50	18.80	0.50	22.50	4.50	0.638	2.99	0.10
EQU	PPT	7.80	8.76	20.18	1.86	35.00	37.60	1.00	45.00	9.00	1.540	5.37	0.05
IRR	WTR	--	--	3.25	2.28	1.75	1.88	0.05	2.25	0.45	0.00	0.68	

WATER FROM GREENRIVER AT JENSEN GYPSUM PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
PPT	PPT	7.80	0.54	0.97	27.65	1.94	2.09	0.06	29.64	0.50	0.049	2.18	0.90
PPT	PPT	7.80	0.61	0.99	27.47	2.18	2.34	0.06	30.24	0.56	0.050	2.24	0.80
PPT	PPT	7.80	0.69	1.01	27.20	2.49	2.67	0.07	30.86	0.64	0.051	2.30	0.70
PPT	PPT	7.80	0.81	1.04	26.92	2.92	3.13	0.08	31.71	0.75	0.053	2.38	0.60
PPT	PPT	7.80	0.97	1.06	26.86	3.50	3.76	0.10	32.49	0.90	0.054	2.48	0.50
PPT	PPT	7.80	1.20	1.10	26.43	4.39	4.72	0.13	33.92	1.13	0.057	2.60	0.40
PPT	PPT	7.80	1.57	1.17	25.93	5.83	6.27	0.17	36.22	1.50	0.062	2.82	0.30
PPT	PPT	7.80	1.85	1.20	26.06	7.00	7.52	0.20	37.49	1.80	0.064	3.01	0.25
PPT	PPT	7.80	2.27	1.26	25.48	8.75	9.40	0.25	40.03	2.25	0.071	3.22	0.20
PPT	PPT	7.80	2.93	1.37	24.82	11.67	12.53	0.33	44.29	3.00	0.081	3.64	0.15
PPT	PPT	7.80	4.16	1.60	23.43	17.50	18.80	0.50	53.84	4.50	0.103	4.45	0.10
PPT	PPT	7.80	7.08	2.24	21.37	35.00	37.60	1.00	82.66	9.00	0.173	6.93	0.05
IRR	WTR	--	--	3.28	2.28	1.75	1.88	0.05	2.25	0.45	0.00	0.68	



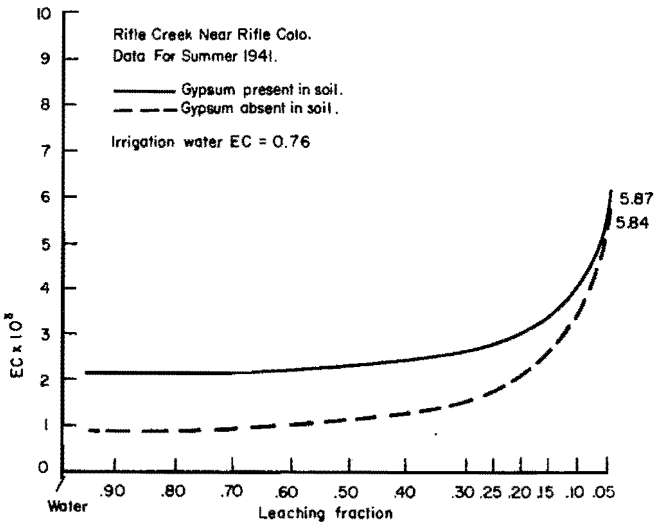


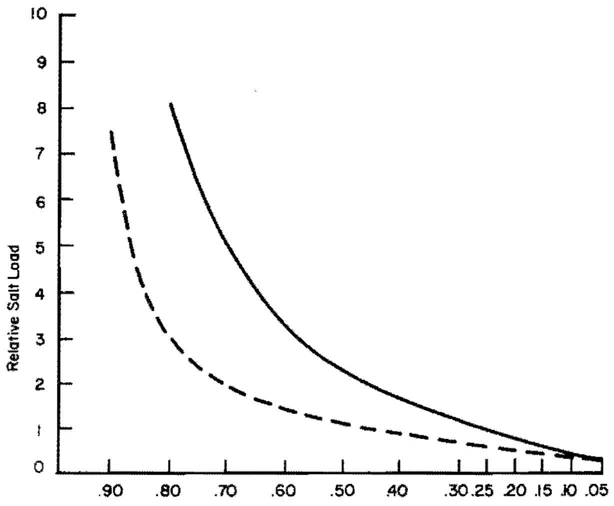
WATER FROM RIFLE CREEK RIFLE, COLO. SUMMER 1941 GYP PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC$_{dw}$	Net Salt
DIS	PPT	7.80	0.23	0.97	27.45	2.94	0.88	0.06	29.94	0.20	0.052	2.17	0.90
PPT	PPT	7.80	0.26	1.00	27.15	3.39	1.01	0.06	30.52	0.23	0.053	2.16	0.78
PPT	PPT	7.80	0.29	1.01	27.19	3.83	1.14	0.07	30.97	0.26	0.054	2.22	0.69
PPT	PPT	7.80	0.33	1.03	26.81	4.42	1.32	0.08	31.70	0.30	0.056	2.26	0.60
PPT	PPT	7.80	0.39	1.06	26.74	5.30	1.58	0.10	32.52	0.36	0.058	2.35	0.50
PPT	PPT	7.80	0.49	1.09	26.28	6.63	1.98	0.12	33.96	0.45	0.062	2.44	0.40
PPT	PPT	7.80	0.63	1.15	26.01	8.83	2.63	0.17	35.98	0.60	0.068	2.62	0.30
PPT	PPT	7.80	0.74	1.20	25.57	10.60	3.16	0.20	37.92	0.72	0.073	2.74	0.25
PPT	PPT	7.80	0.90	1.27	25.05	13.25	3.95	0.25	40.80	0.90	0.081	2.95	0.20
PPT	PPT	7.80	1.15	1.38	24.37	17.67	5.27	0.33	45.48	1.20	0.095	3.30	0.15
PPT	PPT	7.80	1.58	1.60	23.37	26.50	7.90	0.50	54.71	1.80	0.124	3.96	0.10
PPT	PPT	7.80	2.60	2.22	21.13	53.00	15.80	1.00	84.03	3.60	0.221	5.87	0.05
IRR	WTR	--	--	3.92	4.84	2.65	0.79	0.05	4.23	0.18	0.00	0.76	

WATER FROM RIFLE CREEK RIFLE, COLO. SUMMER 1941 GYP ABSENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC$_{dw}$	Net Salt
EQU	PPT	7.80	0.46	3.38	4.42	2.94	0.88	0.06	4.70	0.20	0.111	0.78	0.90
EQU	PPT	7.80	0.51	3.35	4.60	3.39	1.01	0.06	5.40	0.23	0.111	0.81	0.78
EQU	PPT	7.80	0.55	3.33	4.77	3.83	1.14	0.07	6.11	0.26	0.114	0.87	0.69
EQU	PPT	7.80	0.61	3.30	5.01	4.42	1.32	0.08	7.05	0.30	0.120	0.94	0.60
EQU	PPT	7.80	0.69	3.31	5.26	5.30	1.58	0.10	8.46	0.36	0.129	1.06	0.50
EQU	PPT	7.80	0.79	3.23	5.79	6.63	1.98	0.12	10.57	0.45	0.138	1.21	0.40
EQU	PPT	7.80	0.95	3.15	6.54	8.83	2.63	0.17	14.10	0.60	0.152	1.47	0.30
EQU	PPT	7.80	1.06	3.10	7.12	10.60	3.16	0.20	16.92	0.72	0.158	1.65	0.25
EQU	PPT	7.80	1.21	3.02	7.97	13.25	3.95	0.25	21.15	0.90	0.170	1.93	0.20
EQU	PPT	7.80	1.43	2.89	9.44	17.67	5.27	0.33	28.20	1.20	0.183	2.37	0.15
EQU	PPT	7.80	1.79	2.65	12.46	26.50	7.90	0.50	42.30	1.80	0.200	3.33	0.10
EQU	PPT	7.80	2.61	2.27	20.54	53.00	15.80	1.00	83.37	3.60	0.227	5.84	0.05
IRR	WTR	--	--	3.92	4.84	2.65	0.79	0.05	4.23	0.18	0.00	0.76	



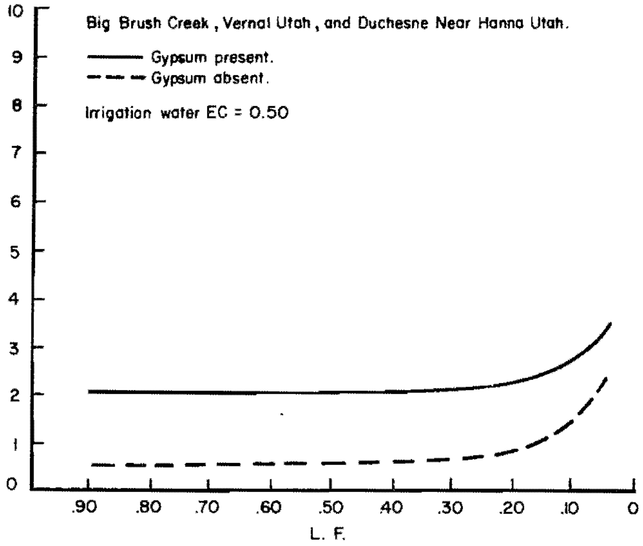


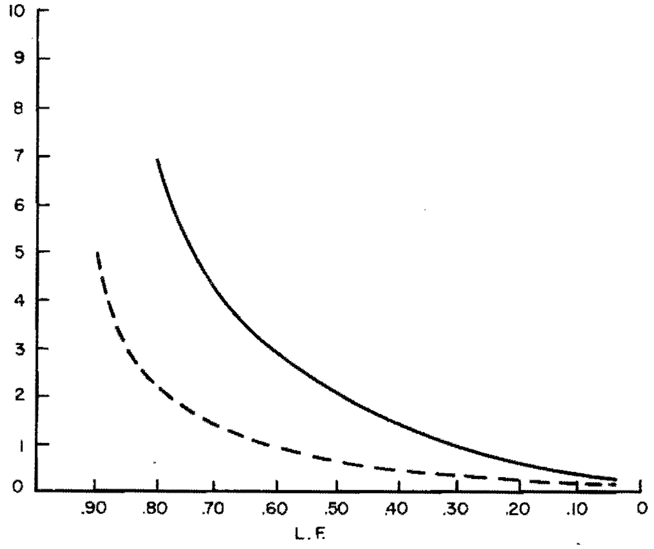
WATER FROM BIG BRUSH CREEK & DUCHESNE-HANNA GYPSUM PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
PPT	PPT	7.80	0.05	0.94	27.93	1.38	0.20	0.02	28.53	0.11	0.048	2.04	0.91
PPT	PPT	7.80	0.06	0.96	27.61	1.63	0.23	0.03	28.89	0.13	0.048	2.04	0.77
PPT	PPT	7.80	0.07	0.95	27.86	1.88	0.27	0.03	28.79	0.15	0.048	2.06	0.67
PPT	PPT	7.80	0.08	0.96	27.60	2.13	0.31	0.03	29.20	0.17	0.049	2.07	0.59
PPT	PPT	7.80	0.09	0.97	27.56	2.50	0.36	0.04	29.42	0.20	0.050	2.09	0.50
PPT	PPT	7.80	0.12	0.99	27.26	3.13	0.45	0.05	30.14	0.25	0.052	2.13	0.40
PPT	PPT	7.80	0.15	1.00	27.42	4.13	0.59	0.07	30.62	0.33	0.054	2.20	0.30
PPT	PPT	7.80	0.18	1.02	27.09	5.00	0.72	0.08	31.47	0.40	0.057	2.25	0.25
PPT	PPT	7.80	0.22	1.05	26.71	6.25	0.90	0.10	32.66	0.50	0.060	2.32	0.20
PPT	PPT	7.80	0.29	1.10	26.23	8.38	1.21	0.13	34.59	0.67	0.066	2.44	0.15
PPT	PPT	7.80	0.41	1.19	25.56	12.50	1.80	0.20	38.25	1.00	0.078	2.71	0.10
PPT	PPT	7.80	0.73	1.44	24.23	25.00	3.60	0.40	48.93	2.00	0.115	3.47	0.05
IRR	WTR	--	--	2.45	2.10	1.25	0.18	0.02	1.00	0.10	0.00	0.50	

WATER FROM BIG BRUSH CREEK & DUCHESNE-HANNA NO GYPSUM

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.12	3.30	3.82	1.38	0.20	0.02	1.10	0.11	0.069	0.50	0.91
EQU	PPT	7.80	0.15	3.81	3.28	1.63	0.23	0.03	1.30	0.13	0.108	0.53	0.77
EQU	PPT	7.80	0.16	3.75	3.37	1.75	0.25	0.03	1.40	0.14	0.097	0.52	0.71
EQU	PPT	7.80	0.19	3.91	3.30	2.13	0.31	0.03	1.70	0.17	0.113	0.57	0.59
EQU	PPT	7.80	0.21	3.98	3.32	2.50	0.36	0.04	2.00	0.20	0.117	0.60	0.50
EQU	PPT	7.80	0.25	4.25	3.22	3.13	0.45	0.05	2.50	0.25	0.137	0.66	0.40
EQU	PPT	7.80	0.31	4.37	3.29	4.13	0.59	0.07	3.30	0.33	0.155	0.75	0.30
EQU	PPT	7.80	0.35	4.53	3.31	5.00	0.72	0.08	4.00	0.40	0.169	0.82	0.25
EQU	PPT	7.80	0.41	4.89	3.23	6.25	0.90	0.10	5.00	0.50	0.200	0.93	0.20
EQU	PPT	7.80	0.50	5.38	3.17	8.38	1.21	0.13	6.70	0.67	0.251	1.11	0.15
EQU	PPT	7.80	0.65	6.38	3.02	12.50	1.80	0.20	10.00	1.00	0.358	1.45	0.10
EQU	PPT	7.80	0.97	8.94	2.78	25.00	3.60	0.40	20.00	2.00	0.705	2.40	0.05
IRR	WTR	--	--	2.45	2.10	1.25	0.18	0.02	1.00	0.10	0.00	0.50	



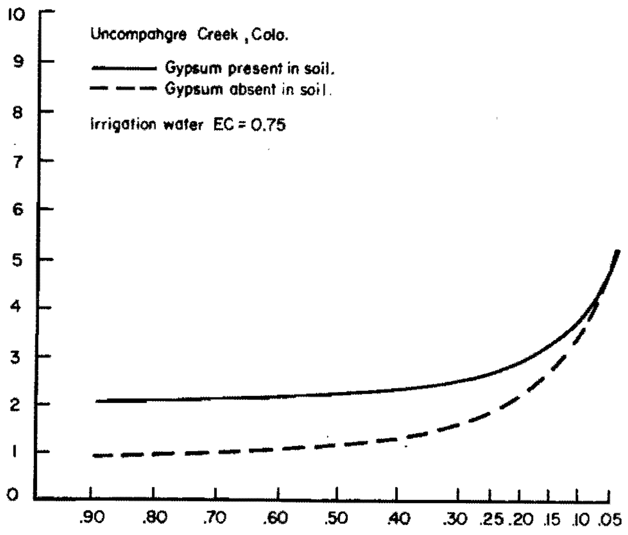


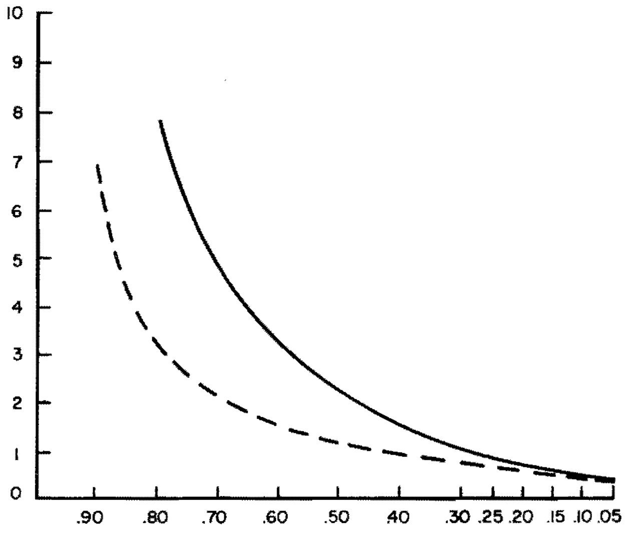
WATER FROM UNCOMPAHGRE CREEK COLO 1958-63   GYP PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
PPT	PPT	7.80	0.35	0.96	27.57	1.46	1.33	0.07	29.15	0.20	0.048	2.10	0.90
PPT	PPT	7.80	0.40	0.98	27.36	1.67	1.53	0.08	29.73	0.23	0.049	2.15	0.78
PPT	PPT	7.80	0.45	0.99	27.41	1.89	1.73	0.09	30.06	0.26	0.049	2.20	0.69
PPT	PPT	7.80	0.52	1.00	27.32	2.18	2.00	0.10	30.34	0.30	0.050	2.23	0.60
PPT	PPT	7.80	0.62	1.02	26.97	2.62	2.40	0.12	31.11	0.36	0.052	2.29	0.50
PPT	PPT	7.80	0.77	1.05	26.88	3.28	3.00	0.15	31.96	0.45	0.053	2.39	0.40
PPT	PPT	7.80	1.02	1.09	26.38	4.37	4.00	0.20	33.59	0.60	0.057	2.52	0.30
PPT	PPT	7.80	1.21	1.14	26.04	5.24	4.80	0.24	35.11	0.72	0.060	2.65	0.25
PPT	PPT	7.80	1.49	1.19	25.76	6.55	6.00	0.30	36.83	0.90	0.063	2.83	0.20
PPT	PPT	7.80	1.95	1.27	25.08	8.73	8.00	0.40	40.05	1.20	0.071	3.10	0.15
PPT	PPT	7.80	2.78	1.44	24.14	13.10	12.00	0.60	46.51	1.80	0.086	3.67	0.10
PPT	PPT	7.80	4.89	1.93	21.91	26.20	24.00	1.20	67.27	3.60	0.137	5.32	0.05
IRR	WTR	--	--	2.03	5.12	1.31	1.20	0.06	5.48	0.18	0.00	0.75	

WATER FROM UNCOMAHGRE CREEK COLO 1958-63   GYP ABSENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.69	2.56	6.06	1.46	1.33	0.07	6.09	0.20	0.069	0.77	0.90
EQU	PPT	7.80	0.76	2.46	6.55	1.67	1.53	0.08	7.00	0.23	0.074	0.86	0.78
EQU	PPT	7.80	0.82	2.38	7.01	1.89	1.73	0.09	7.92	0.26	0.074	0.92	0.69
EQU	PPT	7.80	0.91	2.31	7.53	2.18	2.00	0.10	9.13	0.30	0.076	1.01	0.60
EQU	PPT	7.80	1.02	2.18	8.47	2.62	2.40	0.12	10.96	0.36	0.076	1.13	0.50
EQU	PPT	7.80	1.17	2.01	9.90	3.28	3.00	0.15	13.70	0.45	0.076	1.31	0.40
EQU	PPT	7.80	1.38	1.81	12.35	4.37	4.00	0.20	18.27	0.60	0.077	1.64	0.30
EQU	PPT	7.80	1.54	1.69	14.25	5.24	4.80	0.24	21.92	0.72	0.076	1.91	0.25
EQU	PPT	7.80	1.73	1.52	17.60	6.55	6.00	0.30	27.40	0.90	0.074	2.29	0.20
EQU	PPT	7.80	2.03	1.36	22.40	8.73	8.00	0.40	36.53	1.20	0.075	2.91	0.15
PPT	PPT	7.80	2.78	1.42	24.17	13.10	12.00	0.60	46.10	1.80	0.086	3.63	0.10
PPT	PPT	7.80	4.90	1.92	21.80	26.20	24.00	1.20	67.26	3.60	0.137	5.28	0.05
IRR	WTR	--	--	2.03	5.12	1.31	1.20	0.06	5.48	0.18	0.00	0.75	



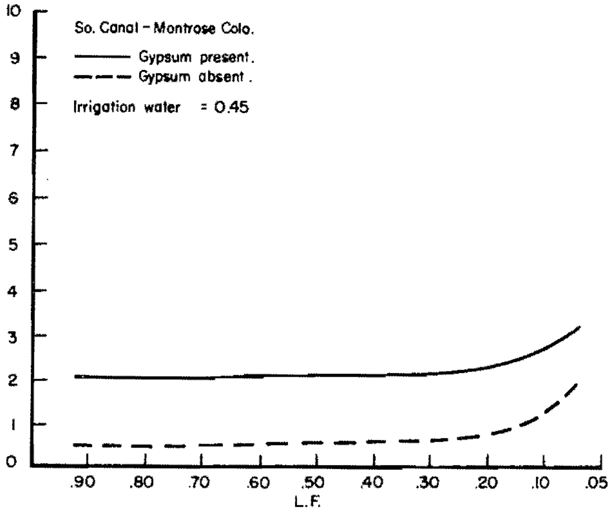


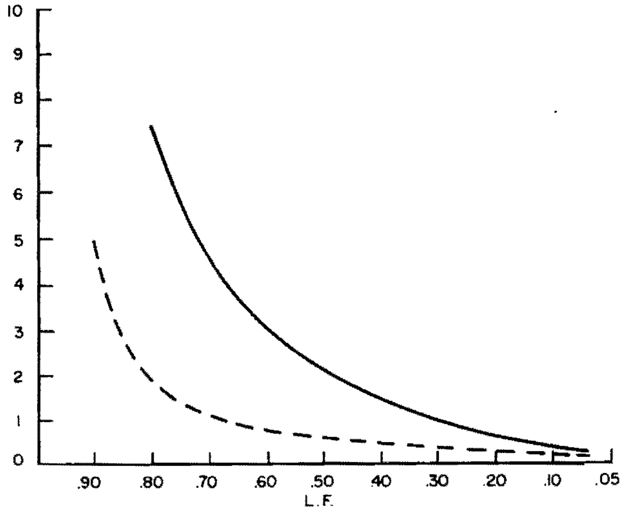
WATER FROM SO. CANAL MONTROSE COLO. GYPSUM PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC$_{dw}$	Net Salt
DIS	PPT	7.80	0.09	0.93	28.18	0.57	0.33	0.06	27.79	0.11	0.045	2.00	0.91
PPT	PPT	7.80	0.10	0.93	27.99	0.68	0.39	0.06	28.11	0.13	0.046	2.02	0.77
PPT	PPT	7.80	0.12	0.94	27.71	0.78	0.45	0.07	28.42	0.15	0.046	2.01	0.67
PPT	PPT	7.80	0.13	0.94	28.06	0.88	0.51	0.08	28.33	0.17	0.046	2.05	0.59
PPT	PPT	7.80	0.16	0.95	27.72	1.04	0.60	0.10	28.61	0.20	0.047	2.04	0.50
PPT	PPT	7.80	0.20	0.96	27.74	1.30	0.75	0.12	28.90	0.25	0.047	2.09	0.40
PPT	PPT	7.80	0.26	0.97	27.69	1.72	0.99	0.16	29.27	0.33	0.048	2.13	0.30
PPT	PPT	7.80	0.31	0.98	27.39	2.08	1.20	0.20	29.86	0.40	0.050	2.16	0.25
PPT	PPT	7.80	0.39	1.00	27.36	2.60	1.50	0.25	30.44	0.50	0.051	2.24	0.20
PPT	PPT	7.80	0.52	1.03	26.96	3.48	2.01	0.33	31.61	0.67	0.054	2.33	0.15
PPT	PPT	7.80	0.75	1.09	26.70	5.20	3.00	0.50	33.50	1.00	0.058	2.54	0.10
PPT	PPT	7.80	1.41	1.23	25.65	10.40	6.00	1.00	39.41	2.00	0.074	3.09	0.05
IRR	WTR	--	--	1.47	1.34	0.52	0.30	0.05	0.64	0.10	0.00	0.45	

WATER FROM SO. CANAL MONTROSE COLO. NO GYPSUM

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC$_{dw}$	Net Salt
EQU	PPT	7.80	0.22	3.45	3.77	0.57	0.33	0.06	0.70	0.11	0.051	0.46	0.91
EQU	PPT	7.80	0.28	3.71	3.23	0.68	0.39	0.06	0.83	0.13	0.091	0.46	0.77
EQU	PPT	7.80	0.29	3.52	3.42	0.73	0.42	0.07	0.90	0.14	0.077	0.46	0.71
EQU	PPT	7.80	0.35	3.73	3.29	0.88	0.51	0.08	1.09	0.17	0.090	0.49	0.59
EQU	PPT	7.80	0.41	3.73	3.34	1.04	0.60	0.10	1.28	0.20	0.089	0.51	0.50
EQU	PPT	7.80	0.49	3.77	3.39	1.30	0.75	0.12	1.60	0.25	0.097	0.56	0.40
EQU	PPT	7.80	0.61	3.79	3.51	1.72	0.99	0.17	2.11	0.33	0.105	0.63	0.30
EQU	PPT	7.80	0.73	4.06	3.38	2.08	1.20	0.20	2.56	0.40	0.114	0.68	0.25
EQU	PPT	7.80	0.86	4.13	3.46	2.60	1.50	0.25	3.20	0.50	0.122	0.75	0.20
EQU	PPT	7.80	1.08	4.41	3.44	3.48	2.01	0.34	4.29	0.67	0.145	0.87	0.15
EQU	PPT	7.80	1.44	4.75	3.53	5.20	3.00	0.50	6.40	1.00	0.181	1.11	0.10
EQU	PPT	7.80	2.28	6.04	3.46	10.40	6.00	1.00	12.80	2.00	0.311	1.79	0.05
IRR	WTR	--	--	1.47	1.34	0.52	0.30	0.05	0.64	0.10	0.00	0.45	



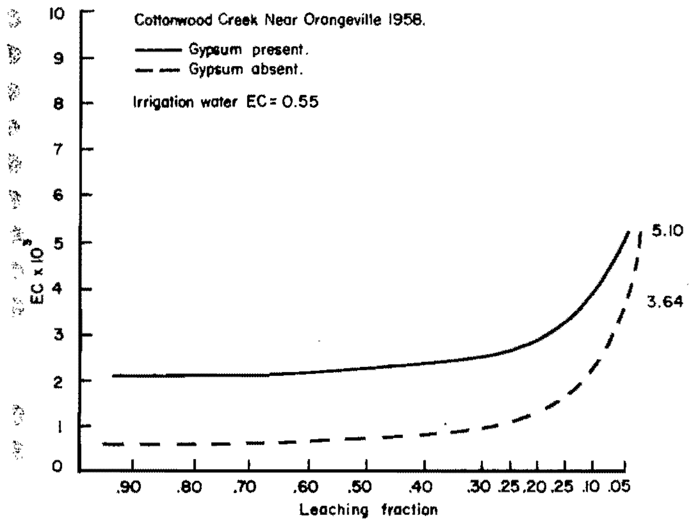


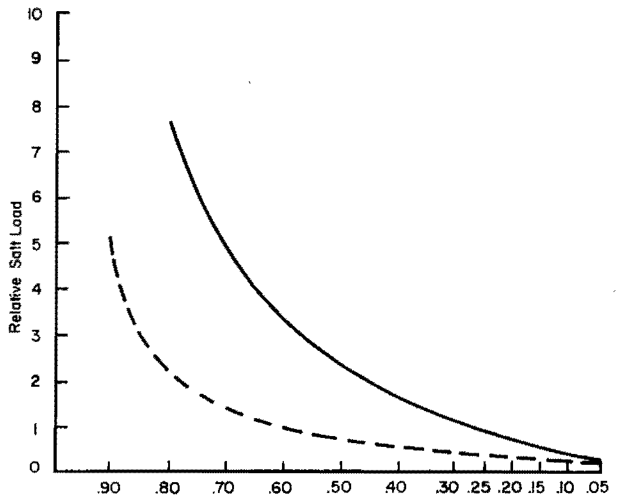
WATER FROM COTTON CREEK NEAR ORANGEVILLE 1958   GYP PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
DIS	PPT	7.80	0.20	0.96	27.68	2.33	0.77	0.03	29.50	0.20	0.051	2.13	0.90
PPT	PPT	7.80	0.23	0.98	27.31	2.68	0.88	0.04	29.94	0.23	0.051	2.12	0.78
PPT	PPT	7.80	0.26	1.00	27.36	3.03	1.00	0.04	30.31	0.26	0.052	2.18	0.69
PPT	PPT	7.80	0.29	1.01	26.99	3.50	1.15	0.05	30.94	0.30	0.053	2.21	0.60
PPT	PPT	7.80	0.35	1.02	27.20	4.20	1.38	0.06	31.30	0.36	0.054	2.28	0.50
PPT	PPT	7.80	0.43	1.05	26.75	5.25	1.73	0.07	32.36	0.45	0.058	2.32	0.40
PPT	PPT	7.80	0.56	1.10	26.32	7.00	2.30	0.10	34.21	0.60	0.063	2.47	0.30
PPT	PPT	7.80	0.67	1.14	25.97	8.40	2.76	0.12	35.88	0.72	0.067	2.60	0.25
PPT	PPT	7.80	0.81	1.19	25.71	10.50	3.45	0.15	37.80	0.90	0.073	2.78	0.20
PPT	PPT	7.80	1.04	1.28	25.04	14.00	4.60	0.20	41.35	1.20	0.084	3.03	0.15
PPT	PPT	7.80	1.45	1.44	24.16	21.00	6.90	0.30	48.40	1.80	0.105	3.56	0.10
PPT	PPT	7.80	2.45	1.96	21.70	42.00	13.80	0.60	71.96	3.60	0.181	5.10	0.05
IRR	WTR	--	--	3.98	2.08	2.10	0.69	0.03	0.74	0.18	0.00	0.55	

WATER FROM COTTON CREEK NEAR ORANGEVILLE 1958 GYP ABSENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.48	4.69	2.73	2.33	0.77	0.03	0.82	0.20	0.117	0.57	0.90
EQU	PPT	7.80	0.54	4.96	2.57	2.68	0.88	0.04	0.95	0.23	0.144	0.58	0.78
EQU	PPT	7.80	0.60	5.18	2.51	3.03	1.00	0.04	1.07	0.26	0.153	0.61	0.69
EQU	PPT	7.80	0.67	5.44	2.44	3.50	1.15	0.05	1.23	0.30	0.170	0.65	0.60
EQU	PPT	7.80	0.77	6.11	2.23	4.20	1.38	0.06	1.48	0.36	0.206	0.71	0.50
EQU	PPT	7.80	0.90	6.73	2.11	5.25	1.73	0.07	1.85	0.45	0.247	0.81	0.40
EQU	PPT	7.80	1.09	8.16	1.84	7.00	2.30	0.10	2.47	0.60	0.344	0.94	0.30
EQU	PPT	7.80	1.23	9.26	1.74	8.40	2.76	0.12	2.96	0.72	0.408	1.09	0.25
EQU	PPT	7.80	1.40	10.68	1.60	10.50	3.45	0.15	3.70	0.90	0.527	1.27	0.20
EQU	PPT	7.80	1.66	13.68	1.36	14.00	4.60	0.20	4.93	1.20	0.785	1.56	0.15
EQU	PPT	7.80	2.08	19.52	1.09	21.00	6.90	0.30	7.40	1.80	1.386	2.13	0.10
EQU	PPT	7.80	2.98	36.52	0.75	42.00	13.80	0.60	14.80	3.60	3.788	3.64	0.05
IRR	WTR	--	--	3.98	2.08	2.10	0.69	0.03	0.74	0.18	0.00	0.55	



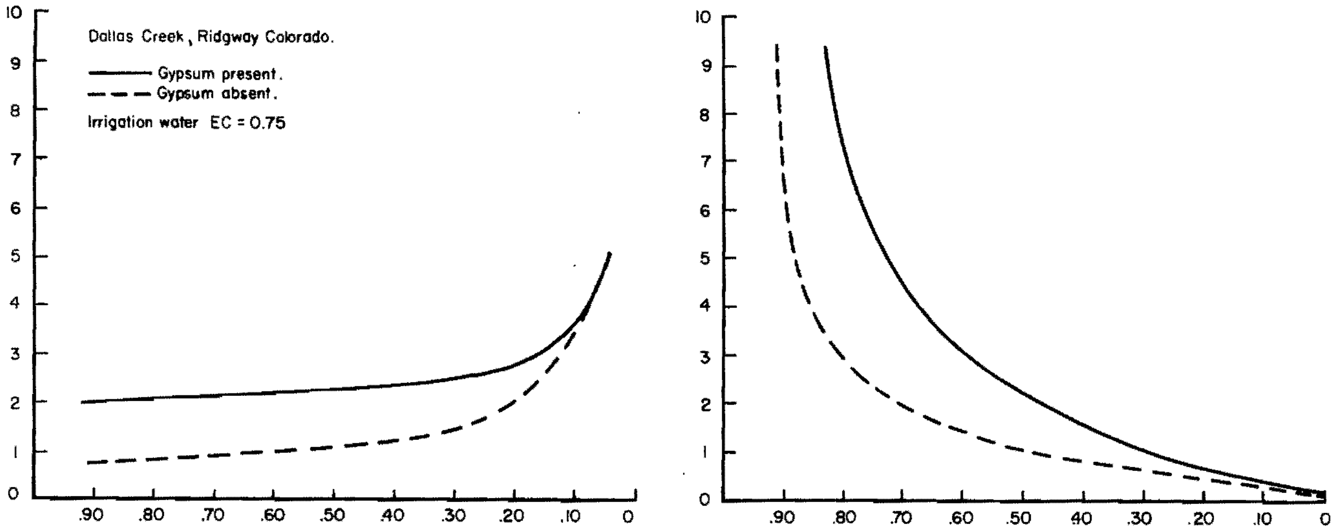


WATER FROM DALLAS CREEK, RIDGWAY COLO. NO GYPSUM

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.43	2.74	5.59	2.11	0.85	0.07	5.65	0.11	0.083	0.77	0.91
EQU	PPT	7.80	0.49	2.69	5.94	2.50	1.00	0.08	6.68	0.13	0.087	0.85	0.77
EQU	PPT	7.80	0.51	2.60	6.26	2.69	1.08	0.08	7.20	0.14	0.084	0.87	0.71
EQU	PPT	7.80	0.58	2.51	6.86	3.26	1.31	0.10	8.74	0.17	0.090	0.99	0.59
EQU	PPT	7.80	0.65	2.41	7.52	3.84	1.54	0.12	10.28	0.20	0.090	1.09	0.50
EQU	PPT	7.80	0.74	2.24	8.69	4.80	1.92	0.15	12.85	0.25	0.092	1.26	0.40
EQU	PPT	7.80	0.88	2.07	10.45	6.34	2.54	0.20	16.96	0.33	0.095	1.52	0.30
EQU	PPT	7.80	0.98	1.92	12.17	7.68	3.08	0.24	20.56	0.40	0.093	1.74	0.25
EQU	PPT	7.80	1.11	1.77	14.58	9.60	3.85	0.30	25.70	0.50	0.094	2.09	0.20
EQU	PPT	7.80	1.30	1.58	18.64	12.86	5.16	0.40	34.44	0.67	0.096	2.66	0.15
PPT	PPT	7.80	1.66	1.46	23.83	19.20	7.70	0.60	48.46	1.00	0.102	3.54	0.10
PPT	PPT	7.80	2.81	2.00	21.48	38.40	15.40	1.20	72.05	2.00	0.173	5.12	0.05
IRR	WTR	--	--	2.84	5.33	1.92	0.77	0.06	5.14	0.10	0.00	0.75	

WATER FROM DALLAS CREEK, RIDGWAY COLO. GYPSUM PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
DIS	PPT	7.80	0.22	0.96	27.60	2.11	0.85	0.07	29.26	0.11	0.050	2.11	0.91
PPT	PPT	7.80	0.26	0.98	27.33	2.50	1.00	0.08	29.84	0.13	0.051	2.12	0.77
PPT	PPT	7.80	0.30	1.00	27.07	2.88	1.15	0.09	30.51	0.15	0.052	2.17	0.67
PPT	PPT	7.80	0.33	1.01	27.36	3.26	1.31	0.10	30.65	0.17	0.052	2.23	0.59
PPT	PPT	7.80	0.39	1.02	26.93	3.84	1.54	0.12	31.32	0.20	0.054	2.24	0.50
PPT	PPT	7.80	0.49	1.06	26.57	4.80	1.92	0.15	32.54	0.25	0.057	2.34	0.40
PPT	PPT	7.80	0.63	1.10	26.35	6.34	2.54	0.20	34.06	0.33	0.061	2.49	0.30
PPT	PPT	7.80	0.75	1.14	25.89	7.68	3.08	0.24	35.64	0.40	0.065	2.59	0.25
PPT	PPT	7.80	0.92	1.20	25.40	9.60	3.85	0.30	37.93	0.50	0.071	2.76	0.20
PPT	PPT	7.80	1.19	1.30	24.74	12.86	5.16	0.40	41.71	0.67	0.082	3.05	0.15
PPT	PPT	7.80	1.66	1.48	23.77	19.20	7.70	0.60	48.95	1.00	0.102	3.59	0.10
PPT	PPT	7.80	2.81	2.01	21.58	38.40	15.40	1.20	72.37	2.00	0.172	5.17	0.05
IRR	WTR	--	--	2.84	5.33	1.92	0.77	0.06	5.14	0.10	0.00	0.75	

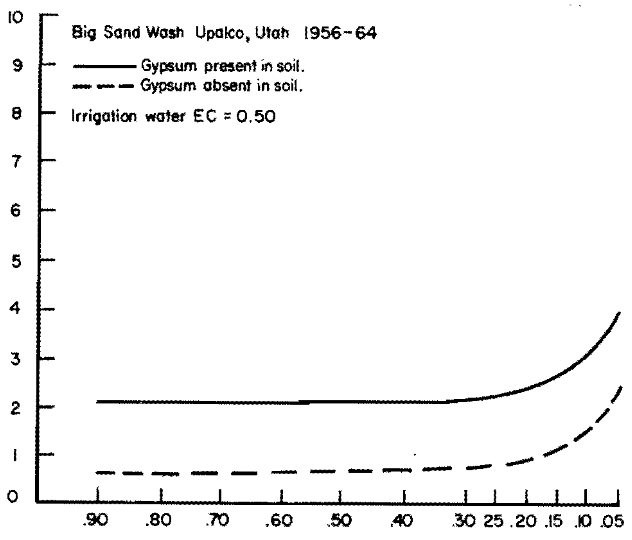


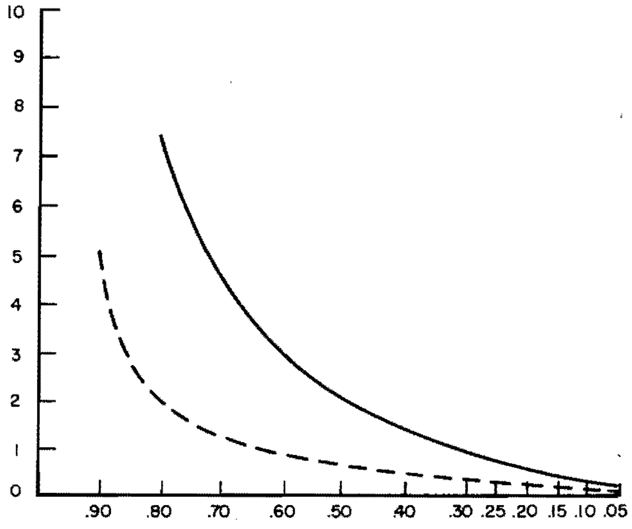
WATER FROM BIG SAND WASH UPALCO UT. 1956-64 GYP ABSENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.27	3.97	3.30	1.44	0.41	0.02	0.62	0.20	0.075	0.56	0.90
EQU	PPT	7.80	0.31	4.24	2.87	1.66	0.47	0.03	0.72	0.23	0.114	0.50	0.78
EQU	PPT	7.80	0.34	4.17	2.96	1.88	0.53	0.03	0.81	0.26	0.109	0.52	0.69
EQU	PPT	7.80	0.39	4.45	2.82	2.17	0.62	0.03	0.93	0.30	0.123	0.55	0.60
EQU	PPT	7.80	0.45	4.63	2.77	2.60	0.74	0.04	1.12	0.36	0.135	0.59	0.50
EQU	PPT	7.80	0.54	5.15	2.57	3.25	0.93	0.05	1.40	0.45	0.163	0.65	0.40
EQU	PPT	7.80	0.67	5.58	2.48	4.33	1.23	0.07	1.87	0.60	0.196	0.75	0.30
EQU	PPT	7.80	0.76	6.04	2.39	5.20	1.48	0.08	2.24	0.72	0.221	0.82	0.25
EQU	PPT	7.80	0.89	6.93	2.18	6.50	1.85	0.10	2.80	0.90	0.281	0.93	0.20
EQU	PPT	7.80	1.07	7.91	2.05	8.67	2.47	0.13	3.73	1.20	0.366	1.12	0.15
EQU	PPT	7.80	1.37	10.84	1.67	13.00	3.70	0.20	5.60	1.80	0.621	1.48	0.10
EQU	PPT	7.80	2.01	19.62	1.16	26.00	7.40	0.40	11.20	3.60	1.618	2.49	0.05
IRR	WTR	--	--	2.35	1.40	1.30	0.37	0.02	0.56	0.18	0.00	0.50	

WATER FROM BIG SAND WASH UPALCO UT. 1956-64 GYP PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
PPT	PPT	7.80	0.11	0.95	27.83	1.44	0.41	0.02	28.71	0.20	0.048	2.05	0.90
PPT	PPT	7.80	0.12	0.95	27.79	1.66	0.47	0.03	28.80	0.23	0.048	2.06	0.78
PPT	PPT	7.80	0.14	0.97	27.56	1.88	0.53	0.03	29.26	0.26	0.049	2.08	0.69
PPT	PPT	7.80	0.16	0.97	27.80	2.17	0.62	0.03	29.20	0.30	0.049	2.11	0.60
PPT	PPT	7.80	0.19	0.98	27.50	2.60	0.74	0.04	29.73	0.36	0.051	2.13	0.50
PPT	PPT	7.80	0.24	1.00	27.18	3.25	0.93	0.05	30.51	0.45	0.053	2.17	0.40
PPT	PPT	7.80	0.31	1.02	27.35	4.33	1.23	0.07	31.16	0.60	0.055	2.28	0.30
PPT	PPT	7.80	0.37	1.03	26.96	5.20	1.48	0.08	32.01	0.72	0.058	2.31	0.25
PPT	PPT	7.80	0.45	1.07	26.61	6.50	1.85	0.10	33.38	0.90	0.061	2.42	0.20
PPT	PPT	7.80	0.59	1.13	26.16	8.67	2.47	0.13	35.56	1.20	0.067	2.60	0.15
PPT	PPT	7.80	0.84	1.23	25.48	13.00	3.70	0.20	39.71	1.80	0.080	2.94	0.10
PPT	PPT	7.80	1.48	1.50	24.14	26.00	7.40	0.40	51.76	3.60	0.119	3.89	0.05
IRR	WTR	--	--	2.35	1.40	1.30	0.37	0.02	0.56	0.18	0.00	0.50	



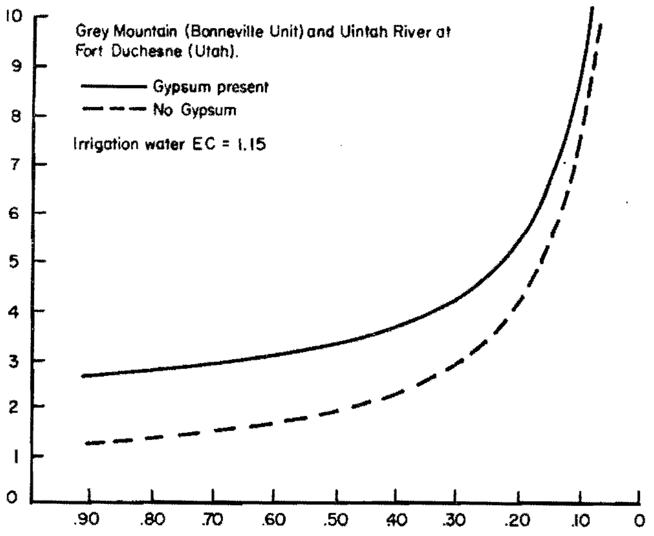


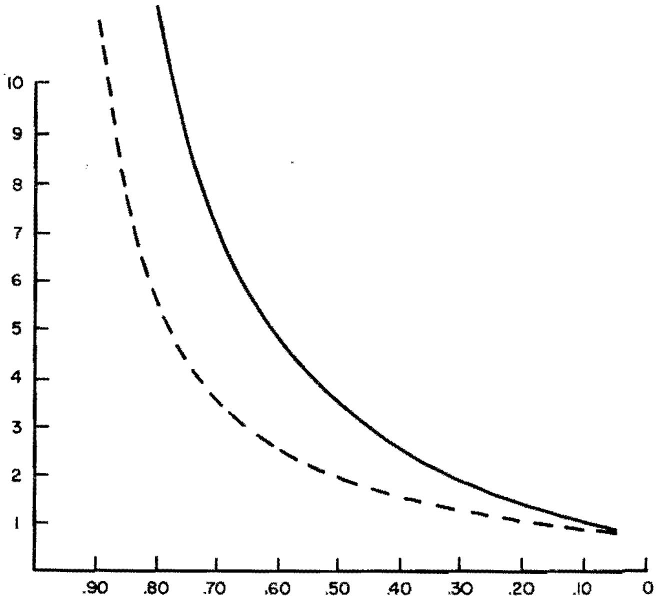
WATER FROM GRAY MTN. AND UINTA RIVER AT FORT DUCHESNE NO GYPSUM

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	3.62	5.74	3.19	4.00	6.87	0.26	8.00	0.50	0.164	1.25	0.90
EQU	PPT	7.80	3.93	5.92	3.18	4.48	7.69	0.29	8.96	0.56	0.182	1.33	0.80
EQU	PPT	7.80	4.32	6.21	3.17	5.12	8.79	0.33	10.24	0.64	0.199	1.48	0.70
EQU	PPT	7.80	4.83	6.71	3.11	6.00	10.30	0.38	12.00	0.75	0.228	1.67	0.60
EQU	PPT	7.80	5.46	7.40	3.03	7.20	12.36	0.46	14.40	0.90	0.267	1.93	0.50
EQU	PPT	7.80	6.34	8.37	2.95	9.04	15.52	0.58	18.08	1.13	0.327	2.32	0.40
EQU	PPT	7.80	7.58	10.06	2.77	12.00	20.60	0.77	24.00	1.50	0.437	2.93	0.30
EQU	PPT	7.80	8.45	11.24	2.73	14.40	24.72	0.92	28.80	1.80	0.510	3.46	0.25
EQU	PPT	7.80	9.64	13.28	2.57	18.00	30.90	1.15	36.00	2.25	0.661	4.16	0.20
EQU	PPT	7.80	11.35	16.67	2.36	24.00	41.20	1.53	48.00	3.00	0.933	5.32	0.15
EQU	PPT	7.80	14.17	23.46	2.06	36.00	61.80	2.30	72.00	4.50	1.562	7.54	0.10
EQU	PPT	7.80	20.34	37.62	1.84	72.00	123.60	4.60	144.00	9.00	3.434	13.72	0.05
IRR	WTR	--	--	5.14	2.78	3.60	6.18	0.23	7.20	0.45	0.00	1.15	

WATER FROM GRAY MTN. AND UINTA RIVER AT FORT DUCHESNE RIVER GYPSUM PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
DIS	PPT	7.80	1.79	1.14	25.36	4.00	6.87	0.26	35.33	0.50	0.059	2.63	0.90
PPT	PPT	7.80	1.98	1.19	25.63	4.48	7.69	0.29	36.59	0.56	0.059	2.86	0.80
PPT	PPT	7.80	2.26	1.24	25.21	5.12	8.79	0.33	38.09	0.64	0.062	2.97	0.70
PPT	PPT	7.80	2.62	1.28	25.02	6.00	10.30	0.38	39.78	0.75	0.065	3.15	0.60
PPT	PPT	7.80	3.11	1.36	24.46	7.20	12.36	0.46	42.42	0.90	0.070	3.37	0.50
PPT	PPT	7.80	3.83	1.47	23.82	9.04	15.52	0.58	46.53	1.13	0.077	3.73	0.40
PPT	PPT	7.80	4.92	1.64	23.00	12.00	20.60	0.77	53.12	1.50	0.089	4.30	0.30
PPT	PPT	7.80	5.76	1.78	22.41	14.40	24.72	0.92	58.63	1.80	0.100	4.77	0.25
PPT	PPT	7.80	6.93	1.98	21.71	18.00	30.90	1.15	66.94	2.25	0.116	5.46	0.20
PPT	PPT	7.80	8.70	2.30	20.83	24.00	41.20	1.53	80.86	3.00	0.144	6.60	0.15
PPT	PPT	7.80	11.76	2.94	19.22	36.00	61.80	2.30	111.15	4.50	0.207	8.83	0.10
PPT	PPT	7.80	18.49	4.58	17.37	72.00	123.60	4.60	199.38	9.00	0.408	15.49	0.05
IRR	WTR	--	--	5.14	2.78	3.60	6.18	0.23	7.20	0.45	0.00	1.15	





WATER FROM SEELEY CREEK JOES VALLEY DAM SITE GYP PRESENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
DIS	PPT	7.80	0.19	0.96	27.54	2.13	0.72	0.03	29.47	0.20	0.050	2.12	0.90
PPT	PPT	7.80	0.21	0.98	27.49	2.45	0.83	0.04	29.69	0.23	0.050	2.13	0.78
PPT	PPT	7.80	0.24	0.99	27.19	2.77	0.94	0.04	30.22	0.26	0.051	2.15	0.69
PPT	PPT	7.80	0.28	1.00	27.48	3.20	1.08	0.05	30.39	0.30	0.052	2.21	0.60
PPT	PPT	7.80	0.33	1.01	27.05	3.84	1.30	0.06	31.05	0.36	0.054	2.22	0.50
PPT	PPT	7.80	0.41	1.05	26.71	4.80	1.63	0.07	32.22	0.45	0.057	2.32	0.40
PPT	PPT	7.80	0.53	1.09	26.52	6.40	2.17	0.10	33.71	0.60	0.061	2.46	0.30
PPT	PPT	7.80	0.63	1.12	26.08	7.68	2.60	0.12	35.14	0.72	0.065	2.55	0.25
PPT	PPT	7.80	0.77	1.17	25.88	9.60	3.25	0.15	36.94	0.90	0.070	2.72	0.20
PPT	PPT	7.80	0.99	1.25	25.24	12.80	4.33	0.20	40.20	1.20	0.080	2.95	0.15
PPT	PPT	7.80	1.39	1.40	24.38	19.20	6.50	0.30	46.67	1.80	0.100	3.45	0.10
PPT	PPT	7.80	2.37	1.88	22.03	38.40	13.00	0.60	68.08	3.60	0.168	4.88	0.05
IRR	WTR	--	--	3.55	1.63	1.92	0.65	0.03	0.50	0.18	0.00	0.55	

WATER FROM SEELEY CREEK JOES VALLEY DAM SITE GYP ABSENT

CASO	CACO	PH	SAR	HCO3	CA	MG	NA	K	SO4	CL	CO3	EC_{dw}	Net Salt
EQU	PPT	7.80	0.45	4.39	2.96	2.13	0.72	0.03	0.56	0.20	0.099	0.57	0.90
EQU	PPT	7.80	0.53	4.93	2.52	2.45	0.83	0.04	0.64	0.23	0.144	0.55	0.78
EQU	PPT	7.80	0.58	5.20	2.44	2.77	0.94	0.04	0.72	0.26	0.149	0.58	0.69
EQU	PPT	7.80	0.65	5.47	2.36	3.20	1.08	0.05	0.83	0.30	0.165	0.62	0.60
EQU	PPT	7.80	0.75	6.18	2.14	3.84	1.30	0.06	1.00	0.36	0.201	0.67	0.50
EQU	PPT	7.80	0.88	6.84	2.02	4.80	1.63	0.07	1.25	0.45	0.242	0.75	0.40
EQU	PPT	7.80	1.07	8.40	1.73	6.40	2.17	0.10	1.67	0.60	0.340	0.88	0.30
EQU	PPT	7.80	1.20	9.05	1.71	7.68	2.60	0.12	2.00	0.72	0.382	1.02	0.25
EQU	PPT	7.80	1.38	10.91	1.49	9.60	3.25	0.15	2.50	0.90	0.522	1.17	0.20
EQU	PPT	7.80	1.63	13.32	1.32	12.80	4.33	0.20	3.33	1.20	0.736	1.44	0.15
EQU	PPT	7.80	2.04	18.70	1.06	19.20	6.50	0.30	5.00	1.80	1.295	1.94	0.10
EQU	PPT	7.80	2.94	39.18	0.65	38.40	13.00	0.60	10.00	3.60	4.004	3.30	0.05
IRR	WTR	--	--	3.55	1.63	1.92	0.65	0.03	0.50	0.18	0.00	0.55