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# **Quality of Percolating Waters**

I. Properties of Deep Substrata Materials in the West Side of the San Joaquin Valley, California

L. D. Doneen

II. A Computer Method for Predicting Salt Concentrations in Soils at Variable Moisture Contents

> K. K. Tanji, G. R. Dutt, J. L. Paul, and L. D. Doneen

III. The Quality of Waters Percolating through Stratified Substrata, as Predicted by Computer Analyses

K. K. Tanji, L. D. Doneen, and J. L. Paul



The San Luis Project, a major new unit in the Central Valley Project, is currently under construction. It will transport Feather River water to the west side of the San Joaquin Valley. The State of California Water Plan envisions a program of cyclic use of ground water during periods of deficiency, and storage of excess surface water when supplies are plentiful. Recharge of underground storage basins will involve the percolation of water through substrata, and the quality of the percolating water will be influenced by salts present in the substrata.

A series of papers in this issue present a method of predicting the quality of percolating waters in substrata (Part III), utilizing field data obtained from substrata profiles in the west side of the San Joaquin Valley (Part I). Theoretical considerations and approximations (Parts II and III) are formulated in the computer programs, for calculating simultaneously the major physicochemical reactions that occur during recharge.

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# III. The Quality of Waters Percolating through Stratified Substrata, as Predicted by Computer Analyses<sup>1,2</sup>

## INTRODUCTION

THE STATE OF CALIFORNIA Water Plan envisions a program in which both surface- and ground-water supplies will be used. With cyclic use of ground water during periods of deficiency, and storage of excess water when supplies are plentiful, it is anticipated that the annual demand for irrigation water will be satisfied. Davis, Lofgren, and Mack (1964) have estimated the quantity of water that can be stored in the substrata underlying the San Joaquin Valley to be 93 million acre-feet for a depth zone of 10 to 200 feet. This quantity is about nine times the capacity of the present and proposed surface reservoirs in the valley.

Whatever method is employed in replenishing ground waters, recharge operations will involve the flow of water through substrata. A general survey was conducted by Doneen (see first paper in this series) on substrata characteristics that may influence groundwater quality for the west side of the San Joaquin Valley, for which the program of ground-water storage and reuse is contemplated.

According to present information, the amounts and kinds of solutes found in effluents from soil profiles or columns are the result of many processes and conditions: distribution of salts with respect to depth (Doneen, 1960); solubilization of crystalline and amorphous salts and minerals (Biggar, 1959; Reeve, Pillsbury, and Wilcox, 1955; Dutt and Tanji, 1962); ion exchange (Rible and Davis, 1955; Bower, Gardner, and Goertzen, 1957; Dutt, 1962a, b); hydrolysis of sparingly soluble substances (Bower and Goertzen, 1958; Doneen, 1960); miscible displacement and hydrodynamic dispersion (Day, 1956; Gardner and Brooks, 1957: Biggar and Nielsen, 1960).

A method for predicting solute concentrations in water percolating through an initially air-dry, nonlayered column of soil was developed and tested by Dutt and Tanji (1962). The computer program utilized in their model has now been modified and extended to treat a column stratified with respect to salinity, gypsum, cation-exchange capacity, equilibrium-exchange

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constant, and initial and final water contents. The new Fortran program computes the solute concentrations in the effluent and the profile distribution of salts during percolation. The purpose of this paper is to present the theoretical considerations and procedures utilized in the computer programs and the resulting predictions on quality of waters percolating through three substrata profiles (see first paper in this series).

Because of the complexity of a stratified soil system, two computer programs were prepared for IBM 7040 Data Processing System. Program 1 considers the processes that occur when an initially moist, stratified column is wetted from the surface and brought to a higher moisture content, before the appearance of effluent. Program 2 considers the physicochemical processes that occur during percolation. Solute concentrations in the effluents and alterations in profile distribution of solutes, exchangeable cations, and gypsum are predicted with the second program.

### PROGRAM 1

# PREDICTION OF CHEMICAL CHANGES INDUCED BY SATURATING A STRATIFIED SUBSTRATA PROFILE

### **Theoretical Considerations**

Doneen has reported that undisturbed core samples of substrata obtained from the west side of San Joaquin Valley were of high bulk densities, and that the moisture-equivalent values often exceeded the saturated moisture content for these cores (see first paper in this series). Thus, water content at which flow takes place cannot be readily deduced from soilmoisture constants determined in the laboratory, on fragmented substrata samples. In the present study the assumption has been made that water movement takes place when the pore spaces are completely filled with water. Doneen also reports saturation or near saturation of pore spaces in the wettest zones of the substrata profiles.

Consider a soil column to be made up of n segments,  $\Delta X$  in length, and of unit cross-sectional area. Assume that these segments vary in initial moisture content, FM, and in pore volume, PV, on volumetric water-content basis. Then the depth of solution,  $q_i$ , required to fill segment  $\Delta X_i$  from  $FM_i$  to  $PV_i$ , is:

$$q_i = \Delta X_i \left( P V_i - F M_i \right) \qquad [1]$$

and the total amount of solution, Q, needed to fill the entire column of stratified soil is:

$$Q = \sum_{i=1}^{n} q_{i} = \sum_{i=1}^{n} \Delta X_{i} (PV_{i} - FM_{i}) \quad [2]$$

If  $q_i$ , the fractional depth of Q, is kept constant, then the length of segments must be adjusted from  $\Delta X_i$  to  $M_i$  so that

$$Q = \sum_{j=1}^{n} q_{j} = \sum_{i=1}^{n} M_{i} (PV_{i} - FM_{i}) \quad [3]$$

where segment  $M_i$  varies in length.

Next consider the wetting front as Q volume of solution is applied on the surface of an initially moist, stratified soil column. Let the concentration of a given solute species in the applied solution be  $C_o$ . As  $q_1$ , the first aliquot of Q, enters the column, the moisture content of segment  $M_1$  is increased from field moisture,  $FM_1$ , to saturated pore volume,  $PV_1$ . The concentration of

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solute C in  $M_1$ ,  $C_1$ , is then:

$$C_1 = C_o \left( \frac{PV_1 - FM_1}{PV_1} \right) + C_1^o \left( \frac{FM_1}{PV_1} \right)$$

$$[4]$$

where  $C_{0_1}^{\circ}$  is the initial concentration of solute C in segment  $M_1$  at field moisture content. Since the initial moisture content was increased to saturated pore volume, the concentration of  $C_o$  is then diluted by the factor  $(PV_1 - FM_1)/$  $PV_1$  and the concentration of  $C_{0_1}^{\circ}$  is likewise changed by a factor of  $FM_1/$  $PV_1$ .

The concentration of a given solute species C in  $M_1$ , as calculated by equation [4], is further altered in the equilibrium cycle developed by Dutt (1962b) and Dutt and Doneen (1963), except for Cl<sup>-</sup> and HCO<sub>3</sub><sup>-</sup>. The chemical reactions occurring within a discrete sample have been outlined in detail by Tanji *et al.* (see second paper in this series).

With succeeding applications of  $q_j$ , the wetting front moves downward into subsequent  $M_i$  segments. The first approximation on the concentration of solute species C in segments  $M_2$  to  $M_n$ is:

$$C_{i} = C_{i-1} \left( \frac{PV_{i} - FM_{i}}{PV_{i}} \right) + C_{i}^{o} \left( \frac{FM_{i}}{PV_{i}} \right)$$

$$[5]$$

where subscript *i* refers to segment numbers  $M_2$  to  $M_n$ ,  $C_i$  is the new concentration of *C* after saturation,  $C_{i-1}$  is the equilibrium concentration of *C* from the preceding *M* segment, and  $C^{o_i}$  is the initial concentration of *C* at field-moisture content. Each  $C_i$  is subjected to the equilibrium cycle to obtain final equilibrium values before the wetting front moves downward.

Let us next consider the concentration of solute species C behind the wetting front. The concentration of Cin a given depth segment,  $M_i$ , after  $q_j$ applications of solution,  $C_{i,j}$ , is:

$$C_{i, j} = C_{i-1, j} \left( \frac{PV_i - FM_i}{PV_i} \right) + C_{i, j-1} \left( \frac{FM_i}{PV_j} \right)$$
[6]

where the subscripts i and j refer to depth segment M and to the number of q aliquots applied, respectively.  $C_{i-1,j}$ is the equilibrium concentration of Cfrom the preceding depth segment,  $M_{i-1}$ , after j applications of q.  $C_{i,j-1}$  is the equilibrium concentration of C in depth segment  $M_i$  from the previous application, j-1, of q.

The first approximation on  $C_{i,j}$  is then successively equilibrated to a new computed value. Solute species that can be considered in equations [4], [5], and [6] are Ca<sup>++</sup>, Mg<sup>++</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>=</sup>, Cl<sup>-</sup>, and also undissociated CaSO<sub>4</sub>. Until a method is developed to handle the chemistry of the calcite system, HCO<sub>3</sub><sup>-</sup> is, at present, held constant.

The calculation for the displacement of solutes during percolation is influenced by the selection of number of M segments in a column, e.g., length of segments. As  $M_n$  approaches infinity in a dry, homogenous column, the transport of all solutes initially present in the column tends toward piston displacement. However, if  $M_n$  is considered to be finite, it is possible to approximate a kind of mixing or dispersion, as indicated by Dutt and Tanji (1962).

In the case of a moist, stratified profile of considerable depth, an additional mechanism for mixing was included. As  $q_i$  enters the surface of segment  $M_i$ , which has an initial moisture content of  $FM_i$ , the resulting moisture content is increased to  $PV_i$ . When  $q_{j+1}$  is applied, the wetting front proceeds to the next depth segment. A volume equal to  $q_j$  leaves  $M_i$  and enters  $M_{i+1}$  to fill this segment to  $PV_{i+1}$ .  $M_i$  is assumed to retain a moisture content of  $FM_i$ . In like manner, as additional  $q_j$  is applied, the wetting front proceeds until the lowest depth segment is filled to  $PV_n$ . The insertion of these mixing mechanisms is not intended to fully account for miscible displacement of solutes, but to serve as an approximation.

Thus, from equations [3], [4], [5],

### Procedure

To illustrate computer calculation techniques, substrata sampling site 3 was selected. Detailed analyses on 35 core samples from this site, to a depth of 330 feet, have been presented (see the first paper in this series). The 6inch cores were considered to represent a depth increment midway between the preceding core sample and the sample in question, and extending midway to the subsequent core sample.

Pore volume,  $q_x$ , of the depth increment can be calculated from the following relationship:

$$q_x = \left(1 - \frac{D_b}{D_p}\right) V_s \qquad [7]$$

where  $D_b$  and  $D_p$  are the bulk density and particle density of the relatively undisturbed core sample, respectively.  $V_s$  is the volume of substrata depth segment on a unit cross-sectional area basis.

The volume occupied by field moisture,  $q_y$ , can be calculated from

$$q_y = \left(\frac{D_b}{D_w}\right) \left(\frac{FM}{100}\right) V_s \qquad [8]$$

where  $D_w$  is density of water and FMis the field-moisture content of the core sample.

Assuming that percolation takes place at saturated pore volume, the depth of solution,  $q_z$ , required to saturate the depth segment is:

$$q_z = q_x - q_y \tag{9}$$

The total depth of solution needed to fill a profile of unit cross-sectional area containing n segments is:

and [6] and the equilibrium cycle (see second paper of this series), it is possible to calculate the equilibrium values of solutes, adsorbed cations, gypsum, and undissociated  $CaSO_4$  in the depth increments of a column filled to pore-volume saturation.

$$Q = \sum_{z=1}^{n} q_z \qquad [10]$$

For substrata site 3, Q is calculated as 13.716 meters for a profile depth of 99.37 meters. A schematic profile distribution of field-moisture content  $(q_y)$ and pore volume  $(q_x)$  in site 3 is shown in figure 1(a). Once Q has been determined, a fractional aliquot  $q_j$  is selected so that j equals 10 or greater. For this substrata,  $q_i$  is 91.44 cm and the number of M segments to be considered is 15. Because  $q_i$  is to be kept constant in the computational procedure (equation [3]), the depth segments in figure 1(a) must be adjusted. A second schematic profile distribution with  $q_i$  constant for each segment is shown in figure 1(b). The new values for field-moisture content  $(FM_i)$  and pore volume  $(PV_i)$  were obtained by the weighted mean procedure. Likewise the weighted mean values of other parameters, discussed in the second paper in this series, were calculated from 1:1 extract data of core samples encompassed by segment  $M_i$ . The average 1:1 extract data for  $M_i$  were converted to field-moisture content basis by computer calculations described in the second paper of this series. These new equilibrium values were then considered as the initial field-moisture values for this computer program.

A computer program was formulated, on the basis of theoretical considerations discussed above, to predict the profile distribution of solutes, undissociated  $CaSO_4$ , gypsum, and exchangeable cation concentrations after the



Fig. 1. Schematic profile distribution of field-moisture content and pore volume in substrata site 3, west side, San Joaquin Valley, California. Subscripted symbols in (a) are measurements (defined by equations [7], [8], and [9] in the text) obtained from core samples. Because q is to be kept constant in the computational procedure (equation [3]), the depth segments are adjusted, as in (b).

profile is saturated to pore volume. The source statement for this program is presented below, and a diagram of the computation scheme is given in figure 2.

The molar concentrations of Ca<sup>++</sup>, Mg<sup>++</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>=</sup>, Cl<sup>-</sup>, and HCO<sub>3</sub><sup>-</sup> of the applied solution, Feather River water, are represented by A5, F5, S5, G5, H5, and W5, respectively, in statement 21. The initial values of native solute concentration and undissociated CaSO<sub>4</sub> concentration, in moles per liter, at field-moisture content, for each of the 15  $M_i$  segments, are also accepted as input data. Initial concentrations are read as CA, AMG, SOS, SO, HO, WO, and CAS5, representing Ca<sup>++</sup>, Mg<sup>++</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>=</sup>, Cl<sup>-</sup>, HCO<sub>3</sub><sup>-</sup>, and undissociated CaSO<sub>4</sub>, respectively. Initial exchangeable Ca<sup>++</sup>, Mg<sup>++</sup>, Na<sup>+</sup>, and gypsum concentrations, in moles per gram soil, are denoted respectively by E5, C5, SA5, and XX5. The Fortran symbols TD and TDA refer to the equilibrium-exchange constants for Ca<sup>++</sup> – Mg<sup>++</sup> and Na<sup>+</sup> – Ca<sup>++</sup> exchange. TB1 and TB2 signify per cent moisture on a weight basis at porevolume saturation and field-moisture



Fig. 2. Computational routing for predicting chemical changes induced by saturating a stratified profile.

content, respectively. The ratio of grams of soil to liter of solution is represented by TB.

In the Fortran source statement, each of the variables mentioned above are subscripted by (J), where J refers to segment  $M_i$ . The source statement shown has J = 1, 10, which may be replaced by J = 1, 15 for the profile under consideration. Each variable of a given kind for the 15 depth segments may have different values. The initial values of a given subscripted variable are placed in memory or internal-core storage locations in the computer by declaring a Dimension Statement. The 15

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memory sites of a given variable are used only once when equation [5] is being considered. An exception to the aforementioned statement is the continued use of dimensioned variables TD(J), TDA(J), TB1(J), TB2(J), and B(J), throughout the program.

In addition to the storage of initial concentrations of subscripted variables, another set of Dimension Statements is declared for storage of computed equilibrium values for each of the subscripted variables. Solutes Ca<sup>++</sup>, Mg<sup>++</sup>, Na<sup>+</sup>, SO<sub>4</sub><sup>=</sup>, Cl<sup>-</sup>, and HCO<sub>3</sub><sup>-</sup> are denoted by Fortran language variables TA, TF, TS, TG, TH, and TW, respectively. Computed equilibrium concentrations of exchangeable Ca++, Mg++, and Na+ are designated as TE, TC, and TSA, respectively. TCASO and TXX stand for computed values of undissociated  $CaSO_4$  and solid-phase  $CaSO_4$ . Statements 30, 41, and 31 are Format statements for input data, output data, and control card, respectively.

M is defined as the number of depth segments being considered in the profile. J counts the number of M segments equilibrated, and may range in value from 1 to 15 for this profile. Located under statement 31 are a series of initializing and substitution statements containing symbols A, F, S, G, H, W, and CASO, which represent the computing form for Ca++, Mg++, Na+, SO4=,  $Cl^-$ ,  $HCO_3^-$ , and undissociated  $CaSO_4$ , respectively, for aliquot  $q_i$  of Feather River water. II is a directional flow symbol to route the operation through statement 12 and branching to statements 201 or 202 (fig. 2).

The route through statement 202 considers equations [4] and [5], which account for the mixing of solutes in the wetting front as it passes through the surface and subsequent segments. Exchangeable cation and gypsum concentrations are also redefined to computing forms. As an approximation, the initial  $HCO_3^-$  concentration in the depth segment is held constant with reference to the limited solubility of CaCO<sub>3</sub>. Note that J increases by 1 each time that statement 202 is encountered, and that the wetting front computation is continued until J = M. B3 is equivalent to the factor  $(PV_i - FM_i/PV_i)$  and B4 is equivalent to the factor  $(FM_i/PV_i)$ in equations [4] and [5].

The variables are then subjected to the equilibrium cycle, 24 through 52, which has been considered previously by Dutt (1962b), Dutt and Doneen (1963), and Tanji et al. (see second paper in this series). Computed equilibrium concentrations for these variables are obtained by a series of approximations. The equilibrium values for depth  $M_i$ , where i = J, are stored in memory sites after statement 8. If J <M, branch 9 is taken, where the subscripted solute variables are redefined to computing form for the next segment in 202. For the wetting front case, a loop is depicted from statement 12 through 202, 24, 8, 9, and back to 12 (fig. 2). This looping is continued until J equilibrations equal M depth segments. Thus, computations for reactions in the moving wetting front are executed in succession. Reactions in segments behind the wetting front are computed by another route, namely, statement 201.

A Conditional, or If, statement is located in statement 8 to branch to statement 10 when J = M. The computer prints stored equilibrium concentrations of each of the solute species, exchangeable cations, undissociated CaSO<sub>4</sub>, and solid-phase CaSO<sub>4</sub>  $\cdot$  2H<sub>2</sub>O for depth segment  $M_{15}$ . At this stage of computation, subscripted variables in preceding depth segments  $M_1$  to  $M_{14}$  all have new computed values which are stored temporarily. Then M, the number of segments, is reduced by 1, since  $M_{15}$  has attained its final equilibrium value.

The computation proceeds to statement 39, where subsequent aliquots of Feather River water are considered. and J is initialized. Equation [6] is considered next in statement 201. The mixing and movement of solutes and equilibration of  $M_i$  segments through 201 are similar to those of 202 except that new computed concentrations of subscripted variables, which were stored in memory sites, are used rather than the initial input values. There is only one memory site for a subscripted variable for each of the  $M_n$  segments so that computed equilibrium concentration of the subscripted variable is stored temporarily at that particular site until a new value replaces it.

The flow of computation proceeds through the 201 route, forming a loop from statements 201 via 24, 8, 9, 12, and back to 201. J equilibrations with M segments continue until J = M, at which time output statements 10 and 34 are executed and the final equilibrium concentrations of subscripted variables are printed for segment  $M_{14}$ .

The computing operation progresses until M = 0, resulting in an output profile in the order of  $M_n$ ,  $M_{n-1}$ , ......  $M_1$  for solutes, exchangeable cations, undissociated CaSO<sub>4</sub>, and solid-phase CaSO<sub>4</sub>  $\cdot$  2H<sub>2</sub>O. The computation for this program requires about 1 minute, 45 seconds for a stratified profile with 15 M segments.

### Results

The descriptions on substrata site 3 indicated that the upper half of the profile is saline, gypsiferous, and dry. The lower half is less saline, nongypsiferous, and relatively higher in moisture content. The profile to be considered has a depth of 99.37 meters with a pore volume equivalent to 39.45 meters of water. The field-moisture content is equivalent to 25.66 meters of water, and if water movement is assumed to take place at pore-volume saturation,

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13.72 meters of Feather River water are required for saturation.

The initial and final profile distributions of total soluble salts in the soil solution at field-moisture content and saturated moisture content are given in figure 3. Pore-volume saturation was attained by applying Feather River water of Q depth on the profile surface. The applied water contains 0.52 Ca<sup>++</sup>, 0.32 Mg<sup>++</sup>, 0.18 Na<sup>+</sup>, 0.06 SO<sub>4</sub><sup>=</sup>, 0.03 Cl<sup>-</sup>, and 0.93 HCO<sub>3</sub><sup>-</sup> in m.e. per liter.

The in-place profile concentrations of total soluble salts (FM in fig. 3) may also be converted to predicted concentrations at pore-volume moisture. This increase in moisture content from FM to PV is computed as if salt-free water were added to each depth. Thus, soluble-salt content on a comparable moisture-content basis, before and after the application of Feather River water, may be compared (fig. 4). Considerable displacement of salts has taken place as Feather River water filled the profile to its pore-volume capacity. The imbalance



Fig. 3. Profile distribution of soluble salts at field-moisture content (FM) and at saturated pore volume (PV).

of total soluble salts before and after pore saturation is due to the dissolution of gypsum from surface stratum, and

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Fig. 4. A comparison between initial  $(PV_i)$ and final  $(PV_f)$  profile distribution of soluble salts at saturated pore-volume moisture.

transport of dissolution and exchange products into deeper, nongypsiferous depths. The addition of solutes from Feather River water may be considered nominal.

A better picture of the movement of solutes is obtained by examining the profile distribution of Cl<sup>-</sup>, at comparable moisture contents, before and after saturation (fig. 5). Since Feather River water contains only 0.03 m.e. per liter of Cl<sup>-</sup>, and Cl<sup>-</sup> is assumed to be unaffected by solubility or sorption reactions, the total Cl<sup>-</sup> in the profile remains



Fig. 5. Chloride distribution of the substrata at field-moisture (initial) content, and following wetting to pore-volume capacity (final).

nearly constant. Thus, by considering Cl<sup>-</sup> as a tracer of solute displacement during the saturation process, it is seen in figure 5 that considerable movement has taken place.

Computed data on solutes, exchangeable cations, and gypsum concentrations, by depth, are presented in the next section, in which the saturated profile is examined before effluent percolation is considered.

## PROGRAM 2

# PREDICTION OF QUALITY OF PERCOLATING WATER AND OF CHANGES IN CHEMICAL PROPERTIES OF THE PROFILE

### **Theoretical Considerations**

In the previous section a computer program was developed to predict chemical changes induced by saturation of an initially moist, stratified profile. The computer program described in this section predicts the solute concentrations in the effluent from a stratified profile, as percolation occurs, and the subsequent changes in chemical properties of the profile.

Consider a column saturated with respect to pore volume and consisting of  $\Delta X_n$  segments. Let the moisture content be  $PV_i$  for segment  $\Delta X_i$ . The total depth of solution, Q, in the profile is:

$$Q = \sum_{i=1}^{n} q_{i} = \sum_{i=1}^{n} \Delta X_{i} P V_{i} \quad [11]$$

where  $q_i$  is the volume of solution occupying the pore spaces in  $\Delta X_i$  segment of unit cross-sectional area.

Suppose the column is stratified with respect to  $PV_i$ . Then  $q_i$  is a variable. If  $q_j$ , the fractional volume of Q, is kept constant, the length of segments must be adjusted from  $\Delta X_i$  to  $M_i$  so that

$$Q = \sum_{j=1}^{n} q_{j} = \sum_{i=1}^{n} M_{i} P V_{i} \qquad [12]$$

where segment  $M_i$  varies in length.

Consider next the displacement of solution in a saturated column during percolation. If  $q_i$  depth of solution is applied on the surface of a saturated column, an equivalent depth,  $q_i$ , percolates out of the column. During percolation, diffusion of solutes takes place between the moving front of the incoming solution and the initial solution, and holdback on solute movement takes place in the smaller pores because of differences in pore velocities (Day, 1956; Gardner and Brooks, 1957; Biggar and Nielsen, 1960). The aforementioned phenomenon will be referred to as miscible displacement.

An empirical approach for approximating miscible displacement in the depth segments is given by:

$$C_{i, j} = \frac{C_{i-1, j} + C_{i, j-1}}{2} \qquad [13]$$

where subscripts i and j refer to  $M_i$  segment and  $q_j$  aliquots, respectively.  $C_{i,j}$  is the concentration of solute species in

depth segment  $M_i$  after  $q_i$  applications of solution.  $C_{i-1,j}$  is the concentration of solute species C from the previous segment,  $M_{i-1}$ , and  $C_{i,j-1}$  is the concentration of C in segment  $M_i$  from the previous  $q_{j-1}$  application. In addition, an arbitrary selection of number of  $M_n$ segments in the column is made to predict breakthrough curves for percolating solutes. The use of equation [13] may be considered as a fixed approximation on miscible displacement in the program, while the number of  $M_n$  segments selected for a specific profile may be considered as a modifying approximation.

The selection of number of  $M_n$  segments and use of equation [13] in this program to approximate miscible displacement of solutes are illustrated in figure 6. The soil column to be considered is saturated, and consists of  $\Delta X_n$ segments of uniform chemical composition and containing 104.0 m.e. per liter of Cl<sup>-</sup>. The column is isotropic with respect to all subscripted variables including moisture content. Breakthrough curves for Cl<sup>-</sup> as a function of number of  $M_n$  segments are given in figure 6. The applied solution, Feather River water, contains 0.03 m.e. per liter of Cl<sup>-</sup>. If the percolation of solutes is assumed to take place by piston displacement, the Cl<sup>-</sup> initially present in the profile will be displaced completely by one pore-volume application of Feather River water, represented by the broken lines in figure 6. By varying the number of  $M_n$  segments in the profile, a family of breakthrough curves for Cl<sup>-</sup> is presented. Note that as  $M_n$  increases and length of segments decreases, the displacement of Cl<sup>-</sup> from the profile approaches piston displacement. A reasonable approximation of breakthrough curves for Cl<sup>-</sup> at relatively low flow velocities, through medium-textured and stratified columns of these lengths, is the selection of  $M_n$  segments between 10 and 40.



Fig. 6. Calculated Cl<sup>-</sup> breakthrough curves as a function of Mn as Feather River water, containing 0.03 m.e. per liter Cl<sup>-</sup>, percolates through a homogenous profile containing 104 m.e. per liter Cl<sup>-</sup>.

### Procedure

Predictions on the quality of waters percolating through substrata sites 3, 8, and 9 (see first paper in this series), with Feather River water as recharge water, were made by computer analyses. A general description of profile characteristics is given in table 1. The information is qualitative, and indicates only differences in substrata properties that influence the quality of percolating waters.

By the method outlined by Tanji *et al.* (see second paper in this series) 1:1 extract data on the substrata samples were converted to new values at field-moisture content. The computed results represent the in-place concentrations, at the time of sampling, for solutes, undissociated  $CaSO_4$ , solid-phase gypsum, and exchangeable cations.

Assuming that percolation takes place at saturated pore volume, a second computer program is used to calculate chemical changes in the profile as it is filled from field-moisture levels to its pore-volume capacity. This program (Program 1, p. 326) computes the profile distribution of solutes, undissociated calcium sulfate, gypsum, and exchangeable cations after the profile is filled and before percolation of effluent. The data obtained from the second program are fed into a third program (p. 334) to compute solute concentrations in fractional pore volumes of percolate, and profile salt distribution as each pore volume of effluent is percolated.

Data pertinent to profile saturation and percolation status for the substrata sites are summarized in table 2. The

	Profile characteristics at:										
Factor	Site 3,* T14, R12, S8	Site 8,* T17, R17, S20	Site 9,* T18, R17, S27								
Texture	loam to clay	loam to clay, with sandy strati- fications in 12- to 24-meter depths	loam to clay, with sandy stratifications in 12- to 21- meter depths								
Field moisture	relatively dry in surface 30 meters, moist below 30 meters	relatively moist throughout	relatively wet in surface 6 meters, moist below 6 meters								
Soluble-salt content	medium in surface 34 meters, low below 34 meters	medium to high stratifications throughout	medium in surface 13 meters, low below 13 meters								
Gypsum content	medium to high in surface 34 meters, none below 34 meters	medium to high stratifications throughout	low to medium in surface 13 meters								
Exchangeable sodium	moderate throughout	high in surface 12 meters, moderate below 12 meters	relatively low throughout								

TABLE 1 PROFILE CHARACTERISTICS OF SUBSTRATA SITES SELECTED FOR COMPUTER ANALYSES

\* Profile locations are cited in fig. 1 and table 1 (see first paper of this series).

TABLE 2 PROFILE STATUS FOR SATURATION AND PERCOLATION IN SUBSTRATA SITES SELECTED FOR COMPUTER ANALYSES

	Site					
Pronie status	3	8	9			
For saturation:						
Profile depth (meters)	99.6	98.8	94.3			
Pore volume, $\sum_{x=1}^{n} q_x$ (meters)	39.4	47.1	41.7			
Field moisture, $\sum_{y=1}^{n} q_y$ (meters)	25.7	39.8	34.8			
Water required, $\sum_{z=1}^{n} q_z$ (meters)	13.7	7.3	6.9			
Fractional $Q, q_i$ (meters)	0.91	0.61	0.46			
Depth segments, $\sum_{i=1}^{n} M_{i,\ldots,i}$	15	12	15			
For percolation:						
Profile depth (meters)	94.1	90.6	91.1			
Total pore volume, $Q$ (meters)	36.6	36.6	36.6			
Fractional $Q$ , $q_j$ (meters)	3.05	3.05	3.05			
Depth segments, $\sum_{i=1}^{n} M_{i}$	12	12	12			

profiles under consideration are stratified, and moisture contents in the depth segments calculated for saturation

(Program 1) are not uniform. The use of equation [12] requires that the data obtained from the saturation program be recalculated so that  $q_i$  is kept constant, and M segments are adjusted. The pore volume, Q, for the percolation program was selected to be 36.6 meters. so that  $q_i$  and  $M_i$  will be identical for all three sites (table 2). The depths of the substrata were thus decreased slightly. By a procedure similar to that described in the previous section, weighted mean values on chemical data for depth segments within the new Msegment were calculated, keeping  $q_i$ constant. Detailed chemical data on new M segments for each substrata profile appear in Appendix tables A, C, and E. These data are the initial values for the percolation computer program.

The source statement for the percolation program is given below, and a diagram of the computation scheme is shown in figure 7.

The average concentration of solutes in  $q_j$  increments of effluent, and the profile distribution of solutes, undissociated calcium sulfate, gypsum, and exchangeable-cation concentrations after each pore-volume displacement are computed by this program. A set of Dimension Statements is declared immediately after BEGIN (fig. 7), to

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ta e 🕌	DIMENSION TE(11), TC(11), TSA(11), TXX(11), TD(11), TDA(11),	TB(11)
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203	K1=0	
201		An and provide the second of the second s
	· A=A5 · [ · [ · ] :	[홍종 문문]
	F=F5	
	_S=S51	
	M=N5	나라 주 주 비
	CAS0=0.0	
202	J=J+1	18 왕 왕 년 <u>-</u> 1
	B=TB(J)	이 것 같 글
지 한 행	D=TD(J)	
	DA=TD4(J)	이번 잘 할 것 같아
	$A = (A + TA(J))/2 \cdot 0$	
4 4 2	$F = (F + i F (J)) / 2 \cdot 0$	
	$G = (G + TG(L))/2 \cdot 0$	김 사람은 일 날 수 있는 것이 좋아 있다.
	H = (H + TH(J))/2.0	나라 봐 많 다 많이
	W=TW(J) 中国人民的教育教育的问题和 10 日日日日日日日日日日日日日日日日日日日日日日日日日日日日日日日日日日日	
	CASO= (CASO+TCASO(J))/2.0	na lan siyan siyan saya lan lan lan saya saya saya saya saya saya saya sa
	ET=TE (J) - 등 등 년 월 월 월 월 월 월 월 일 달 달 달 달 달 달 달 달 달 달 달 달	
- C - S		
and a second sec		
24		[응용물로 2]
	IF(XXT)4,4,26	[응생 꽃 통 것]
4	U=SQRT(2.0*(A+F+G)+0.5*(S+H+W))	1월 28년 28년
يتم بنا حت	AA=EXP(-9.366*U/(1.0+U))	[순영문문]]
	IF(2.4E-5-A*G*AA)26,18,18	[12] 왜 잘 두 있]
26	X=0.0	的复数医肾白白
	U=SQR[(2.0*(A+F+G)+0.5*(S+H+W))]	
	$PD^{-A^{\prime}U}$	
	CC=A*G-12,4F-5)*FXP(FX)	
	R=SQRT(BB*BB-4.0*CC)	[[임 관 및 기 ]
지 한 정	X=(-SB+R)/2.0	
	CAS1=4.9E-3-CASD	[[ 물봉물 ] ]
	DEL=B*XXT-CAS1	自意議員主
	1F(UEU-X)2/,28,28	[11] 값 삶 볼 날 [
4		
3 - 1	실망 것 <mark>이 있는 것 같 것 같 것 같 않 않 않 않 것 것 것 것 것 것 것 것 것 것</mark>	[[] 홍콩 홍 종]

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### HILGARDIA • Vol. 38, No. 9 • June, 1967

工作で	· · · ·		目相美国語	b; et 25	8 8 1	医筋 带手	和21件	通过的。	同時時代でも日
	CAS1=C	.0		日間間	전 전기	일 쉽 물급	「招目」	승진 문화	专任 許強 美口 [
	A = A + X	بسيافية بسة شهادي	ديكش المشرد يجبس بسودين	5 6 5	100 B.	nia de la comunita No de la comunita			
	G=G+X	물건 문제 값	1 등 위 것 등	日息時	황물님	좋 혐 옮는		8 a a f	
in the sea	H=SORT	12.0*(A+E+	G1+0-5+(S+	HHWYY	<u> 19-13-</u>			1997 - 29 - 2017	
고말	AA-EYE	1-0 366*11	(1 0+11))		걸렸다	直接 私長	3 念 [4]		
		05-3+114	+ / / # C )	and the second second					승규는 승규는 물건을 다 물건을 다 다 다 다 다 다 다 다 다 다 다 다 다 다 다 다 다 다 다
1		• 9E-3TAA*A		は読録		비원 많은	승 있는 [1]	装装推动	
S. Lana	CC=AA*	A*G-4.9E-2	+CASU		<u></u>				
1 1 2	X1=(-E	B-SURICEB	88-4.0*AA		(2.0*	AA)		著 倉 하는	한 문 문 한 감 이 같이
15 ( <sub>12</sub> - 5) (12 - 5)	CASU=C	ASU+X1	물용 몸 좀 없.	[2] 몸 31	<u> </u>	전 전 전 문		<u> 19 19 19 1</u>	
8 12 13	A = A - X I	이 같은 것 같아?	비원 왕 왕 동	「「鼻腦」	资源!	김 왜 생님		황상 동물	이 너 옷 좀 거 것
A 1: 41	G=G-X1		비행 왕 문 문	的意题。			1 14 12	홍 물 물 :	이 네 왜 왜 한 것
	GO TO	44			82 83			동 왕 구 [	
18	IF(G)1	,1,6	이 잘 온 안 날.	13 号 麗	말 읽는	김 않 감구	신은 물	참 참 같 :	방송 김 왕은 가지
6	IF(A)1	,1,7		3.61	福息	1 1 1 1		김 씨 역 1	正確ななど
1	IF (CAS	0)44,44,7	불 옷 옷 물 물		創業日	김 태 성감	이 좀 많.	김 권 꽃을	승규는 감독을 가지?
28	A = A + X			12 10 10					한 김 김 김 김 씨
370	G=G+X	너희도 영문.	医骨骨骨 医白	방송 문		이 집 집 집		물 옳 문 !	2 [6 2] 봄 김 글 [
	XXT=XX	T-X/B							
	CASO = C	450+0451	물 잘 잘 물 간.	日間間			한 문 문	拉 鉛 韵子	황봉왕 법 것 이
in the	XXT=XX	T-CASI/B					an a	등 품 품 (	3. 여름 등 것 같아.
44	A2=A		目接受 這 65		台周日	기업 성극	3 월 (종)	전 집 것 :	집 문 문 을 봐 군 [
	TE/A=E	145.46.46			195 - 25 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 -				
15	1 1 - 1 - 1	743,40,40	的复数自动	國際局	8 Q	김 영제	刘继 []	성 은 옷을	蒙爾德爾 日日
1 <b>12</b> 12	1 J-1	한 한 종 종 왕		11 53 53 Franklin (***		ۇ. ئىل. <del>ب</del> ۇرىك	9. M. N.	<u>9. s. c.</u>	이 이 가지 않는 것 같아.
	AZ=A			물질을		일 안 같다	물 옷 [4]	물 좀 넣고	이 것 같 것 같 ^
13   1 - 13 24   1 - 144		김 김 가 있 같.	12 / 12 / 14 12 / 15 / 16	13.5				전 전 전	1. 그 날 날 다 나 !
	F=AZ	[2 중 동 영 율]	13 등 실험 전 1			기 등 집 :	2월 문	通台 招子	이 물 한 물 수 대
	C12=C1	말 한 한 번 한 .	<u> 문 한 한 한 한</u>			김 성 성 :		이 같다.	
14 M	CT=ET	문 문 문 문 문	문항 문 좀 할.	國際會		김 왕 왕극	3 X A	성 동 것 ]	
	ET=CTZ	. 안 볼 번 책	물건 한 번 번	14 日日	관 안 [	한 것 않는	신 권 영.	꼰 더 레를	물려 있는 것이다.
	DAZ=DA	고 말 많 않는다.		12.2				法国 調子	
승규는 영	DA=DA*	D	물을 걸 잘 잘	自然病				김 것 집 문	新聞記録を目
100 (Mar.) 100	GOTO	5	이 가 나는 것 같		26 (3)		3 23 25	民國者子	「「「「「「「「」」」
46	IJ=2	[1] [2] 含 [2]	[] 고 값 봐 요.	[상황 문]	전 영제	동물 관람	한 월 (철)	김 문 물을	방법 문 탄 문 나
19 <b>5</b> 10 12	Z=1.0E	-6		24.4	調整す	이 없는	ते स्ति ि		
	EX=EXP	((-2.341*)	)/(1.0+U))		位置	计编号的		8883	
شیر در از شیر ۱۹۰۱ - از از	AA=-2.	0*B*B	a <u>19 17 18 18</u>	111 A.A. 1411 (3) A.A. 257		상황 성공	문화 문		
김 글 글	AAA=1.	5*ET+1.5*0	T+SAT	國著憲		이 없 않는	물 왕 목	影 影 儀 :	
14 (14 H	BB=4.0	*B*B*AAA-2	.0*B*(ET*E	+5)+4	.0+B*	DA*EX	물건 [[]	문한국 (	
	CC=4.0	*B*(ET*B+S	) * AAA-0.5:	*S*(S+	4.0*€	T*B)-4	.0+DA+	EX*(B*	SAT+A)
	DD=S*(	S+4.0*ET*E	) * AAA-0.5:	*S*S*E	T+B+S	AT + SAT	EX +DA	+4.0*E	X*DA*SAT*A
	EE=S*S	*ET *AAA-SA	T*SAT*A*E	(*DA		제 왜 집 !	이 몸 너희	対対対し	
15	ZZ=-((	((AA*Z+BB)	*Z+CC)*Z+[	D) + Z + 1	EE)		화 함 물		
11	ZZZ=((	(4.0*AA*Z+	3.0*BB)*Z+	2.0+C	C)*Z+	DD)+Z	# 23 [3]	法官员!	
ينبق منا بد	ZZ=ZZ/	zzz			最景日	la litta da la S NA da la	이 없다는	영 영 영 영 영	
	Z=Z+()	-0+ZZ)	남김 문원물.			이 좀 집구	이 같다.	常常教育	
	TF(ZZ+	1.0E-3115.	16.16	물 전 영			na 1763 - 1783 Managana - Marina Managana - Marina		
16	IF(77-	1-0F-3123	23.15	물 몸 몸	图 招 [	1881	新聞日	复展贫主	
23	A=A-R#	z					4 <u>82</u> 13 7 14 13	공습-광극	
1	S=S+2	0*B*Z	周間間間間	医白 潤	12 12	이 번 월 문	1篇欄:	的复数	合物 被害 日子
جيمه المجار	ET=ET+	7		<u>10 53 53</u>		김 아이 신 문	3-83-83- 8-	영국 영국 영국	
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1, - 0	A7-A			自居昌	國國主			的复数	
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法保護	H-F E-A7	[] 물 집 금 용.	이 물 집 거 가.	日日間	音感し	이 않 않다	1813	동물문 (	新局部 自己 [
122	F-AZ	<u> 위 티 (3 월</u>	기 문 문 는 그		ND	1821		월 년 년 년	日本調整周囲
19.15° 65	24 A.4. 303 -	128 N. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1.	NG 591.501.228 888.	ttu né ⊒bé.	. 214 - 612 <u>-</u> 6	ar 623 . 627 . 6	allina kiki,	فريقل يقتقد فتد	虹局 經 括

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CT2=CT CT=CT CT=CT CT=CT DA=DAZ A3=A BB=A+E*(CT+D*ET)+D*F AA=B*(1.0-D) CC=(A*CT-D*F*ET)+D*F AA=B*(1.0-D) CC=(A*CT-D*F*ET)+D*F A=SQRT(BB*BB-4.0*AA*CC) Y=(-BB*R)/(2:0*AA) IF(1.0-D)3,2,3 A=A+B*Y F=F=N*Y CT=CT+Y OEL=A-A1 IF(DEL+1:0E=5)24;48;48 A=A+B*Y F=F=N*Y ET=ET-Y CT=CT+Y OEL=A-A1 IF(DEL+1:0E=5)24;48;48 IF(DEL+1:0E=5)24;50,50 SO IF(DEL+1:0E=5)24;50,50 SO IF(DEL+1:0E=5)24;52,52 IF(DEL+1:0E=5)18;8,24 IF(DEL+1:0E=5)18;8,24 IF(DEL+1:0E=5)18;8,24 IF(DEL+1:0E=5)18;8,24 IF(J)=F TS(J)=S TG(J)=G TH(J)=H TX(J)=XT IF(J)=F TC(J)=CT TS(J)=S TG(J)=CS TC(J)=CT TS(J)=S TC(J)=CT TS(J)=S TC(J)=CT TX(J)=XT IF(J)=F T(CJ)=CT TX(J)=XT IF(J)=F T(CJ)=CT TX(J)=XT IF(M=K1) 34;34;201 DEL=A(J),TC(J),TS(J),TG(J),TH(J),TM(J),TCASO(J) K1=K1+1 IF(M=K1) 34;34;201 DEL=A(J),TC(J),TS(J),TG(J),TH(J),TM(J),TCASO(J) K2=K2+1 IF(K=K2) 21;21;203 END	31:0		h Alder		च सम	トな際	S 33	日 ② > 8 4	化透露器形	接合之一
LI=E] ET=CTZ DA=DAZ DA=DAZ BB=A+B*(CT+D*ET)+D*F AA=B*(1.0-D) CC=(1a <ct-d*f*et) R=SQRT(BB*BB-4.0*AA*CC) Y=(-BB+R)/(2.0*AA) IF(1.C-D)3,2,3 Z Y=-(A*CT-D*ET*F)/BB A=A*B*Y F=F=B*Y ET=ET-Y CT=CT+Y DEL=A-A1 IF(DEL+1.0E-5)24,48,48 48 IF(DEL+1.0E-5)24,54,52 IF(DEL+1.0E-5)24,52,52 Z IF(DEL+1.0E-5)24,52,52 Z IF(DE+1.0E-5)24,52,52 Z IF(DE+1.0E-5)24,52 Z</ct-d*f*et) 		CTZ=CT	تبير أمته ساريا				ي و در اي م مرجع مرجع م	11232		
<pre>L=L=0.2 J= DA=DA2 A3=A A3=A B=A+B*(CT+D*ET)+D*F AA=B*(1.0-D) CC=(ACT-D*F*ET) R=SQRT(BB*B-4.0*AA*CC) Y=(-BB*R)/(2.0*AA) IF(12.0*AA) IF(12.0*AA) Y=-(A*CT-D*ET*F)/BB A=A+B*Y ET=ET-Y CT=CT+Y DEL=A-A1 IF(DEL+1.0E-5)24;48;48 48 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;50,50 F1 DEL=A-A2 IF(DEL+1.0E-5)24;50,50 F0 IF(DEL+1.0E-5)24;52,52 F1 DEL=A-A3 F1 COL+1:0E-5)24;52,52 F1 COL+1:0E-5)24;52 F1 COL+1:0E-</pre>								医骨膜间的	机过度装置机	停着自己
DA=DA2 BB=A+8*(CT+D*ET)+D*F A=B*(10-0) CC=(A*CT-D*F*ET) R=SQRT(BB*BB-4.0*AA*CC) Y=(BB*R)/(2.0*AA) JF(1.0-D)3.2,3 Z Y=-(A*CT-D*F*F)/BB A=A+8*Y F=F-B*Y ET=ET-Y CT=CT+Y DEL=A-A1 IF(DEL+1.0E-5)24;48;48 48 IF(DEL-1.0E-5)24;949;24 49 DEL=A-A2 IF(DEL+1.0E-5)24;52;52 JF(DEL+1.0E-5)51;51;24 51 DEL=A-A3 IF(DEL+1.0E-5)24;52;52 JF(DEL+1.0E-5)8;8;24 8 TA(J)=A TF(J)=F TS(J)=S TG(J)=G TH(J)=H TW(J)=W TCASO(J)=CASO TE(J)=SAT' TSA(J)=TE(J)=TC(J			رده سرم روست وسی در	.라.[라.소.	. شبه . درموه . همچه					
A3=A BB=A+E * (CT+D+ET)+D*F AA=B*(1.0-D) CC=(A+CT+D+ET)+D*F AA=B*(1.0-D) R = SQRT(BB+BB+4.0*AA*CC) Y = (-BB+R)/(2.0*AA) IF(10-D)3,2,3 2 Y=-(A+CT-D+ET*F)/BB A = A+B*Y ET=ET-Y CT=CT+Y DEL=A-A1 IF(DEL+1.0E=5)24;48;48 48 IF(DEL+1.0E=5)24;48;48 IF(DEL+1.0E=5)124;50;50 50 IF(DEL+1.0E=5)124;50;50 50 IF(DEL+1.0E=5)124;52;52 51 DEL=A-A3 IF(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 53 IF(DEL+1.0E=5)124;52;52 54 IF(DEL+1.0E=5)124;52;52 55 IF(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 53 IF(DEL+1.0E=5)124;52;52 54 IF(DEL+1.0E=5)124;52;52 55 IF(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 53 IF(DEL+1.0E=5)124;52;52 54 IF(DEL+1.0E=5)124;52;52 54 IF(DEL+1.0E=5)124;52;52 55 IF(DEL+1.0E=5)124;52;52 56 IF(DEL+1.0E=5)124;52;52 57 IF(DEL+1.0E=5)124;52;52 51 DEL=A-A3 1F(DEL+1.0E=5)124;52;52 52 IF(DEL+1.0E=5)124;52;52 52 IF(DE+1.0E=5)124;52;52 52 IF(D+1.0E=5)124;52;52 52 IF(D+1.0E=5)124;52;52 52 IF(D+1.0E=5)124;52;52 52 IF(D+1.0E=5)124;52;52 52 IF(D+1.0E=5)124;52 52 IF(D+1.0E=5)124;52 52 IF(D+1.0E=5)124;52 52 IF							공연.	開設部。	法法法法法	
DD-ACTOR (L) - D) CC= (A *CT-D *F *ET) R = SQR1 (B * B * A < 0 * A * CC) Y = (-BE+R) / (2.0 * AA) IF (1.0 - D) 3, 2, 3 A = A + B *Y F = F - B *Y ET = ET - Y CT = CT + Y DE L = A - A1 IF (DE L + 1.0E - 5) 24, 48, 48 IF (DE L - 1.0E - 5) 24, 94, 9, 24 JF (DE L + 1.0E - 5) 24, 50, 50 S0 IF (DE L + 1.0E - 5) 24, 50, 50 S1 DE L = A - A2 IF (DE L + 1.0E - 5) 24, 52, 52 IF (DE L - 1.0E - 5) 8, 8, 24 TF (DE L - 1.0E - 5) 8, 8, 24 TF (J) = F TG (J) = G TH (J) = H TC (J) = G TH (J) = K TC (J) = ST TS (J)	<u>_</u> ∦? []	A3=A	- / CT + D+	CT 140-1						. المتعمر .
AA-B-V-C-U-DF+ET R=SQRT(BB+BB-4.0*AA*CC) Y=(-BG+R)/(2:0*AA) IF(1.0-D)3,2,3 Y=-(A4CT-D*ET*F)/BB A+B*Y F=F-B*Y F=F-B*Y F=ET-Y OEL=A-A1 IF(DEL+1.0E-5)24,48,48 48 IF(DEL-1.0E-5)24,50,50 50 IF(DEL-1.0E-5)54,51,224 51 DEL=A-A2 IF(DEL+1.0E-5)24,52,52 52 IF(DEL-1.0E-5)54,8,24 8 TA(J)=A TF(J)=F TS(J)=S TG(J)=C TG(J)=C TG(J)=C TG(J)=C TG(J)=C T(J)=C			*(CI+D*	CI / TU*I					비 김 영 김 동	
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<pre>N=SQR 10B=00+.0FAACCJ Y=-BH+R)/(2.0+AA) IF(1.0-D)3,2,3 Y=-(A+CT-D*ET*F)/BB A=A+B*Y F=F=B*Y ET=ET-Y CT=CT+Y DEL=A-AA1 IF(DEL+1.0E=5)24,548,48 48 IF(DEL-1.0E=5)24,50,50 50 IF(DEL-1.0E=5)51,51,24 51 DEL=A-A32 IF(DEL+1.0E=5)51,51,24 52 IF(DEL+1.0E=5)8,8,24 8 TA(J)=A TF(J)=F TS(J)=S TG(J)=G TH(J)=H T(J)=H T(J)=H T(J)=ET TC(J)=CT TS(J)=CAS0 TE(J)=CAS0</pre>							\$ 2.	[1] [1] [1] [1] [1] [1] [1] [1] [1] [1]	封國營營 白色	
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<pre>A = A+0 + 0 + 7 ET = ET - Y CT = CT + Y DEL = A - A1 IF (DEL + 1.0E - 5) 24 + 48 + 48 48 IF (DEL - 1.0E - 5) 24 + 9 + 9 + 24 49 DEL = A - A2 IF (DEL + 1.0E - 5) 24 + 52 + 52 51 DEL = A - A3 IF (DEL - 1.0E - 5) 24 + 52 + 52 52 IF (DEL - 1.0E - 5) 24 + 52 + 52 52 IF (DEL - 1.0E - 5) 8 + 8 + 24 8 TA(J) = A TF(J) = F TS(J) = S TG(J) = G TH(J) = H TW(J) = W TCASD(J) = CASD TE(J) = CT TSA(J) = SAT TXX(J) = SAT TXX(J) = XXT IF (J - M) 202 + 10 + 10 NU = 202 + 10 + 10 NU = 202 + 10 + 10 NU = 10 + 10 + 10 + 10 NU = 10 + 10 + 10 + 10 + 10 + 10 + 10 + 10</pre>	4	Y=-(A+	CI-D#EI	**1/88	いたと	目出詞	황 율.		이 옷을 하는 것	
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K2=K2+1 IF (K-K2) 21,21,203 END	35 🔅	PRINT	41,TE(J	),T(C(J)	,TSAL	i),TXXI	(J)	12 (2) (2) (2) (2) (2) (2) (2) (2) (2) (2	11 : 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이 이	
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store initial values and subsequent computed values of subscripted variables for each M segment. The source statement shown has M = 11, which may be replaced by M = 13 for the profiles under consideration. The variables in  $M_{13}$  are assigned a value of zero. Depth  $M_{13}$  is utilized for spacing in the printing of computed values. The Fortran language used in this program is identical with the computer program in Program 1 (p. 326). The molar concentrations of solutes in the applied solution,

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Feather River water, are read in statement 21. Initial profile concentrations in moles per liter and moles per gram soil of subscripted variables (Appendix tables A, C, and E) are also accepted in addition to TB, TD, and TDA.

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Control symbol M is defined as the number of M segments making up the substrata profile, while K is the number of pore volumes of effluent to be percolated. K2 counts the number of pore volumes of effluent computed, K1 counts



Fig. 7. Computational routing for predicting effluent composition and chemical changes in a stratified profile during percolation.

the number of fractional pore volumes computed, and J counts the number of M segments equilibrated.

Under statements 31, 203, and 201 are initializing statements for K2, K1, and J, respectively. Substitution statements for solutes in the applied solution to the computing form are also made under statement 201. The flow of computation proceeds to 202, where J is increased by 1 and subscripted variables for  $M_1$  are read. Equation [13] is also considered. Segment  $M_1$  is equilibrated by successive approximations in the equilibrium cycle, 24 through 52, designated as loop A.

Equilibrium values for  $M_1$  are placed in storage by statement 8, replacing the initial values. The next computation involves the passage of  $q_j$  volume of solution from  $M_1$  into  $M_2$  by going back to 202 (fig. 7). The loop J formed from 202 to 8 and back to 202 computes J equilibrations with M segments.

If J = M, branch 10 is taken, where the solute concentrations in  $q_j$  volume of percolate are printed. K1 is increased by 1, and branch 201 is taken where J is reset to zero again. Another application of  $q_j$  volume of Feather River water is considered, and calculations are again made in loop J until J = M. Output in statement 10 continues in loop K1, statements 201 to 10 and back to 201, until K1 = M. K1 is defined as the number of fractional pore volumes making up one pore volume of effluent.

If K1 = M, branch 34 is taken, where a Do Loop is used to print out the profile distribution of subscripted variables after one pore-volume displacement. K2, which counts the number of pore volumes computed, is increased by 1, and branch 203 is taken, forming loop K2 from 203 to 35 and back to 203. The operation progresses in loop K2 until K2 = K, where K is a pre-set number of pore volumes to be percolated. K was set at 5 for this problem.

Thus, for these profiles, each of the 12 M segments is equilibrated by loop A. Then 12 iterations are made in loop J to calculate the equilibrium solute concentration for each  $q_j$  percolate. Loop K1 is executed 12 times to print out fractional pore volumes, the sum of which equals one pore volume of effluent. And finally, five iterations are made in loop K2 to percolate five pore volumes of the effluent. In addition, profile distributions of subscripted variables are printed after each pore-volume displacement. The computer time required for these operations was about 2 minutes, 45 seconds for each substrata.



Fig. 8. Profile distribution of total soluble salts at field-moisture (FM) content and at saturated pore volume (PV).

### Results

The profile distribution of total soluble salts at field-moisture content, denoted by FM, and at pore-volume saturation, denoted by PV, for sites 3, 8, and 9 is presented in figure 8. At field moisture, moderate amounts of soluble salts are located in the upper third of these profiles. Q depth of Feather River water is applied on the surface of the profile in  $q_i$  increments (table 2) to fill these profiles to pore-volume saturation. Considerable displacement of solutes occurred during saturation with a relatively salt-free recharge water (fig. 8). The next step involves effluent percolation from these profiles. Detailed data on the saturated profiles are found in Appendix tables A, C, and E for sites 3, 8, and 9, respectively. These tabulated data are the input data for the percolation computer program.

As  $q_j$  depth of water, 3.05 meters, is applied on the surface of the saturated profile, a like amount of effluent percolates out of the bottom. Since the profile consists of  $12 M_n$  segments, and  $q_j$ was defined as the amount of solution in each  $M_i$  segment, then  $12 q_j$  fractions are equivalent to one pore volume, or 36.6 meters, of water. The average concentration of a given solute in each  $q_j$ volume of percolation is computed by the percolation program. After each pore volume of effluent, the profile distribution of solutes, undissociated calcium sulfate, gypsum, and exchangeable bases is printed.

# Site 3—Salt and gypsum in top third of profile

The solute concentrations in the effluent, as a function of pore-volume fractions, are shown in figure 9 for substrata site 3. The concentration curve for Cl<sup>-</sup> illustrates the leaching of an ion assumed to be unaffected by solubility or sorption reactions. As indicated in Appendix table A, the middle portion of the profile contains large amounts of Cl<sup>-</sup>, while at the lowest



Fig. 9. Total salts and ionic concentrations as a function of pore-volume percolate from substrata site 3, west side, San Joaquin Valley, California.

depth, 87.4 meters, the amount is relatively low. The leaching pattern of Clis influenced by its profile distribution in the saturated state. Consequently the Cl- concentration in the initial porevolume fraction is relatively low, rises rapidly, and reaches its maximum at about 0.5 pore-volume displacement (fig. 9). It then decreases rapidly, followed by smaller concentration gradients. For all practical purposes, Clwas leached from the profile with 1.5 pore volumes of effluent.

Initial values for  $SO_4^=$  were moderately high throughout the profile (Appendix table A). With continued leaching,  $SO_4^=$  steadily increased in concentration until a peak of 70 m.e. per liter was attained at pore volume 1.5 (fig. 9). The large amounts of  $SO_4^=$  percolating out may be attributed to the dissolution of gypsum from the upper depths and transport through the lower, nongypsiferous depths. In excess of 1.5 pore volumes, SO<sub>4</sub><sup>=</sup> is the predominant anion in the percolating waters. Relatively high concentrations of solutes are maintained throughout five pore volumes of percolate even though the applied water contains only a concentration of 1 m.e. per liter. Profile distributions of gypsum after each pore-volume displacement are given in table 3. In the surface depth, 0 to 7.5meters, gypsum was leached out after application of one pore volume of water. After five pore-volume displacements, appreciable amounts of gypsum are still present in the 7.5- to 39-meter depth, and with 10 pore-volume displacements, large amounts still remain at 23.3 to 30.7 meters. Even with limited solubil-

TABLE 3
PROFILE DISTRIBUTION OF GYPSUM AFTER
$n$ PORE-VOLUME PERCOLATIONS $(PV_n)$

(Site	3)
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0.11.4	$CaSO_4 \cdot 2H_2O$										
Soll depth	$PV_0$	$PV_1$	PV2	$PV_3$	PV4	$PV_5$	PV10				
meters			n	n.e./100 gm so	il	·					
0.0-7.5	5.7	0.0	0.0	0.0	0.0	0.0	0.0				
7.5-16.0	33.2	31.1	24.8	18.7	12.8	7.1	0.0				
6.0–23.3	31.3	29.4	28.7	28.3	27.8	27.4	3.3				
3.3.30.7	29.6	28.3	27.5	27.2	27.0	26.8	25.2				
0.7-39.0	11.2	10.8	9.5	9.0	8.8	8.6	7.5				
9.0-47.7	2.9	3.0	1.8	0.7	0.2	0.0	0.0				
7.7-55.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
5.5-63.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
3.4-71.6.	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
1.6-79.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
9.8-87.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
7.4-94.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0				

ity, the presence of gypsum in the substrata has a profound effect on the solute concentration of percolating waters.

The moderate amounts of soluble Na<sup>+</sup> in the substrata profile were indicated (Appendix table A), but the concentration curve for Na<sup>+</sup> (fig. 9) is seen to be unlike that of Cl<sup>-</sup> because of cation exchange. Exchangeable sodium at pore saturation (Appendix table A) is relatively low when compared with exchangeable Ca<sup>++</sup> and Mg<sup>++</sup>. However, if exchangeable sodium is expressed in terms of sodium percentage of the exchange capacity, the range is from 8 to 16 per cent in the profile.

Sodium ion concentrations in the effluent (fig. 9) are shown to be relatively constant because of the simultaneous replacement of adsorbed Na<sup>+</sup> by divalent cations and displacement of soluble Na<sup>+</sup> by the percolating water. However, the percentage of Na<sup>+</sup> to total cations shows considerable variation. For example, at 0.5 pore volume of effluent the Na<sup>+</sup> is 40 per cent, whereas at 5 pore volumes it has increased to 76 per cent. Because of the moderate amounts of gypsum in the upper half of the profile, substantial replacement of exchangeable Na<sup>+</sup> has occurred (fig. 10). The surface 50 meters are nearly Na<sup>+</sup>-free after 5 pore-volume displacements, and the computer analysis predicts that the entire profile will be low in Na<sup>+</sup> before the gypsum is exhausted.

The leaching patterns for Ca<sup>++</sup> and  $Mg^{++}$  are similar (fig. 9). The initial rise in concentration of these solutes is mainly due to displacement from the saline horizons, and with progressive percolation the concentration decreases. As noted in Appendix table B, gradual increases in exchangeable Ca<sup>++</sup> occur throughout the profile at the expense of exchangeable Na<sup>+</sup> and Mg<sup>++</sup>, with the exception of the lowest depth. Thus Ca<sup>++</sup> in the percolate is limited by the solubility of gypsum in the gypsiferous horizons and by cation exchange in the lower depths. The Mg<sup>++</sup> concentrations in the effluent are largely controlled by cation exchange.

In addition to ionic species of  $Ca^{++}$ and  $SO_4^{-}$ , computed concentrations of undissociated  $CaSO_4$  are presented. The concentration levels are lower than 4.9 millimoles per liter, indicating that the percolate is unsaturated with respect to gypsum.

The  $\text{HCO}_3^-$  concentrations were held constant in their respective  $M_i$  segment,



Fig. 10. Exchangeable sodium, by depth, after percolation of various pore volumes (PV) through the profile of substrata site 3, west side, San Joaquin Valley, California.

and the estimated concentration in the percolate was 2 m.e. per liter—the same concentration as in the depth segment 87.4 to 94.1 meters. However, it should be noted that, as the profile is leached free of salts, the concentration of  $HCO_3^-$  from  $CaCO_3$  may become increasingly important.

Figure 11 summarizes salinity status after each pore volume of percolation. Computed equilibrium concentrations of solutes, undissociated  $CaSO_4$ , solidphase  $CaSO_4 \cdot 2H_2O$ , and exchangeable cations in the profile after 1 and 5 pore-volume displacements are given in Appendix table B.

# Site 8—Salt and gypsum stratified throughout profile

Profile distribution of ions and salts at pore saturation, for site 8, is given in Appendix table C. The highest level of salinity is located in the 6.8- to 38.5meter depths, with Na<sup>+</sup> and SO<sub>4</sub><sup>=</sup> predominant. The profile is gypsiferous throughout, with layers of high concentration. Moderate levels of adsorbed



Fig. 11. Total soluble-salt content, by depth, in substrata site 3, west side, San Joaquin Valley, California, after various pore-volume (PV) displacements.

Na<sup>+</sup> are located in the upper half of the profile.

The effluent composition and concentration (in pore-volume fractions) are shown in figure 12. The low level of Clin the profile limits its concentration in the effluent, except for the first pore volume. On the other hand,  $SO_4^{=}$  remains at moderately high concentration throughout the percolation of 5 pore volumes because of the continued solubilization of gypsum. Unlike that in site 3, the  $SO_4^{=}$  concentration is high from the very onset of percolation because of the presence of gypsum in the lower depths. Ion pair CaSO<sub>4</sub> concentrations were 4.9 millimoles per liter in the effluents, which indicates gypsum-saturated percolate.

Profile distribution of gypsum at site 8 after percolation of n pore volumes is given in table 4. With increasing volumes of percolate, the surface depths are progressively leached free of gypsum. Actually, in the lower depths, slight increases in gypsum are noted as a result of precipitation. Large



Fig. 12. Total salt and ionic concentrations as a function of pore-volume percolate from substrata site 8, west side, San Joaquin Valley, California.

amounts of gypsum are present in the profile after 5 and even 10 pore-volume displacements.

Sodium ion concentrations (fig. 12) were nearly constant for about the first 1.5 pore volumes, and then increased to a peak of 3.5. The appearance of moderate concentrations of Na<sup>+</sup> in the effluents is the integrated effect of a mass of high Na<sup>+</sup> solution from the 6.8- to the 38.5-meter depth, modified by dispersion and cation exchange. The sudden increase in Na<sup>+</sup> concentration is illustrated by examining the profile distribution of ESP (exchangeable sodium percentage) (fig. 13). At saturation, the surface depths were high in ESP, which became low with continued application of water. However, adsorbed Na<sup>+</sup> increased in the lowest depths after 3 pore volumes, which coincides with the finding of peak concentrations of Na<sup>+</sup> in the effluents.

Magnesium ion concentrations were

low and relatively constant throughout 5 pore volumes of effluent, whereas the Ca<sup>++</sup> content was higher but also fairly uniform. The concentrations of Ca<sup>++</sup> were largely controlled by the solubility of gypsum and exchangeable Mg<sup>++</sup> (Appendix table D). The HCO<sub>3</sub><sup>--</sup> concentrations were fixed at 1.2 m.e. per liter.

The salinity status of profile 8 after different pore volumes of effluent is shown in figure 14. In contrast to substrata site 3, the concentration of solutes in the effluent remains relatively high with progressive leaching, and is expected to remain so until gypsum is depleted from the profile.

### Site 9—Small amounts of salt and gypsum in top 13 meters

The initial distribution of salts for site 9 at saturation is given in Appendix table E. In the 6.1- to 29.7-meter depths, levels of salinity are high, while at lower depths the concentration is

(Site 8)											
Gell denth	CaSO <sub>4</sub> · 2H <sub>2</sub> O										
Son depth	$PV_0$	$PV_1$	$PV_2$	PV3	PV4	PV.	PV10				
meters	m.e./100 gm soil										
0.0- 6.8	20.5	10.4	3.2	0.0	0.0	0.0	0.0				
6.8-14.3	22.2	19.5	18.8	16.1	10.0	6.0	0.0				
14.3-23.7	2.5	0.0	0.0	0.0	0.0	0.0	0.0				
23.7-31.3	6.1	4.3	2.2	1.1	0.2	0.0	0.0				
31.3-38.5	36.9	37.5	35.5	34.7	34.1	32.9	10.7				
38.5-45.8	15.0	18.9	17.3	16.3	15.8	15.4	12.5				
45.8-53.2	8.3	11.1	10.9	9.9	9.6	9.5	7.7				
53.2-60.7	1.3	3.2	4.0	3.2	2.8	2.9	2.3				
60.7-68.4	10.5	11.5	13.0	12.5	11.6	11.4	12.0				
68.4-76.2	20.5	21.2	22.7	23.0	22.0	21.2	22.1				
76.2-84.0	20.5	20.9	21.8	22.6	22.2	21.2	21.1				
84.0-91.5	28.3	27.9	28.3	29.0	29.1	28.3	27.0				

TABLE 4 PROFILE DISTRIBUTION OF GYPSUM AFTER n PORE-VOLUME PERCOLATIONS  $(PV_n)$ 



Fig. 13. Exchangeable sodium, by depth, after percolation of various pore volumes (PV) through the profile of substrata site 8, west side, San Joaquin Valley, California.

lower. Small amounts of gypsum are present in the 0- to 21.8-meter depths.

The Cl<sup>-</sup> concentration in the percolate is low (fig. 15), reflecting the small amounts in the profile. In the effluent,  $HCO_3^-$  was held constant at 1.6 m.e.



Fig. 14. Total soluble-salt content, by depth, in substrata site 8, west side, San Joaquin Valley, California, after various pore-volume (PV) displacements.

per liter—the same concentration as in the lowest depth segment. With the first 0.5 pore volume of effluent, a rapid increase in  $SO_4^{=}$  is indicated. After 1.5 pore volumes, concentration decreases rapidly with depletion of gypsum from the profile. All the gypsum in the surface depths was leached by 3 pore vol-



Fig. 15. Total salt and ionic concentrations as a function of pore-volume percolate from substrata site 9, west side, San Joaquin Valley, California.

ume displacements, but some precipitated in the three lower segments at  $PV_1$  (table 5). This corresponds with peak concentrations of solutes other than Cl<sup>-</sup> and of undissociated CaSO<sub>4</sub> in the effluent (fig. 15).

The Na<sup>+</sup> increases in concentration to about 20 m.e. per liter with 0.5 pore volume, and remains fairly constant until the amount of percolate approaches 3 pore volumes. The leaching curve for Na<sup>+</sup> reflects the continued replacement of exchangeable Na<sup>+</sup> from the upper depths as gypsum is dis-

TABLE 5
PROFILE DISTRIBUTION OF GYPSUM
AFTER n PORE-VOLUME
PERCOLATIONS $(PVn)$
(Site 9)

		CaSO4	$\cdot 2H_{2}O$	
Soll depth	$PV_0$	PV1	PV2	$PV_3$
meters		m.e./100	) gm soil	
0.0- 6.1	8.5	0.0	0.0	0.0
6.1-13.2	10.3	6.7	0.0	0.0
3.2-21.8	2.6	1.9	0.7	0.0
21.8-29.7	0.0	0.0	0.0	0.0
29.7-37.2	0.0	0.0	0.0	0.0
37.2-45.3	0.0	0.0	0.0	0.0
5.3-54.0	0.0	0.0	0.0	0.0
54.0-61.7	0.0	0.0	0.0	0.0
61.7-69.6	0.0	0.0	0.0	0.0
<b>39.6–77.2</b>	0.0	0.3	0.0	0.0
7.2-84.8	0.0	0.1	0.0	0.0
84.8-91.0	0.0	<0.1	0.0	0.0

solved (fig. 16). In contrast, since Clis not involved in exchange reactions, it is rapidly leached out (fig. 15).

The concentration of  $Ca^{++}$  and  $Mg^{++}$ in the effluent is determined to a large degree by the dissolution of gypsum, and with its depletion, these ions rapidly decrease in the percolate. Because of the low level of gypsum near the surface in site 9, rapid changes in profile salinity occur with leaching (fig. 17), in contrast to sites 3 and 8. With 3 pore-volume displacements, the profile is nearly salt-free (Appendix table F).

### DISCUSSION

To determine water quality percolating through substrata, certain boundary conditions must be established before theory and underlying assumptions can be appropriately applied. It is assumed that the surface soil and the substrata are permeable to the applied recharge water. The velocity during percolation is assumed to be of a magnitude that allows chemical equilibrium or near equilibrium to be attained between the flowing solution and the substrata materials. Although the model also assumes that only vertical flow takes place throughout the depths of the profile, it is recognized that stratifications and/or impermeable layers may impede vertical movement, and that considerable flow other than vertical may take place. The water content during percolation was fixed at saturated pore volume, but it is readily admitted percolation may take place under unsaturated conditions. The water content



Fig. 16. Exchangeable sodium, by depth, after percolation of various pore volumes (PV) through the profile of substrata site 9, west side, San Joaquin Valley, California.

during percolation may be set to any values, from saturated pore space to field-moisture content, in these computer programs.

The theoretical considerations involved in the equilibration of discrete substrata-salt water systems are subject to limitations discussed elsewhere by Dutt (1962*a*), Dutt and Doneen (1963), and Tanji *et al.* (see second paper in this series). By an empirical approach, the displacement of solutes from one depth increment to another is approximated. Thus the mixing mechanisms used in the computation are not intended to account for the entire miscible displacement of solutes.

The results show that ionic species and concentration of solutes may be rapidly altered as water percolates through the substrata. When soluble salts are layered in the surface depths, with a relatively salt-free profile be-



Fig. 17. Total soluble-salt content, by depth, in substrata site 9, west side, San Joaquin Valley, California, after various pore-volume (PV) displacements.

neath, the concentration of the initial percolating water from the saline horizons may become diluted, by dispersion, as the water passes through saltfree zones (substrata sites 3 and 9). On the other hand, if readily soluble salts are present throughout the profile, as in substrata site 8, the solute concentration in the percolating water may be high from the very onset of percolation.

The presence and concentration of gypsum greatly influence the quality of percolating waters. The percolation of water through gypsiferous horizons leads to marked increases in salinity from the dissolution of  $CaSO_4 \cdot 2H_2O$  and the simultaneous replacement of adsorbed Na<sup>+</sup> and Mg<sup>++</sup> by Ca<sup>++</sup>. This results in a percolate dominated by Na<sup>+</sup> and SO<sub>4</sub><sup>=</sup> and, to a lesser extent, by Mg<sup>++</sup>. Moderate to high salinity in the effluent persists so long as gypsum is present in the profile, as illustrated

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by sites 3 and 8 substrata. If the amount of gypsum is relatively low, the salinity content of percolating waters may be abruptly reduced upon depletion of gypsum from the profile, as at site 9. Therefore, the quality of the underground water will result from a mixture of percolating water, native ground water, and water flowing into the basin from any other source.

While the computer method for predicting the quality of water percolating through substrata gives only an approximation, the results are more comprehensive than any previous findings, and the method is of practical significance. The procedure may be extended and modified to include additional variables, reactions and more complex conditions.

Laboratory models simulating substrata profiles have been set up to test the applicability of the computer program presented in this publication. To date, the validity of the computer method has been confirmed by a twolayered, salinized, gypsiferous model.

### SUMMARY

A computer method for predicting quality of waters percolating through stratified profiles has been developed. Field data compiled from three substrata sites in the San Joaquin Valley of California were utilized in the Fortran programs.

Comprehensive predictions on solute concentrations in the percolate and on chemical changes in the substrata profile are presented. The formulations in the computer programs were based on theoretical considerations concerning the solubility and dissociation of gypsum and cation exchange. Approximations were made on water content during percolation and on displacement of solutes.

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	Water	content	gm per 100 gm	27.6	28.1	27.7	27.2	21.9	20.2	23.9	23.8	22.6	22.9	22.4	33.6
ION		Gypsum	m.e. per 100 gm	5.7	33.2	31.3	29.6	11.2	2.9	0.1	0.0	0.0	0.0	0.0	0.0
SATURAJ	Suc	Na <sup>+</sup>	m	0.2	2.0	3.2	3.1	3.0	3.6	3.0	2.8	2.1	1.8	1.8	2.2
OLUME	changeable i	Mg++	m. e. per 100 g	4.7	6.0	5.0	4.2	4.9	6.6	10.9	11.7	14.4	13.1	12.7	15.0
PORE-V	Ex	Ca+		17.6	15.0	12.6	11.4	12.7	16.4	12.5	11.7	0.0	6.7	6.3	10.9
atta at	Undissoc.	CaSO4	mM per l	3.9	4.9	4.9	4.9	4.9	4.9	4.3	3.8	2.2	1.6	0.9	1.0
TABLE A		HCO <sub>3</sub> -		0.9	0.8	0.8	0.8	1.0	1.2	1.2	1.3	1.6	1.6	1.7	2.0
PENDIX ( SALTS IN (Site 3)		с <mark>і-</mark>		<0.1	0.1	1.9	23.0	106.0	152.0	93.3	80.8	39.8	34.3	20.1	10.4
A AND 8	e ions	-*0S	er liter	18.2	53.9	74.7	67.1	42.6	35.4	45.4	44.0	36.8	33.4	26.9	24.6
N OF ION	Solubl	Na+	m.e. po	3.5	29.3	54.0	62.8	80.6	87.9	63.6	57.1	34.8	33.3	27.4	21.4
IBUTIO		Mg++		5.1	9.3	8.6	9.8	24.6	35.8	41.2	39.0	29.4	25.6	16.0	9.8
E DISTR		Ca+		10.5	16.3	15.0	18.6	44.1	62.6	33.5	28.5	12.8	9.3	4.5	5.0
PROFIL	4-1	Tridan Hoc	meters	0.0- 7.5	7.5-16.0.	16.0-23.3	23.3-30.7.	30.7-39.0.	39.0-47.7.	47.7-55.5.	55.5-63.4	63.4-71.6	71.6-79.8	79.8-87.4	87.4-94.1.

APPENDIX TABLE B DFILE DISTRIBUTION OF IONS AND SALTS IN SUBSTRATA AFTER 1 AND 5 PORE-VOLUME DISPLACEMENTS
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			Solub	le ions			T adian	Ц Ц	schangeable i	Suo	
Soil depth	Ca+	Mg++	Na <sup>+</sup>	-*0S	ci-	HC03-	CaSO	Ca++	Mg <sup>++</sup>	Na+	Gypsum
meters			m.e. p	er liter			mM per l		m.e. per 100 g	u	m.e. per 100 gm
				Aft	er 1 pore-vol	ume displace	ment				
0.0- 7.5.	9.5	2.7	0.5	11.6	0.03	0.9	1.6	18.7	3.7	0.04	0.0
7.5-16.0.	19.5	6.8 1	5.0	32.5	0.03	0.8	4.9	1.71	5.5	0.29	31.1
16.0-23.3. 23.3-30.7	17.6 16.2	2 2 2	15.6 28.5	40.9 51.5	0.03	× ×	4.4	14.8	5.1	0.86	29.4
30.7-39.0	15.3	8.1	40.9	63.2	0.10	1.0	4.9	13.4	4.9	2.4	10.8
39.0-47.7.	15.1	8.6	47.0	69.4	0.35	1.2	4.9	16.4	6.6	3.6	3.0
47 7-55.5.	12.9	13.7	46.6	1.17	1.1	1.2	4.1	13.2	9.8	3.4	0.0
55.5-63.4.	12.7	17.1	45.0	71.2	2.6	1.3	4.0	11.8	11.2	3.2	0.0
63.4-71.6.	11.7	23.5	42.3	71.3	5.4	1.6	3.5	9.4	13.3	2.7	0.0
71.6-79.8.	11.4	28.9	40.5	70.5	9.4	1.6	3.3	7.0	12.5	2.1	0.0
79.8-87.4.	11.8	32.9	39.7	68.8	14.7	1.7	3.2	6.4	12.4	1.9	0.0
87.4-94.1.	14.8	33.1	39.1	65.4	20.9	2.0	3.8	10.0	15.6	2.4	0.0
				Afte	er 5 pore-volı	ime displace	ments				
0.0-7.5.	0.6	0.2	0.2	<0.1	0.03	0.9	<0.1	18.6	3.8	0.05	0.0
7.5-16.0.	21.9	3.1	0.2	24.2	0.03	0.8	4.9	20.8	2.1	0.01	7.1
16.0-23.3.	21.2	6.1	0.2	26.6	0.03	0.8	4.9	17.2	3.5	0.01	27.4
23.3-30.7.	20.9	7.9	0.2	28.1	0.03	0.8	4.9	14.8	3.9	0.10	26.8
30.7-39.0.	20.7	9.0	0.4	29.1	0.03	1.0	4.9	15.9	4.8 7.8	0.02	8.6
47.7-55.5	191	11.4	8.4	31.4	0.03	1.2	4.0	17.4	8.7	0.34	0.0
55.5-63.4	11.6	12.3	10.8	33.7	0.03	1.3	3.0	14.6	10.8	0.81	0.0
63.4-71.6.	7.2	11.4	18.5	36.2	0.03	1.6	2.0	11.4	12.5	1.5	0.0
71.6-79.8.	4.8	10.2	23.7	37.8	0.03	1.6	1.4	8.0	11.8	1.9	0.0
79.8-87.4	3.9	9.6	26.1	38.6	0.03	1.7	1.1	6.8 2	11.8	2.1	0.0
87.4-94.1.	3.7	9.1	27.2	39.1	0.03	2.0	1.1	9.2	15.8	3.1	0.0

(Site 3)

	Water	content	gm per 100 gm	30.5	24.5	23.6	25.1	27.3	26.9	26.9	26.9	26.1	25.3	25.3	26.2
		The second	m.e. per 100 gm	20.5	22.2	2.5	6.1	36.9	15.0	8.3	1.3	10.5	20.5	20.5	28.3
	SUG	Na <sup>+</sup>	2	3.7	2.8	2.5	2.5	2.5	1.4	1.2	1.0	1.4	1.8	1.8	2.3
	changeable ic	Mg <sup>++</sup>	.e. per 100 gr	7.7	3.5	3.9	5.4	6.3	5.9	4.9	3.8	4.5	5.3	5.3	5.7
	Exe	Ca++	Ξ	12.4	3.3	2.0	3.3	6.9	12.8	12.9	13.0	16.0	19.3	19.3	18.4
	Undissoc.	CaSO.	mM per l	3.6	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
8)		HCO <sub>3</sub> -		1.9	0.7	1.2	1.4	1.1	1.0	0.9	0.9	1.0	1.1	1.1	1.2
(Site		CI-		1.1	7.9	36.2	40.6	34.0	14.4	10.9	7.3	5.9	4.3	4.3	4.3
	le ions	- <b>*</b> 08	er liter	69.4	158.0	189.0	131.0	92.4	47.4	44.4	41.3	43.0	45.0	45.0	51.3
	Solubl	Na+	m.e. p	50.3	128.0	159.0	111.0	78.4	28.7	25.1	21.4	23.1	25.0	25.0	30.9
		Mg <sup>++</sup>		10.3	23.6	49.4	42.4	28 8	12.9	10.4	8.0	7.4	6.9	6.9	7.5
		Ca++		10.9	14.6	16.9	17.9	18.8	19.5	19.2	18.9	18.3	17.6	17.6	16.9
	14 - F	undan noc	meters	0.0- 6.8.	6.8-14.3.	14.3-23.7.	23.7-31.3	31.3-38.5	38.5-45.8.	45.8-53.2	53.2-60.7.	60.7-68.4	68.4-76.2.	76.2-84.0.	84.0-91.5.

PROFILE DISTRIBUTION OF IONS AND SALTS IN SUBSTRATA AT PORE SATURATION APPENDIX TABLE C

		2	2	(Site	8)						
			Solub	le ions			Undissoc.	Ē	xchangeable i	ions	
	Ca++	Mg++	Na <sup>+</sup>	so4-	cI-	HCO <sub>3</sub> -	CaSO <sub>1</sub>	$Ca^{++}$	Mg <sup>++</sup>	Na <sup>+</sup>	Cypsum
			m.e. p	ver liter			mM per l		m.e. per 100 g	m	m.e. per 100 gm
				Afte	er 1 pore-volt	ume displace	ment				
:	19.2	9.2	7.0	34.5	0.03	1.9	4.9	17.5	5.9	0.43	10.4
:	17.3	12.3	16.3	45.0	0.03	0.7	4.9	6.1	3.0	0.40	19.5
:	16.0	15.8	29.7	60.4	0.06	1.2	4.8	4.6	3.2	0.64	0.0
:	15.2	20.1	47.7	81.9	0.14	1.4	4.9	5.1	4.8	1.3	4.3
:	14.7	22.5	66.3	102.0	0.38	1.1	4.9	6.4	6.8	2.6	37.5
:	14.5	17.4	74.4	104.0	0.88	1.0	4.9	20 0 20 0	4.2	0, x 0, 0	18.9
:	14.7	11.9 6.F	00.0	89.82 71 9	3.0	6.0 0	6. <b>4</b>	9.9 0.11	0.0 •	0.9 9 6	1.11
: :	16.5	0.0	37.5	55.7	9.6 4.6	1.0	4.9 4.9	14.9	4.6	2.3	0.2 11.5
	17.8	7.2	29.5	47.0	6.4	1.1	4.9	18.9	5.3	2.1	21.2
:	18.8	7.4	26.8	43.6	8.2	1.1	4.9	19.2	5.3	1.9	20.9
	19.1	8.2	27.4	43.7	6.9	1.2	4.9	18.9	5.6	1.9	27.9
				Afte	er 5 pore-volt	ume displace	ments				
	0.7	2.0	0.2	<0.1	0.03	1.9	<0.1	19.7	4.0	0.04	0.0
:	22.0	2.5	0.2	23.7	0.03	0.7	4.9	8.9	0.7	<0.01	6.0
:	19.7	5.9	0.2	24.7	0.03	1.2	4.4	6.9	1.4	<0.01	0.0
:	17.7	8.7	0.2	25.6	0.03	1.4	4.0	8.4	2.9	<0.01	0.0
:	20.1	13.0	0.2	32.3	0.03	1.1	4.9	10.8	4.9	<0.01	32.9
:	19.7	16.2	0.4	35.2	0.03	1.0	4.9	12.7	7.3	0.02	15.4
:	19.5	16.7	1.0	36.2	0.03	0.9	4.9	11.9	7.1	0.04	9.5
:	19.4	14.9	2.3	35.7	0.03	0.0	4.9	11.6	6.2	0.10	2.9
:	19.1	11.4	6.1	35.6	0.03	1.0	4.9	15.2	b.4	0.33	11.4
:	17.9	8.3	14.2	39.5	0.03	1.1	4.9	19.1	62	1.0	21.2
:	16.7	7.0	24.0	46.7	0.03	1.1	4.9	19.0	5.6	1.8	21.2
:	15.9	6.8	32.2	53.9	0.03	1.2	4.9	18.5	5.5	2.4	28.3
-			-								

PROFILE DISTRIBUTION OF IONS AND SALTS IN SUBSTRATA AFTER 1 AND 5 PORE-VOLUME DISPLACEMENTS APPENDIX TABLE D

APPENDIX TABLE E	E DISTRIBUTION OF IONS AND SALTS IN SUBSTRATA AT PORE SATURATION	(Site 9)
	PROFILE DISTRI	

	Water	content	gm per 100 gm	39.5	31.5	20.8	23.2	25.9	22.7	20.2	25.0	23.8	24.2	24.2	24.2
	Į	mnsd &p	m.e. per 100 gm	8.5	10.3	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	ns	Na <sup>+</sup>	4	1.1	1.7	1.2	1.5	1.3	1.1	0.9	1.0	1.1	1.3	1.3	1.3
	changeable ic	Mg <sup>++</sup>	.e. per 100 gn	7.9	7.8	4.6	9.7	15.9	15.4	14.9	14.3	13.7	13.9	13.9	13.9
	Exc	Ca++	m	15.8	7.6	5.4	3.7	8.4	0.0	4.0	0.0	9.5	12.4	12.4	12.4
	Undissoc.	CaSO4	mM per l	2.6	4.9	4.9	4.7	3.5	2.1	1.1	1.2	1.2	1.0	1.0	1.0
()		HCO <sub>3</sub> -		1.4	1.4	1.1	1.3	1.7	1.7	1.7	1.4	1.5	1.6	1.6	1.6
22-21		cı-		0.7	7.1	21.2	22.7	11.6	7.8	5.0	4.1	3.4	2.8	2.8	2.8
	e ions	so4-	sr liter	28.4	84.5	129.0	114.0	60.3	47.2	38.0	31.9	24.6	19.7	19.7	19.7
	Solubl	Na <sup>+</sup>	m.e. pe	12.5	47.5	79.6	54.5	23.0	19.0	16.5	14.4	13.3	11.8	11.8	11.8
		Mg^++		8.0	28.3	53.6	64.2	36.2	28.6	23.2	17.6	10.5	7.3	7.3	7.3
		Ca++	-	9.5	16.3	16.6	17.3	13.3	8.2	4.4	4.5	5.1	4.6	4.6	4.6
	11-12 11-12	Tridan Hoc	meters	0.0- 6.1.	6.1-13.2.	13.2-21.8.	21.8-29.7.	29.7-37.2.	37.2-45.3.	45.3-54.0.	54.0-61.8.	61.8-69.6.	69.6-77.2.	77.2-84.8.	84.8-91.1

	Gypsum	m.e. per 100 gm		0.0	6.7	1.9	0.0	0.0	0.0	0.0	0.0	0.3	0.1	<0.01		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	00	0.0
ns	Na+	u		0.11	0.20	0.33	0.87	6.1 1 6	1.2	1.2	1.2	1.3	1.3	1.3		0.07	0.04	0.02	0.07	0.45	0.81	1.0	1.2	1.4	1.6	1.5	1.4
changeable ic	Mg <sup>++</sup>	.e. per 100 gr		6.0	6.2	4.7	8.7	14.7	14.2	14.7	14.5	14.6	14.1	14.0	-	6.0	4.3	3.7	7.8	15.9	14.9	14.1	14.8	15.0	15.0	14.2	14.0
Ex	Ca+	Æ		18.7	10.7	6.1	5.2	0.1 9 7	4.4	5.5	8.6	11.7	12.3	12.4		18.7	12.8	7.4	7.0	9.3	6.8	4.8	53	7.8	11.1	12.0	12.3
Undissoc.	CaSO4	mM per l	ient	0.6	4.9	4.9	6.7	2.0	2.5	2.7	4.0	4.9	4.9	4.9	ients	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	03	0.6	0.0
	HC03 <sup>-</sup>		me displacen	1.4	1.4	1.1	ю. I	1.7	1.7	1.4	1.5	1.6	1.6	1.6	me displacen	1.4	1.4	1.1	1.3	1.7	1.7	1.7	1.4	1.5	1.6	1.6	1.6
	ਰ <u>'</u>		r 1 pore-volu	0.03	0.03	0.05	0.11	0.20	1.1	1.8	2.6	3.6	4.5	5.4	r 3 pore-volu	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
e ions	-'OS	sr liter	After	6.5	38.4	48.3	54.5	9.76 60.6	63.9	65.6	65.5	65.3	62.1	60.9	Afte	0.06	0.06	0.11	0.33	0.90	2.0	3.9	6.5	9.6	13.2	16.9	20.6
IduloS	Na <sup>+</sup>	m.e. pe		0.9	4.9	12.5	22.5	27.1	25.1	23.4	22.2	21.8	21.2	20.9		0.22	0.18	0.17	0.38	1.2	2.3	3.9	5.7	7.7	9.3	10.7	11.7
	Mg <sup>++</sup>			2.1	15.5	19.2	20 20 1	26.5	33.6	35.5	33.1	30.6	28.6	28.4		0.25	0.27	0.37	0.55	0.48	0.51	0.78	1.4	2.2	3.2	4.5	6.1
	Ca+t			4.5	18.9	17.5	20. a 29. a	0.0 0.0	7.2	9.3	13.7	17.2	17.5	17.7		0.54	0.57	0.52	0.35	0.20	0.16	0.19	0.34	0.79	1.6	2.7	3.8
	Dold depth	meters		0.0-6.1	6.1-13.2.	13.2–21.8	21.8–29.7.	29.1-31.2. 37.2-45.3	45.3-54.0	54.0-61.7	61.7-69.6	69.6-77.2.	77.2-84.8.	84.8-91.1		0.0- 6.1	6.1–13.2.	13.2-21.8.	21.8–29.7.	29.7–37.2.	37.2-45.3.	45.3-54.0.	54.0-61.7.	61.7-69.6.	69.6-77.2.	77.2–84.8.	84.8-91.1.

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