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Prediction Modeling for Salinity Control in Irrigation Return Flows

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March 1973

PREDICTION MODELING FOR SALINITY CONTROL

IN IRRIGATION RETURN FLOWS

A State-of-the-Art Review

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FOREWORD

This report has been prepared to fulfill several needs expressed by the National Irrigation Return Flow Program. A concise, up-to-date summation of the current state-of-the-art of prediction modeling as applied to salinity control in irrigation return flows was needed for program planning and evaluation. Secondly, a reference source was needed by research personnel who are interested in undertaking prediction modeling related to irrigation return flows. Interdisciplinary research is being required to solve complex water resource problems which bridge several scientific disciplines. Participants of such research endeavors must have a conversant understanding of some disciplines other than their own specialties to be an effective part of the group. This report can serve as an overview for those not directly involved in irrigation return flow problems and assist in bringing about the needed information exchange.

Presentation of equations is primarily meant to aid understanding of the conceptual models and, therefore, does not include rigid mathematical derivations. Details of the individual models can be found in the original publications. Sections VII and VIII contain references cited and a selected bibliography of related references.

Although every effort has been made to include all references pertinent to the objectives of this report, the author recognizes that some may have been overlooked. Comments in this regard would be gratefully received.

ABSTRACT

A review of the current state-of-the-art of prediction modeling as applied to salinity control in irrigation return flows is presented. Prediction models are needed to assess the effects of proposed changes in irrigation management practices on the quality of return flows. The processes which affect salinity levels in return flows are enumerated and their interactions are alluded to. Models used to predict the quantity and quality of return flows are briefly discussed to show the development of the current level of technology. The readers are referred to the original documents for more rigid development of the models and incumbent assumptions. It was concluded that technology of water and salt flow in soil systems is sufficiently developed to permit formulation of models using systems analysis to evaluate proposed changes in management practices. Development of systems models to study irrigation return flow problems and conjunctive water resource uses was recommended. A bibliography of selected references is given in addition to the references cited.

Key words: Irrigation return flow, prediction modeling, water quality degradation, resource management.

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FIGURES

SECTION I

CONCLUSIONS

1. A review of the literature has shown that only recently has prediction modeling been used to any extent for predicting the quality of irrigation return flows. The accuracy of the prediction model depends on the ability to define the hydrologic system flow as well as the chemical reactions and interactions taking place within the system.

2. The theory of movement of water on the surface and in streams, through the soil profile, and in the groundwater is highly advanced. The individual components of flow have been intensively studied by disciplinary scientists and mathematical models formulated for their behavior. Many of these models have been shown to give reliable results for predicting quantity of flow when applied to actual situations without the usual laboratory restrictions.

3. The theory of salt movement with the individual components of water flow is not as advanced as the theory of water movement; however, the past decade has seen a rapid increase in knowledge in this field. For irrigation systems, the movement of salts on the surface can be modeled using a material balance equation and the surface hydrologic model. Changes in salinity levels may be caused by evaporation of water or dissolution of salts previously deposited on the soil surface. Changes in salinity levels of waters percolating through the soil profile are not so simple. In addition to concentrating the salt by evaporation of water from the soil surface and transpiration of water from the root zone by plants, the ionic composition of the percolating water may change significantly. These composition changes result from ion exchange with the soil colloid, and precipitation and dissolution reactions occurring within the soil profile. Further degradation in quality of percolating water is caused by leaching previously accumulated salts from the profile and salt pickup from zones of natural salt deposits below the root zone. The above factors, as well as diffusion, dispersion, pore-water velocity, pore geometry and soil type have been studied in an effort to quantify the flow of salts through soils.

4. Flow of salts in the groundwater can be predicted using groundwater hydrologic models and the materials balance concept. Mixing the more saline percolating water with the groundwater can be described by miscible displacement theory. After the percolating water is thoroughly mixed with the groundwater, the salinity level will not change significantly since salinity is a conservative quantity.

5. Quantitative data on the quantity and quality of subsurface flows is difficult and expensive to obtain and its meagerness will limit the application of detailed models to this portion of the system.

6. Systems analysis approach to prediction modeling of salinity in irrigation return flows has not been widely used. Orlob and Woods (1967) were among the first to develop a prediction model with the system concept. Walker (1970), Hyatt et al. (1970), and Thomas (1971) have followed this lead with systems models for quantity and chemical quality of irrigation return flows. These models have been successful in predicting the quality of return water in the test areas and can be applied to other areas to be studied by making minor adjustments.

7. Two characteristics of prediction modeling which cannot be overstressed are: (1) the potential of evaluating the result of proposed management practices before they are instituted; and (2) the tremendous savings in both time and resources over that needed to find the same answers by field experimentation. With the pressing need to find immediate solutions to salinity control problems in the arid west, prediction modeling is an essential tool.

SECTION II

RECOMMENDATIONS

1. Comprehensive, systematic prediction models should be developed which can be easily and unambiguously adapted to field areas where knowledge of salinity flow is necessary to institute management practices to reduce the salinity contributed to river systems by irrigation return flow. Such comprehensive models should be sufficiently flexible to permit inclusion of parameters which might be unique to a given area yet would allow the model to be generally applicable to any area needing study.

2. After adequate verification, the prediction models should be used in lieu of expensive and time-consuming field experiments to: (a) predict the salinity contribution of existing irrigation return flow; (b) evaluate the influence of management practices, such as irrigation scheduling, irrigation efficiency, application rates, irrigation water quality, etc., on the quality of the return flow; (c) evaluate the effect of irrigating new lands on the quality of the return flow; (d) determine the relative contributions of the individual processes occurring within the system, thus identifying those processes which need to be examined closely to effect better salinity control in return flows; and (e) develop optimal basin-wide programs of salinity control and management.

3. Prediction models should be developed using systems methodology and unified terminology with comprehensive user's manuals developed to permit widespread usage of the computer programs by water resource researchers and planners.

4. Prediction modeling of salinity in irrigation return flows should play an important role in water resource management where conjunctive use of the water resource is contemplated since the effect of quality degradation caused by irrigation on other uses of water resources can be identified and appropriate measures taken to correct or alleviate the problem.

5. An increasing commitment must be made to total water resource planning to assure that maximum benefits are derived from that resource while preserving its quality.

6. A larger data base of quantitative information on the flow of water and salts in the groundwater system should be acquired to verify basin models

SECTION III

THE NEED FOR CONSERVING QUALITY IN RETURN FLOWS

Irrigation agriculture uses more water than any other single consumer of water resources. Ninety percent of the water diverted from impounding structures and consumptively used goes to irrigation (Wadleigh, 1968). Some estimates indicate that as much as sixty percent of the total water applied as irrigation water is lost to evapotranspiration. Water lost by this process is essentially salt free thus the net effect on salt concentration could be a 2 1/2-fold increase in the return flow if only this mechanism is active. Drainage waters usually have some crop producing value remaining but, depending upon the fraction of applied irrigation water that has been evapotranspired, their salt concentration can be from 2 to 7 times greater than that of the applied irrigation water (Utah State University Foundation, 1969). Thus, the return of highly saline drainage water to the stream degrades the quality of the stream for further use. In addition, due to precipitation, dissolution, and ion exchange reactions occurring in the soil system, the proportions of the various salt constituents in the irrigation water as it becomes drainage water are usually altered and these changes contribute to the degradation of quality in the receiving stream.

The demand for irrigation water in areas where water resources are limited both in quantity and quality further aggravates the problem. In many river basins in the western states, irrigation return flow may contribute substantially more than half the stream flow during summer low flow periods. Nearly all of the summer flow in the lower reaches of the Yakima River in Washington is composed of irrigation return water (Browning, 1970).

Two excellent comprehensive reviews have been published which describe the effects and magnitude of irrigation return flows. The first was published in 1960 entitled "Return Irrigation Water--Characteristics and Effects" by E. F. Eldridge, USDHEW-PHS and the second published in 1969 was entitled "Characteristics and Pollution Problems of Irrigation Return Flow" prepared by the Utah State University Foundation for the FWPCA-USDI (now EPA). These publications discuss in detail the characteristics and problems associated with irrigation return flows, document their findings from the literature, and set forth recommendations and research needs. A typical irrigation return flow system is presented in Figure 1.

As more new lands are brought under irrigated culture, the demand for available water will increase and return flows will be increasingly reused to meet these demands. The reuse of return flows and the consumptive nature of irrigated agriculture constitutes a major contribution to salinity increase in western rivers and streams. The technology of detection and measurement of these quality changes is sufficiently advanced to permit identification and quantification of the various processes which contribute to the increase of salinity.

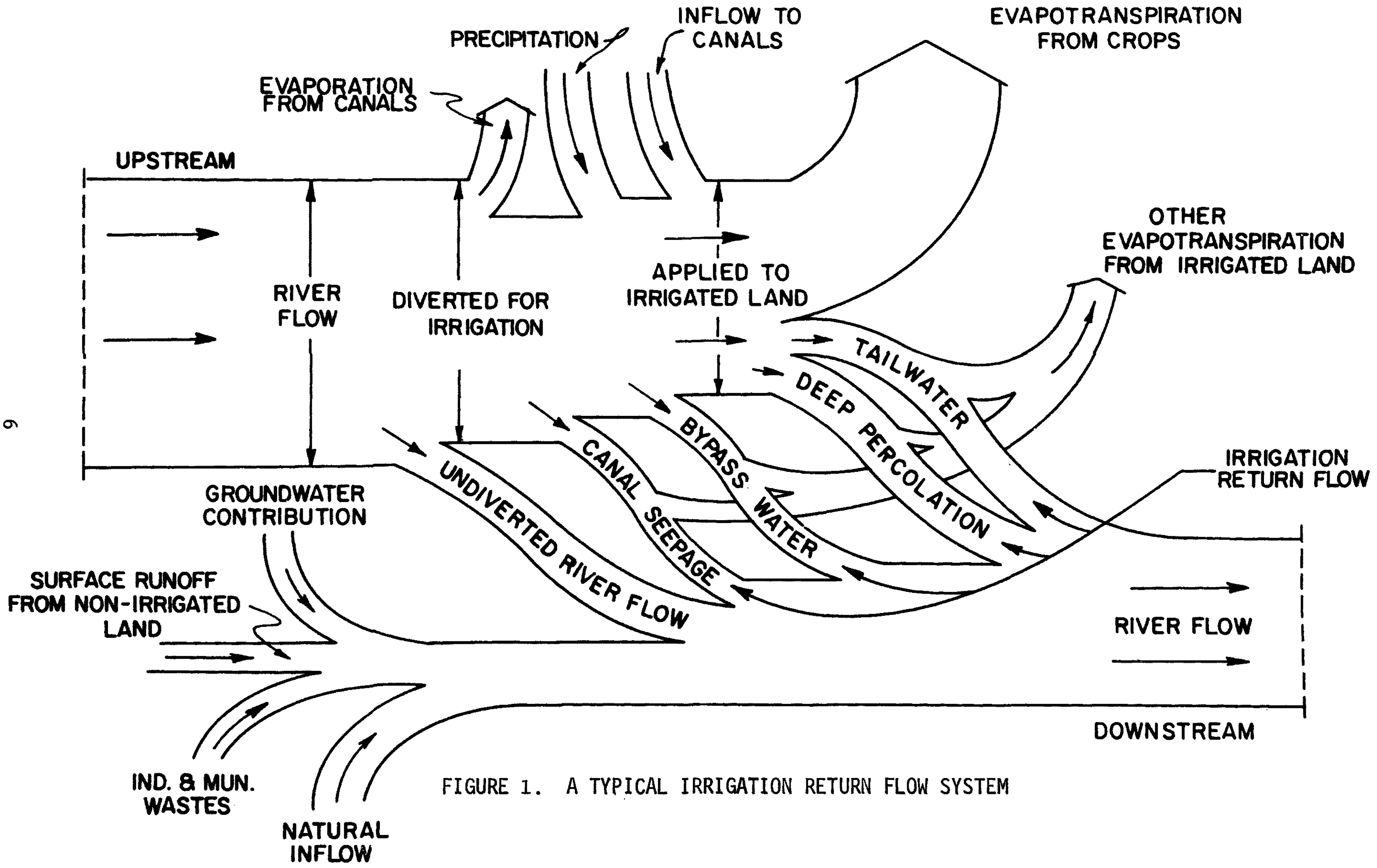


FIGURE 1. A TYPICAL IRRIGATION RETURN FLOW SYSTEM

To anticipate the changes in salinity that must necessarily occur with increased use and reuse of irrigation water, prediction modeling provides a tool to be used in order that management practices can be instituted in time to prevent serious impairment of water quality for downstream users. Prediction models can not only anticipate changes in salinity in the return flows, but also aid in establishing the relative contributions of the individual processes that lead to the salinity increase. Assessment of these relative contributions leads to improved management practices with the ultimate goal of reducing salinity levels in irrigation return flows while maintaining a viable agricultural operation.

SECTION IV

PROCESSES WHICH AFFECT SALINITY LEVELS IN IRRIGATION RETURN FLOWS

Irrigation return water can be subdivided into two general categories based on potential degradation levels. These are (1) surface return flow and (2) percolation through the plant root zone. The processes which affect each are varied and are reflected in their relative contributions to the increased salinity of irrigation return flows.

Surface return flows contribute relatively little to the concentration of salines. Surface overflows and resulting tailwater will retain approximately the same levels and composition of salines as the applied irrigation water, if relatively short application times are used. However, if the irrigation water is not properly managed the following characteristics may develop in the receiving stream:

1. an increase in sediment load,

2. an increase in agrichemical (pesticides, herbicides, etc.) concentration due to adsorption onto particulate matter carried in the sediment load,

3. a slight increase in concentration of salines due to evaporation from the free water surface and dissolution of salts previously deposited on the surface of the soil, and

4. an increase in the numbers of bacterial organisms present in the surface water.

With correct management practices these contributions can be reduced to negligible amounts. Tailwater can be eliminated by regulations of amount and rate of application or it can be reused by pumping back to the point of initial application or used to irrigate fields adjacent to the original site. More propitious management can result from modeling surface flows to optimize salinity control.

By far, the majority of the increase in salinity in return flows occurs during percolation through the soil profile. Salts are concentrated in this region by the evapotranspiration process. Water is in intimate contact with the soil constituents as it passes through and can react with these constituents resulting in degradation in the quality of the percolating water. Processes which may contribute to some extent to this degradation are:

1. ion exchange reactions with the soil minerals,

2. precipitation and dissolution reactions occurring within the soil profile,

3. ion composition change due to differential valence charges and the lyotropic series effect,

4. dissolution and leaching of soluble plant nutrients applied as fertilizer,

5. leaching to maintain salt balance in the soil profile,

6. salt "pickup" resulting from the presence of natural salt deposits in the soil profile or near the aquifer which conducts the groundwater back to the stream,

7. temperature changes which may effect the rate of reaction of exchange, precipitation and dissolution processes, and

8. filtration and oxidation or reduction of biological and chemical components of the applied water. This process may actually enhance the quality of the return water in some cases.

Since many of these processes interact, the net result may not be simply a summation of the individual process results but rather a complex situation where the processes are simultaneously operating and interacting. In managing such a situation, a better comprehension is needed of the effects of each process and the degree of interaction with other processes. This is best explored by a systematic approach which identifies and quantifies the individual processes and their interactions. A deterministic systems model needs to be developed and verified with experimental data to predict changes in salinity level and composition of irrigation return flow water. The results would lead to a better understanding of the basic processes and more efficient management of the total system as a unit.

SECTION V

MODELS USED TO PREDICT RETURN FLOW QUANTITY AND QUALITY

Dissolved solids concentration is one of the major factors affecting the quality of waters receiving irrigation return flows; therefore, it is desirable to be able to estimate the concentration of salts in return flows from existing and new irrigation projects. Any study of the quality aspects of return flows must necessarily include the quantity of flow.

Mathematical models have been developed to describe many of the processes which are active in return flows, and in a few cases they attempt to describe the system as a whole. These systems are simulated by either stochastic or deterministic models. Stochastic analysis is aimed at predicting a probable value of some observable result using statistical theory. This approach does not consider the individual processes within the system at a microscopic level, thus precludes elucidation of the fundamental processes that occur within. The result is an expectation value which is an overall time average for the entire system.

A review of stochastic models used in hydrology has been presented by Scheidegger (1970). Investigations of growth and steady state phenomena in hydrology have revealed that essentially two types of growth models and one steady state model are possible. The first two are the cyclic growth model and the random configuration model,and the third is restricted to a Gaussian type with or without autocorrelation. The hazard of extrapolating beyond the time range over which the measurements have been made was examined.

Upton (1970) presented a stochastic model for water quality management under uncertainty, where the variance of stream flow was considered. Analysis has shown that problems of uncertainty may be dealt with by selecting a critical value of stream flow and then treating the pollutants sufficiently to maintain the desired water quality standard. The economics of the system was also considered.

These models are concerned with stream flow, but the methods of approach could be used to study the hydrology of irrigation return flow systems. Although the results obtained using these models may closely approximate the measured values, little is learned about the individual processes within the system. For salinity control within an irrigation system, the effect of these processes must be known in order to develop management practices which will control their effect. The salinity levels of return flows are not stochastic in nature in that they do not grow or decay with time.

Deterministic models, on the other hand, consider the individual processes within the system and their interaction. This approach leads to a clear definition of each process and its contribution to the system as a whole. In deterministic theory, the correct prediction will simply state the value of the observable result that will be obtained. The accuracy of the prediction depends on how well the model represents the components of the physical system. Leeds (1970) has described a general characteristic of a "good" mathematical model as the simplest model that will adequately describe the real world. For systems with both spatial and temporal effects of importance, partial differential equations must be used to describe the system.

Modeling hydrological systems in general and irrigation systems in particular has been primarily deterministic in nature. The model may be a materials balance type which will account for the material mass transfer through the system. The individual processes which contribute to the quality of the return flows have been studied in depth and will be presented separately in this review to facilitate development of an overall model.

Since the flow of salts in the system is directly linked to the flow of water, prediction of the latter is a necessary part of any prediction model for salinity. Following the format set forth previously, prediction models for water and salt flows will be discussed for surface flows, followed by a more detailed treatment of deep percolation.

Surface Flow

The occurrence and magnitude of surface flows or runoff are affected by the slope and condition of the surface, antecedent soil moisture content, infiltration rate, intensity of precipitation or rate of irrigation applied, vegetative cover, and management practices. In irrigation systems, surface return flow can be measured and controlled such that prediction of runoff volume is not a difficult task. However, for natural precipitation and ungaged watersheds, prediction techniques are needed to assess the quantity and quality of surface return flows.

Knisel *et al.*(1969) have elaborated on the model developed by Hartman *et al.*(1960) to predict runoff volume from daily climatic data. The general equation developed for runoff computation is

$$Q = [P(P - P_1)] \ / \ [1/b + (P - P_1)] \qquad (1)$$

where Q is the daily runoff volume in inches over the watershed, P is the daily rainfall in inches over the watershed. P_1 is the inches of rainfall before runoff begins, and b is an empirical constant. Both P_1 and b are functions of available soil moisture. The accumulation of moisture in the profile is given by P - Q. Moisture loss was determined by the decay type function

$$SM_t = SM_o K^t \qquad (2)$$

where SM_t is the soil moisture at time, t; SM_o is the soil moisture at some initial time, t_o; and K is the dissipation rate and is a function of available soil moisture , pan evaporation, and season. For a reservoir of soil water defined as the top three feet of the soil profile, the dissipation rate is given by the expression

$$K = c_0 + c_1 SM + c_2 PE \quad (3)$$

where SM is the inches of available soil moisture in the top three feet; PE is the average daily open pan evaporation in inches; and c_0, c_1, c_2 are empirically determined constants for each season. The major weakness of this model is in predicting the soil moisture at the beginning of rainfall. Greatest errors in prediction occurred during periods of extremely high or extremely low soil moisture levels.

The model was revised to include a second soil moisture reservoir (3-5 feet) and equation (2) was modified as follows

$$SM_t = SM_o - Ct \quad (4)$$

Where C is a constant depending on values of K. The revised runoff model was tested with data for an 11-year period on a native grass-meadow watershed. Good agreement between measured and calculated results was found, indicating a valid model. Accumulated computed amounts for the period agreed within 1% of the accumulated observed amounts.

Since there is only slight increase in salinity in surface waters due to overland flow, the concentration of salinity in surface return flow can be estimated from the concentration of the applied irrigation water and the amount of measured or predicted runoff. This can be represented by the equation

$$SL = QC_i \quad (5)$$

where SL is the salt load in the runoff water, Q is the daily runoff volume, and C_i is the concentration of salts in the applied irrigation water. In areas where infiltration rates are low and water must be ponded for extended periods to allow sufficient penetration, equation (5) may be modified as follows

$$SL = Q(C_i + \Delta C_E + \Delta C_s) \quad (6)$$

where ΔC_E and ΔC_s are changes in concentration due to the evaporation of water and dissolution of salts on the soil surface respectively. These changes would be difficult to quantify since they would be time variant while infiltration is taking place. ΔC_E would be a function of time, evaporation rate, and infiltration rate; and ΔC_s would be a function of time, solubility rate, and infiltration rate. The contribution of these components would need to be determined for each particular location and condition. As a first approximation, equation (5) can be used without great error in most irrigated regions.

Hyatt et al. (1970) estimated surface runoff rates, Q_r, by difference between total rate at which water is diverted from the stream or reservoir, W_{tr}, and the rate at which diverted water enters the soil through seepage and infiltration, W_{dr}, as given by

$$Q_r = (W_{tr} - W_{dr}) . \tag{7}$$

Evapotranspiration losses are included in the W_{dr} term and are accounted for elsewhere in the overall system model. Salt carried in the surface flow can then be estimated by the relationship

$$S_r^Q = Q_r C_s \tag{8}$$

where S_r^Q is the rate of salt flow from the area, and C_s is the average water salinity level of the surface flow.

Subsurface Flow

Mechanics of Water Movement in Soil Systems

The mechanics of flow of water through soil systems has been intensively studied in the quest for understanding the fundamental physical and chemical processes affecting the flow behavior of water. Comprehensive treatises on this subject are given in the books Physical Principles of Water Percolation and Seepage by Bear, Zaslavsky, and Irmay; and Soil Water prepared by the Western Regional Research Technical Committee, W-68, Water Movement in Soils. Since salt movement through soil depends upon water as a solvent and vehicle of transport, an understanding of the behavior of water flow is tantamount to any study of salt movement through soils.

Movement of water through soils has generally been described by the Darcy equation given by

$$Q/At = -K \, d\Phi/dZ \tag{9}$$

where Q is the quantity of flow through a cross-sectional area, A, in time t; K is the hydraulic conductivity, and $d\Phi/dZ$ is the potential gradient acting across the system. In describing steady flow, equation (9) is strictly valid only when K is independent of time, space, direction, pressure, flux, hydraulic gradient, and length of flow path. These assumptions are rarely met in natural soil systems, since K is known to be a function of water content. For a saturated soil, however, K may be considered to be a constant and the equation used to describe saturated flow.

Using the principle of conservation of mass and the Darcy equation, an equation describing water movement in a partially saturated soil is given by

$$\frac{\partial \Theta}{\partial t} = \frac{\partial}{\partial t}\left(K\frac{\partial \Psi}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad (10)$$

where Θ is the volumetric water content, t is time, Ψ is the soil moisture potential, z is depth, and K is the soil water conductivity. The effects of hysteresis on $\Psi(\Theta)$ and $K(\Theta)$ relationships can be accounted for.

Recently, researchers have used numerical methods to solve this equation to predict moisture movement in soils. Staple (1969) using an explicit finite difference form of equation (10) computed the expected redistribution of soil moisture following a period of infiltration. Agreement between measured and computed moisture profiles was considered satisfactory. The computational procedure required assessing the values for conductivity and diffusivity from the Ψ vs. Θ relationships. Rubin (1967, 1968) used implicit finite difference solutions to equation (10) to study redistribution and transient flow of water in soils. His work shows the importance of hysteresis in the redistribution process.

Wang and Lakshminayana (1968) developed a numerical technique to solve equation (10) for the case of unsaturated nonhomogenous soils. This is the situation most prevalent in natural soils in the zone of aeration. This technique is of more general use since idealized soil conditions are not a requisite for this solution. The simulated moisture profiles were in excellent agreement with the experimental data of Nielsen et al. (1964).

Hanks et al. (1969) described a numeric method for estimating infiltration, redistribution, drainage, and evaporation of water from soil. The computed results were compared with measured values and found to adequately predict the soil moisture behavior. Limitations caused by natural variability of soils are recognized by the authors.

Black et al. (1969) applied a simplified flow theory to both evaporation and drainage processes and were able to predict water storage in the soil profile. Using daily rainfall data, the water storage in the upper 150 cm of the profile was predicted over the season to within 0.3 cm. The authors emphasized that evaporation from the finer textured soils may not be described as well as for the soil used in this experiment and that layered soils may require special treatment. However, for the soil studied, good agreement was found between predicted and measured evaporation, drainage, and storage.

Freeze (1969, 1970) examined the mechanism of natural groundwater recharge and discharge for a one-dimensional, vertical, unsteady, unsaturated flow above a recharging or discharging groundwater flow system. The flow was simulated with a numerical mathematical model involving transient flow. The model was verified using both laboratory and field data. The mathematical model was derived from Darcy's equation and considered both the unsaturated and saturated zone of the soil profile. The parameters which controlled the integrated saturated-unsaturated flow system were found to be: the rate and duration of rainfall or evaporation at the upper boundary; the groundwater recharge or discharge rate; the antecedent soil moisture conditions and water-table depth; the allowable depth of ponding; and the hydrological properties of the soil. It was also concluded that soil moisture conditions, in general, and evaporation and infiltration rates, in particular, show areal variations, even under homogeneous meteorological conditions and soil type due to the influence of areal variations in the rates of groundwater recharge and discharge.

Bhuiyan et al. (1971a,b) used dynamic simulation language to develop a computer model that simulated the vertical infiltration of water into unsaturated soil from both surface and subsurface sources. The net water flux through each layer, at any particular time, was established by using the principles of conservation of mass and Darcy's law. The water content and cumulative infiltration was then calculated using a fourth order Runge-Kutta integration method. Results obtained compared favorably with those of Philip (1957a,b) and field data of Nielsen et al. (1961) obtained for Yolo light clay with surface application of water. The principle advantage of the numerical procedure is its complete generality and the ease with which numerical data on the hydraulic characteristics of the soil may be used without arbitrary assumptions or function-fitting procedures. Water distribution efficiency can be evaluated for subsurface irrigation systems.

Many other excellent research papers are available where the movement of soil water has been studied with a variety of imposed conditions and assumptions, allowing simplified mathematical solutions to be made. The description of soil water movement can be considered to be in an advanced state of development.

Mechanics of Salt Movement in Soil Systems

The movement of salt through the soil profile is affected by many physico-chemical reactions. Among these are ion exchange, ion exclusion, precipitation, and dissolution. In an irrigated soil system where a salt balance is maintained, some degree of equilibrium must be obtained to avoid degeneration of the productivity of the soil.

Under steady-state water flow rates in an irrigated area, the salt balance is given by

$$V_iC_i + S_m - V_dC_d - S_p - S_c = 0 \tag{11}$$

where V_i and V_d are the volumes of irrigation and drainage waters, respectively, with corresponding salt concentrations C_i and C_d; S_m is the amount of salts dissolved from soil materials; S_p is the amount of salts added to the soil by precipitation from the irrigation water; and S_c is the amount of salt removed by crops. To maintain viable agriculture in an irrigated area, a favorable salt balance must exist at least in the root zone of the soil. This concept has been in use since developed by Scofield (1940).

Bresler (1967) modeled salt flow through soils using a salt balance relationship applied to individual layers in the soil profile.

The basic relationship is given by

$$VC - V_dC_d - S_p = (C_1^* - C_0^*)\ \theta\Delta X \tag{12}$$

where V is the depth of irrigation water applied;

C is the salt concentration in the irrigation water;

ΔX is the depth of the relevant soil layer;

V_d is the depth of water leached from ΔX;

C_d is the salt concentration of drainage water;

S_p is the amount of salt absorbed by plants per unit area of soil;

θ is the volumetric water content;

C_0^* is the initial average salt concentration in the soil solution at water content θ; and

C_1^* is the average salt concentration in soil solution at moisture content θ after irrigation water is applied.

To estimate V_d and C_d, it was assumed that: (a) the movement of salt was with the mass of flowing water and in the downward direction only; (b) water and salt movement takes place at moisture content θ and that θ remains relatively constant for the period of movement; (c) the average salt concentration of the water which leaches out is the arithmetic mean of the salt concentration before and after irrigation; and (d) the salts are noninteracting. These assumptions are clearly not met in the field; however, the predicted salt distributions in the soil profile agreed with measured values in direction of change, if not in magnitude.

Bresler and Hanks (1969) developed a model to handle simultaneous flow of salt and water in a soil system. For one-dimensional flow, and neglecting such factors as flow induced anisotropy, the distribution of pore velocities, and diffusion, the rate of flow of salt is given by

$$[dQ/dt]_x = [-D_p(dC/dx) + \overline{V}\theta C + S]_x \quad (13)$$

where Q is the amount of a solute transferred per unit area;

t is time;

D_p is the effective dispersion coefficient of the solute;

x is distance in direction of flow;

$\overline{V}$ is the average velocity of the solution;

θ is the volumetric water content;

C is the concentration of solute; and

S is the rate of change with time of solute per unit area due to all sinks and sources.

By assuming that no sources or sinks exist and that $D_p(dC/dx) << \overline{V}\theta C$, equation (13) reduces to

$$[dQ/dt]_x = [\overline{V}\ C]_x. \quad (14)$$

Equation (14) can be solved by a finite difference scheme.

Comparison of computed with measured data indicated that the source-sink term, S, should not be omitted. The procedure gave good agreement for non-interacting solute in soil. No accounting was made for evapotranspiration losses of moisture or for interacting salts in exchange reactions or solution-dissolution reactions. The effects of dispersion were also neglected but may in some instances become significant.

Hyatt et al. (1970) expressed the deep percolation rate as

$$G_r = F_r - ET_r,\ [M_s(t) = M_{cs}]$$

and

$$G_r = 0,\ [M_s(t) < M_{cs}] \quad (15)$$

where G_r is the rate of deep percolation;

F_r is the rate of infiltration;

ET_r is the actual rate of evaporation;

$M_s(t)$ is the quantity of water available for plant consumption which is stored in the root zone at any instant of time; and

M_{cs} is the root zone storage capacity of water available to plants.

The assumption was made that deep percolation occurs only when the available soil moisture is at its capacity level. No serious error resulted from this assumption, probably due to the fact that most of the percolation takes place shortly after irrigation application when the zone of transmission is near saturation. It was recognized, however, that percolation continues slowly in partially saturated soils.

The flow of salt in this system would then be given by

$$S_r^G = [F_r - ET_{cr}]C_{ga} = G_r C_{ga}, \quad [M_s(t) = M_{cs}]$$
$$S_r^G = 0, \quad [M_s(t) < M_{cs}] \qquad (16)$$

where S_r^G is the rate of salt flow from the plant root zone;

C_{ga} is the average salinity concentration within the soil solution at the lower boundary of the plant root zone;

ET_{cr} is the potential evapotranspiration rate; and

all other terms are as previously defined.

This procedure does not account for the individual ion species and thus does not take into consideration changes in the ion composition of the drainage water and resident soil solution.

Lai (1970) considered ion exchange reactions in a study of salt transport through soil undergoing miscible displacement. A model was developed which allows prediction of both the solution and exchanger phase concentration of the cation in question. Using both implicit and explicit finite difference techniques, the flow equation was solved considering exchange reactions. The predicted concentration distributions gave good agreement with the measured values. Non-linear exchange isotherms were found for both Mg $\rightarrow$ Ca and Na $\rightarrow$ Ca systems. The flow equation, modified to consider exchange reactions, is given by

$$D \frac{\partial^2 X}{\partial Z^2} - \bar{V} \frac{\partial X}{\partial Z} = (1 + \frac{\rho Q}{\alpha C_0} f')\frac{\partial X}{\partial t} \quad (17)$$

where D is the dispersion coefficient;

X is the concentration of an individual ion species;

Z is the distance in direction of flow;

$\bar{V}$ is the average interstitial flow velocity;

ρ is the bulk density;

Q is the cation exchange capacity per unit weight of exchanger;

α is the pore fraction;

C_0 is the total cation concentration; and

f' is the slope of the adsorption isotherm.

This model requires assessment of the exchange properties of the soil and of the flow behavior. For application to a field situation, the spatial variation of exchange and flow properties would need to be evaluated.

Alfaro and Keller (1970) used dimensional analysis to treat a model for predicting the process of leaching. The prediction model was verified for both layered and non-layered soils using physically scaled models. The use of scaled models to predict leaching from the prototype requires exact scaling of the soil profile since the accuracy of the prediction depends upon the closeness by which the prototypes represent the real world.

Oster and McNeal (1971) have presented three mathematical models which predict the change in soil solution composition and electrical conductivity as water content is changed by evaporation or extraction by plants. Two of the models included consideration of precipitation of salts, bicarbonate and carbonate ion pairs of calcium, sodium, and magnesium, and partial pressure of carbon dioxide. The third model was similar but considered only the ion pair calcium sulfate. The reliability of the models was evaluated by comparing calculated electrical conductivities to those measured with in situ salinity sensors. The best model considered the maximum number of ion pairs and used a form of the Debye-Hückel equation with individual ion parameters. This model resulted in an average error of about 6% when compared to the average measured value.

Sadler *et al*. (1965) tested miscible displacement theory in a field experiment designed to study reclamation of saline soil. They concluded that both hydrodynamic dispersion and ionic diffusion contributed salt to the effluent that was measured and analyzed during this experiment. Velocity flow was most probably responsible for the bulk of the chlorides removed from the soil adjacent to the centerline of the drain. Diffusion was of increasing importance in removing salt from the soil more distant from the drain. They indicated a need for further development of miscible displacement theory for two-dimensional cases. However, it was found that if proper account was taken of the two-dimensional nature of the field leaching studies, miscible displacement theory gives a qualitative explanation of several observed results.

Simultaneous solute and water transfer for an unsaturated soil was examined by Warrick *et al*. (1971). The simultaneous transfer of solute and water during infiltration was studied both in the field and numerically. The advance of a solute front introduced as irrigation water was shown to be nearly independent of the initial soil moisture content, but highly dependent upon the moisture content maintained at the soil surface during infiltration. Field results showed that the displacement of chloride applied in irrigation water and leached with additional chloride-free water can be quantatively predicted by linking the equations of solute and water movement through an unsaturated soil. The numerical simulation provides an examination of the influence of soil moisture on solute transfer during infiltration.

Dutt (1962a,b, 1964) and Dutt *et al*. (1962, 1963) studied the effects of changes in the ionic composition of percolating irrigation waters. Beginning with simple models for water percolating through soil containing gypsum and exchangeable Ca^{++} and Mg^{++}, computer programs were developed to predict the quality of the percolating water. The procedure for making these predictions assumes that the total activity coefficient of the ionic species in the soil solution can be calculated by the Debye-Hückel theory. Predictions made in this manner were found to be within the experimental error of measured values found for soil systems containing Ca^{++}, Mg^{++}, Na^{+}, $SO_4^{=}$, Cl^{-}, and $CaSO_4 \cdot 2H_2O$ at saturation moisture content. Some deviation from the predicted values was expected since the constants used were developed from solution chemistry and do not consider the effects of the interacting clay surfaces. Dutt and Anderson (1965) found that the soil solution does not differ greatly from true solution for a range of 15-33 percent gravimetric moisture content. This was determined by electrical conductance methods using both true solutions and soil solutions.

Tanji *et al*. (1967a) developed a computer method to predict the salt concentration in soils at variable moisture contents. The calculations were based on ionic activities, solubility product constant of $CaSO_4 \cdot 2H_2O$

(gypsum), dissociation constant of $CaSO_4$, and cation-exchange equations. Five agricultural soils were used to test the procedure and excellent agreement was found between predicted and experimental values for all ions examined.

Precipitation of $CaCO_3$ resulting from high bicarbonate water has been examined by Tanji and Doneen (1966). The overall reaction for precipitation of $CaCO_3$ in an open system is

$$Ca^{++} + 2HCO_3^- \rightleftarrows CaCO_3\downarrow + CO_2\uparrow + H_2O \qquad (18)$$

This reaction proceeds stepwise through several equilibria stages. Using Debye-Hückel theory and ionization constants from solution theory, the authors developed a computer prediction model which gave excellent agreement with measured values. Precipitation reactions were important in solution composition changes which may lead to increased sodium levels in the soil profile.

Stratified soils present a special problem in predicting the quality of the percolating water. The complexity of flow due to changes in hydraulic and mineralogical properties from layer to layer are difficult to model. Tanji et al. (1967b) developed two computer models to predict chemical changes in percolating water due to stratified soils. The first program predicts the chemical changes induced by saturation of an initially moist stratified profile and the second program predicts the solute concentration in the effluent from the stratified profile as percolation occurs, and the subsequent changes in chemical properties of the soil profile. These programs have been verified by laboratory studies of a two-layered, salinized, gypsiferous soil model. The above procedure may be extended and modified to include additional variables, reactions, and more complex conditions. This is exemplified by Tanji (1970) where the approach was used to predict the leaching of boron from stratified soil columns. A Langmuir adsorption isotherm was assumed and predicted results were in good agreement with experimental values.

Tanji and Biggar (1972) developed a specific conductance model for natural waters and soil solutions of limited salinity levels. They point out that specific conductance (electrical conductivity) is one of the most widely used parameters monitored to estimate the salinity of water and soils, thus it is appropriate to develop a model with this parameter. One disadvantage of specific conductance as a measure of salinity is that it is a measure of only the ionic activity of the solute species and thus may underestimate the analytically determined salt concentration. This would be of particular importance when ion association or ion-pairing is prominent.

The model estimates temperature-dependent conductance from measured or predicted solution composition in water and soil solutions. The specific conductance in multicomponent aqueous systems is given by

$$L = \sum_{i=1}^{n} \ell_i = \sum_{i=1}^{n} \lambda_i C_i \qquad (19)$$

where L is the conductance in micromhos/cm, and ℓ_i, λ_i, and C_i are, respectively, the ionic specific conductance in micromhos/cm, ionic equivalent conductance in cm^2/equiv-ohm, and concentration in meq./liter for the ith solute species. The term λ_i may be related to concentration by the equation

$$\lambda_i = \lambda_i^0 - aC_i^{1/2} \qquad (20)$$

where λ_i^0 is the ionic equivalent conductance of the ith ion species at infinite dilution in cm^2/equiv-ohm, and the coefficient, a, is an adjustable empirical coefficient for salt concentration and ion association effects.

Equations (19) and (20) are applicable at a reference temperature, usually 25°C. Variations caused by temperatures other than the reference may be expressed by

$$L_T = L_{25} + 0.02(T - 25)L_{25} \qquad (21)$$

where L_T and L_{25} are the specific conductances at some temperature T and at 25°C, respectively.

This conductance model was tested on representative river waters and soil solution extracts from the Western United States. Over a limited salt concentration range, the conductance was predicted satisfactorily by the model. For high salt concentrations, the coefficients must be adjusted to obtain a good fit. The model has been described by the authors as a compromise between analytical and empirical approaches.

System Flow

In an assessment of the characteristics and pollution problems of irrigation return flow, the Utah State University Foundation (1969) described both the quantity and quality of irrigation return flow as dependent variables, with the soil and soil moisture playing important roles in the functional relationship. The quality of irrigation return flow can be described as:

$$IRF_q = f(Q_{iq}, C_{sq}, B_q, T_a, M_a, S_{mq}, S_{cc}, ET, D_{pq}, C_q, F_{pq}, F_a, P_a, C_f, O_i) \quad (22)$$

where IRF_q is the irrigation return flow quality;

Q_{iq} is the quality and quantity aspects of applied irrigation water;

C_{sq} is the canal seepage quality change;

B_q is the bypass water quality;

T_a is the time of application;

M_a is the method and rate of application;

S_{mq} is the soil moisture quality;

S_{cc} represents the additional soil characteristics such as cation exchange capacity, basic soil compounds, bacteriological activity, chelation, fixation, oxidation, and other factors which may alter the soil-chemistry-bacteria-water system;

ET is the evapotranspiration;

D_{pq} is the quality of water percolating below the root zone;

C_q is the crop influence on quality;

F_{pq} is the farm practice effect on quality;

F_a is the fertilizer application;

P_a is the pesticide application;

C_f is the climatological factors; i.e., temperature, precipitation, wind, radiation, etc.; and

O_i is other influences; i.e., elements carried from the air to the farm land, by precipitation, industrial pollution of soils and water, municipal inputs from runoff or sewage, etc.

The intricate nature of the soil-water quality complex makes prediction of return flow quality variables very difficult. Equation (22) indicates the complexity of the system and the possibility of interactions among the variables which combine to effect a given quality in irrigation return flows.

A general model which will simulate the water quality in irrigation systems is needed for planning and maintenance of viable irrigated agricultural areas. Such a model should include all the identifiable subsets or units which contribute to the water quality behavior of the system as a whole. This would result in a systemized approach for predicting the quality response of this system of units to changes in irrigation practices.

Orlob and Woods (1967) have presented such a model where an idealized hydrological "unit" is composed of three basic storage elements--surface, soil moisture, and groundwater--between which water is transferred either according to operational plan or in accord with physical relationships. For each of the storage elements in the system it is possible to write a continuity equation such that

$$\frac{dS}{dt} = \Sigma Q \qquad (23)$$

where S is the total stored water, Q is the flow into or out of the unit by any mechanism, and t is time.

The storage elements are given by the following equations.

Surface water:

$$\frac{dS_c}{dt} = Q_{ci} - Q_{co} + Q_s + Q_g - Q_d + Q_i - Q_p + P' - E \qquad (24)$$

Soil Moisture:

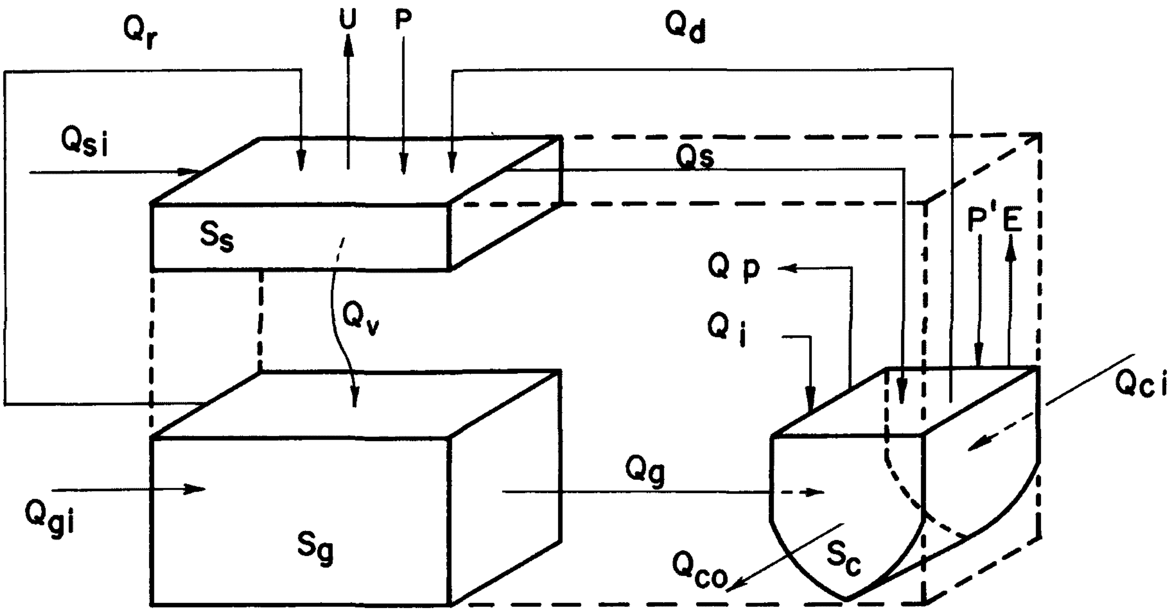
$$\frac{dS_s}{dt} = Q_{si} - Q_s + Q_d + Q_r - U + P - Q_v \qquad (25)$$

Groundwater:

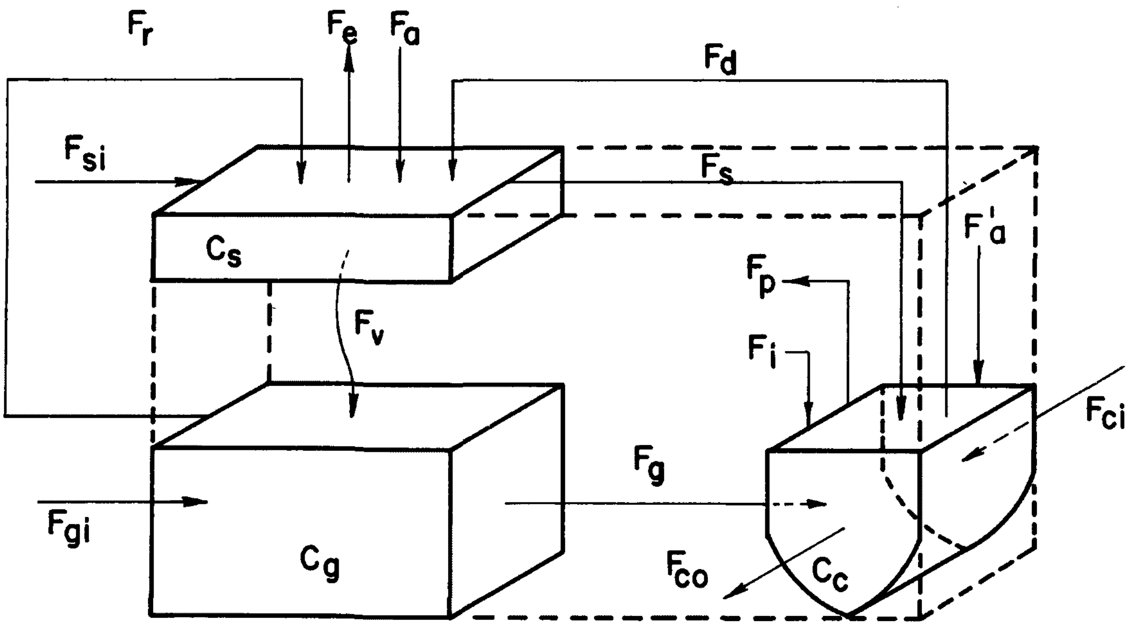
$$\frac{dS_g}{dt} = Q_{gi} - Q_g + Q_v - Q_r \qquad (26)$$

where the subscripts c, g, and s refer to surface, ground, and soil water storage elements, respectively; i and o refer to inflow and outflow from the element; d refers to diversion for irrigation use; p denotes extractions from surface water element for export to other units; v denotes vertical flow; r denotes recirculation; P' denotes precipitation onto a free water surface, P denotes precipitation on a land element; E denotes evaporation from a surface element; and U denotes evapotranspiration from a land element. A sketch of this hydrologic model is given in Figure 2.

Changes in water quality in an irrigation system are closely related to the hydrologic behavior of that system. A water quality model which has



Hydrologic Model



Water Quality Model

FIGURE 2. HYDROLOGIC AND WATER QUALITY MODELS

the same storage elements as the hydrologic model can be used. The amount of salt in a given element is given by the product of the storage quantity and the concentration of salt in that element. The flow of a salt ion from one element to another might be at a rate defined by

$$f_x = q_x K_x C_x \tag{27}$$

where q_x is the flow from the hydrologic model, C_x is the concentration of a salt species, and K_x is the distribution coefficient. Each of these quantities may be space and time dependent in the system. The total flow of salt in an element would be given by

$$F = \sum_{x=1}^{n} f_x \tag{28}$$

where the subscript x denotes the particular ion specie. The water quality model is shown in Figure 2. Subscripts are the same as for the hydrologic model except a and e which represent salt additions or removal from an element respectively.

Such a combined hydrologic-salinity model facilitates inclusion of the individual processes which contribute to salinity flow in the system. Sensitivity analysis on these individual processes can result in knowledge of the relative contribution made by each process to the system as a whole. Such knowledge is necessary to make efficient management decisions and to develop control measures which would lead to reducing the salinity level of the return flow.

Dixon and Hendricks (1970) considered the spatial and temporal changes in water quality within a hydrologic unit. A water quality simulation model was developed in conjunction with a hydrologic simulation model and verified with actual field data from a prototype system. Dissolved oxygen concentration, biochemical oxygen demand, temperature, and dissolved mineral concentration were selected as the water quality parameters to be measured. The simulation submodel for each water quality parameter has an input phase and an in-transit phase. The input phase simulates the time distribution of the quality parameters in each component of flow, while the in-transit phase deals with changes in the water quality parameters as it is carried through the reach being simulated.

In irrigated agriculture, dissolved mineral concentration (salinity) is an important measure of water quality. Because salinity, and thus specific electrical conductance, is not subject to dissipation or decomposition, no in-transit phase model need be developed. The conductivity of the outflow from the reach is the sum of the conductivities and flows of the input streams. Assuming complete mixing, the conductivity of the combined flows is calculated by

$$ECI = \sum_{j=1}^{n} EC_j \cdot q_j / \sum_{j=1}^{n} q_j \qquad (29)$$

where ECI is the conductivity of the combined flows; EC_j is the conductivity of the jth hydrologic input stream; q_j is the rate of flow for that input; and n is the number of inputs to the reach being simulated. Good agreement was found between measured and simulated values for the parameters studied.

Margheim (1967) studied some of the major factors which affect the quality of irrigation return flows and expressed them in mathematical forms which could be fitted into an overall computer program to predict the quality of the return flows. The four-phase system is composed of (1) a solution phase, (2) an exchange phase, (3) a crystalline salt phase, and (4) a groundwater-deep percolation phase. Consideration of exchange phase-solution phase and crystalline salt phase-solution phase relationships was in the form of an extension of the theory developed by Dutt (1962). The groundwater-deep percolation phase submodel was developed using Maasland's (1965) data. This allowed determination of the fraction of the flow which is groundwater at any given time. The concentration of effluent from the groundwater aquifer was determined by the equation

$$C_t = C_1 + f(C_2 - C_1) \qquad (30)$$

where C_t is the effluent concentration at any given time in ppm; C_1 is the concentration of the recharge water at any given time in ppm; C_2 is the concentration of the groundwater in ppm; and f is the fraction of flow which is groundwater at any given time.

The method used to calculate the volume of the return flow was developed by Glover (1960) and later used by Hurley (1961, 1968). With the hydrologic characteristics of the system known, i.e., the coefficient of permeability, k, in feet per second; the effective porosity, n; the original saturated depth, D, in feet; and the half spacing between drains, L, in feet; then the fraction of the original volume returned (1-P) to the drain, in time t, is given by

$$(1-P) = 1 - \sum_{m=1}^{\infty} \frac{8}{m\pi^2} \exp \frac{-m^2\pi^2 kDt}{4L^2 n} \quad ; m=1,3,5,7.. \qquad (31)$$

where P is the fraction of original volume of water remaining in transient storage. Using data from Dutt's (1962) column studies the computer program developed gave good agreement between theoretical and experimental results.

The deviation present was attributed to evaporation losses. The effects of continuous versus intermittent recharge were examined. Glover's method has been successfully applied to field conditions by the United States Bureau of Reclamation (Hurley, 1968) and was found to be well suited to areas of known homogeneous aquifer characteristics and well-defined uniform drainage patterns.

A hydro-salinity model, Figure 3, of the Grand Valley in Colorado was developed by Walker (1970) where the various parameters of water and salt budgets were examined. Since the budgets for the whole of the Grand Valley are generalized, the model or budgeting procedure is simply the adjustment of the water and salt flows according to a set of weighted data to arrive at a fair representation of the area. The budgets are characterized by inflows and outflows. The inflows represent the total water available for use within an area and the salts carried with this water. Outflows represent the total water leaving the area and the salts carried with it.

Inflow waters may come from rivers, tributaries, groundwater, imports, and precipitation. Outflows are in the form of evapotranspiration, river outflow, exports, and groundwater flowing under the gauging station. The model consists of a main program which inputs data to and controls subroutines which compute various parameters of the water and salt budgets. The subsurface characteristics of the area must be identified in sufficient detail to be capable of mathematically describing the entire water system and thus detect errors in surface water flow estimates. The time unit in the computations is on a monthly basis and as such gives a long term average of the hydraulic conductivities. This is sufficient for the saturated zone, however, can be very erroneous in the unsaturated zone where conductivity is a strong function of water content.

Hyatt et al. (1970) developed a computer simulation model of the water and salinity flow systems within the upper Colorado River basin using an analog computer. The model is macroscopic in scale using monthly time increments and large space increments and is based on fundamental and logical mathematical representation of the hydrological processes and routing functions. The physical processes modeled are not specific, thus, the model can be translated to another hydrologic unit. The basic concept of the model is the conservation of mass in the total flow through the system. For this study the total flow was divided into (1) surface flows, (2) subsurface flows, and (3) groundwater flows.

Mathematical representations were developed for inflows and outflows for each of the three components of the total flow. These representations were sensitive to the physical processes which impinge upon the components of flow and require determination of the coefficients and constants.

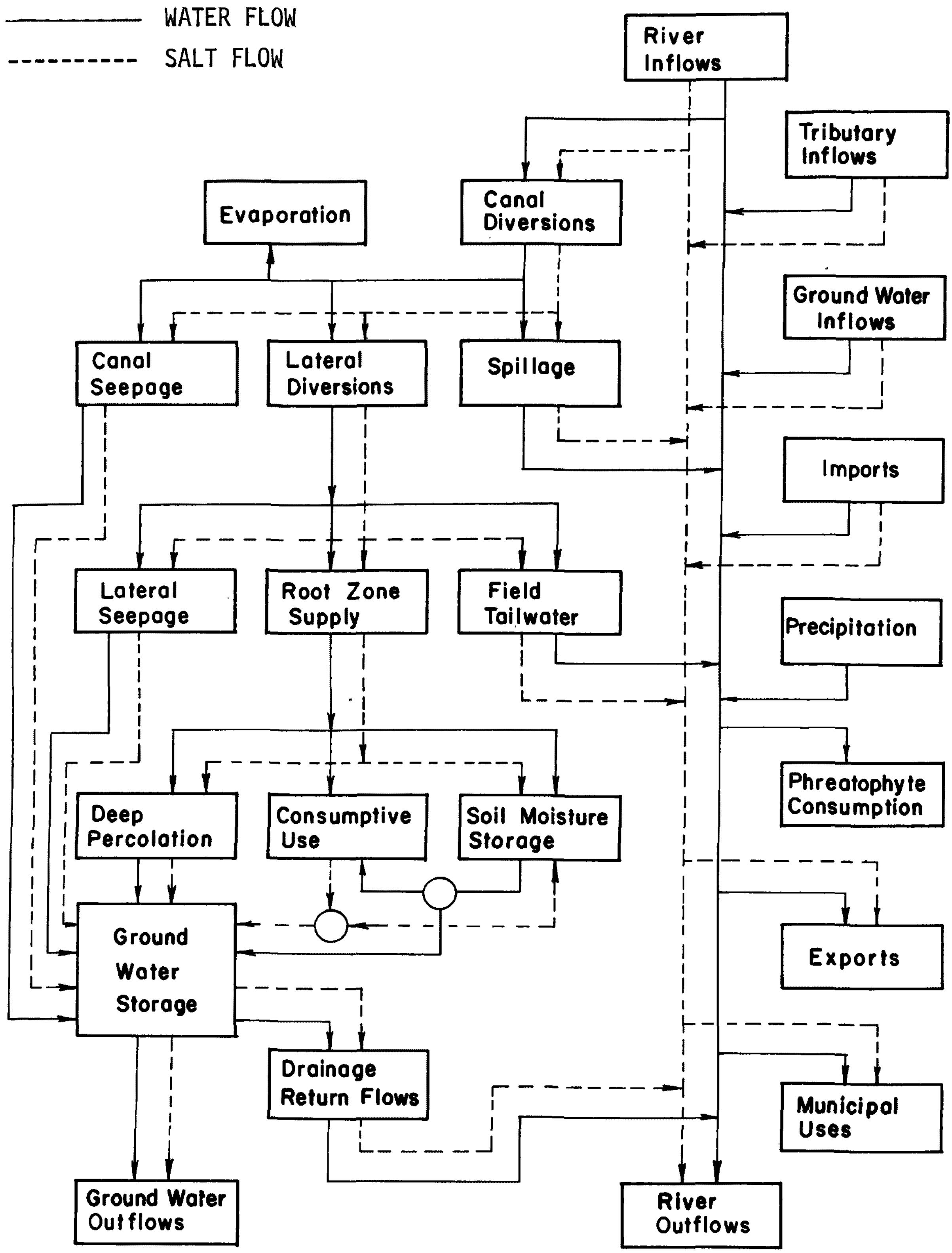


FIGURE 3. CONCEPTUAL DIAGRAM OF GENERALIZED HYDRO-SALINITY MODEL

The flow of salts in the system was modeled similarly so that the influence of water flow on salt flow could be properly assessed. This was accomplished by superimposing the salinity model upon that of the hydrologic model. The two models are linked by relationships which express salinity as a function of water flow rate. Thus, the rate of salt flow at any point is the product of the water flow rate times the appropriate concentration of total dissolved solids at that point in the hydrologic system. The authors note that additional research is needed to relate the role of irrigation to increased salt loading within the agricultural system and point out that physical constants and coefficients and water quality data must be ascertained in order to adequately verify the model to the area simulated. Factors such as irrigation practices, soil types, leaching of salts, ion exchange within the soil complex, efficiency of water use, and other parameters related to the irrigation system, all require additional investigation to provide the proper perspective of the role of agriculture in the salinity flow system.

Comparison of computed and measured water and salt flows for the study areas used shows good agreement, indicating that the analog simulation technique can predict with considerable accuracy the salinity level in the hydrologic system. Decreasing the time and space increments of the study and better evaluation of the physical constants and coefficients will lead to better agreement between predicted and measured results.

Thomas et al. (1971) developed a hybrid computer program to predict the water and salt outflow from a river basin in which irrigation was the major water user. A chemical model which predicted the quality of water percolated through a soil profile was combined with a general hydrologic model to form a system simulation model. The chemical model considered the reactions that occur in the soil, including the exchange of calcium, magnesium, and sodium ions on the soil complex, and the dissolution and precipitation of gypsum and lime. The chemical model was developed from the work of Tanji et al. (1967) and Tanji, Doneen, and Paul (1967). The chemical composition of the outflow is a function of these chemical processes within the soil, plus the blending of undiverted inflows, evaporation, transpiration, and the mixing of subsurface return flows with groundwater.

The quality of the outflow water was calculated from the following relationship

$$Qso\ Pso_j = \sum_{i=1}^{n} QS_i PS_{ij} + \sum_{k=1}^{m} QG_k PG_k \tag{32}$$

where QS_i is amount of water from surface source i in the inflow;

QG_k is amount of water from underground source k in the outflow;

Qso is the quantity of surface outflow;

Pso_j is concentration of chemical constituent j in the outflow;

PS_{ij} is concentration of chemical constituent j in QS_i; and

PG_{kj} is concentration of chemical constituent j in QG_k.

The j subscripts on the quality factors refer to the different ions being modeled. The i subscripts refer to the various sources of surface inflow and the k subscripts refer to the groundwater inflow sources.

Six common ions found in western waters, namely calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+), sulfate ($SO_4^=$), chloride (Cl^-), and bicarbonate (HCO_3^-) were studied. The total dissolved solids in the outflow was obtained by adding the individual ions. The overall model operates on monthly time increments. In a test using data from a portion of the Little Bear River Basin in northern Utah, the model sucessfully simulated measured outflows of water and each of the six ions for a 24-month period. Only sodium, which occurred in small concentrations, exhibited significant discrepancies between predicted and observed values. All other ions agreed within 10 percent on a weight basis for the two-year period, with correlation coefficients ranging from 0.87 to 0.97. With minor adjustment the model can be used in other areas.

A digital computer systems model developed by Dutt et al. (1970) describes the dynamic soil-water system along a vertical flow line from the surface to a nonfluctuating water table and predicts the distribution and concentration of the constituents in the effluent reaching the water table. The constituents considered were: Ca^{++}, Mg^{++}, Na^+, NH_4^+, $SO_4^=$, $CO_3^=$, HCO_3^-, Cl^-, NO_3^-, $CaSO_4 \cdot 2H_2O$, $CaCO_3$, $CO(NH_2)_2$, and Organic-N. The processes considered were (1) moisture additions; (2) evapotranspiration; (3) nitrogen transformations; (4) changes in solute concentration of soil-water due to ion exchange, solubility of gypsum and lime ($CaCO_3$), and dissociation of certain ion pairs; and (5) nitrogen uptake by crops. Each major process was calibrated individually and the model was verified against cropped lysimeters treated with ^{15}N enriched fertilizers. The computer model consists of two programs. The first is a moisture flow program whose output serves as input data to the second which is the biological and chemical program. The moisture flow program uses a finite difference method to solve the moisture flow equation. The behavior of inorganic constituents except nitrogen was developed from thermodynamic considerations. The behavior of organic and inorganic nitrogen was developed from statistical treatment of data found in the literature. The model was corrected and verified by comparing its predicted output with observed data from the literature. Comparison of computed and measured data for Ca^{++}, Mg^{++}, Na^+, ammonia and nitrate-nitrogen resulted in a correlation coefficient of better than 0.97.

SECTION VI

THE ROLE OF PREDICTION MODELING IN IRRIGATION RETURN FLOW STUDIES

Irrigation return flows are the result of a multitude of natural flow phenomena and humanly controlled management practices. The movement of water and salts in soils is influenced by soil properties such as texture, bulk density, water content, hydraulic conductivity, and exchangeable ions, as well as, soil moisture and gravitation potentials. These parameters may vary considerably from one location to another within an irrigated area further complicating the flow behavior. The loss of water from the surface by evaporation and from the root zone by plant transpiration not only interrupts the flow behavior but also concentrates salts in the remaining soil water. Thus, the characterization and prediction of the quality of irrigation return flow waters are considerably more difficult than quantity of water flow, although the two are closely related. Both are dependent upon a large number of variables which may be interrelated.

Study of such a system composed of many variables and interrelationships dictates the use of systems analysis techniques whereby the individual, fundamental processes occurring within the system can be identified and examined in detail and the degree of interrelationship can be assessed. Each fundamental process occurring in the system can be represented by the process model given in Figure 4. Associated with the model are input variables, internal variables, model parameters, and output variables which characterize the particular process being modeled. The sophistication of the model depends upon the completeness of identifying these variables and parameters as well as formulation of the mathematical equations which represent their interrelationships. The accuracy of the model output is dependent upon the accuracy of the input and internal variables used as well as the accuracy with which the model parameters and mathematical relationships represent the process being modeled.

Many processes occurring in irrigated agriculture are closely related. Sometimes they share the same input or output variables and can be grouped to show this close association. A conceptual diagram of a soil system submodel, Figure 5, shows the interrelationship of several process models which depend upon each other. The net result of this soil system submodel is the combined responses and interactions of the individual processes to the input variables imposed on the system. System submodels such as this can be easily handled by digital computer programs which provide simultaneous output for the individual process models as well as the total system submodel output. This capability provides insight into the cause and effect relationships occurring within the system and individual process which are particularly sensitive to changes in input variables can be readily identified.

Several related system submodels may be grouped to form a system model. An irrigation systems model is presented in Figure 6 and is composed of

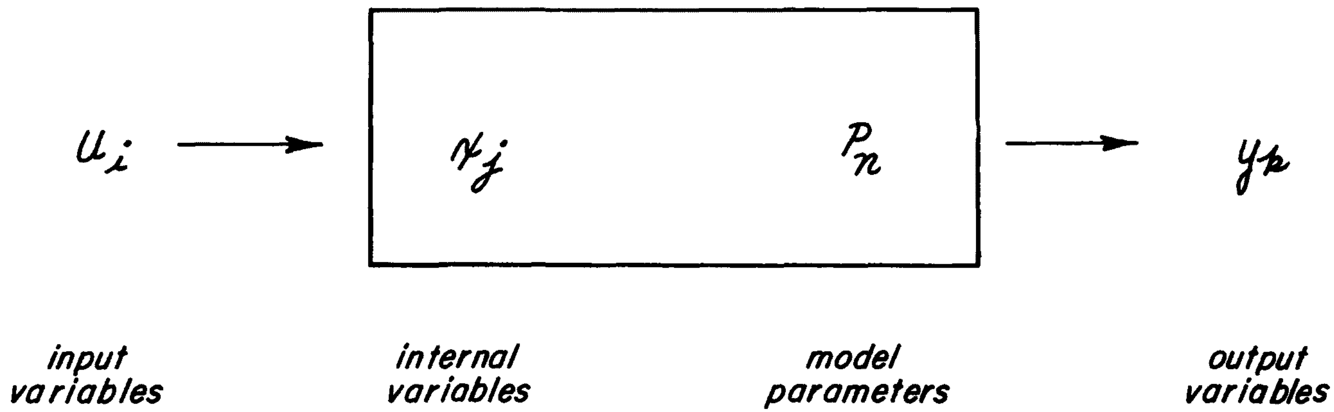


FIGURE 4. CONCEPTUAL DIAGRAM OF A PROCESS MODEL

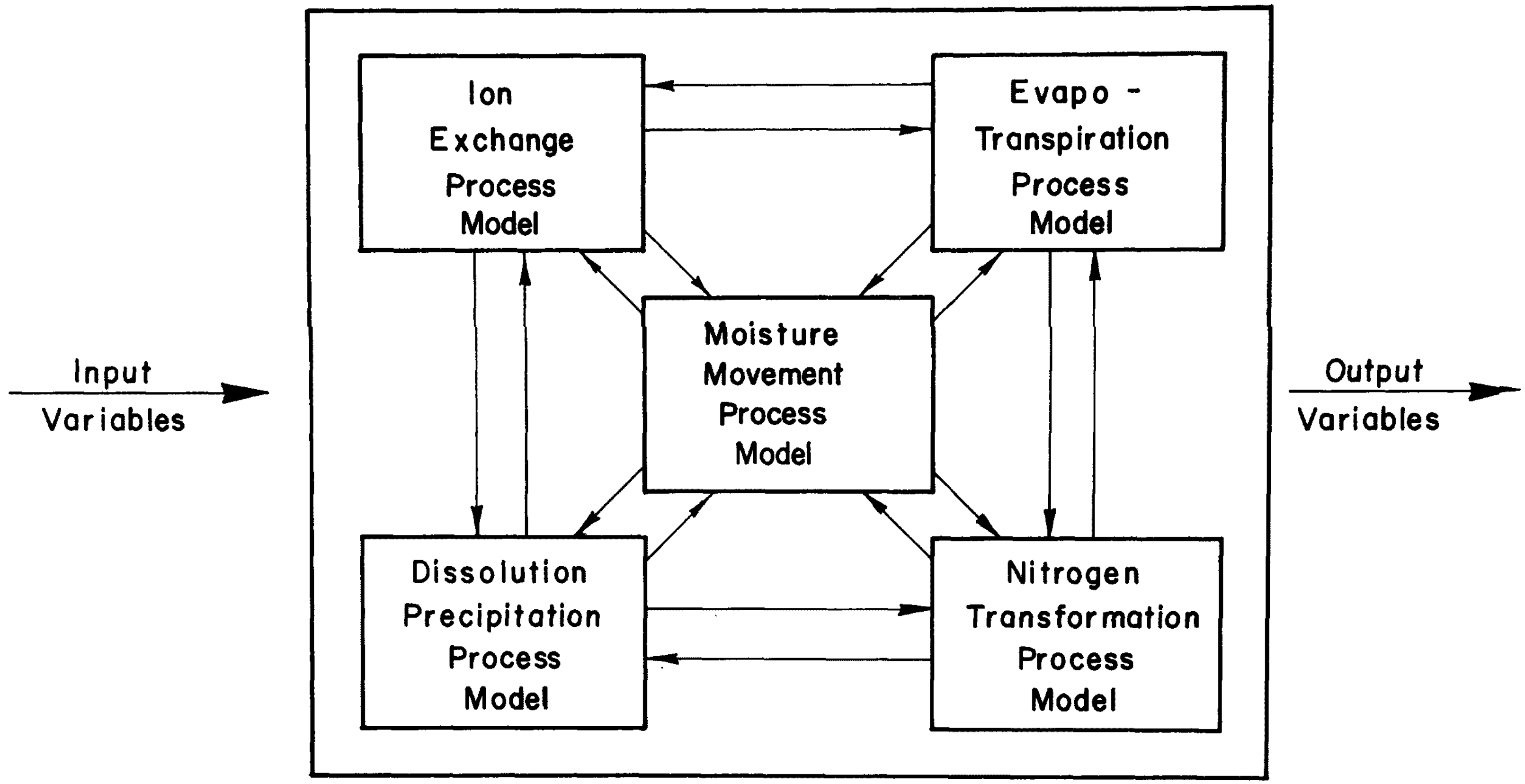


FIGURE 5. CONCEPTUAL DIAGRAM OF A SOIL SYSTEM SUBMODEL

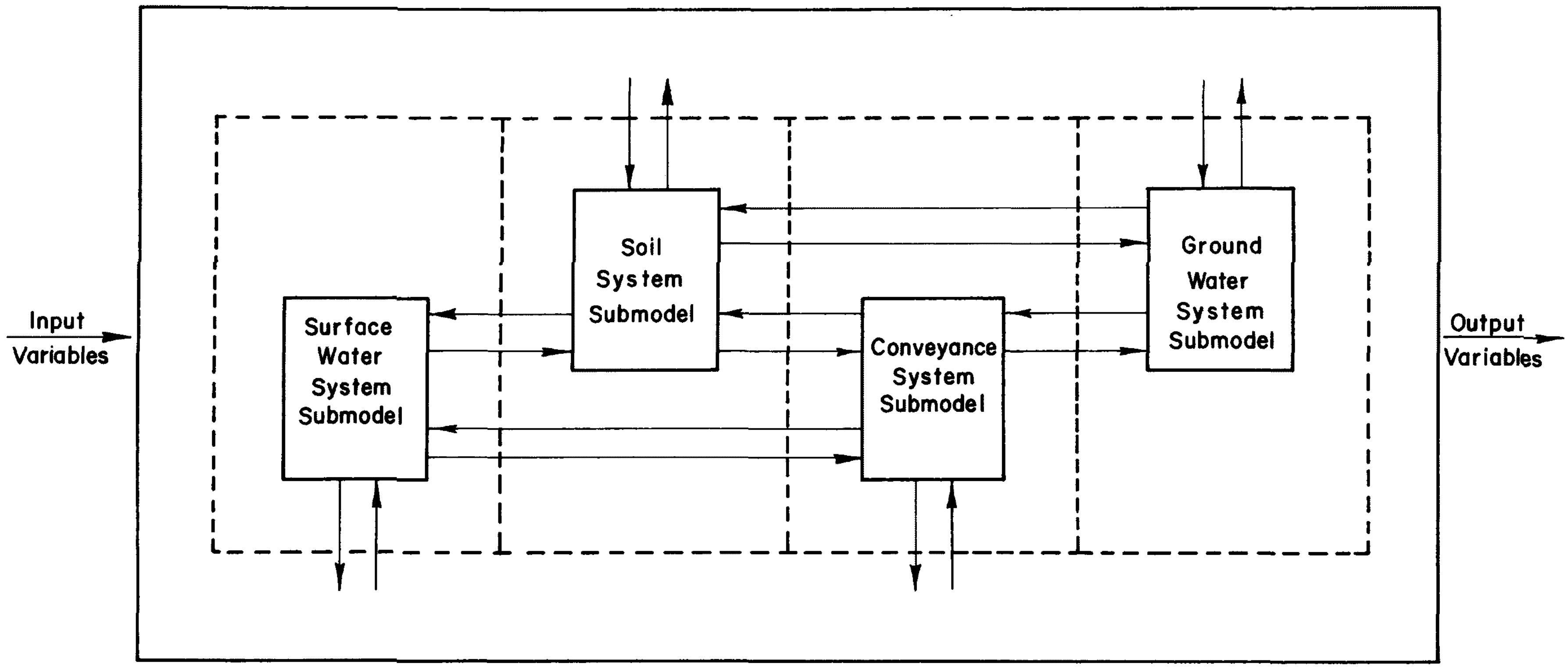


FIGURE 6. CONCEPTUAL DIAGRAM OF AN IRRIGATION SYSTEM MODEL

the soil system submodel given in Figure 5 as well as other system submodels which are associated with irrigation systems. Each of these submodels are composed of individual process models which simulate the system in question.

Systematic development of a model in this manner facilitates the study and solution of complex problems which are concerned with controlling and abating salinity levels in irrigation return flows. Since the system model contains individual process models, the sensitivity of the processes to changes in input variables to the model can be assessed. In managing a system for a desired output, the behavior of an individual process may need to be identified and altered in order to obtain the desired output.

Field research has long been the fount of technology development for improved irrigation management practices. Methods have been developed for increasing water use efficiency yet maintaining a desirable salt balance in the soil profile. Depth and spacing of drain tiles for proper drainage has been extensively studied and the theory of drainage is well defined. Movement of water in unsaturated soils has also been well characterized. While the technology of water management in irrigation systems has been investigated in depth, salinity in the return flow water has not been studied so thoroughly.

Only recently has field research been directed toward improving the quality of drainage or return flow waters. These studies have shown that control and improvement of salinity levels in irrigation return flows is technologically feasible. Subsurface application, scientific irrigation scheduling, and proper drainage offer means of reducing salinity levels while maximizing yields. Growers are not likely to use these techniques, however, unless they can be shown that the improved methods are indeed advantageous to them. Demonstration projects have been designed with this aim, but the time and expense involved and the variable conditions from one agricultural area to another prevent widespread education by this means. A rapid, economical means of examining alternatives to present management practices is urgently needed to facilitate implementation of improved management practices in widespread areas.

Prediction modeling can provide the means of examining alternative approaches for control of salinity levels. Application of systems analysis, sensitivity analysis, and optimization procedures to irrigation return flow problems can greatly enhance understanding the ramification of the problems as well as provide alternative irrigation management schemes. Freedom from the real time frame and resource outlay of field demonstration projects allows rapid, economical evaluation of proposed management schemes.

On-the-farm water management has been cited (Skogerboe and Law, 1971) as perhaps the area of greatest potential for improving salinity levels in return flow waters. Since changes in current management practices may not be reflected as immediate changes in the quality of the return water, expected long term improvements and benefits must be assessed by prediction techniques. Knowledge of the manner in which water behaves in soils has permitted development of prediction techniques for water movement in soil. These techniques can then be used to estimate the amount and timing of irrigation applications resulting in increased water use efficiencies. Such increases in efficiency lead to better management of salinity in return flows since excessive leaching can be avoided.

Models which include optimization procedures can predict the best management schemes for reducing salinity levels and improving crop yields as well as simulating water and salinity flow in the system. Optimization procedures allow the system to be simulated with constraints on salinity levels while maximizing crop yields.

The effectiveness of recent developments in methods of application of irrigation water in reducing or controlling salinity in drainage waters should be evaluated before they are recommended for widespread use. The high cost of installation of subsurface and trickle irrigation systems may make their use restrictive unless comparable benefits can be shown to accrue as a result of their installation. Prediction modeling can be used to evaluate their usefulness both in reducing salinity in the drainage waters and in improving yields as a result of better water management and increased efficiencies. Likewise, the effects of irrigation scheduling on both yield increases and drainage water quality can be assessed.

When the quality of applied irrigation water is marginal with respect to specific ions or total dissolved solids, models which simulate the quality changes resulting from ion exchange reactions and ion precipitation-dissolution reactions in the soil can be of considerable aid in managing such waters since the probable effects can be determined before their use. This is especially helpful in managing high sodium and/or high bicarbonate waters where precipitation of $CaCO_3$ may give rise to increased "sodium hazard."

Drainage studies have long been made using simulation techniques, however, only recently have quality aspects been considered from the standpoint of minimizing salinity in the return flow water. The salinity level of drainage water which results from consumptive use, ion exchange, salt pickup, and mixing phenomena which occur as a result of irrigation practices can be predicted by models. In areas where poor drainage has resulted in high salt levels in the soil profile, planning for subsurface drains can be enhanced by use of prediction techniques which not only handle the hydraulics but also the quality aspects of the proposed drainage system. Development of adequate drainage facilities is necessary in many irrigated areas to maintain a viable agricultural industry.

Irrigation return flows often constitute a major portion of summer stream flows in many western rivers, thus their management may greatly affect the river basin system in which they are located. In river basins such as the Colorado where salinity levels are of prime importance in the development of new areas and maintenance of present project areas, prediction modeling is a useful tool in managing the total water resource system. The benefits of salinity control measures implemented in a given area may accrue to some downstream users. If an equitable sharing of the expense of upstream improvements in control measures is to be found, then some mechanism for identifying the benefits accruing to both areas must be developed. Prediction modeling can be used to assess these quality improvements and arrive at an adequate estimate of benefits accrued to each area.

In the management of a river basin, irrigation may be only one of several resource uses which are considered in water resource planning. The relative importance of quality degradation caused by irrigation return flows may dictate a shift in water resource uses to comply with salinity standards. To date, most planning of this nature has relied on seat-of-the-pants estimates of the salinity contribution that can be attributed to agriculture. Definitive prediction models are needed to impact this level of planning.

In some states, water laws and water duties are structured such that they may be the chief deterrent to establishing salinity control measures in those areas. If institutional changes must be brought about to ensure success of salinity control measures, prediction models can be very helpful in generating possible alternatives to present practices. Subjecting these potential alternatives to economic analysis by optimization procedures can result in better insight to the probable success of the proposed changes. Changes in water laws are not likely to occur unless the quality benefits of doing so are considerable. Prediction models used for this purpose must necessarily be comprehensive and reliable in projecting the benefits of suggested changes.

Prediction modeling will play an increasingly important role in water resource management, especially in examining alternative approaches to irrigation management practices and to improved control of salinity in irrigation return flows. These predictive models will impact the legal and economic constraints to improved management practices.

SECTION VII

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16. Abstract

A review of the current state-of-the-art of prediction modeling as applied to salinity control in irrigation return flows is presented. Prediction models are needed to assess the effects of proposed changes in irrigation management practices on the quality of return flows. The processes which affect salinity levels in return flows are enumerated and their interactions are alluded to. Models used to predict the quantity and quality of return flows are briefly discussed to show the development of the current level of technology. The readers are referred to the original documents for more rigid development of the models and incumbent assumptions. It was concluded that technology of water and salt flow in soil systems is sufficiently developed to permit formulation of models using systems analysis to evaluate proposed changes in management practices. Development of systems models to study irrigation return flow problems and conjunctive water resource uses was recommended. A bibliography of selected references is given in addition to the references cited.

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Irrigation systems, surface flow, subsurface flow, salt movement, ion exchange, system analysis, water resource management, simulation, evapotranspiration, soil physical properties, soil moisture.

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