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A COMPUTER MODEL OF THE QUANTITY

AND CHEMICAL QUALITY OF RETURN FLOW

by

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ABSTRACT

A hybrid computer program is developed to predict the water and salt outflow from a river basin in which irrigation is the major water user. A chemical model which predicts the quality of water percolated through a soil profile is combined with a general hydrologic model to form the system simulation model. The chemical model considers the reactions that occur in the soil, including the exchange of calcium, magnesium, and sodium cations on the soil complex, and the dissolution and precipitation of gypsum and lime. 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 six common ions of western waters, namely calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), sulfate ($SO_4^{=}$), chloride (Cl^{-}), and bicarbonate (HCO_3^{-}) are considered in the study. Total dissolved solids (TDS) outflow is obtained by adding the individual ions. The overall model operates on monthly time increments.

The model is tested on a portion of the Little Bear River Basin in northern Utah. The model successfully simulates measured outflows of water and each of the six ions for a 24-month period. Only sodium ions, which occurred in small concentrations comprising approximately 2 percent of the total salt outflow, exhibit significant discrepancies between predicted and observed values. All other ions agree within 10 percent on a weight basis for the two-year model period, with correlation coefficients ranging from .87 to .97. The usefulness of the model is demonstrated by a management study of the prototype system. For example, preliminary results indicated that the available water supply could be used to irrigate additional land without unduly increasing the salt outflow from the basin. With minor adjustments the model can be applied to other areas.

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CHAPTER I

INTRODUCTION

General

In their undisturbed state, most river basins are in more or less of an equilibrium with respect to the rate of production of soluble salts on the watershed and the rate of transport of these salts out of the basin and into the sea. Man, however, with his enormous capacity to change the environment, in many cases has upset this equilibrium by interrupting and modifying the established hydrologic flow patterns. He has built diversion dams, reservoirs, and canals to direct water to the land, where part of it is used consumptively by the crops and the remainder evaporates or returns to the hydrologic system as surface water or groundwater flow. This "return flow" from irrigation is usually of lower quality than the natural water. Irrigated crops consume nearly pure water in their growth processes; the dissolved minerals originally in the applied water are left within remaining water. These minerals must be removed in the drainage waters or they will accumulate and eventually render the land unfit for agriculture. Thus a likely consequence of a successful irrigation project is degradation of downstream water quality, not only because of increased concentration of the minerals resulting from withdrawals of essentially pure water by the crops, but also because of chemical reactions that occur as the unconsumed diverted waters return to the stream through the soil network.

In man's enthusiasm to bring land under irrigation he has historically been concerned only with getting a sufficient quantity of water on his field to grow a crop and with the return of excess surface water to the stream. More recently, the "salt balance" concept (Scofield, 1940) has prescribed that enough water be supplied, along with artificial drains if necessary, to prevent salts buildup in the soil. The soluble salts brought into an area by irrigation waters must be removed in the drainage water. The salt balance idea has proven useful in the management of irrigation projects, but can be misleading if applied to a large area since salts may accumulate in some parts of the area while being leached from other parts, indicating favorable salt balance.

The proper management of irrigation projects, however, requires more than simply providing facilities to supply water to the land and to remove the excess while maintaining a favorable salt balance. The impact of operating these facilities on the quality and quantity of water available for downstream users must also be considered. In the face of increased demand for more and better quality water by other users, it is imperative that irrigation projects be planned and managed more efficiently, so that the quality of return flows is not unduly degraded.

Irrigation currently accounts for 83 percent of all water consumed in the United States (Water Resources Council, 1968). There are 42 million acres under irrigation in the 17 Western States, and more projects are in various stages of planning, construction, and development. According to the Utah State University Foundation (1969), return flows from existing irrigation projects in 1965 amounted to approximately 46 billion gallons per day (bgd), or 42 percent of all water diverted for irrigation. Much of this water was reused for subsequent downstream irrigation or for other purposes. In view of the enormous amount of water withdrawn for irrigation (111 bgd in 1965), it is essential that means be found to predict the effects of proposed projects, or changes in the management of existing projects, on the quality of downstream water.

Legally, return flow is a beneficial resource and is treated as any other water right in most of the Western States. The Utah court, for example, decreed that an upstream junior appropriator could not intercept return flow from irrigation which, if not intercepted, would return to the stream and supply prior appropriators downstream. "In such cases the rights of prior appropriators may not be interfered with, not even by the owners of lands from, through, or underneath the surface of which the seepage and percolation water passes on its return to the stream or river system" (Hutchins and Jensen, 1965). Most legislation and court cases, however, have been concerned only with the quantity of water, not with its quality. Only in recent years, with the mounting concern at many levels over water pollution, have the public, legislators, and courts become cognizant of the pollutional aspects of irrigation. The 1965 Water Quality Act, which authorized states to establish water standards on all interstate streams, focused attention on the quality problems associated with return flows from irrigation. In the future, irrigation practices will surely come under closer scrutiny as authorities attempt to identify and control all sources of water pollution.

Principal Processes Affecting the Quality of Irrigation Return Flows

Many factors interact to alter the quality of water as it passes through an irrigation cycle. The principal factors

are evaporation, transpiration, ion exchange, leaching, and precipitation of salts. These processes are influenced by the quality and quantity of applied water, physical and chemical characteristics of the soil, type of crops, method of water application, type of drainage system, climatic conditions, and biochemical reactions.

Evaporation and transpiration

Evaporation and transpiration occur continuously from the time water is diverted until it returns to the stream or groundwater. The rate of evaporation and transpiration depends upon many factors, principally temperature, wind, humidity, radiation, type of crop, and characteristics of the soil. The effect of these processes is to increase the concentration of salts in the return flow.

Ion exchange

Ion exchange occurs to varying degrees as the water penetrates the soil mantle. Some of the substances dissolve in the soil water and dissociate into positive and negative ions, which will replace ions present in the soil complex. Most agricultural soils in arid and semiarid zones have a predominance of calcium ions. When these calcium ions are replaced by sodium ions the soils exhibit undesirable physical characteristics. As a general rule, soils have a greater affinity for the bivalent ions, calcium and magnesium, however, than for the monovalent ions, sodium, and potassium. Therefore, it is possible to replace the exchangeable sodium with calcium or magnesium to improve the soil properties, but such a treatment increases the sodium hazard of the drainage water. Thus, ion exchange is capable of significantly altering the relative proportion of ions in the water.

Leaching and precipitation

Leaching and precipitation often occur as water passes through the soil. Leaching is the process by which water dissolves minerals from the soil and transports them downward into lower layers of the soil, into the groundwater aquifer, or out of the soil with the drainage water. Excess irrigation water is often applied purposely in order to leach salts from the root zone. The concentrating effects of evapotranspiration, on the other hand, may cause salts to precipitate out of the water as it percolates through the soil profile. The salts of lowest solubility present in natural waters are magnesium and calcium bicarbonates, which precipitate as carbonates (lime). Gypsum will also precipitate when the soil solution is concentrated sufficiently. Sodium salts, however, are highly soluble; the precipitation of calcium and magnesium salts therefore tends to increase the percentage of sodium in the water, an undesirable effect for subsequent water users.

Scope of Study

No single parameter can be used to measure the quality of water. Total dissolved solids (TDS), hardness,

turbidity, dissolved oxygen, sediment load, biochemical oxygen demand, coliform count, temperature, and pH are some of the common parameters used to describe the physical, chemical, and biological properties of water. The suitability of a particular water for irrigation depends mainly upon the amount and kinds of dissolved minerals. Therefore, this modeling endeavor considers only the chemical quality of water as measured by TDS and the individual ions: calcium, magnesium, sodium, sulfate, chloride, and bicarbonate. The selected ions represent the major concentrations in the chosen system and are only a sample of the total number of ions present. The choice of ions is completely dependent upon the system and the goals of the study.

Objective

The objective of this study was to develop a hybrid computer model to predict the mass of water and salt outflow from a river basin in which irrigation is the major user of water. The salt outflow was subdivided into the six dominant ions of western waters, namely calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^{+}), sulfate ($SO_4^{=}$), chloride (Cl^{-}), and bicarbonate ($HCO_3^{=}$).

Procedure

The model utilizes the following elements:

1. A hydrologic model of the irrigated portion of the basin.
2. A chemical submodel to predict the composition of return flow that has percolated through the soil profile.
3. The integration of the chemical model and other quality functions into the overall hydrologic model.
4. Verification of the model by comparison of simulated results with actual field data.

No strictly mathematical model of the complex physical and chemical processes occurring in a hydrologic system has yet been attempted because of limitations of data, knowledge, and time. Simulation methods, however, help overcome some of these restrictions. Simulation may be defined as ". . . the operation of a model or simulator which is a representation of the organism. The model is amenable to manipulations which would be impossible, too expensive or impractical to perform on the entity it portrays. . ." (Shubik, 1960). The model described herein, if quality is included in the context of hydrology, is nothing more than hydrologic simulation, which involves the following steps:

1. An understanding of the qualitative concepts of a hydrologic system.
2. The development of mathematical relationships to describe the processes occurring within the hydrologic system.
3. The representation of those mathematical re-

lationships by computing devices, i.e., electronic elements on an analog computer, or by mathematical programs on a digital computer. (A hybrid computer, which is a combination of an analog and a digital computer, was utilized in this study.)

4. Verification of the model by operation with known input and output until the simulation model adequately represents the physical system.

The simulation process is necessarily one of trial and error.

Discussion

If each of the hydrologic concepts could be represented by exact mathematical equations which accurately describe all important physical processes, simulation techniques would be unnecessary and a unique model could be obtained for each watershed. Such a model is impossible, however, because of imperfect knowledge of hydrologic processes and the prohibitive quantity of input data required.

A practical hydrologic model must compromise the ideal and the feasible. It must represent the fundamental components of the hydrologic cycle while reducing them to a workable level of complexity. Since numerous theories can be advanced to relate hydrologic processes, it is important to select concepts that meet the objectives of the model without introducing unwarranted complications. For example, hourly rainfall data may be required for a model simulating flooding on a small watershed, but would be an unnecessary burden for a model of monthly runoff.

The goal of this study has been to utilize quantitative hydrologic concepts which are applicable to large space and time increments and which require a moderate amount of reliable input data. The chemical submodel, on the other hand, because of the more delicate relationships involved, required substantially more detailed information on the physical system it represented. In order to make the overall modeling procedure as practical as possible, attempts were made to simplify quantitative relationships and reduce data requirements to a minimum level, while still retaining a useful skeletal representation of the hypothetical system.

Description of Prototype

The Little Bear River above Hyrum Reservoir in Utah (Figure 1) was selected as the basin on which the model would be tested. This area was intensely monitored from 1966 through 1968 as part of another research project at Utah State University (Dixon et al., 1970) and therefore offered more data than are normally available for an agricultural watershed.

The Little Bear River, a tributary of the Bear River, drains the mountainous zone at the southern end of Cache Valley. The Paradise gaging station just above Hyrum Reservoir, with 203 square miles drainage area, has recorded an average annual runoff of 60,000 acre feet. Most of the runoff is from spring snowmelt that lasts into June. Late summer and fall flows are sustained by springs and return flows from irrigation. The flow is regulated by the 12,000 acre feet Porcupine Dam built on the East Fork in 1962.

The basin topography ranges from rugged high mountains to a nearly flat valley floor, with elevations from 4,500 to 9,445 feet. The climate of the region exhibits four well defined seasons. Average monthly temperatures range from 21° F in January to 73°F in July at the Logan USU weather station, located a few miles north at nearly the same elevation and exposure as the irrigated area. Normal annual precipitation at this station is 16.6 inches per year occurring primarily as winter snows and spring rains. The valley area is semiarid and irrigation is required for the successful growing of most crops.

Three major canals divert water from the East Fork between Porcupine Dam and Avon. One additional canal diverts from South Fork. Approximately 10,000 acres are irrigated from these diversions, 7,000 of which are below the Paradise gaging station. All diversions are measured by a water commissioner appointed by the Utah State Engineer.

Additional information on water and land in the area is available from various sources. The Soil Conservation Service has recently completed a soil survey of the valley area (Soil Conservation Service, 1966). Utah State University has published a land use classification of the Bear River (Haws, 1969) including the area covered by this project. The geology and groundwater are adequately described by Peterson (1946), Beer (1967), Mullens and Izett (1964), and Bjorklund and McGreevy (1970). Appendix A contains a more detailed description of the area.

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LITTLE BEAR RIVER STUDY AREA

⊗ USGS GAGING STATION
10-1046 South Fork Little Bear River
10-1047 Little Bear River blw Davenport Cr.
10-1049 East Fork Little Bear River
10-1060 Little Bear River nr Paradise
10-1070 Hyrum Reservoir nr Hyrum
10-1072 Wellsville East Field Canal
10-1074 Wellsville-Mendon Lower Canal
10-1075 Little Bear River nr Hyrum
10-1076 Little Bear River at Wellsville

☐ PRINCIPAL CANAL DIVERSIONS
1 Highline Canal
2 Hyrum Canal
3 Paradise Canal
4 Lofthouse Ditch
5 White's Trout Farm Diversion
   Wellsville East Field Canal
   Wellsville-Mendon Upper (Pump) Canal
6 Wellsville-Mendon Lower Canal
   Hyrum Little Feeder Ditch
   Darley Ditch

▨ DEVELOPED LAND IN WELLSVILLE SUBAREA

■ DEVELOPED LAND IN PARADISE SUBAREA

▦ WATERSHED AREA TRIBUTARY TO WELLSVILLE SUBAREA

▦ WATERSHED AREA TRIBUTARY TO PARADISE SUBAREA

Figure 1. Map of the Little Bear River Basin.

CHAPTER II

LITERATURE REVIEW

Introduction

A few investigators have proposed various models to predict the changes in water quality resulting from irrigation and other quality-degrading uses. This chapter will review the development, application, and limitations of some of the more important models.

General Concepts of Modeling

It would be an extremely difficult task to develop a general model that could accurately simulate all situations and processes encountered in every river basin. Such a model should consider all the elements influencing water quality and trace all constituents, both conservative and non-conservative, through all phases of the physical system. Functions would be required to describe the concentrating effects of evaporation and transpiration, the chemical and biological reactions between various constituents, the decay of non-conservative elements, and the transfer of matter between points in the system. All such functions should be time and space dependent.

Natural river basins are generally heterogeneous with respect to soils, geology, drainage patterns, and other physical features. In addition, inputs to the basin, consisting of precipitation, solar energy, wind, ground and surface water and their dissolved constituents, and items supplied by man such as fertilizers and pesticides, and outputs from the basin consisting of ground and surface water flow, evaporation and transpiration, and elements removed in harvested crops, can be measured accurately only on extremely small, well instrumented areas. For a large region the cost of obtaining these quantities, including setting up the data collection network, recording and analyzing all the information collected, and interpreting the results, would be prohibitive. Furthermore, any model that utilized all possible data, including the physical system and all the above inputs, would be exceedingly complicated, require a large computer to perform all the calculations, and consume an enormous amount of man and computer time.

In short, it is not physically or economically feasible at the present time to develop a model that considers all aspects of the changes that occur in the quality and quantity of water as it moves through a river basin. Because of this maxim all models can at best only approximate the prototype to varying degrees. The following discussion describes several models which take various approaches to modeling the quality of return flow from irrigation.

Water Quality Models

Consumptive use model

One of the simplest models of irrigation return flow quality considers only one of the factors listed by Sylvester and Seabloom (1963)--evapotranspiration. Evaporation and transpiration do not increase the quantity of salts in return flow, but rather only concentrate them. Von Seggern (1962) proposed a model that estimates return flow quality based only on the concentrating effects of evapotranspiration. Bailey (1969) applied a similar, but more detailed model, to the Central Valley Project in California. Basically, they assumed that the total mass of salt in the water is unchanged during the processes of storage, irrigation, and drainage. The outflow contains the entire quantity of salts initially present or introduced into the system during the time interval.

The following equation describes Von Seggern's consumptive use model

$$\frac{\text{Concentration in outflow}}{\text{Volume of inflow}}$$
$$= \frac{\text{Concentration in inflow}}{\text{Volume of outflow}} \quad \cdot \cdot \ (2.1)$$

Von Seggern admits that his model neglects several important factors, but justifies its use by stating ". . . after a number of years, the soil adjusts to the irrigation water so that on an average no further exchange takes place. This is termed salt balance. . . ."

Such an equilibrium, however, may require many years or decades before it is established. Ion exchange and leaching often influence quality changes indefinitely after irrigation is commenced. Thus, a consumptive use model is of limited value and must be used with prudence.

Analog computer model

Hyatt, Riley, and McKee (1970) developed an analog computer model of the salinity (total dissolved solids) flow in subbasins of the Upper Colorado River Basin. Using the hydrologic model described by Israelsen and Riley (1968) and associating a concentration of salts with each element of water moving through the hydrologic system, they were able to reproduce historical outflows of salts at selected gaging stations. The basic equation for salt outflow rate from a basin, $S_r{}^{Q}s$, is:

$$S_r^{Q_s} = S_r^{Q_{is}} - W_{tr}C_i(m) + OF_rC_s$$

$$+ Q_{ob}C_g - Q_eC_e + S_r^{NS} \quad \ldots \ldots \quad (2.2)$$

in which

Q_s	=	total rate of outflow from the system
Q_{is}	=	rate of total surface inflow to the subbasin including both measured and unmeasured flows
W_{tr}	=	total rate at which water is diverted from the stream or reservoir
OF_r	=	total of overland flow and interflow rates
Q_{ob}	=	rate of outflow from the groundwater basin of routed deep percolating waters and subsurface inflows to the subbasin
$S_r^{Q_{is}}$	=	rate of salt flow associated with surface inflow waters to the subbasin
$C_i(m)$	=	measured concentration of total dissolved solids associated with inflowing surface waters diverted for irrigation
C_s	=	salinity level associated with the overland flow and interflow components of return flow
C_g	=	salinity level of the groundwater within the subbasin
Q_e	=	rate of water diversions from surface sources for use outside the boundaries of the basin
C_e	=	average salinity level of water exported from the subbasin
S_r^{NS}	=	rate of salt flow contributed from natural sources within the basin

The change in salinity resulting from deep percolation was ignored; instead the quantity of deep percolation water was combined with groundwater outflow and was assigned a salinity level equal to the average concentration of waters in the groundwater basin. This simplification was necessary because of the lack of data on salinity concentrations within the soil solution and the difficulty of programming on an analog computer mathematical models which describe the salt movement and ionic exchanges processed within the soil profile.

An additional parameter was introduced into the salinity model to account for apparent "natural inbasin salinity contributions." They assumed that a given stream was influent (contributing to the groundwater aquifer) in the upper reaches and effluent (receiving water from the groundwater aquifer) in reaches farther downstream. Since groundwater is generally higher in dissolved solids content than surface water, the salinity level of a surface stream is increased by this interchange or recirculation. The rate of recirculation was related to the rate of water flow in the surface channels by the empirical equation:

$$k_p = n(Q_r)^m \quad \ldots \ldots \ldots \ldots \quad (2.3)$$

in which

k_p	=	percentage of surface flow to be interchanged or recirculated through the stream alluvium Q
Q_r	=	monthly surface flow rate in cfs
m	=	slope of line plotted on log-log paper
n	=	intercept on the y-axis (percentage axis) of a log-log plot

Equation (2.3) plots as a straight line on log-log graph paper. Parameters m and n were determined experimentally through normal verification procedures for each subbasin.

Salt flow rate attributed to interchange can be written as follows:

$$S_r^{NS} = k_pQ_rC_g \quad \ldots \ldots \ldots \ldots \quad (2.4)$$

in which

S_r^{NS}	=	rate of salt flow contributed from natural sources within the basin
k_p	=	percentage of surface flow allowed to interchange or recirculate through the stream alluvium or groundwater basin
Q_r	=	monthly rate of surface water inflow, outflow, or average of inflow and outflow to a subbasin
C_g	=	average water salinity level within the groundwater basin or stream alluvium of a hydrologic system. This quantity was assumed to be constant throughout the simulation period

Equation (2.4) neglects several important parameters, which could affect recirculation, including channel characteristics such as slope, width, and bed porosity and geologic factors.

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In summary, the analog computer model was able to reproduce historically water and salt flows for the sub-basins of the Upper Colorado River Basin fairly accurately. It requires only generally available data for inputs and yields a reasonable first approximation of the physical system. It is by design, however, a rather gross approximation of the complex processes actually occurring on the watershed and includes salinity as the only parameter, although in theory another parameter could be included.

Use factor model

The use factor model is predicated on determining the average number of contacts at the surface of an irrigated field that water will make while circulating through the system. It is applicable to conservative elements and assumes an incremental accumulation of material by the water during each contact with the soil. The minerals left behind in the soil by evapotranspiration are assumed to be diluted and carried away by subsequent irrigations. A specific stable relationship is assumed to exist between a given water and soil type.

Orlob and Woods (1964) developed and tested the use factor model on the Lost River Basin in California. They assumed initial contaminant concentrations of zero for all inflows into the system. Each irrigation use was assumed to add one unit of pollutant to the water. Further, "it was presumed in this study that the concentrations of the hypothetical pollutant were always below saturation and that the concentration in any reused water was equal to the mean concentrations prior to application plus unity. . . the hypothetical pollutant can be classed as 'conservative' and not in any way affected by physical, chemical, or biological forces; only simple mechanical dilution."

Clearly, the implied linear relationship of constant increments of contaminant pickup per soil contact is not valid for all constituents over all field conditions, particularly for the various soluble elements in the soil that are subject to different rates of water application. The authors claim, however, that ". . . the use-factor model seems to function reasonably well when used over the fairly narrow operational ranges which are normally found in a particular soil-water system."

The use factor model is subject to some of the same limitations as the consumptive-use model although its proponents claim that it does account "specifically for leaching and indirectly for most of the other factors influencing conservative water quality constituents" (Woods, 1967). But it, too, assumes that a steady state condition between the soil and water has been established.

Modified use factor model

Recognizing the limitations of their use factor model, Orlob and Woods (1967) proposed a general water quality model that would meet the following criteria:

1. Compatibility with a "dynamic" hydrologic model of the same system.
2. Facility for accommodation of time-dependent decay functions.
3. Facility for time-delay of quality constituents brought about by interaction with the physical media through which the constituents must pass.

This model is similar to the use factor model but has provisions for extraction of constituents from each storage element of the system. It is based on determining the average number of contacts with the soil and the average residence time of water within various elements of the system.

Figure 2 depicts schematically the modified use factor model. The F elements shown refer to the pollutants entering the system, leaving the system, or being extracted (decaying) from the system. M elements represent storage of pollutants in the various zones. The overall model would be represented as an arrangement of nodes and links, nodes symbolizing storage elements and links symbolizing the transfer elements.

Nodes represent such physical features of the hydrologic system as irrigated areas, swamps and wet areas, groundwater zones, reservoirs, etc. In addition each node has certain water quality parameters, "surface area exposed to the air, a surface mass transfer coefficient, pollutant storage capacity, base exchange capacity, and a media surface decay coefficient" associated with it.

Links may be one of several transfer functions that effect the flow of mass through the system. Such physical properties as area, shape, and roughness of channels, porosity and permeability of groundwater reservoirs, plus water quality parameters of ". . . dispersion and/or diffusion coefficients, base exchange capacity, media surface area, and a distribution coefficient (exchangeable cations)" are associated with each link.

The flow of a pollutant would be described by the following equation:

$$f_x = K_x q_x C_x \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot (2.5)$$

in which

q_x = flow rate
C_x = concentration of pollutant
K_x = distribution coefficient
f_x = mass rate of flow of pollutant

Each quantity could be space and time dependent.

The authors applied their modified use factor model to the Sacramento River Basin in California. They achieved some correlation between water reuse and the conservative constituents total dissolved solids, calcium,
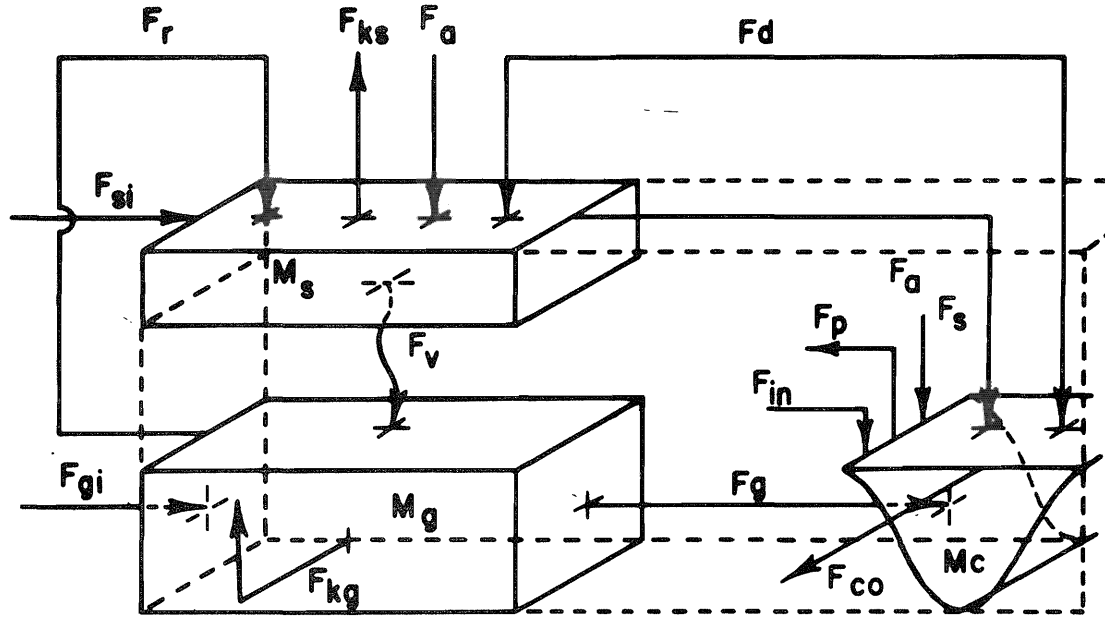
Figure 2. Schematic diagram of the use-factor model.

magnesium, and sodium, but no significant relationship was established for non-conservative elements. Their study did, however, provide a basis for interpretation of the overall effects of irrigation water reuse, irrigation efficiency, soil properties, and other parameters on water quality in the basin.

The modified use factor model is a rational approach and is sufficiently general to cover a variety of field conditions. The main difficulty in applying it to a particular area is obtaining enough information to accurately describe the nodes and links representing the physical system. Perhaps further testing and refinement of the model will overcome some of the drawbacks.

Fiering-Pisano mathematical model

Maass et al. (1966) of the Harvard Water Resources Research Group have developed a comprehensive mathematical procedure for hydrologic simulation which is based upon synthetic or "operational" hydrology. Several outgrowths of their work have been reported. Hufschmidt and Fiering (1966) describe the successful application of the Harvard Technique to the hydrologic simulation of the Lehigh River system. Pisano (1968) developed a computer program based on Fiering's work that will simulate up to five water quality parameters. The Federal Water Pollution Control Administration (1967) describes the Fiering-Pisano mathematical model and its application to the Red River of the North. The simulation effort adequately modeled the total dissolved solids and streamflow at several stations within the Red River basin.

The so-called Fiering-Pisano model relies heavily on historical data, requiring the following inputs: historical flows, locations of reservoirs, water inputs, and water users, "background water quality relationships" (in the case of the Red River of the North this information was obtained by historical water quality records at several water quality monitoring stations), reservoir evaporation, measures of water use, waste input, and reservoir volumes, waste scheduling, and reservoir operating rules. The hydrologic model utilizes historical arithmetic averages of monthly streamflow, their standard deviation and log correlation coefficients. Mean monthly concentration is related to discharge by the following equation:

$$C = aQ^b \quad \ldots \ldots \ldots \ldots \ldots \ldots (2.6)$$

in which

C = concentration of total dissolved solids
Q = rate of water flow, and a and b are constants. The values for a and b must be determined independently for each gaging station.

Dixon et al. (1970) presented procedures for modeling water quality charges in time and space for four parameters, including electrical conductance, temperature, dissolved oxygen, and bio-chemical oxygen demand. He fitted Equation (2.6) to several stations on the Little Bear River for electrical conductivity and derived values for the constants ranging from 363 to 1000 for a and -.002 to -.16 for b.

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Chemical model

This type of model determines changes in water quality on the basis of chemical thermodynamic equilibria between the soil and the soil solution. It corresponds closely with the actual physical processes that occur in nature and can describe complicated leaching and ion exchange phenomena quite accurately with the use of high speed digital computers. Substantial field data, however, are required as inputs to the computer program.

Some researchers, including Eaton (1950), Thorne and Thorne (1954), Wilcox, Blair, and Bower (1954), Doneen (1954), Brooks, Goertzen, and Bower (1958), and Bower (1962) laid the ground work for this approach by investigating the effects of irrigation water on soil properties. Dutt (1962a) spearheaded development of a computer program based on chemical theory that predicted the quality of water percolated through a soil column. This program was improved and modified by Dutt (1964), Paul, Tanji, and Anderson (1966), Tanji et al. (1967), Tanji, Doneen, and Paul (1967) until it could accommodate rather complicated soil water systems, and accurately predict the quality of effluent, as well as changes in the soil complex itself.

A search of the literature revealed few actual applications of this type of model to prototype conditions. Margheim (1967), extending techniques developed by Dutt, predicted the quality of irrigation return flows. He used only hypothetical data, however, and made no effort to incorporate the chemical model into an overall hydrologic model. The United States Bureau of Reclamation (Maletic, 1969) has used a modified form of Dutt's program in some of its project studies. Tanji, Doneen, and Paul (1967) used their computer program to predict the quality of groundwater on the west side of the San Joaquin Valley resulting from a recharge operation using Feather River water. Dyer (1967) developed a complicated program which incorporated the effects of carbon dioxide on the chemical reactions and used it to predict the quality of groundwater after percolating from an irrigated field through a substrata of known chemical characteristics. Tanji (1970) reports that he is attempting more precise predictions of changes in a cropped, irrigated soil profile by modifying the basic computer program, but his work is still in the experimental stage.

In as much as it is theoretically sound and has been laboratory tested for most groups of ions, the chemical model will form an important segment of this modeling endeavor. (See Chapter IV.)

Use of Computers in Hydrologic Modeling

The use of electronic computers to model hydrologic systems is a fairly recent innovation. The use of the analog computer to simulate hydrologic processes at Utah State University began in 1963 (Bagley et al., 1963). The first basic model utilized large space and time increments to model basin hydrology. Subsequent investigators extended application of the analog computer to a wide range of hydrologic problems. Riley (1970) summarizes the hydrologic simulation program at Utah State University and lists all the publications that have resulted from analog computer modeling at the Utah Water Research Laboratory. Others have applied the analog computer to selected hydrologic processes. Falk (1962), Rennerfelt (1964), Cohen and O'Connel (1963), for example, utilized the analog computer in water quality studies. Shen (1965) performed flood control studies on an analog computer.

The analog computer solves problems by behaving electronically in a manner analogous to the prototype. Such mathematical operations as addition, subtraction, multiplication, and integration are performed by a system of electronic devices which are interconnected by wiring a "patch panel" according to the program requirements. The analog computer is ideal for real time solutions where high speed solutions of linear differential equations are required. Many of the hydrologic processes are functions of time and may be described by time dependent differential equations. Since the analog computer is a parallel device, with all operations performed simultaneously, it is easily adapted to time dependent functions where continuous integration of the problem variables is required. The results of analog simulation are usually displayed visually on an oscilloscope or plotter, thus giving the operator insight into the dynamic system being modeled.

Hydrologic simulation on digital computers was spearheaded by two groups, one at Harvard University (Maass et al., 1966, and Hufschmidt and Fiering, 1966) and the other at Stanford University (Crawford and Linsley, 1966). Rather sophisticated digital programs have been developed to successfully model many hydrologic phenomena.

A general-purpose digital computer performs calculations sequentially and with great speed and accuracy. Since hydrologic simulation often involves the processing of a quantity of data, the digital computer, with its capabilities for processing and storing large quantities of data and for solving problems involving numerous arithmetical and logical operations, has found wide application in hydrology. Digital computers are also required to calculate the changes resulting from the complex chemical reactions that occur when water percolates through the soil medium. Hand methods are available to predict the exchange of two cationic species and to predict the solubility of salts in solution, but no routine procedures exist to predict the solubility of salts in the presence of an exchanger containing two or more cationic species. The extreme length of the calculations, including possible trial and error solutions and successive approximations, precludes non-computer analysis. Integration on a digital computer, however, can be done only by numerical approximation and in a sequential manner, thus extending the computing time and storage capacity required.

Hybrid computers, which link digital and analog computers in one unit, offer many opportunities for improving hydrologic models. Hydrologic simulation often involves the rate of change of physical processes that occur both in parallel and serially, as well as routine data processing. The hybrid computer is capable of more accurately representing the various processes that occur in a physical system than either the analog or digital computer when used separately. It retains ". . . the speed advantage, man-machine capability (for changing parameters and verification studies), and instant display of results in graphical form (on an oscilloscope or a plotter) of the analog computer, while taking advantage of the greater precision, dynamic range, and information storage capability of the digital computer for arithmetical computation" (Morris, 1970). The Utah Water Research Laboratory hybrid computer, consisting of an EAI 580 analog computer linked to an EAI 640 digital computer, was utilized in this study.

CHAPTER III

GENERAL HYDROLOGICAL-CHEMICAL QUALITY MODEL

This chapter describes in detail a general model to represent the physical and chemical processes that occur in a hydrologic unit consisting of a river valley dominated by irrigated agriculture. Processes considered include precipitation, snowmelt, evapotranspiration, surface water and groundwater movement, chemical changes as water percolates through the soil, and the mixing of irrigation return flows with surface water and groundwater.

Hydrologic Simulation Model

The general hydrologic model has been adequately described by Riley, Chadwick, and Bagley (1966). The model is based on the conservation of mass concept applied to the irrigated portion of watershed. Inputs to the area include outflow from upstream reaches, precipitation, subsurface inflows, and imports. Outputs include surface stream outflows, evaporation and transpiration from land and water surfaces, subsurface outflows, and exports. The model considers reservoir operation, diversions for irrigation, municipal and industrial uses, return flows, snowmelt, evapotranspiration, and the soil moisture and groundwater regimes.

Figure 3 conceptually represents the quantities of water involved in the hydrologic unit under consideration. The continuity of mass for a portion of a river basin can be represented by the following equation for a discrete time interval:

$$\text{Inflow-Outflow} = \text{change in storage}$$

$$\ldots \ldots \ldots \ldots (3.1)$$

or more explicitly

$$(\text{PRE-EVT}) + (Q_{si} - Q_{so})$$

$$+ (Q_{gi} - Q_{go}) = \Delta S \ldots \ldots (3.2)$$

in which

PRE	=	precipitation on the area
EVT	=	evapotranspiration from the area
Q_{si}	=	surface inflow
Q_{so}	=	surface outflow

Q_{gi}	=	underground inflow
Q_{go}	=	underground outflow
ΔS	=	net change in storage within the unit, including snow, surface reservoirs, soil moisture and groundwater

For modeling purposes Equation (3.2) may be further refined and written as:

$$Q_{so} = (\text{PRE-EVT}) + (Q_{gi} - Q_{go} - Q_{gp})$$

$$+ \text{SNMLT} + (Q_{sim} + Q_{siu}$$

$$- (\text{DIV} + Q_{gp} + Q_{sr}) - \text{EXPORTS} . \quad (3.3)$$

in which

DIV	=	amount of water diverted to the land from streams
Q_{sr}	=	surface return flow from irrigation
Q_{gp}	=	amount diverted to the land from groundwater sources
Q_{sim}	=	measured surface inflow
Q_{siu}	=	unmeasured surface inflow
Q_{sr}	=	surface return flow
EXPORTS	=	water exported from the area
SNMLT	=	snowmelt

The modeling procedure involves solving the above equation for Qso, the surface outflow. Each of the quantities on the right side of Equation (3.3) must be measured, calculated, or estimated in order to solve the equation.

Precipitation records are normally available from the network of weather stations supervised by the National Oceanic and Atmospheric Administration (NOAA). Such stations furnish only point measurements, however. Some judgment is required to properly extend these records to cover the model area. Frequently, two or more stations are combined to obtain weighted average precipitation and temperature values for a given hydrologic unit.

Evapotranspiration, consisting of water transpired by plants in their growth process or evaporated from the surface of lakes, streams, canals, and the ground, is normally computed as part of the simulation. Numerous formulae are available to compute evapotranspiration. (Refer
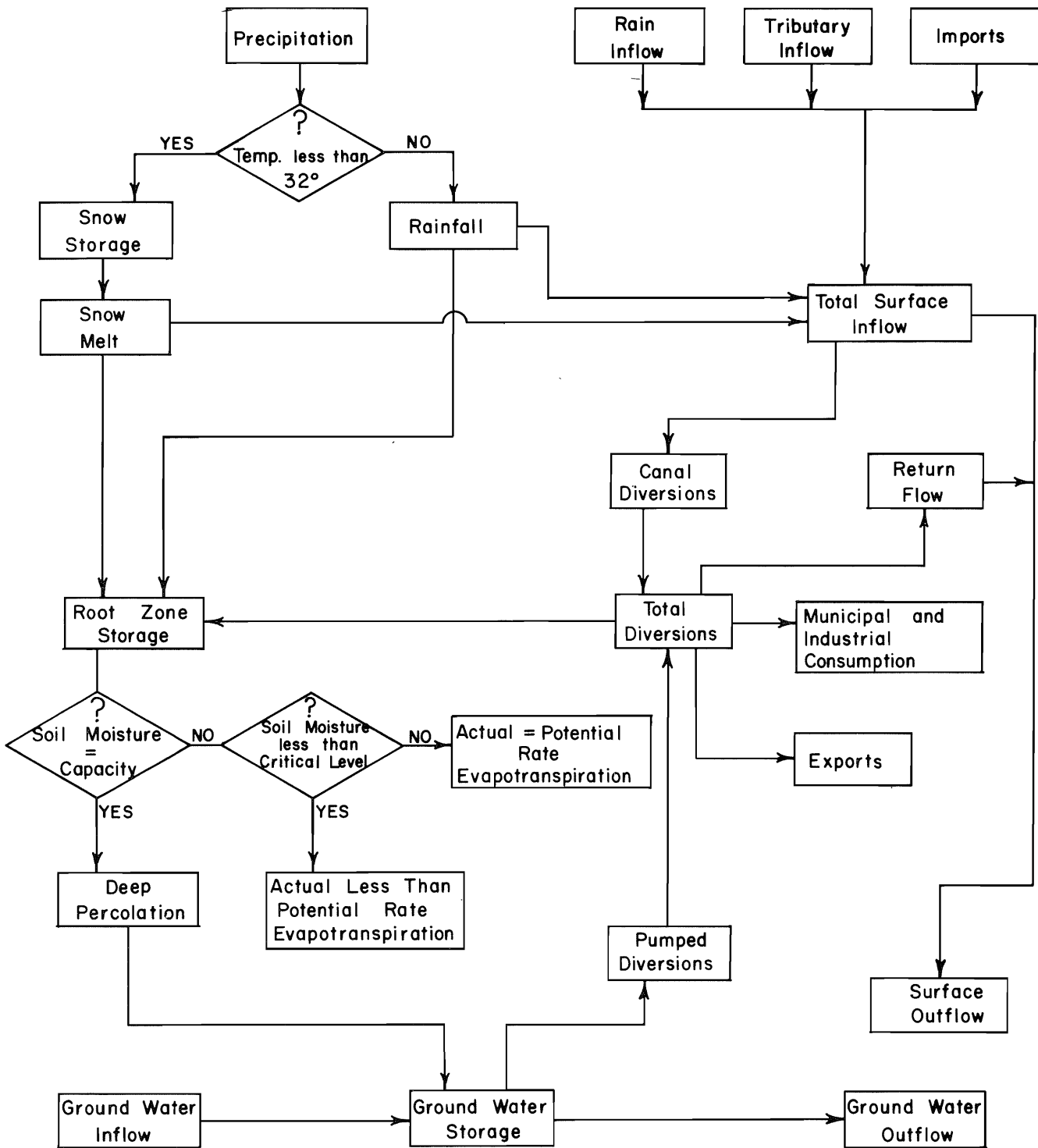
Figure 3. Flow diagram for hydrologic flow system.

to Christiansen, 1966, for a review of methods for estimating evaporation and evapotranspiration.) The modified Blaney-Criddle method (Soil Conservation Service, 1964) has proved convenient for monthly models of basins in the Western United States, mainly because of the limited amount of input data required and the rather extensive work done to determine Blaney-Criddle coefficients for vegetation common to that area. For parts of the world with different climates, crops, and data collection techniques, other procedures of computing evapotranspiration may be more accurate than the Blaney-Criddle.

Measured surface inflow, Qim, is generally available from water commissioner or state engineer publications. Accuracy, however, is generally lower than for stream flow records because of lack of money, equipment, and trained personnel to measure the water.

Surface return flow, Qsr, is determined from the equation:

$$Qsr = DIV (1-eff) \quad \ldots \ldots \ldots \quad (3.4)$$

in which eff is the irrigation efficiency. Qsr thus includes tailwater runoff and bypass water. It is assumed that all other diverted water, eff times Qsr, is applied to the land or seeps through the soil profile and thus might contribute only to subsurface return flow.

Pumped groundwater, Qgp, is seldom measured accurately. Many states, however require that groundwater diversions be appropriated and measured just as surface waters are. In the present study pumped groundwater was insignificant.

There are four types of storage units within the basin: surface storage, groundwater storage, soil moisture storage, and water stored as snow. Records are normally available for the contents of major surface water reservoirs. Such factors as evaporation, seepage, and bank storage can affect the records, however, and may have to be included in water budget studies involving certain reservoirs. These processes can also alter the quality of water passing through the reservoir.

Groundwater storage changes could theoretically be determined by an analysis of water level changes in selected observation wells and by the characteristics of the aquifer. Such refinement, even if sufficient information were available, would seldom be justified for the model considered in this study. Instead it is more convenient to consider together water storage, base flow, and deep percolation.

If the groundwater basin is assumed to act as a linear reservoir, i.e., the rate of discharge is proportional to the amount in storage, the following equation is applicable:

$$q_g = Sg/Kg \quad \ldots \ldots \ldots \ldots \quad (3.5)$$

in which

q_g	=	discharge rate during a given time interval
Sg	=	storage within the basin at any time, t
Kg	=	proportionality constant

Soil moisture is modeled by assuming a one-dimensional soil reservoir as shown in Figure 4. Inflow to the reservoir consists of snowmelt, precipitation, and irrigation water which infiltrates the surface of the ground. Outflow consists of evapotranspiration upward and deep percolation downward. The system is modeled continuously on the analog part of the hybrid computer. Deep percolation occurs only when the soil moisture reservoir is full, i.e., at field capacity, and the rate of infiltration exceeds the rate of evapotranspiration.

The quantity of water stored as snow and the rate of melt were modeled according to the empirical procedure proposed by Riley and Chadwick (1967), which assumes that the rate of snowmelt is proportional to the quantity of precipitation stored as snow and to the energy available to melt it. For valley areas, available energy is assumed to be related only to air temperature. In discrete form the equation is:

$$WS_{i+1} = WS_i \exp(ks (T-32)) \quad . \quad (3.6)$$

in which

WS_{i+1}	=	water equivalent of snowpack at the end of period i + 1
WS_i	=	water equivalent of snowpack at beginning of period i + 1 (end of period i)
ks	=	constant
T	=	average monthly air temperature

Snow accumulates when T is less than 32°F and melts according to the above equation when T exceeds 32 degrees. The quantity of snowmelt, SNMLT, for any time period is the difference in water equivalent of the snowpack at the beginning of successive time periods, or

$$SNMLT = WS_i - WS_{i+1} \quad \ldots \ldots \quad (3.7)$$

Snowmelt ceases, of course, when WS_i equals zero. The value of ks is determined during verification; it is usually in the range from -.10 to -.25.

Logically, the fewer quantities which must be estimated the better the model. But unmeasured inflows can

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Infiltration

Evapotranspiration

M_{es} = Capacity

Deep Percolation
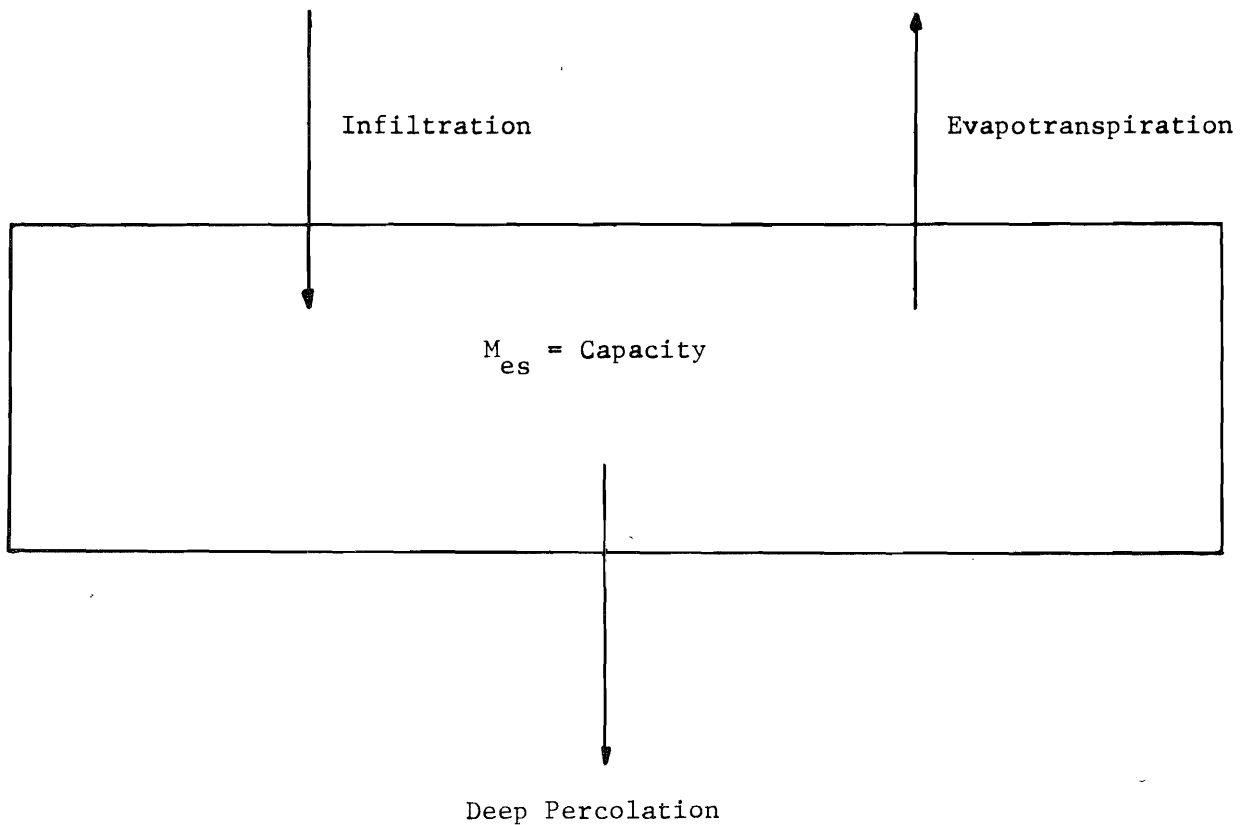
Figure 4. Soil moisture regime.

often be reliably correlated with measured quantities so that the resulting model represents the physical system quite well. Three distinct approaches to the problem of estimating unmeasured surface inflows are possible: correlation with measured surface stream in the vicinity, with precipitation, or with snowmelt.

Stream records are generally preferred for correlation because they reflect the end result of the various processes producing runoff, whereas precipitation and snowmelt are but intermediate phenomena in the runoff process. The stream used for correlation purposes should drain a watershed "similar" to the ungaged portions of the basin being modeled. The similarity pertains to geology, elevation, vegetative cover, slope, aspect, latitude, and precipitation--all factors influencing the hydrology of the area. Satisfactory records on nearby similar streams are sometimes inadequate or not available for correlation purposes.

Correlation of ungaged surface inflow with precipitation and snowmelt is generally not as reliable as stream correlations but is often sufficiently accurate (and necessary) to arrive at a "best fit" model. Unfortunately, snowmelt is not a measured quantity but is computed as part of the simulation effort. In spite of this inherent weakness snowmelt correlations are frequently quite useful when modeling watersheds where spring snowmelt contributes a significant portion of the runoff. The equa-

tion for unmeasured surface inflow is:

$$Qsiu = F (Qr, PRE, SNMLT) \ . \ . \ . \ (3.8)$$

in which

Qr	=	quantity of water measured at the correlation stream station during the time period considered
PRE	=	measured precipitation
SNMLT	=	calculated snowmelt

Although other functions are possible, a simple linear equation, such as

$$Qsiu = C_1 (Qr - C_2)$$

$$+ C_3 (PRE - C_4) + C_5 (SNMLT - C_6) \ . \ (3.9)$$

in which the C's are constants, proved adequate for this study.

Groundwater inflow, Qgi, may be correlated with known or calculated quantities, also, or assumed to be a constant rate. A logical correlation is with the water available for infiltration at the ground surface. This quantity consists of rainfall plus snowmelt for a given time period. Thus the correlation equation becomes:

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$$Qgi = C_7 (PRE + SNMLT - C_8) \quad . \quad . \, (3.10)$$

The calculated quantity of water, Qgi, is then routed through a groundwater delay network before it appears as effluent. The length of the delay, and values for the constants in Equations (3.9) and (3.10) are established during model verification.

With all quantities on the right side of Equation (3.3) represented in the model by measured inputs or mathematical functions, it is possible to calculate the output, Qso, and compare it with recorded data. Values of many of the parameters influencing the output can only be estimated initially. Verification consists of systematically varying the values of the parameters and observing the effect on the output. The model is assumed to be verified when it faithfully reproduces the measured output for a specified time period. In effect, the model is calibrated for a specific prototype hydrologic basin by establishing values of the parameters through verification procedures. Thereafter, the model may be used with confidence in management studies of the area.

General Water Quality Model

Each quantity of water described above for the hydrologic model has a measureable quality associated with it. If the quality of each input element can be identified and the dynamic processes within the basin which alter the quality can be simulated, then the quality of the output can be predicted by simply combining the quality parameters of each element making up the outflow. For example, if the outflow for a given month consisted only of 300 acre feet of base flow with total dissolved solids of 500 milligrams per liter (mg/l), and 700 acre feet of surface flow with total dissolved solids of 500 mg/l, the concentration in the outflow would be 800 mg/l, or 1090 tons. This oversimplified calculation illustrates the underlying principal of the water quality model. It is predicated on being able to identify the quantity and quality of each component of water composing the outflow. In equation form,

$$Qso \; Pso_j = \sum_{i=1}^{n} QS_i \; PS_{ij}$$

$$+ \sum_{k=1}^{m} QG_k \; PG_{kj} \quad . \; . \; . \; . \; . \; . \, (3.11)$$

in which

QS_i	=	amount of water from surface source i in the outflow
QG_k	=	amount of water from underground source k in the outflow
Pso_j	=	concentration of chemical constituent j in the outflow
PS_{ij}	=	concentration of chemical constituent j in QS_i

PG_{kj}	=	concentration of chemical constituent j in QG_k

The surface outflow terms, QS_i, represent the various surface source components of the surface water outflow: measured and unmeasured stream flow, surface return flows from irrigation, and reservoir discharges. Groundwater outflows, QG_k, represent native groundwater, spring discharges, and subsurface return flows from irrigation, all of which may be further subdivided according to the chemical characteristics of the various geological formations through which groundwater moves. The j subscript on the quality factors refer to the different ions being modeled. The following section describes how the quality parameters are obtained for inclusion in Equation (3.9).

Return flow from irrigation

Considering only that portion of the outflow composed of return flow from irrigation, which can be a substantial part of the total outflow, the Utah State University Foundation (1969) described the outflow quality by the following function:

$$IRF_q = f(Q_{iq}, C_{sq}, B_q, T_a, M_a,$$

$$S_{mq}, S_{cc}, ET, D_{pq}, C_q, F_{pq},$$

$$F_a, P_a, C_f, O_i) \; . \; . \; . \; . \; . \; . \; . \; . \; . \, (3.12)$$

in which

IRF_q	=	irrigation return flow quality
Q_{iq}	=	quality and quantity aspects of applied irrigation water
C_{sq}	=	canal seepage quality change
B_q	=	bypass water quality
T_a	=	time of application
M_a	=	method and rate of application
S_{mq}	=	soil moisture quality
S_{cc}	=	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	=	evapotranspiration
D_{pq}	=	quality of water percolation below the root zone
C_q	=	crop influence on quality
F_{pq}	=	farm practice effect on quality
F_a	=	fertilizer application
P_a	=	pesticide application
C_f	=	climatological factors, i.e.,

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O_i = other influences, i.e., elements carried from the air to the farmland by precipitation, industrial pollution of soils or water, municipal inputs from runoff or sewage, etc.

temperature, precipitation, wind, sunshine, etc.

Equation (3.10) is, of course, only qualitative and can never be solved analytically for a general solution. It does, however, indicate the complexity of the interactions among the various factors which combine to affect a given quality in irrigation return flows. Most of the factors listed are considered in this study. A few are neglected because of their insignificance or the impracticality of including them in a model of this scope.

Return flows consisting mainly of surface runoff from irrigation lands normally differ little in chemical composition from the applied water because of limited contact with the soil. This water does pick up impurities from the land including such things as fertilizers, pesticides, organic matter, debris, and sediment. Surface return flow may be up to 10 percent higher in dissolved minerals concentration because of the contact with the soil and the concentrating effects of evaporation while the water is on the field.

Irrigation return flow water which moves through the soil profile, on the other hand, may be greatly changed chemically because of its exposure to the processes that occur in the soil moisture regime. The root zone acts as a storage reservoir for the water required by growing plants. If the moisture content of this zone falls below the "wilting point" the plants will suffer permanent damage. Therefore the purpose of irrigation is to maintain the moisture level above the wilting point. The addition of water beyond "field capacity," the maximum amount of water the soil will hold against gravity, will cause "deep percolation" below the root zone. Although many irrigators consider deep percolation as wasted water and try to minimize it, irrigation experts now recognize that some deep percolation is necessary in order to prevent the accumulation of undesirable salts in the root zone. Subsurface return flows consist of deep percolation water which has returned to the stream or the groundwater reservoir. Water passing through the soil as deep percolation will generally have high concentrations of dissolved salts and a distribution of cations and anions different from the applied water. The total salt load may be more or less, depending upon whether leaching or deposition occurred. Chapter IV describes in detail the reactions that occur in the soil profile and the model proposed to represent them.

Quality determination of other factors

The quality associated with the other water quantities, undiverted inflow, baseflow, imports, and exports,

must be measured or estimated. In the present study most of the surface inflow and outflow was sampled weekly throughout a one to two year period. Quality of the unmeasured surface inflows was correlated with quality measurements on gaged input streams. Groundwater samples from several springs and wells were collected and analyzed on approximately a monthly schedule.

Mixing of deep percolation water with groundwater

One of the most difficult problems was that of deriving a suitable mathematical description of the mixing phenomenon as subsurface return flows from irrigation join the groundwater reservoir. Much theoretical and experimental work has been done on diffusion, dispersion, and miscible displacement as applied to the movement of soluble salts in a porous material. Limited work has been directed toward field investigations of the mixing process.

Miscible displacement. Biggar and Nielsen (1960, 1962, 1963, 1964) and Nielsen and Biggar (1961, 1962, 1963) published a series of papers on miscible displacement in porous media, in which they examined earlier theories, such as those advanced by Scheideggar (1954), Day (1956), and Bear (1961), and attempted to develop new functions to describe the phenomenon. They postulated that Darcy's law, which describes the flow of water through soils as bulk movement, is inadequate for defining the movement of transient dissolved solutes. They reasoned that the major factors in miscible displacement studies are measurement of tracer concentration distribution moving through a porous material, tracer diffusion rates, and chemical processes. Their experiments showed that the distribution of dissolved constituents used as a tracer depends upon the geometry of the porous material and the physical and chemical reactions between the tracer solution and the media. Biggar and Nielsen (1962) emphasized the need to include molecular diffusion in the dispersion theory.

Nielsen and Biggar (1962) and Biggar and Nielsen (1963) proposed new equations to describe miscible displacement for two cases: (1) no interaction between the fluid and the media and (2) when cation exchange reactions do occur. The following equation was derived for the instance when exchange of a cation of a certain species for a cation of a different species occurs:

$$\frac{C}{C_o} = 1/2 \ \text{erfc} \ \left(\frac{[x(Q + \varepsilon C_o - C_o V]}{\dfrac{4DVC_o(Q + \varepsilon C_o)}{v}}\right)$$

$$\exp \ \left(\frac{vx}{D}\right) \ \text{erfc}$$

$$\left(\frac{x(Q + \varepsilon C_o) + C_o V}{\dfrac{4DVC_o(Q + \varepsilon C_o}{v}}\right) \ \ . \ \ . \ \ . \ \ . \ \ (3.13)$$

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in which

<div>

Q = exchange capacity per unit length (m.eq/cm)

V = volume of effluent (cm^3)

D = apparent diffusion coefficient

v = average flow velocity

ε = pore volume per unit length (cm^3/cm)

x = length of column (cm)

C_o = concentration of ion in influent

C = concentration of ion in effluent

</div>

Sallam (1966) presented an excellent review of most of the theoretical models of miscible displacement, including the work of Biggar and Nielsen, and concluded (as did Biggar and Nielsen, 1963) that none of them accurately described the physical and chemical processes during displacement.

Hanks and Bresler (1969), neglecting such factors as diffusion, flow induced anisotropy, the distribution of pore velocities, and ion exchange, and considering only bulk movement of salt with water, developed an equation solvable by numerical techniques on a digital computer to describe the movement of salt in an unsaturated porous media. The procedure was tested on several controlled experiments involving infiltration redistribution and evaporation under various wetting and drying conditions. The procedure yielded "reasonable" results for noninteracting solutes.

Keller and Alfaro (1966) showed that miscible displacement and salt flow in soils are related to the rate of water application and degree of soil saturation. Alfaro (1968) used dimensional analysis techniques to model salt movement in soils. He related the results of laboratory tests of salt movement in soil columns to field conditions through dimensionless parameters.

The above procedures for describing the mixing and movement of solutes in soil were all rejected as being too microscopic in character and requiring too much man and computer time for the model considered in this study. Two recent works of a more practical nature were considered more pertinent.

Aquifer flushing. Maasland (1965) conducted a laboratory study utilizing a parallel plate Hele-Show model on the problem of removing saline water from an aquifer by the surface application of fresh water. The results were given as a series of dimensionless graphs relating concentration of drain effluent versus time for various initial concentrations of saline water in the aquifer, drain spacing, aquifer thickness, permeability, and different application rates. Maasland concluded that the concentration of the effluent at any time is inversely related to the recharge rate, directly related to the drain spacing only for very small values of the spacing, directly related to the thickness of the aquifer, and inversely related to the permeability.

Margheim (1967) applied the least squares curve fitting method to Maasland's data to obtain the following equation for effluent concentration:

$$f = w - x\log\ (hL^2/KD^2)$$

$$- y\log\ (DK\ t/nL^2)\quad \ldots \ldots \ldots (3.14)$$

in which

f = fraction of flow which is groundwater at any time

h = recharge rate

L = half spacing between drains

n = effective porosity

K = permeability

D = saturated thickness of aquifer

t = time

w,x,y = constants

Margheim found values of w, x, and y equal to 0.44, 0.64, and 0.69 respectively for aquifer concentrations less than 15,000 ppm and values of 0.60, 0.57, and 0.72 for aquifer concentrations of 30,000 ppm.

Carlson (1968) studied the same problem using sand tank models of aquifers and obtained results generally consistent with those of Maasland. Glover (1965) as an adjunct to Carlson's study, developed a mathematical description of the mixing phenomenon based on the assumption that the rate of flow of saline water is proportional to the amount of removable saline water remaining in the aquifer. Glover's equation is given below:

$$S = So\ e^{-b\ qt}/vw\quad \ldots \ldots \ldots (3.15)$$

in which

S = concentration at time t

So = concentration at time o

v = ratio of drainable void volume to gross volume

w = porosity volume above the ultimate fresh water-saline water interface

b = a constant, equal to 2 if the drainage flow passes to two drains

Figure 5 is a plot to Glover's equation applied to Maasland's experimental data. The fit is remarkably good.

Both Maasland and Carlson considered only the case of fresh water being applied to a saline aquifer and neglected the salinity of the applied water. In many field situations the groundwater is not saline and the percolating water is not entirely free of dissolved salts. In these situations the process is not one of flushing the saline
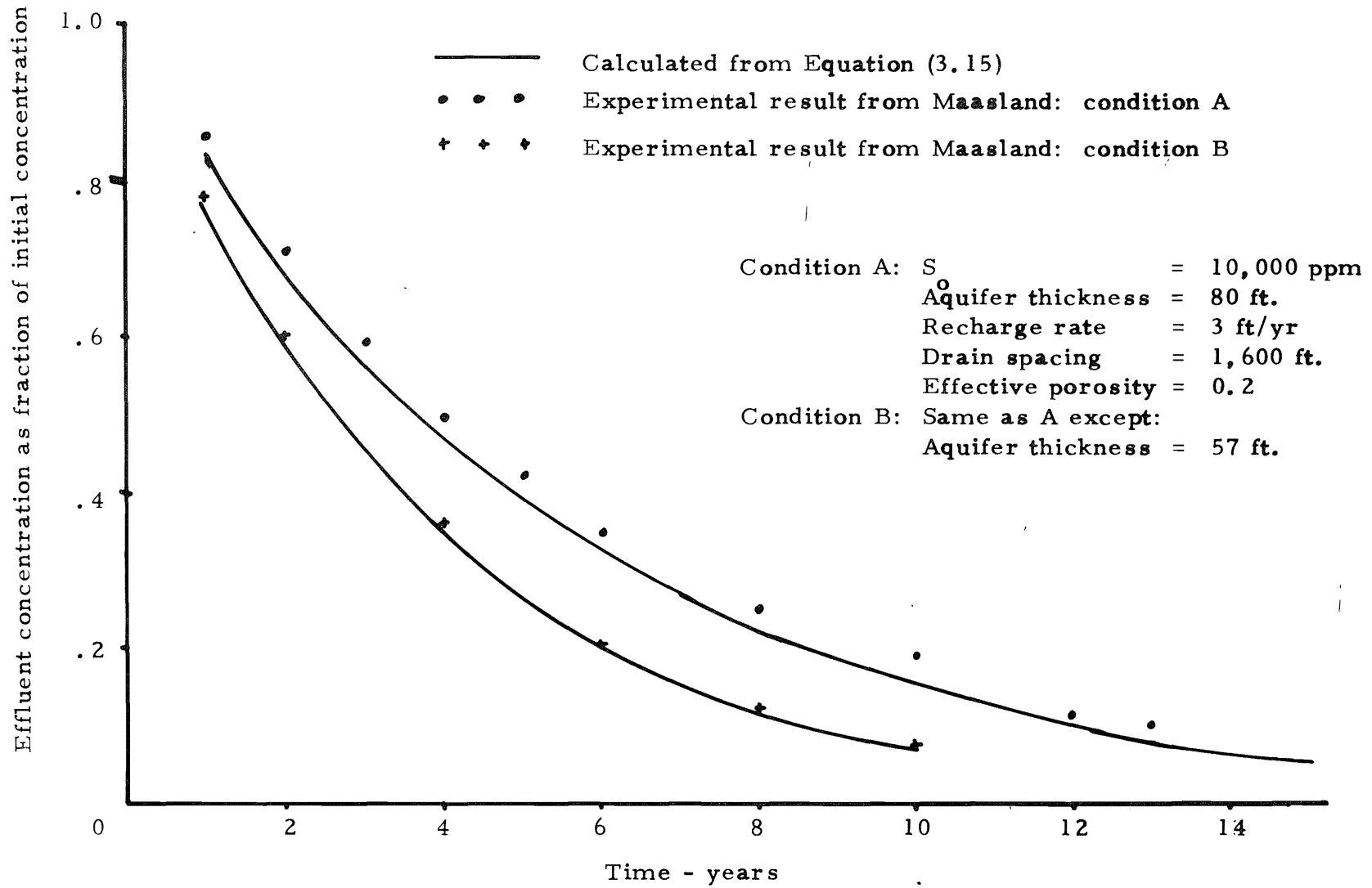
Figure 5. Plot of Glover's equation applied to Maasland's experimental data onaquifer flushing.

water from the aquifer, but rather one of both ground-water and recharge water contributing to the concentration of minerals in the effluent. Mathematically, the effluent concentration may be represented by the following equation:

$$C_t = Cg \, \phi + Cr \, (1 - \phi) \qquad \dots \dots (3.16)$$

in which

C_t = concentration of the effluent at any time

Cg = the concentration of the groundwater

Cr = concentration of the recharge water

ϕ = fraction of the total effluent that comes from groundwater

C may represent total dissolved solids or any of the constituent ions. ϕ is probably a function of the rate of water application and the physical properties of the soil.

Glover (1960) derived an equation based on the physical properties of the aquifer to predict the volume of deep percolation water appearing as subsurface return flow. He considered that the percolated water raises the groundwater level and induces additional flow into the drain or effluent stream. Glover's equation is expressed as follows:

$$p = \sum_{n=1}^{\infty} \frac{8 \, \exp \, \dfrac{(-n^2 \pi^2 \alpha)}{4 \, L^2 \, V}}{\pi^2 \, n^2} \quad n = 1,3,5,7$$

$$\dots \dots \dots (3.17)$$

p = that part of the original volume of water added to the aquifer which remains in transient storage after a period of time t

L = drain spacing

α = KD/V

K = permeability of aquifer

D = saturated thickness of aquifer

V = effective porosity

The amount of the original volume which has been discharged is then 1-p. Solutions to Equation (3.18) are read-

ily obtained from charts of p as a function of α or from a digital computer program. Glover's method has been successfully applied to field conditions by the United States Bureau of Reclamation (Hurley, 1968). It is well suited to areas with known homogeneous aquifer characteristics and well-defined, uniform drainage patterns.

Stream-aquifer simulation. Another possibility involves the use of digital computers to simulate the conjunctive use of ground and surface waters in stream aquifer systems. Such programs have been described by Bittinger (1968) and Longenbaugh (1967). They are in the development stage, however, and are currently not adequate for the model under consideration.

Analog computer program for deep percolation and base flow. As mentioned previously, Glover's Equation (3.18) can be programmed readily on a digital computer, and would probably be adequate for inclusion in the overall model. It was decided, however, because of the variability of L and α in many natural situations to utilize the integration properties of the analog side of the hybrid computer.

If the groundwater system is assumed to function as a linear reservoir the rate of change of storage is given by

$$dSg/dt = q_{ni} - q_g \qquad \dots \dots \dots (3.18)$$

in which q_{ni} is the net inflow to the groundwater reservoir and q_g is the outflow. From Equation (3.5)

$$Sg = Kg q_g \qquad \dots \dots \dots \dots \dots (3.19)$$

in which Kg is the groundwater reservoir storage coefficient. From this equation

$$dSg/dt = Kg \, \frac{dq_g}{dt} \qquad \dots \dots \dots (3.20)$$

Substituting into Equation (3.18) the following expression results

$$\frac{dq_g}{dt} = \frac{1}{K_g} (q_{ni} - q_g) \qquad \dots \dots \dots (3.21)$$

Equation (3.21) can be programmed readily on an analog computer.

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CHEMICAL MODEL FOR QUALITY OF PERCOLATING WATER

Introduction

Normally, the greatest changes in the chemical quality of return flows from irrigation occur in the deep percolation water that flows through the subsoil and returns to the stream or the groundwater reservoir. These changes are the result of complex interactions between the soil and the applied water, and depend upon many factors, including ion exchange, initial distribution of salts, miscible displacement, dispersion, dissolution and precipitation of salts, hydrolysis of some substances, and possibly others.

For example, some materials in the soil are ion exchangers. These materials control the cation composition of the water percolating through them by substituting ions present in the exchanger for ions present in the water. In western soils the adsorbed ions are usually mixtures of calcium, magnesium, and sodium. Thus the effluent from these soils contains dissolved salts of calcium, magnesium, and sodium.

Predicting the composition of the soil solution would be fairly easy if only ion exchange were involved, but dissolution and precipitation of soluble salts also occur. Gypsum and various carbonate salts, which have a limited solubility in water, are frequently present in the soil to complicate the analysis. The solubility of gypsum, as an illustration of the interactions involved, depends upon the concentration of calcium in the water, and the concentration of calcium is related to the cation exchange process; thus, the dissolution or precipitation of gypsum and the cation exchange process must be considered simultaneously.

Normally, as water passes through the soil profile, the proportions of magnesium, calcium, bicarbonate, and sulfate decrease with concomitant increases in the proportions of sodium and chloride. The relative increase in sodium increases the sodium hazard of the water, and the increase in chloride content may adversely affect the growing of chloride sensitive crops such as fruit trees.

Thus the usual result of applying water to the land is to degrade the quality of drainage water returning to the stream, both by increasing the concentration of total dissolved solids and by increasing the relative proportion of undesirable ions. It becomes important, therefore, to be able to predict the quality changes as water percolates through the soil. In this chapter a mathematical model is presented to describe the most important processes affecting the quality of percolating waters.

Theoretical Considerations

The following discussion is adapted from Tanji et al. (1967) and Tanji, Doneen and Paul (1967). The computer program resulting from their work determines the equilibrium relationship for the solubility of gypsum ($CaSO_4 \cdot 2H_2O$) and the simultaneous exchange of calcium, magnesium, and sodium between the solution and adsorbed phases of these ions at field moisture levels. It is capable of treating a soil column stratified with respect to soluble ions, gypsum, exchangeable cations, equilibrium exchange constants, moisture levels, and apparent specific gravity. The original program has been expanded to include lime in the analysis, and modified for inclusion in a general hydrologic-water quality model.

Calcium-magnesium exchange

For symmetrical cation exchange between Ca^{++} and Mg^{++} the exchange equation may be expressed as:

$$\frac{C_{Ca}}{C_{Mg}} = K \frac{E_{Ca}}{E_{Mg}} \qquad \ldots \ldots \ldots \ldots (4.1)$$

in which C_{Ca} and C_{Mg} denote the concentrations of solution Ca^{++} and Mg^{++}, E_{Ca} and E_{Mg} refer to concentrations of adsorbed Ca and Mg, and K' is the equilibrium exchange constant. The change in relative composition of Ca^{++} and Mg^{++} resulting from the interaction of the adsorbed and solution phases can be computed from the above equation.

Let y represent the moles of Mg^{++} per gram of soil that go into solution and are adsorbed. If the initial concentrations of Ca^{++} and Mg^{++} are denoted by b_{Ca} and b_{Mg} moles per liter in the solution phase, and B_{Ca} and B_{Mg} are the moles per gram adsorbed on the soil exchange complex, then the following expressions hold:

$$E_{Ca} = B_{Ca} - y \qquad \ldots \ldots \ldots \ldots (4.2)$$

$$E_{Mg} = B_{Mg} + y \qquad \ldots \ldots \ldots \ldots (4.3)$$

$$C_{Ca} = b_{Ca} + \beta y \qquad \ldots \ldots \ldots \ldots (4.4)$$

$$C_{Mg} = b_{Mg} - \beta y \qquad \ldots \ldots \ldots \ldots (4.5)$$

in which β is the ratio of grams of soil per liter of solution. Combining these four with Equation (4.1) gives the quadratic expression:

$$[\beta (1-K)] \, y^2 + [\beta (B_{Mg} + K \, B_{Ca})$$
$$+ \, b_{Ca} + k \, b_{Mg}] \, y$$
$$+ [b_{Ca} \, B_{Mg} - K \, b_{Mg} \, B_{Ca}] = 0 \quad . \quad (4.6)$$

Calcium-sodium exchange in presence of magnesium

The nonsymmetrical cation exchange system has been described by various equations, including the kinetic (Vanselow, 1932), mass action, (Gapon, 1933), thermodynamic (Krishnamoorthy, Davis, and Overstreet, 1949) and double layer (Erickson, 1952). Although the equations were derived under quite different chemical-physical bases, Maletic (1962) reports that results are similar. Using the thermodynamic approach the equilibrium distribution of Na^+ and Ca^{++} in the presence of Mg^{++} is given by:

$$\frac{C_{Na}^2}{C_{Ca}} \frac{\gamma_{Na}^2}{\gamma_{Ca}}$$
$$= K \frac{E_{Na}^2}{E_{Ca} (E_{Na} + 1.5 \, E_{Ca} + 1.5 \, E_{Mg})}. \quad (4.7)$$

in which C and E refer to the equilibrium concentrations in the solution and adsorbed phases, respectively, of the subscripted cationic species. γ is the ion activity coefficient of the subscripted cationic species and K' is the Na^+-Ca^{++} equilibrium exchange constant.

The ion activity coefficient γ_j of ion species j in solution can be approximated from the Debye-Huckel theory (Sawyer and McCarty, 1967)

$$-\log \gamma_j = \frac{\alpha \, Z_j^2 \, U^{1/2}}{\lambda + U^{1/2}} . \quad \ldots \ldots \quad (4.8)$$

where Z_j is the valence of the ion species j. α and λ are temperature dependent constants. Appropriate values for average field temperature are .5 and 1.0, respectively. Ionic strength, U, is defined by

$$U = 1/2 \sum_{i=1}^{n} C_j \, Z_i^2 \quad \ldots \ldots \quad (4.9)$$

in which n is the number of ion species in solution, and C_j and Z_i are the concentration and valence, respectively, of ion species i.

In a cation exchange reaction the total number of equivalents of Ca^{++}, Mg^{++}, and Na^+ going into (or out of) the solution phase must be balanced by an equal amount going into (or out of) the adsorbed phase. If y is the moles of Na^+ per gram of soil that go into solution or are adsorbed, b_{Ca} and b_{Ma} are the moles per liter of Ca^{++} and Na^+ in the solution phase, and B_{Ca}, B_{Mg} and B_{Na} are the moles per gram adsorbed on the soil exchange complex, then the relative change in the composition of the solution and adsorbed phases may be described by:

$$E_{Ca} = B_{Ca} + y \quad \ldots \ldots \ldots \ldots (4.10)$$

$$E_{Na} = B_{Na} - 2y \quad \ldots \ldots \ldots (4.11)$$

$$E_{Mg} = B_{Mg} \quad \ldots \ldots \ldots (4.12)$$

$$C_{Ca} = b_{Ca} - \beta y \quad \ldots \ldots \ldots (4.13)$$

$$C_{Na} = b_{Na} + 2\beta y \quad \ldots \ldots \ldots (4.14)$$

in which β is the ratio of grams of soil to liters of solution.

When Equations (4.10) through (4.14) are combined with Equation (4.7), the following fourth power equation, solvable by Newton's approximation method, results:

$$ay^4 + by^3 + cy^2 + dy + e = 0 \quad . . (4.15)$$

in which

$$a = -2\beta^2 \quad \ldots \ldots \ldots \ldots \ldots (4.16)$$

$$b = 4 \beta \, K_{\gamma Ca}/_{\gamma Na}^2 - 2 \beta(b_{Na} + \beta \, B_{Ca})$$
$$+ 4\beta^2 (B_{Na} + 1.5 \, B_{Ca} + 1.5 \, B_{Mg}) \quad . (4.17)$$

$$c = 4 \beta (B_{Na} + 1.5 \, B_{Ca} + 1.5 \, B_{Mg})$$
$$(b_{Na} + B_{Ca}) - .5 \, b_{Na} (b_{Na} + 4 \beta \, B_{Ca})$$
$$- 4K_{\gamma Ca}/_{\gamma Na}^2 (\beta \, B_{Na} + b_{Ca}) \quad \ldots \ldots (4.18)$$

$$d = K_{\gamma Ca}/_{\gamma Na}^2 \beta \, B_{Na}^2$$
$$+ 4 \, K_{\gamma Ca}/_{\gamma Na}^2 B_{Na} \, b_{Ca}$$
$$+ b_{Na} (B_{Na} + 1.5 \, B_{Ca}$$

$$+ 1.5 \ B_{Mg} \ (b_{Na} + 4 \ \beta \ B_{Ca}) - .5 \ b_{Na}^2 \ B_{Ca}$$

$$\dots \dots \dots \dots (4.19)$$

$$e = b_{Na}^2 \ b_{Ca}(B_{Na} + 1.5 \ B_{Ca} + 1.5 \ B_{Mg})$$

$$- K_{\gamma Ca}/\gamma_{Na}^2 \ B_{Na}^2 \ b_{Ca} \ \dots \dots (4.20)$$

For conditions of chemical equilibrium the distribution of Ca^{++}, Mg^{++}, and Na^+ is given by Equations (4.6) and (4.15). Similar expressions result for Na^+-Mg^{++} exchange by substituting Mg^{++} for Ca^{++} in Equation (4.7).

Gypsum reactions

The presence of gypsum in the soil will influence the quality of percolating water in two ways: It will increase the dissolved solids by solution, and it will alter cation composition by exchange reactions. The solubility of gypsum is approximately 30 me/l. As percolating water dissolves gypsum, Ca^{++} will exchange for Na^+ and Mg^{++} on the exchange complex. $NaSO_4$ and $MgSO_4$ are extremely soluble and will allow some additional gypsum to dissolve as soluble Ca^{++} decreases. Since Ca^{++} replaces Na^+ on the exchange complex, the concentration of Na^+ tends to increase in the percolating water. These two processes involving gypsum are described quantitatively as follows.

One change involving gypsum is associated with the part that dissolves or precipitates, and the other with the part that remains undissociated. The solubility of $CaSO_4 \cdot 2H_2O$ is described by the solubility product constant, K_{CaSO_4}. Thus

$$K_{CaSO_4} = C_{Ca} \ C_{SO_4} \ \gamma^2 \ \dots \dots (4.21)$$

in which K_{CaSO_4} is the solubility product constant, C_{Ca} and C_{SO_4} are the equilibrium concentrations of subscripted ion species and γ is the mean activity coefficient. If x is the moles per liter of Ca^{++} and $SO_4^=$ that dissolve or precipitate and C'_{Ca} and C'_{SO_4} are the initial molar concentrations of Ca^{++} and $SO_4^=$, then the change in relative composition of Ca^{++} and $SO4^=$ is:

$$C_{Ca} = C'_{Ca} + x \ \dots \dots \dots \dots (4.22)$$

$$C_{SO_4} = C'_{SO_4} + x \ \dots \dots \dots (4.23)$$

Combining Equations (4.22) and (4.23) with (4.21) yields:

$$x^2 + (C'_{Ca} + C'_{SO_4})x$$

$$+ C'_{Ca} \ C'_{SO_4} - K_{CaSO_4}/\gamma^2 = 0 \ . (4.24)$$

When Equation (4.8) is solved for γ and substituted into Equation (4.24) the result is:

$$x^2 + (C'_{Ca} + C'_{SO_4})x + C'_{Ca} \ C'_{SO_4}$$

$$- K_{CaSO_4}/\exp\frac{(0.366 \ U^{1/2})}{1 + U^{1/2}} = 0 \ \dots (4.25)$$

Furthermore, the $CaSO_4$, Ca^{++}, $SO_4^=$, and H_2O system involves the formation of undissociated $CaSO_4$. The dissociation constant, $K_{[CaSO_4]}$, for the system is given by:

$$K_{[CaSO_4]} = \frac{C_{Ca} \ C_{SO_4} \ \gamma^2}{C_{CaSO_4} \ \gamma} \ \dots \dots (4.26)$$

where C_{CaSO_4} is the molar concentration of the ion pair and γ for the ion pair is taken at unity.

If x represents the moles per liter of Ca^{++} and $SO_4^=$ which form undissociated $CaSO_4$ and the initial concentrations of Ca^{++}, $SO_4^=$, and $CaSO_4$ as C'_{Ca}, C'_{SO_4}, and C'_{CaSO_4}, respectively, then the change in concentrations will be:

$$C_{Ca} = C'_{Ca} - x \ \dots \dots \dots (4.27)$$

$$C_{SO_4} = C'_{SO_4} - x \ \dots \dots \dots (4.28)$$

$$C_{CaSO_4} = C'_{CaSO_4} + x \ \dots \dots (4.29)$$

Combining Equations (4.27), (4.28), and (4.29) with (4.26) yields:

$$\gamma^2 x^2 - (\gamma^2 \ C'_{Ca} + \gamma^2 \ C'_{SO_4} + K_{[CaSO_4]}) \ x$$

$$+ (\gamma^2 \ C'_{Ca} \ C'_{SO_4}$$

$$- K_{[CaSO_4]} \ C'_{CaSO_4}) = 0 \ \dots \dots (4.30)$$

Lime reactions

Lime is the least soluble of the common salts affecting the quality of percolating water and has only a minor influence in the presence of gypsum or high salinity. If the more soluble salts are leached out, however, the concentrations in the percolating water will decrease, resulting in a change from a predominantly sulfate water to a bicarbonate water.

The dissolution or precipitation of lime can be similarly computed by application of solubility product principle. The overall reaction for the precipitation of $CaCO_3$ is

$$Ca^{++} + 2HCO_3 \overset{\rightarrow}{\leftarrow} CaCO_3\downarrow + CO_2\uparrow + H_2O$$

$$\dots \dots \dots (4.31)$$
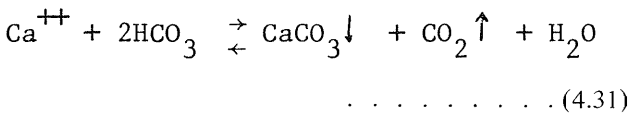
The first and second ionization constants, K_1 and K_2, of carbonic acid may be expressed as follows (Tanji and Doneen, 1966):

$$K_1 = \frac{A_{HCO_3} A_H}{C \, P_{CO_2}} = 4.16 \times 10^{-7} \quad . \, . \, (4.32)$$

$$K_2 = \frac{A_{CO_3} A_H}{A_{HCO_3}} = 4.84 \times 10^{-11} \quad . \, (4.33)$$

in which A is the activity of the ion species, C is the molar concentration of dissolved CO_2 at standard temperature and pressure, and P_{CO_2} is the partial pressure of CO_2 in atmospheres.

The ion product of water, K_w, is defined as

$$K_w = A_H A_{OH} = 1.00 \times 10^{-14} \quad . \, . \, . \, (4.34)$$

A_H may be calculated from pH as

$$A_H = 10^{-pH} \quad . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, (4.35)$$

The solubility of $CaCO_3$ is described by the following equation:

$$K_{CaCO_3} = A_{Ca} A_{CO3} \quad . \, . \, . \, . \, . \, . \, . \, . \, . \, (4.36)$$

in which K_{CaCO_3} is the activity product constant.

The concentration of $CO_3^=$, however, is a function of the CO_2 partial pressure, and the HCO_3^- concentration is usually the predominant form in which CO_2 occurs in a soil-water system. Thus it is convenient to consider the following reactions:

$$H_2CO_3 + CaCO_3 \overset{\rightarrow}{\leftarrow} Ca^{++} + 2HCO_3^- \quad . \, . \, (4.37)$$
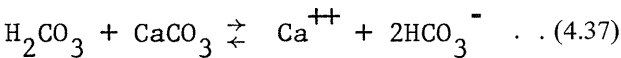
$$K = \frac{A_{Ca} A_{HCO_3}^2}{A_{H_2Ca_3}} \quad . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, (4.38)$$

Provided an equilibrium system is under a constant CO_2 pressure, Equation (4.38) may be written as

$$Z = KC_{H_2CO_3} = C_{Ca} C_{HCO_3}^2 \quad . \, . \, . \, . \, (4.39)$$

in which C represents the equilibrium concentration of the species indicated by the subscript.

The following stochiometric relations are valid:

$$C_{Ca} = C'_{Ca} + x \quad . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, . \, (4.40)$$

$$C_{HCO_3} = C'_{HCO_3} + 2x \quad . \, . \, . \, . \, . \, . \, . \, (4.41)$$

in which C'_{Ca} and C'_{HCO_3} are the initial concentration of $C_{Ca^{++}}$ and HCO_3^-, respectively, and x is the change in moles to reach equilibrium. Substituting Equations (4.40) and (4.41) into Equation (4.39) yields the relation

$$4x^3 + 4(C'_{HCO_3} + C'_{Ca})x^2$$

$$+ ((C'_{HCO_3})^2 + 4C'_{Ca} C'_{HCO_3}))x$$

$$+ (C'_{HCO_3})^2 C'_{Ca} - Z = 0 \quad . \, . \, . \, . \, (4.42)$$

which can be solved for x, which in turn allows the solution of Equations (4.40) and (4.41).

Chloride

The Cl^- ions are assumed not to enter into the sorption or solubility reactions. The Cl^- concentration in the effluent reflects only the mixing of the applied water with the pore water and the effects of percolation through the soil.

Simultaneous solution

Assuming ion activities to be adequately described by Equation (4.8), the equilibrium concentrations of ions in the solution and adsorbed phases can be calculated from Equations (4.6), (4.15), (4.25), (4.30), and (4.42) for a soil water system containing quantities of gypsum

be slow enough to allow chemical equilibrium to be attained between the percolating water and the soil and water initially present in each layer.

An expanded flow chart of the equilibrium cycle, modified for the consideration of lime according to techniques suggested by the U.S. Bureau of Reclamation (Poe, 1970), is shown in Figure 11. The diagram is explained in detail by Tanji et al. (1967), and will only be summarized here.

Statements 24 to 44 consider the changes in Ca^{++}, $SO_4^{=}$, and undissociated and solid phase gypsum. The dissociation constant, K_{CaSO_4}, and the solubility product, K'_{CaSO_4}, of gypsum were assigned the values 4.9×10^{-3} and 2.4×10^{-5}, respectively, for use in solving Equations (4.25) and (4.30).

The exchange reactions are computed by statements 44 through 3. Statement 44 compares the concentrations of Ca^{++} and Mg^{++}. If Ca^{++} is greater than Mg^{++}, Na^{+} - Ca^{++} exchange is considered through branch statement 46. Na^{+} - Mg^{++} exchange is computed through branch statement 45 if Mg^{++} is greater than Ca^{++}. Statements 5 through 16 evaluate Equation (4.15) by Newton's approximation method. An initial small value of 10^{-6} is assigned to the root of the equation. Here, as elsewhere in the program where successive approximations are required, a counter (KCl in this case) is inserted so that the computer will not consume an excessive amount of time if a particular combination of values never allows the program to converge to the real root. This condition never occurred with actual data used in this program but it is a possibility, and can easily happen if erroneous values are input to the program. After the true root, z, is evaluated, the concentrations of Ca^{++}, Na^{+}, exchangeable Ca^{++}, and exchangeable Na^{+} are altered according to Equations (4.10), (4.11), (4.13), and (4.14). Under statement 13, Ca^{++} - Mg^{++} exchange is considered. Equation (4.1) is solved for y, with which the concentrations of Ca^{++}, Mg^{++}, exchangeable Mg^{++}, and exchangeable Ca^{++} are changed in accordance with Equations (4.2) through (4.5).

After statements 400 through 500 evaluate the changes in the system resulting from the presence of lime according to Equation (4.42), a series of approximations are made in which the computed concentration of Ca^{++}, A, is compared with the initial value, A1, and with the values A2, A3, and A4 calculated after consideration of

the various reactions involving Ca^{++}. Iteration continues in this cycle from 24 to 8 until the difference in Ca^{++} concentrations is within $\pm 10^{-5}$ moles per liter.

J counts the number of soil segments equilibrated. When J equals M, the concentrations of the effluent are stored under statement 10, where KK counts the number of fractional pore volumes of effluent. Computation continues in loop 201 to 34 until the total volume of deep percolation for month L has gone through the cycle. In other words, when FK, which measures the volume of effluent, equals or exceeds XN, the volume of deep percolation, control proceeds to statement 200 and the next month's deep percolation is routed through the soil. Computation continues in the loop between 200 and 933 until each month has been considered.

Computation next proceeds to the DO loop ending with statement 5500. This loop calculates the average quality of the subsurface return flow for each month. The quantity of subsurface irrigation return flow, SUBSRF(I), determined previously in the hydrologic calculations is composed of soil profile effluent whose quality was computed and stored as CCA(KK), CMG(KK), etc. The DO loop simply calculates the quality of SUBSRF(I) as the average of the quality of the number of pore volumes of effluent comprising SUBSRF(I). For example, if SUBSRF(1) equals six inches, PV equals 20 inches, and M equals 10 then XNN, the number of fractional pore volumes of effluent in SUBSRF(1), equals three. Therefore, the average concentration of calcium in SUBSRF(1) is the average concentration of CCA(1), CCA(2), and CCA(3). Concentrations of other ions are obtained in the same manner. If SUBSRF(2) equals four inches, similar reasoning would yield the concentration of calcium from the average of CCA(4) and CCA(5). These average monthly concentrations in SUBSRF(I) are stored for each month I and soil JJ as SCA(I,JJ), etc., thus ending the long DO loop when JJ equals NS.

The next series of statements to 3006 weights the effluent from each soil in order to produce one concentration to represent the subsurface return portion of the total outflow.

The last phase of the program solves Equation (3.11). All concentrations are converted to tons and printed for each month. Additionally, the program listed compares the total quantity of salts leaving the basin with measured values and computes the correlation coefficient.
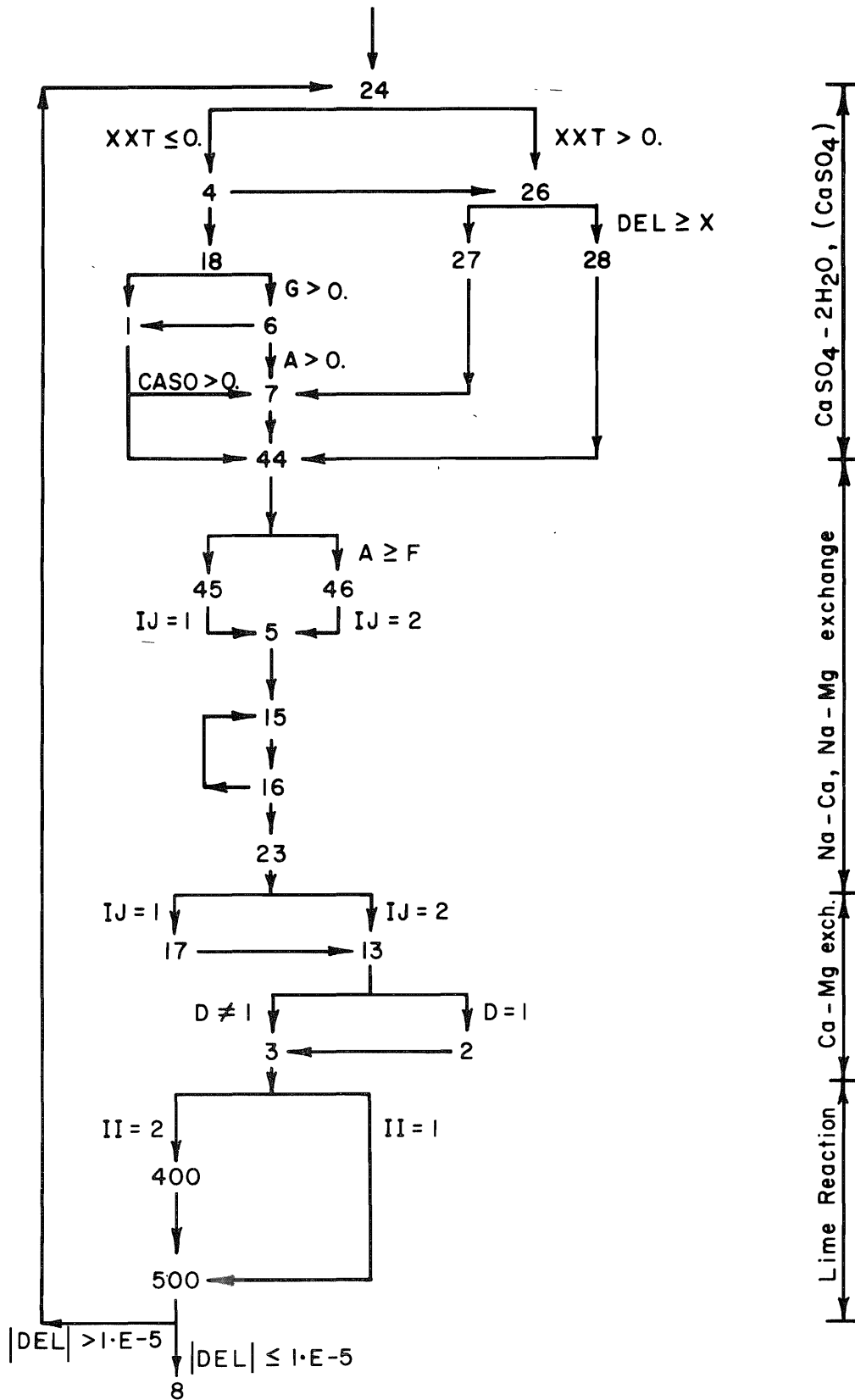
Figure 11. Expanded flow chart of chemical equilibrium cycle.

CHAPTER VI

APPLICATION OF MODEL TO THE LITTLE BEAR RIVER

The previous chapter described a hybrid computer program to model the hydrology and to predict the quality of outflow from a river basin where irrigation is the major water user. This chapter will relate the results of applying that model to a prototype, the Little Bear River basin in northern Utah. A general description of the prototype is given in Appendix A. Some additional information specifically related to the model is presented in this chapter.

Irrigated Area and Canal System

The present model directly considers only the irrigated portion of the valley, which consists of approximately 3,250 acres. Figure 12 shows the irrigated land and the canals which supply the water. A detailed breakdown of the crops and soils is given in Appendix A.

Two major canals, Paradise and Highline, and several minor ones, convey water from the Little Bear River to the cropland. Highline canal was constructed in the early 1960's to carry water from Porcupine Reservoir to the rolling lands east of Paradise. It supplies water for approximately 1,500 acres, 80 percent of which are in the model area. This land is located between the Highline and Paradise canals and is irrigated by sprinklers because of the rolling topography. Paradise canal was constructed before the turn of the century. It diverts water from the East Fork for the irrigation of approximately 3,000 acres, 70 percent of which are in the model area. Land watered by the Paradise canal is generally flat, thus favoring furrow irrigation. Hyrum canal diverts from the South Fork, but only a few hundred acre feet of water is used in the subbasin. It is treated essentially as an export in the model.

Sources of Data

Climatological records

Climatological data were obtained from records of the Logan USU Weather Bureau station located at Utah State University. This station is situated approximately 10 miles north of the model area at about the same elevation and exposure. Studies reported by Dixon et al. (1970) indicate no appreciable differences in precipitation and temperature between the Logan USU weather station and the irrigated portion of the Little Bear River Valley. Plots of mean monthly temperature and precipitation are given in Appendix A.

Streamflow

The U.S. Geological Survey maintains stream gages on the major streams in the basin (Figure 12). Station 10-1060 on the Little Bear River north of Paradise measures the basin outflow; Station 10-1047 on the South Fork and the outflow from Porcupine Reservoir constitute the principal inflow to the area. Unfortunately, no continuous records are available on either the outflow from Porcupine Reservoir or the storage in it. Most of the inflow is measured at Station 10-1049, located on East Fork 1.7 miles above the dam. There are approximately eight square miles of drainage area between the gage and the dam, however, including Porcupine Creek and several springs which contribute an unknown, but appreciable quantity of inflow to the reservoir. Some crude measurements made under the direction of the water commissioner (Hansen, 1969) indicated that unmeasured inflows ranged from 4 to 7 cfs during the summer months, or perhaps as much as 30 percent of total inflow.

During the irrigation season, late May through September, some information on outflow and storage is recorded and published by the water commissioner. These data, together with records from Station 10-1049, allow the calculation of probable reservoir outflow for the summer months. Information for the rest of the year is scanty, consisting chiefly of an occasional reservoir stage observation by the U.S. Geological Survey. Ordinarily, nonirrigation season releases are quite small, so the effect on total basin outflow is not significant. During the spring snowmelt period, however, outflows from the reservoir may be appreciable if runoff greatly exceeds the storage capacity, as it normally does. Therefore, the inflow to the model subbasin from Porcupine Reservoir was a source of error, particularly during the spring runoff months.

Canal diversions

Flows in most of the canals are measured and reported by the water commissioner in his annual report. (See Hansen, 1969, for example.) Since the area usually has plenty of water, no great pains are taken to assure accuracy. The larger canals are equipped with Parshall flumes or crest gage devices on which the stage is observed and the discharge estimated from a rating curve or table. Many of the measuring devices are suspect, however, because of age and neglect. The gage on the Paradise canal was inoperative throughout the 1967 irrigation season, but water was plentiful and the flows were simply
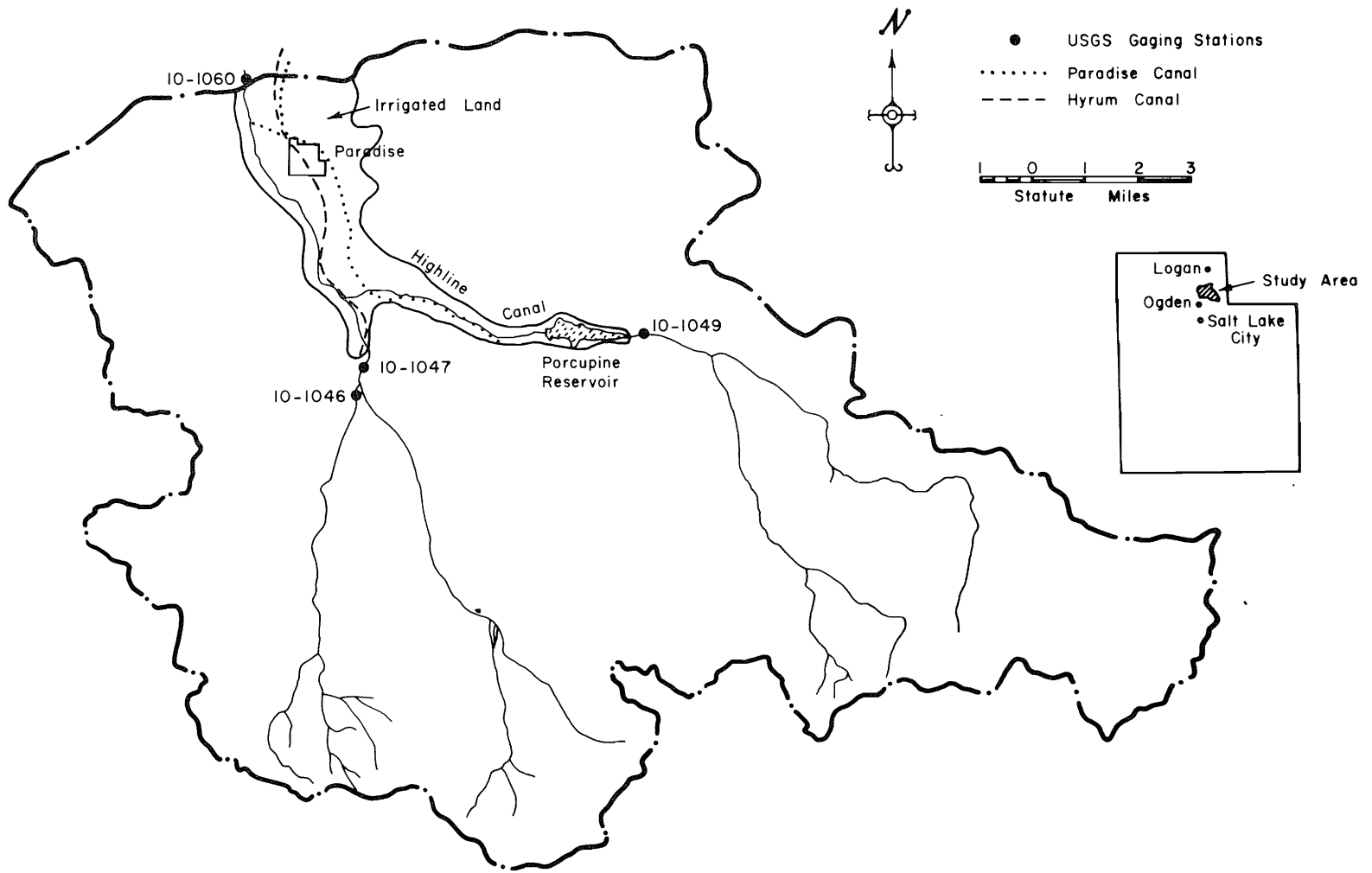
Figure 12. Map of irrigated land, canal system, and stream gages of the Little Bear River.

estimated by the water commissioner. None of the gages are recorded continuously; they are observed once per week during the irrigation season. Although efforts have been made to improve the quality of the gages in recent years, the reported canal diversions are subject to some degree of error.

Quality data

Streamflow. Several water quality sampling stations were established in the basin and operated for approximately a two-year period as part of another research proj-ect at the Utah Water Research Laboratory (Dixon et al., 1970). Locations of these stations are shown in Figure 13. Table 2 lists the stations and the period of sampling. In general, samples were collected weekly and analyzed for all important quality parameters, including the chemical constituents considered in this study. Laboratory tests were all conducted according to standard procedures.

For this study it was necessary to convert weekly data to average monthly values for input to the model. On the South Fork, where accurate flow records were available, the weekly measurements were weighted by time

Table 2. Little Bear River water quality sampling stations.

Station No.	Description of Sampling Point	Period of Sampling
S-20.5	At Paradise Telemetry site	031268 - 031169
S-21.3	Adjacent ot bridge N. S. of Paradise	060366 - 041768
S-22.4	At trout farm diversion	110867 - 071068
S-24.6	Adjacent to bridge N. S. of Avon	060366 - 031169
S-27.0	At U. S. G. S. gaging station downstream from Davenport Creek	070766 - 031169
S-27.5	At U. S. G. S. gaging station upstream from Davenport Creek	070766 - 031169
SEC-0.4	Adjacent to bridge south of Avon	112067 - 102268
SEC-4.3	100 feet downstream from Porcupine Reservoir outlet	062967 - 111368
SEC-6.2	At U. S. G. S. gaging station upstream from Porcupine Reservoir	062967 - 111368
SD-0.0	Adjacent to bridge crossing Davenport Creek	070766 - 031169
STF-0.0	Above check structure	101166 - 031169
U3198	Spring at Forsberg Road	101767 - 121868

S - 20.5

S - 20.3 Paradise

S7F - 0.0

Little

Bear

River

S - 22.4

S - 24.6 U3198

△

Avon

SEC - 0.4

Highline

Canal

Porcupine
Reservoir

SEC - 6.2

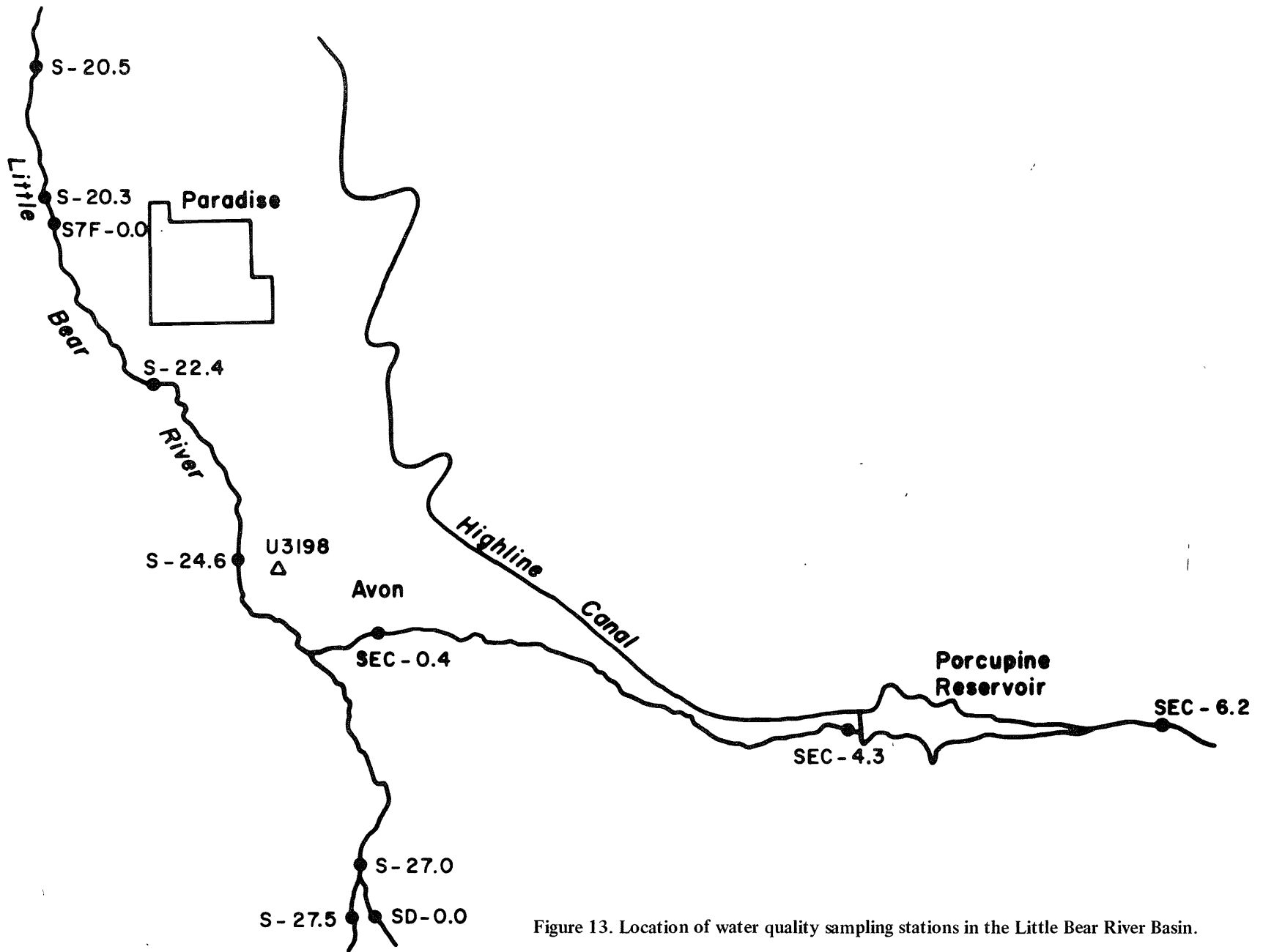SEC - 4.3

S - 27.0

S - 27.5 SD - 0.0

Figure 13. Location of water quality sampling stations in the Little Bear River Basin.

and discharge to produce "time-discharge-weighted" averages of each constituent. On the East Fork, however, where continuous flow records are not available, a time-discharge-weighted average could not be accurately determined. Therefore, the weekly samples were simply time-weighted to produce average monthly values. Since flows generally do not change rapidly, differences between time-weighted and time-discharge-weighted values are usually insignificant.

Monthly input values for the South Fork were not available from measured data, but were determined from the records for Davenport Creek, S27.5, and South Fork above Davenport Creek, SD0.0, which together measure all flows of the South Fork. These values should therefore be reliable for each month modeled.

Concentrations on the East Fork are less reliable than those of the South Fork for two reasons: (1) Samples were collected during fewer months of the year on the East Fork and (2) samples were not collected every week even during the months with records. During the 24-hour period, January 1967-December 1968, 73 samples were collected on the South Fork and 49 on the East Fork. Only 16 monthly averages could be computed from the 49 samples, thus necessitating the estimation of eight months of data.

Of the six chemical quantities required for input to the program, three, Na^+, $SO_4^=$, and Cl^-, occurred in low and fairly constant concentrations each month. Sodium ranged from .17 to .21 me/l; sulfate from .08 to .18 me/l; and chloride from .16 to .28 me/l. Concentrations of the other ions were on the order of 2 to 4 me/l each. Consequently, little error resulted from estimating concentrations of the three minor ions, Na^+, $SO_4^=$, and Cl^-. They were estimated by simple extrapolation and interpolation from plots of concentration versus months, supplemented by personal judgment.

More refined techniques were employed to estimate concentrations of the other three ions, Ca^{++}, Mg^{++}, and HCO_3^-. Although definite information on the releases from Porcupine Reservoir into East Fork was sporatic, a water budget analysis was run on the reservoir in order to estimate outflows. Inputs were recorded flows at the gaging station above the reservoir, unmeasured inflows, and precipitation. Outputs were evaporation and reservoir releases. Sufficient stage readings had been made to estimate the storage changes for each month, although there were some gaps in the records. Results of the budget analysis were generally satisfactory although lack of winter data hampered the study.

Measured concentrations were fitted to the regression equation

$$C = aQ + bQ^2 + cQ^3 + dT$$
$$+ eQT + fQ^2T + gQT^2 + hT^2 \quad . . . \quad (6.1)$$

in which

C	=	the average monthly concentration
Q	=	the monthly flow in acre feet determined from the reservoir budget analysis
T	=	month of year, 1-12
a,b,...h	=	constants

Calculated R^2 values were .54, .72, and .93 for Ca^{++}, Mg^{++}, and HCO_3^-, respectively, indicating generally poor agreement between observed values and those predicted by the equation. In lieu of anything better, however, the regression equation for HCO_3^- was used to predict missing values. The sum of Ca^{++} and Mg^{++} could then be computed from the following equation:

$$Ca^{++} + Mg^{++} = HCO_3^-$$
$$+ Cl^- + SO_4^= - Na^+ \quad . . . . . . \quad (6.2)$$
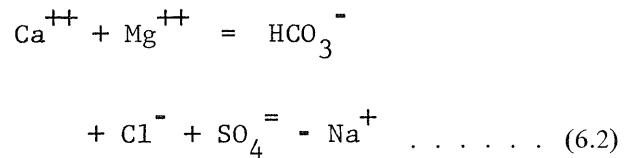
where all concentrations are in me/l. Ca^{++} averaged 63 percent more than Mg^{++} for the months with measurements so their sum was partitioned accordingly.

Groundwater. No regular network has been established to periodically sample groundwater quality in the Little Bear River Valley. Peterson (1946), Beer (1967), and Bjorklund and McGreevy (1970) reported some quality analyses of well and spring waters. Dixon et al. (1970) sampled one spring near Avon on approximately a monthly schedule for a one-year period. Practically all analyses indicated water of excellent quality with the salinity generally less than 500 parts per million. The only exceptions were samples from deep wells which are generally unproductive and used sparingly. Water in the shallow water table aquifer exhibited no undesirable properties.

Soils. The major soils of the area are described in Appendix A, which also includes a table of their chemical and physical properties reported by the Soil Conservation Service (1966). Supplemental information was obtained from laboratory analyses of 23 soil samples collected with hand augers. These borings were generally limited to the root zone because of the rocky nature of the soils. A few, however, were 20 to 40 feet below the land surface. The Utah State University Soils Laboratory analyzed these samples for the properties needed for input to the computer program, including such items as cation exchange capacity; exchangeable and soluble sodium, calcium, and magnesium; soluble sulfate, chloride, and bicarbonate; saturation percentages; and gypsum and lime content.

Information on the subsurface properties was obtained from well logs filed in the Utah State Engineer's office. Generally, the substrata consist of gravel or cobbles intermixed with some apparently discontinuous

clay layers. The cation exchange potential of the gravel was assumed to be negligible. This assumption was reasonable because of the relatively insignificant surface area of a gravel sample as compared to that of an equal volume of clay or loam. Initial concentrations of the various ions in the subsoil were established from records of wells and springs.

For modeling purposes, the irrigated area was divided into five sectors to represent each of the five major soils shown in Figure 14. Other soils occur in the valley but they are either mixtures of the five dominant ones or closely related to them. These minor soils comprise less than 10 percent of the total irrigated land so no great error was introduced by lumping them with the others. Each of the five major soil areas was assumed to have homogeneous chemical and physical properties.

Results

Hydrology

Since it is assumed that salts are transported with the water, an adequate representation of the hydrology of a basin is requisite to the successful modeling of the flow of dissolved minerals. In spite of the fact that much of the surface inflow to the Little Bear River basin is accurately measured by USGS stream gages, the hydrology of the basin was not easy to establish. Lack of adequate records on the operation of Porcupine Reservoir, sizable diversions by three major canals, and the large groundwater component of the basin outflow served to complicate the system. Nevertheless, after a prolonged verification procedure which involved establishing values for 15 parameters, a satisfactory reproduction of basin hydrology was obtained.

The agreement between observed and predicted monthly outflows at Station 10-1060, Little Bear River near Paradise, Utah, is illustrated by Figure 15. Values for model parameters were established during normal verification procedures for the two-year period from January 1967 through December 1968. The parameters were then held constant while the model was applied to the entire four-year period, 1966-1969. The calculated outflows agree quite well with the measured ones throughout the four-year period, yielding a correlation coefficient of .99. The sum of the calculated values was within 2 percent of the total measured flow for the four years.

It was necessary to adjust some of the published records which were apparently in error. For example, reported diversions for some months exceeded the measured streamflow by several hundred acre feet, an obvious impossibility probably caused by inaccurate measurement of the canal flows. Such diversions were reduced to conform with actual streamflow. Even without these minor adjustments, however, the correlation between computed and observed outflows was high, with a correlation co-

efficient near .98. A computer printout of the hydrology portion of the model for 1966-1969 is shown in Appendix C.

Dissolved minerals

Modeling of dissolved minerals involved identifying the concentration of each ion in the various components of the basin outflow. The concentrations in some of these components, such as undiverted streamflow and surface return flow from irrigation, were fairly simple to obtain. The major effort required fixing values on the concentrations of the correlated and groundwater flows. After some trial and error, the quality of unmeasured flows was correlated with the concentrations measured on the South Fork and East Fork. Subsurface return flows from irrigation were, of course, computed from the model described in Chapter IV. The results of the quality portion of the model are discussed below for each ion.

Bicarbonate. Bicarbonate accounted for approximately two-thirds of the total salt outflow and thus was the most important of the six ions modeled. Figure 16 is a plot of measured and calculated outflows for the 24-month period considered. The agreement is generally good. The first few months of calculated values are low, but this is probably a result of poor records during that period plus the difficulty of establishing initial groundwater flows and corresponding concentrations. Overall, the total calculated mass of bicarbonate ion outflow was approximately 2 percent less than the measured value with a correlation coefficient of .96, n = 24.

Calcium. Calcium ion, like bicarbonate, was low the first few months (Figure 17). Thereafter there was close agreement between observed and predicted values. For the two-year period computed calcium averaged approximately 5 percent less than the measured outflow, with a correlation coefficient of .97, n = 24.

Magnesium. Computed values for magnesium ion agreed well with the measured values except for the winter months of 1967 (Figure 18). Low computed flows during that period resulted in total magnesium outflows being approximately 4 percent less than measured values during the model period. The correlation coefficient was .97, n = 24.

Sulfate, chloride, and sodium. The minor ions, sulfate, chloride, and sodium, accounted for less than 10 percent of the total salt outflow. Figures 19, 20, and 21 illustrate the agreement between observed and computed outflows of sulfate, chloride, and sodium, respectively. Only sodium exhibits a poor fit; the other two are in general accord with measured values, although not matching the high correlations exhibited by the major ions. Correlation coefficients were .49 for sodium, .87 for sulfate and .89 for chloride, n = 24. Possible explanations for the low sodium correlation are: (1) Routine laboratory anal-
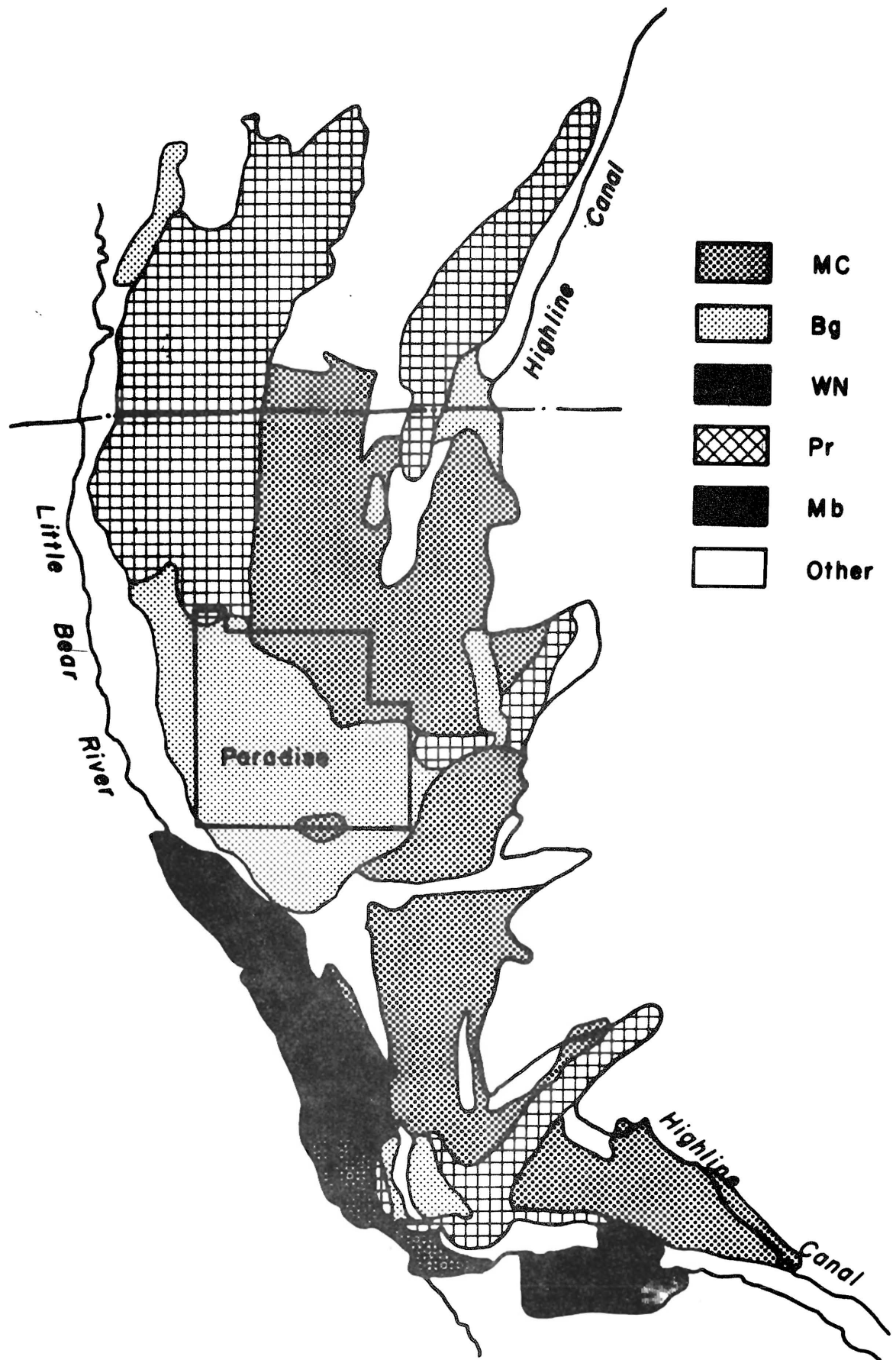
Figure 14. Areal extent of the five soils modeled.
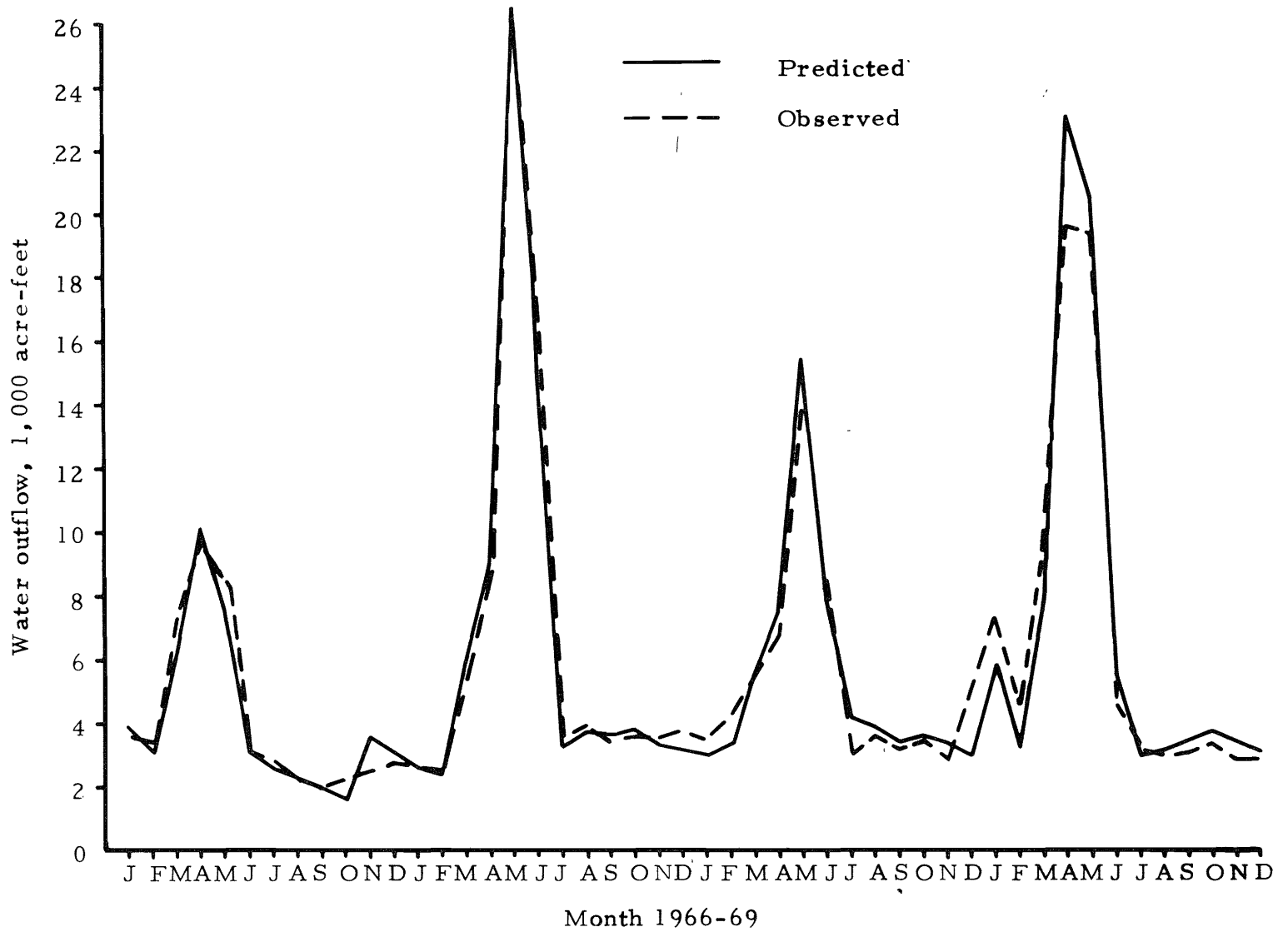
Figure 15. Observed and predicted water outflow.
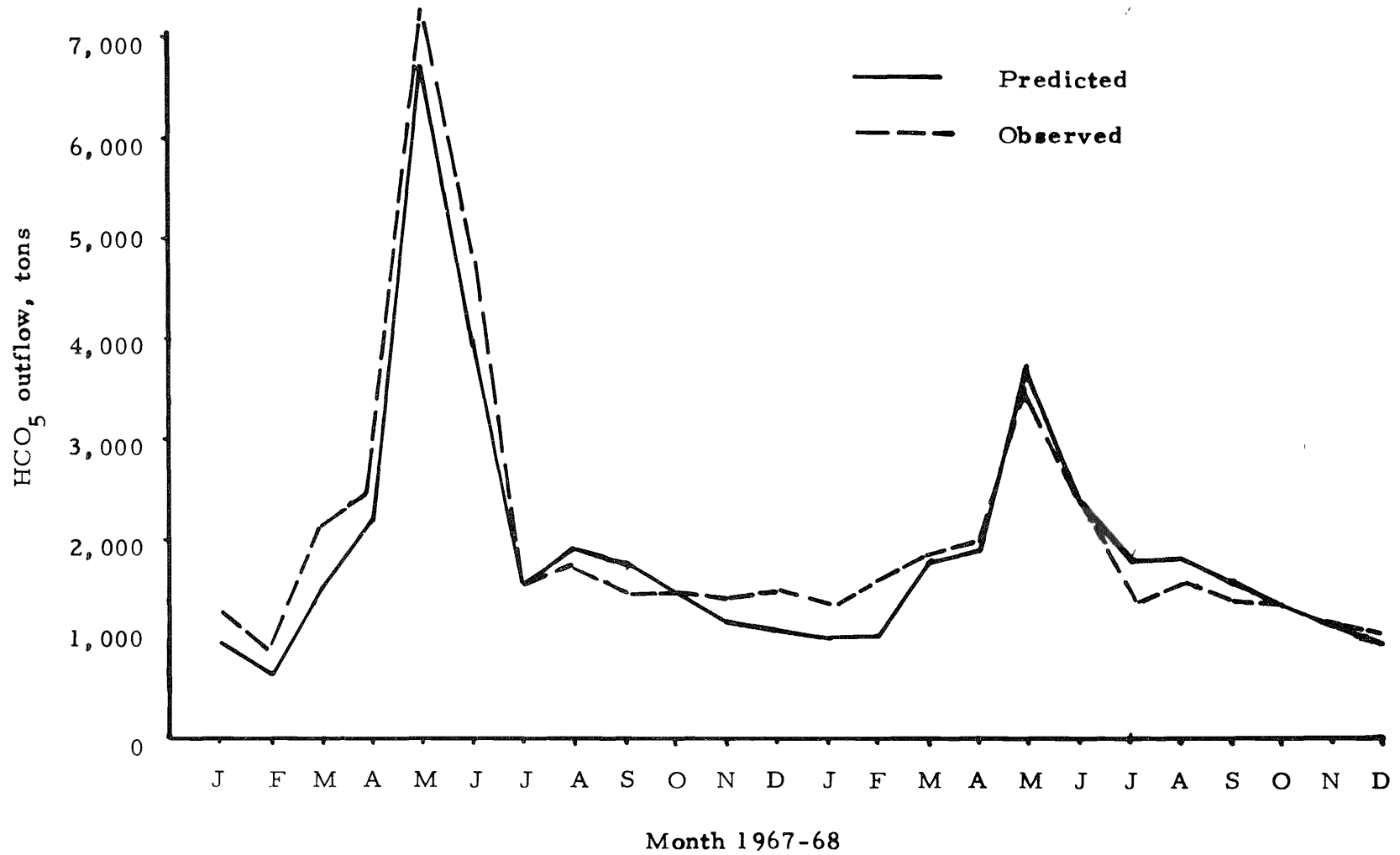
Figure 16. Observed and simulated bicarbonate (HCO$_3^-$) outflow.
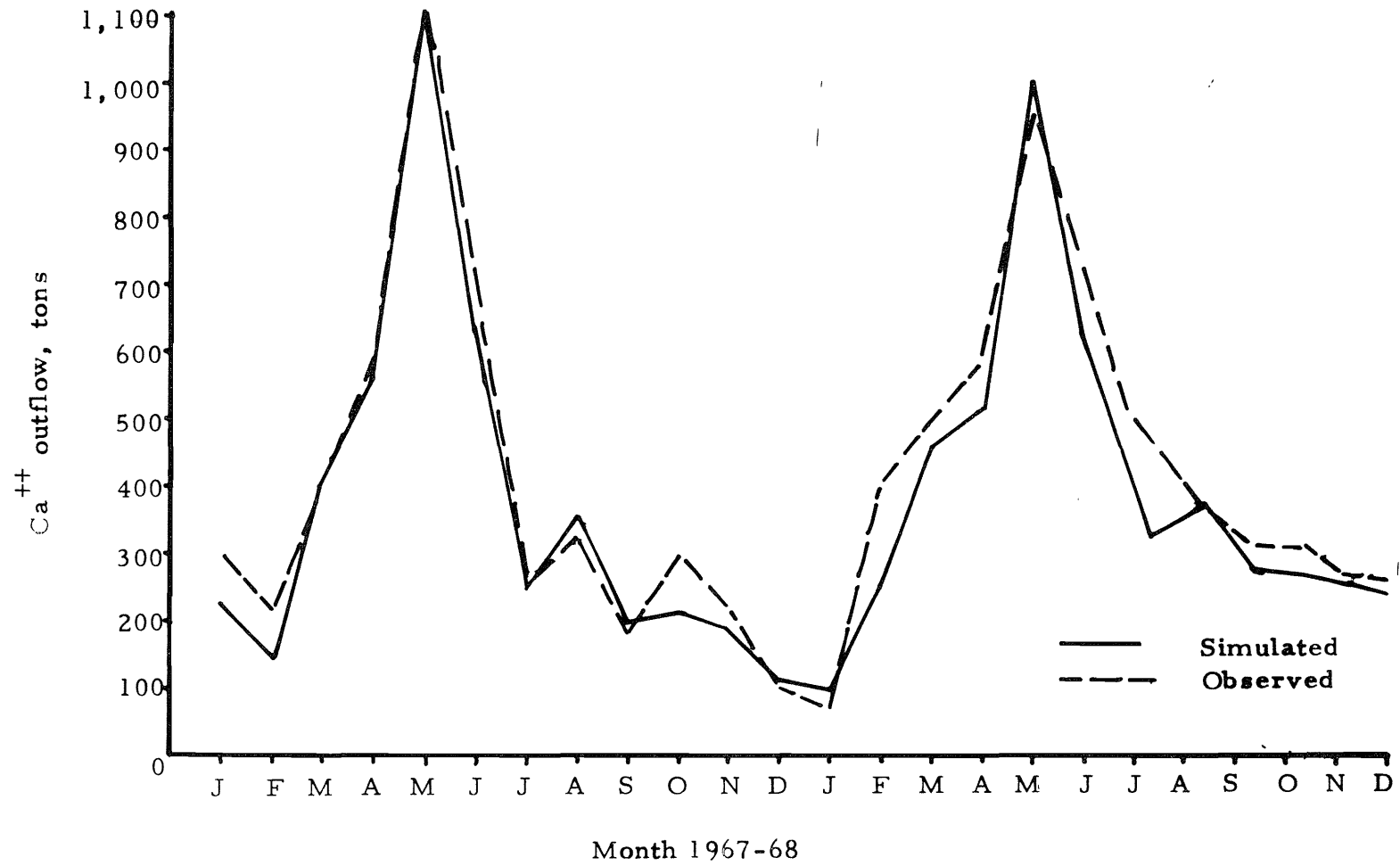
Figure 17. Observed and simulated calcium (Ca^{++}) outflow.
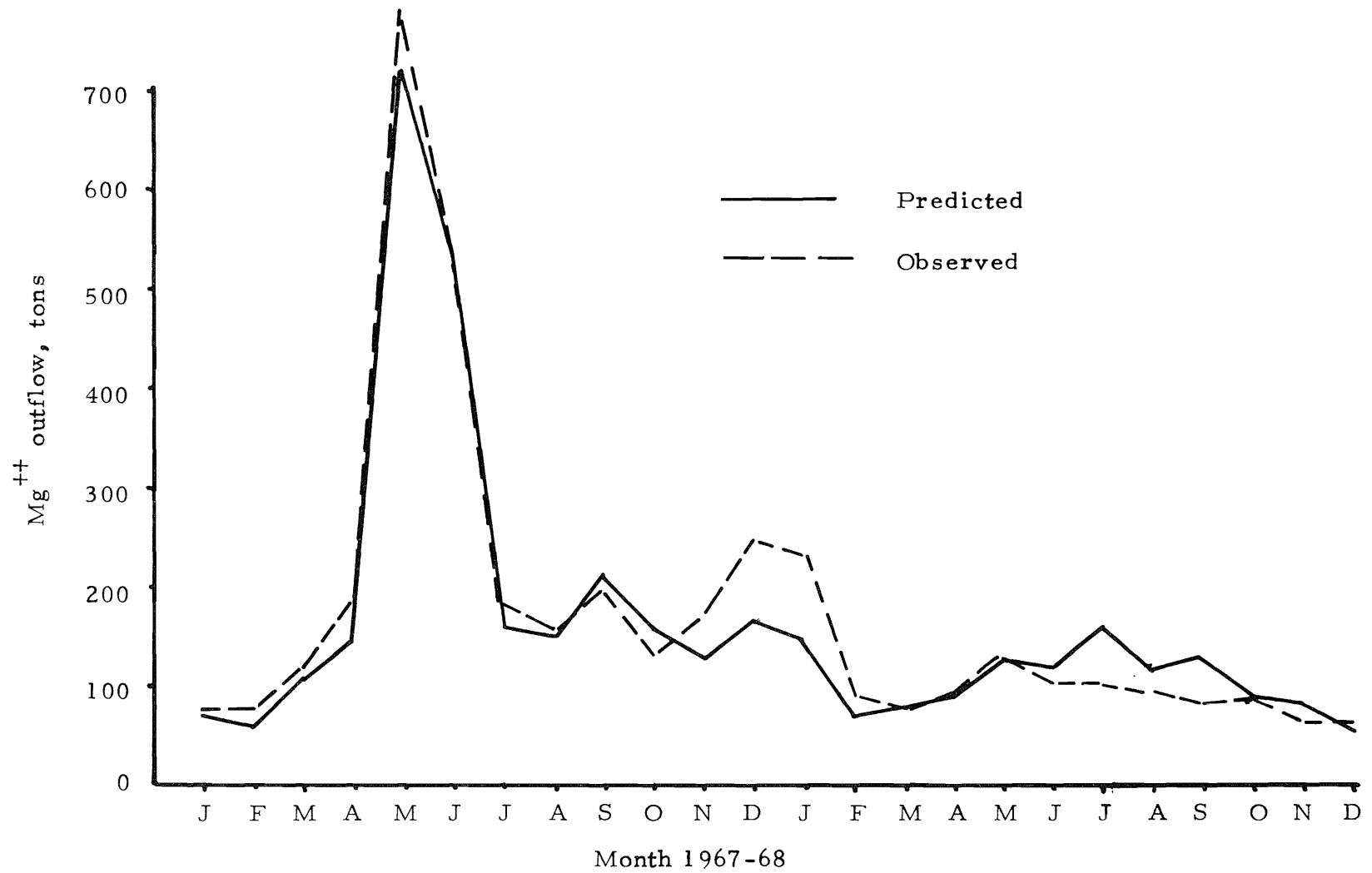
Figure 18. Observed and simulated magnesium (Mg^{++}) outflow.
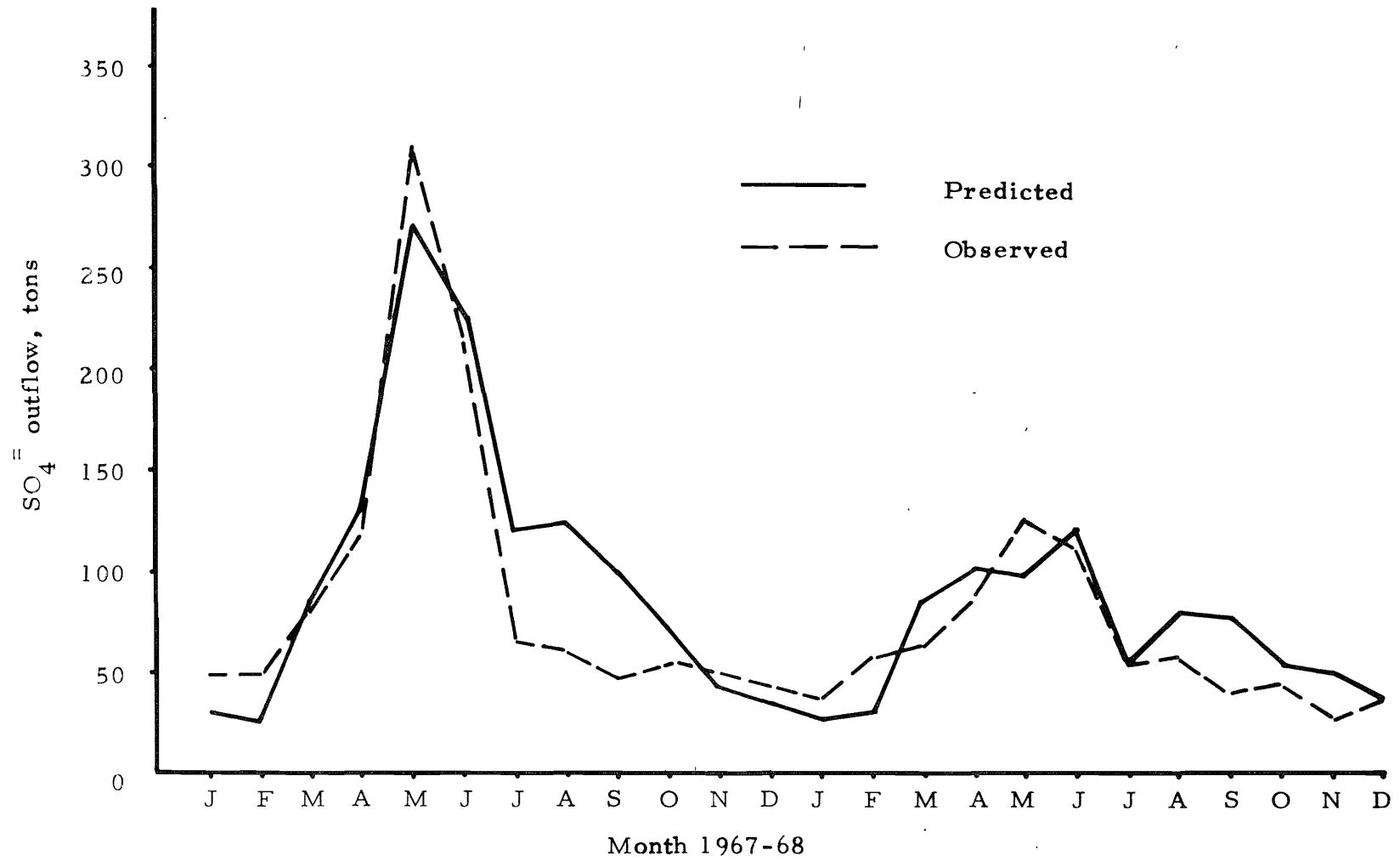
Figure 19. Observed and simulated sulfate ($SO_4^=$) outflow.
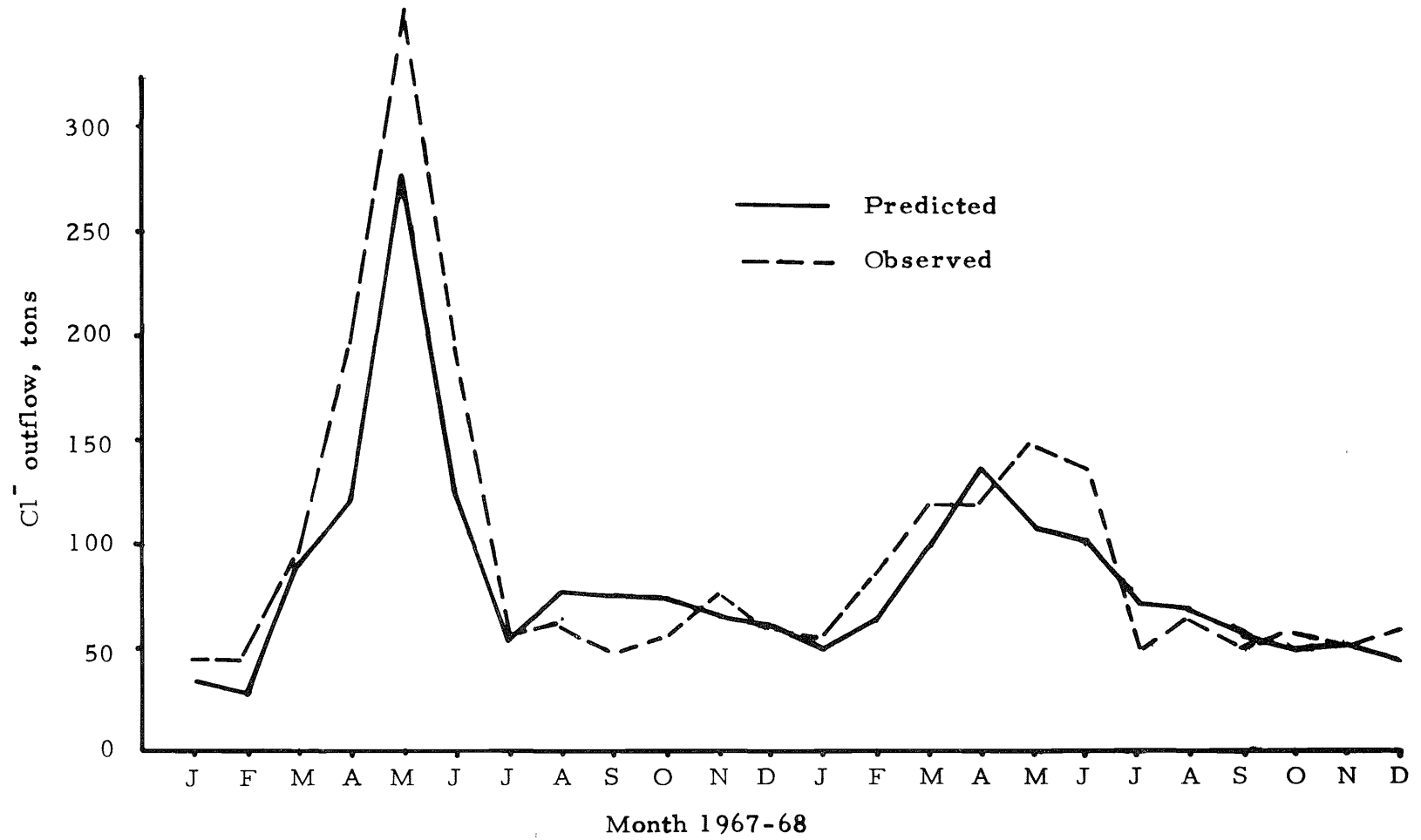
Figure 20. Observed and simulated chloride (Cl⁻) outflow.
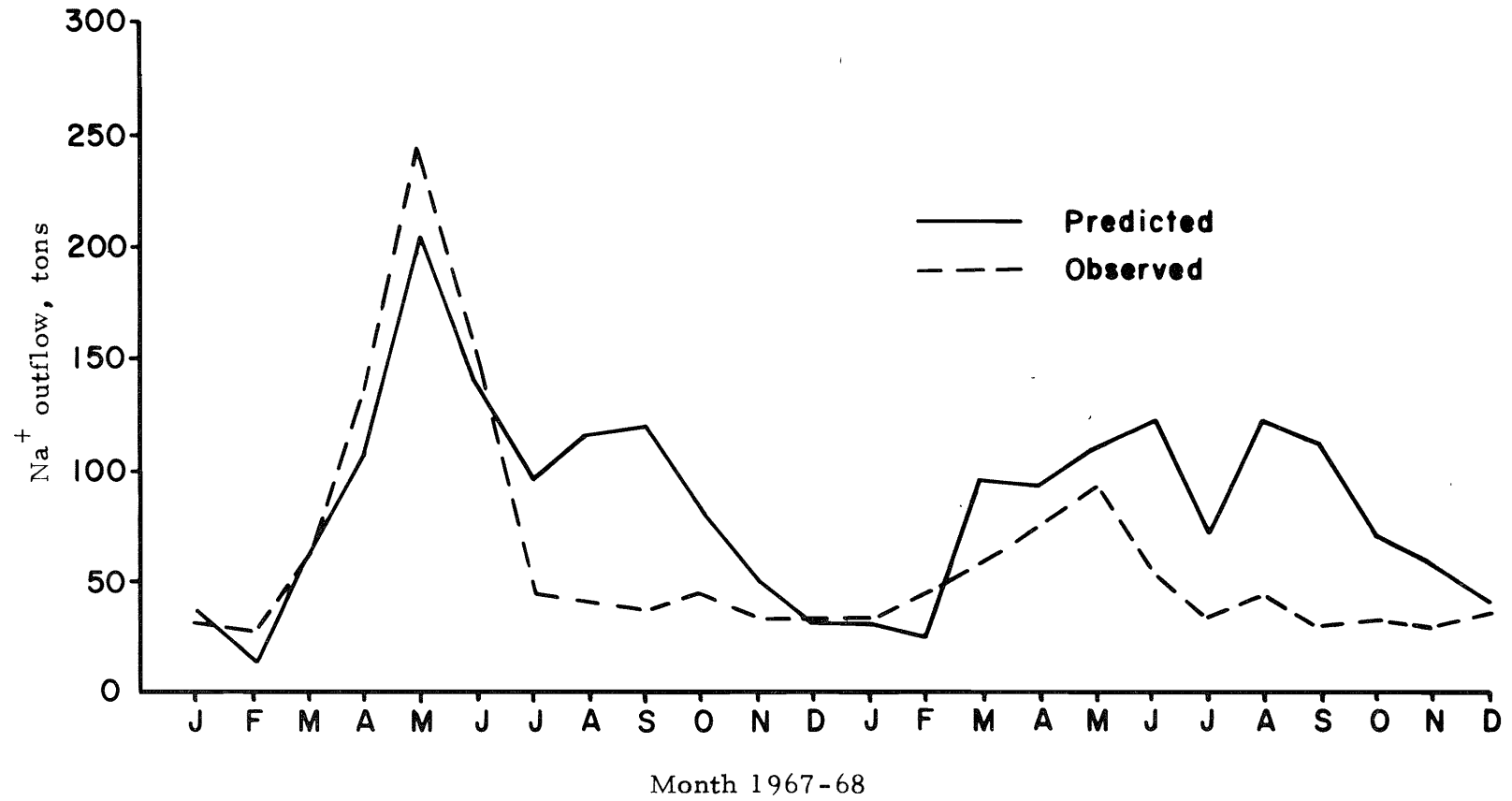
Figure 21. Observed and simulated sodium (Na$^+$) outflow.

ysis failed to identify it accurately when it occurred in such low concentrations, (2) the soil samples were not representative, or (3) the model does not adequately describe the sodium reactions. Further testing would be necessary to pinpoint exact reasons for the failure to model sodium more accurately.

Total dissolved solids. The sum of the individual ions yielded the total salt load of the Little Bear River at the outflow station. (Theoretically, before summing the individual ions, bicarbonate should be multiplied by a factor of .4917 because during routine laboratory determinations of residue on evaporation the bicarbonates are presumably converted to the carbonate form by heating. The values thus obtained represent dry residue rather than actual material in solution. In this study both observed and simulated TDS were obtained by summing the ions actually in solution.) Figure 22, a plot of observed and simulated total dissolved solids, reflects the dominant influence of bicarbonate, calcium, and magnesium ions on the composite salt flow. Simulated loads generally followed the observed values, resulting in a correlation coefficient of .97, n = 24. Appendix C contains computer printout of calculated salt flows for each of the 24 months modeled.

Management study

The portion of the Little Bear River basin modeled in this study has no particular water management problems. The area generally receives enough runoff to provide irrigators with an adequate supply of good quality water. Soils are fairly productive and drainage is adequate. The area does have the potential to bring more land under irrigation, however, by supplying water to the bench land on the east side of the valley. Several hundred acres currently dry-cropped could be successfully irrigated by sprinklers obtaining water from Highline canal. Seepage losses in Highline canal may amount to as much as 50 percent of the total flow (Skogerboe, 1967). A canal lining project currently underway should reduce transmission losses considerably and make more water available for irrigation.

To demonstrate the utility of the model, it was assumed that 500 acres of soil of, or closely related to, the McMurdie series would be brought under sprinkler irrigation. It was further assumed that overall irrigation efficiency would increase as more land is irrigated by sprinklers. With these two changes, 500 more acres of McMurdie soil and an efficiency increase of 15 percent, the model was rerun for the 1967-68 period, yielding the results described in the next paragraph.

Total salt and water outflow was not changed appreciably, but concentration of dissolved minerals increased somewhat. For the two-year period, water outflow decreased less than 1 percent, and salt outflow increased approximately 1 percent. Consumptive use by crops on the 500 additional acres reduced the water outflow, while subsurface return flows from the area accounted for the salt pickup. Figure 23 illustrates the increased concentration of TDS resulting from the assumed changes. Each ion was affected to approximately the same degree as TDS. Na^+ showed the largest percentage increase, Figure 24, because effluent from McMurdie soils is slightly higher in soluble sodium than most of the other soils. Although the results of the management study are not dramatic, they do indicate the usefulness of the model in predicting what effect changes within the basin will have on water and salt outflow.
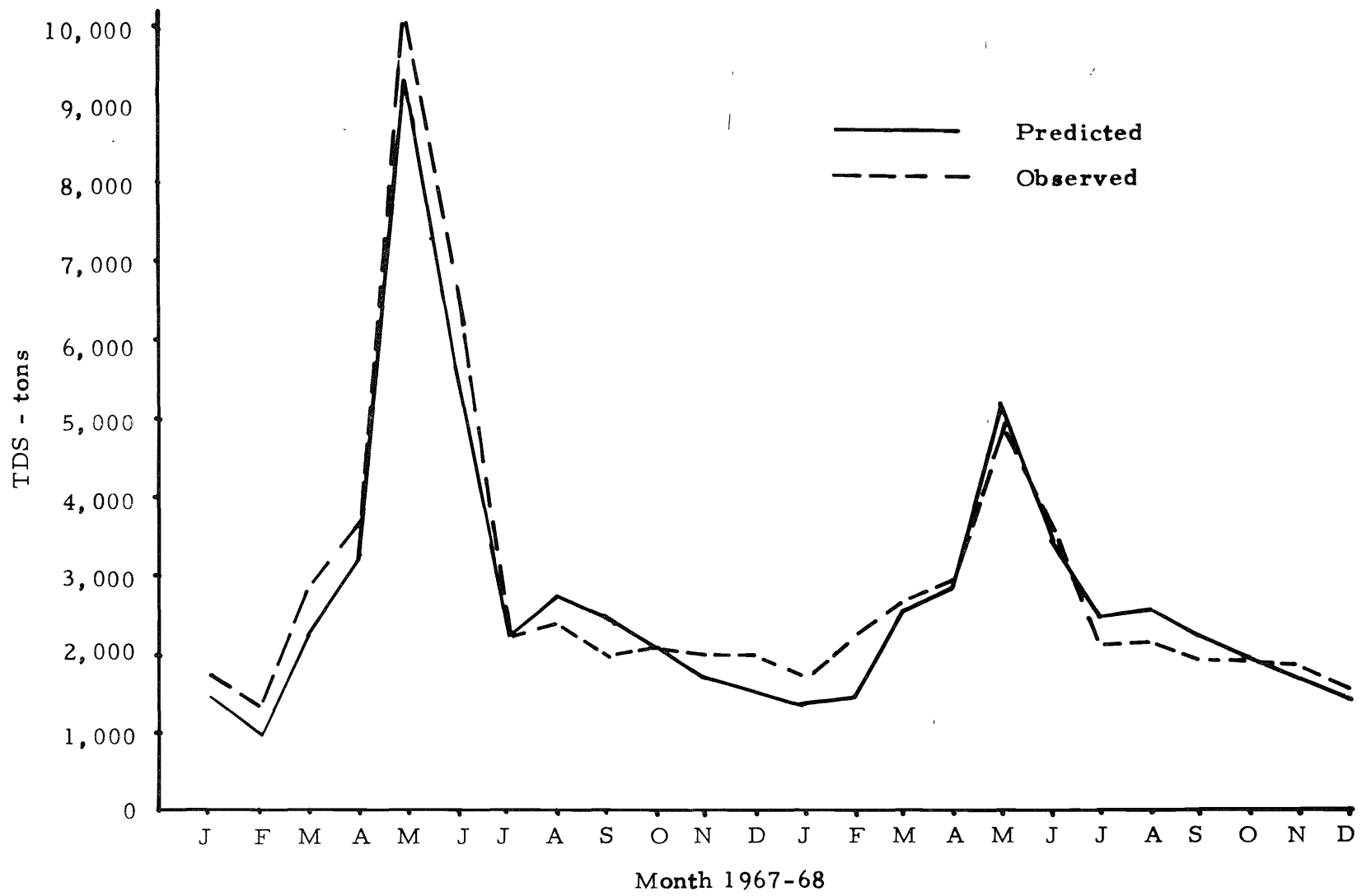
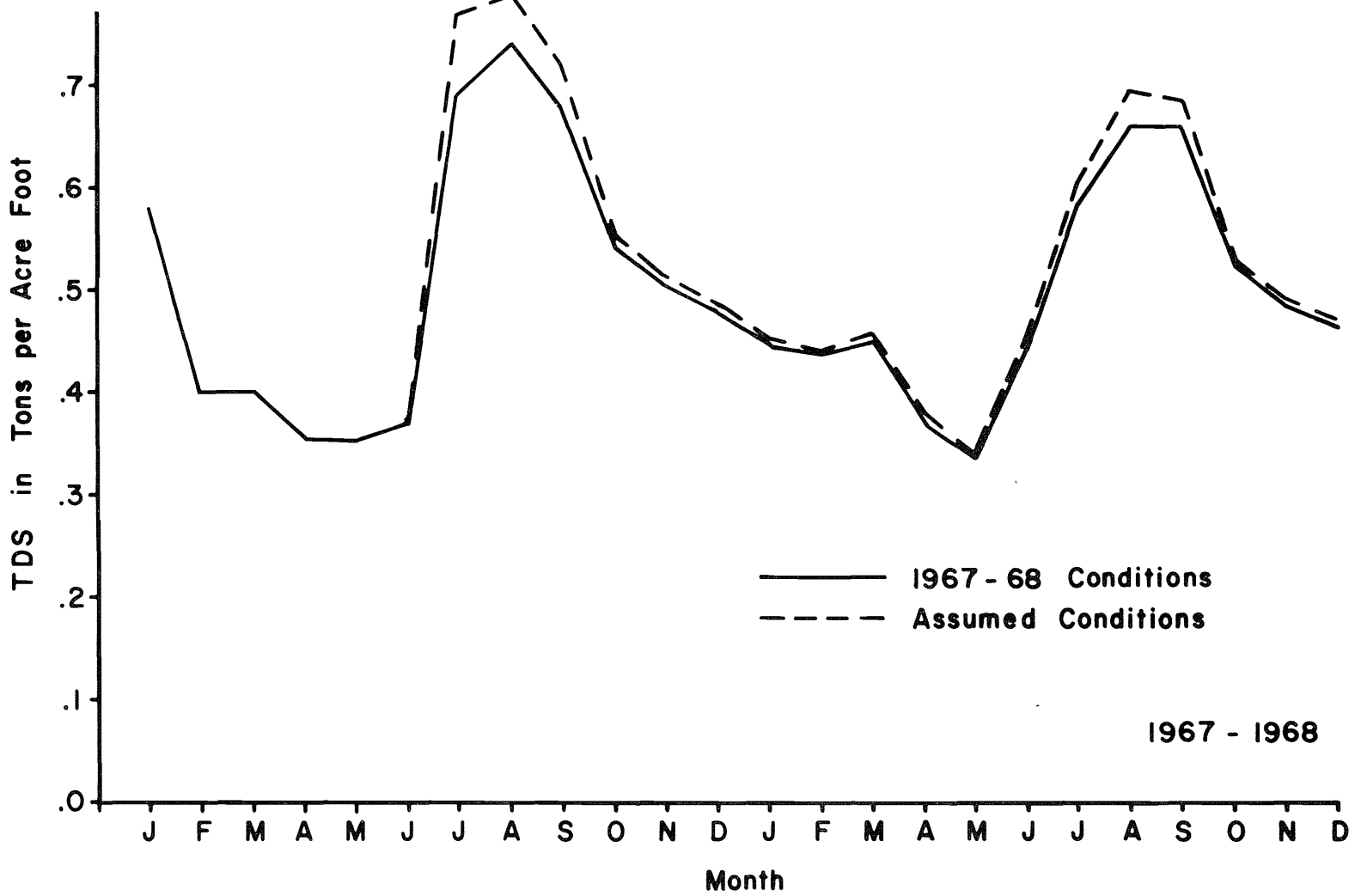Figure 22. Observed and simulated total dissolved solids (TDS) outflow.

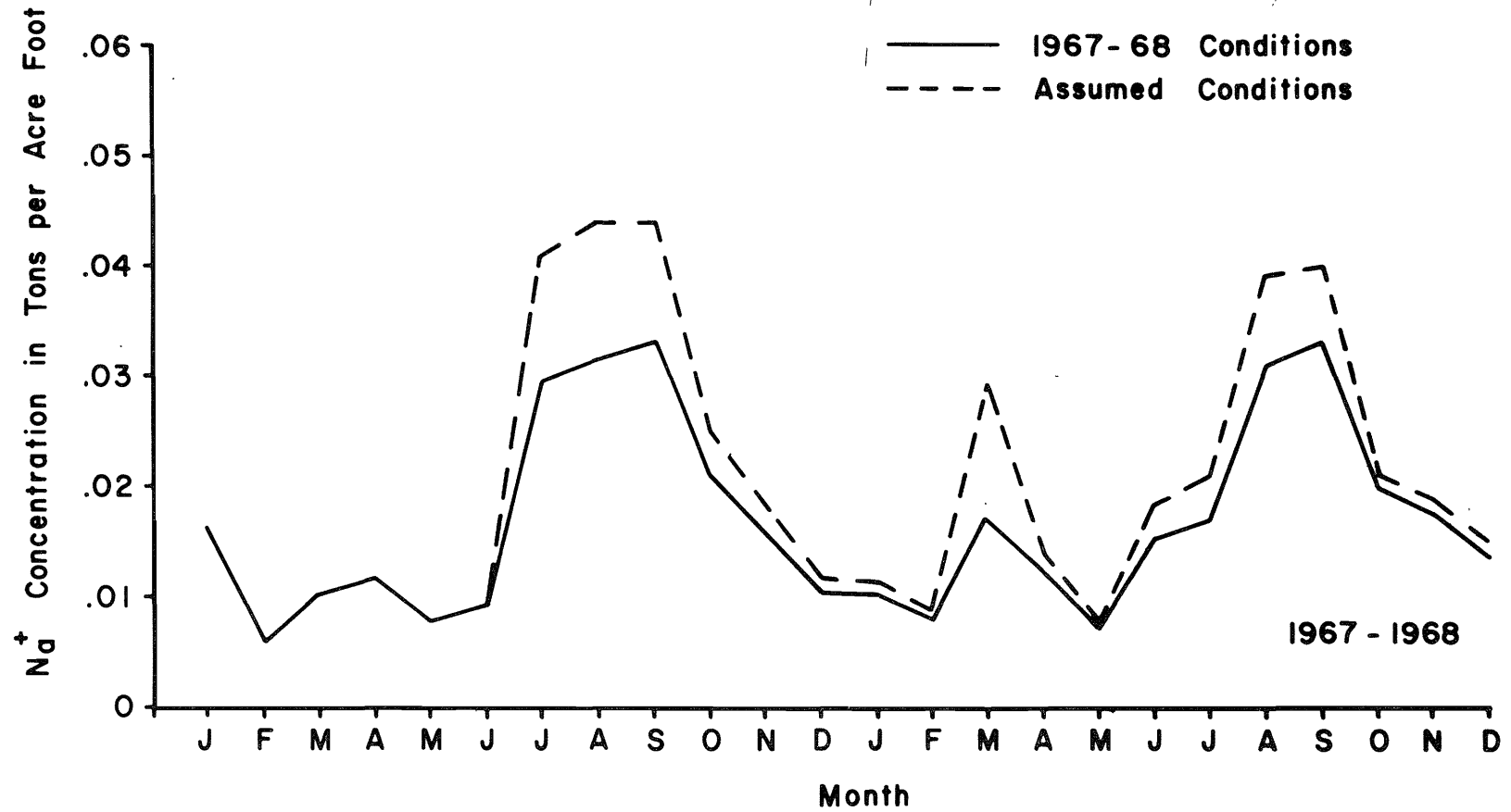Figure 23. Effect of assumed management changes on TDS concentrations.

Figure 24. Effect of assumed management changes on Na$^+$ concentration.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Summary

A hybrid computer program was developed which combined a modified form of the chemical model described by Tanji et al. (1967), which predicts the quality of water percolated through a soil profile, with a hydrologic model of a river basin. The composite model operates on a monthly time unit to simulate the outflow of water and salt from a basin in which irrigated agriculture is the major user of water. The chemical composition of the outflow is a function of numerous processes, including the blending of inflows; evaporation; transpiration; and mixing, cation exchange, precipitation, and leaching as excess irrigation water percolates through the subsoil and returns to the stream. The present study was limited to the six common ions of western waters, namely calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+), sulfate ($SO_4^=$), chloride (Cl^-), and bicarbonate (HCO_3^-).

The model was tested on the Little Bear River basin in northern Utah. The model successfully simulated measured outflows of water and each of the six ions for a 24-month period. Only Na^+, which occurred in small concentrations comprising approximately 2 percent of the total salt outflow, exhibited significant discrepancies between predicted and actual values. All others agreed within 10 percent on a weight basis for the two-year model period, with correlation coefficients greater than 0.9. The usefulness of the model was demonstrated by a management study of the prototype system.

The hybrid computer proved to be an extremely useful tool for the type of model developed. During verification it was possible to plot the output on an X-Y plotter and to obtain a printout of pertinent quantities, including a comparison of observed and calculated values. Such information was invaluable in deciding which parameters to adjust in order to calibrate the general model for the prototype. Parameter values were easily changed by adjusting pots on the analog, changing data cards to be read by the digital, or by inserting a new value via the teletype keyboard. The solid state circuits of the analog exhibited negligible variations and were able to reproduce results quite accurately.

The program as written can handle 24 months of record and up to five separate soils per basin with 19 layers in each soil. As such it utilizes practically all of the
memory available on the 16,000 word digital computer. Before more soils, longer periods of time, or other parameters could be modeled it would be necessary to extensively revise the program or to expand the capability of the computer. Three to five minutes of computer time were required for each soil modeled.

Applications

The model should prove useful in practical field applications. Once it is calibrated for a particular basin by the use of historical data, it may be used to predict the effects of proposed management changes on the quantity and chemical quality of streamflow below the irrigated area. A sensitivity analysis of the model could identify the parameters which have the greatest effect on the outflow. For example, the results of changing crops, applying the water more efficiently (perhaps by converting from surface irrigation to sprinkler systems), lining leaky canals, altering the time distribution of application, installing artificial drains, or irrigating additional land could all be predicted by making the necessary changes in model parameters.

In addition the model could be applied to areas where irrigation systems are proposed. Assuming sufficient historical hydrologic records were available to supply data for the hydrology portion of the model, and that the quality of the irrigation water and the chemical and physical properties of the soil and subsoil could be measured, it would be possible to simulate the effects of a proposed irrigation project on the water and salt outflow from the basin. Several alternatives could be modeled to help planners choose a project to best meet their criteria.

Suggestions for Further Research

1. Develop self-optimizing techniques to reduce the time required for verification.
2. Test the model on an area where the concentration of all ions is significant, particularly Na^+ and $SO_4^=$.
3. Improve the equations involving the precipitation and dissolution of lime.
4. Include other ions in the analysis, such as

nitrate(NO_3^-), phosphate ($PO_4^=$), carbonate ($CO_3^=$), and potassium (K^+).

5. Improve the equations for miscible displacement, i.e., the mixing of deep percolation with soil water and groundwater.

6. Include functions to represent quality changes caused by other users, such as industrial and municipal.

7. Combine this model with models for other water quality parameters, such as dissolved oxygen, biochemical oxygen demand, and temperature.

LITERATURE CITED

Alfaro, Jose Felix. 1968. Distribution of salts in a vertical soil profile during leaching. Ph.D. Dissertation. Utah State University Library, Logan, Utah. 132 p.

Bailey, John W. 1969. Problems of management of irrigation and drainage waters in the San Luis Unit, Central Valley Project, California. Presented at the International Conference on Arid Lands in a Changing World, June 3-13, Tucson, Arizona. 40 p.

Babcock, K. L. 1963. Theory of the chemical properties of soil colloidal systems at equilibrium. Hilgardia 34(11):417-542.

Babcock, K. L., R. M. Carlson, R. K. Shulz, and R. Overstreet. 1959. A study of the effect of irrigation water composition on soil properties. Hilgardia 29:155-164.

Bagley, Jay M., Robert B. Hickok, Duane G. Chadwick, Marvin J. Rosa, and D. L. Brakensiek. 1963. Report on feasibility of an electronic analog approach to the Sevier River Basin investigations for water resources development and conservation planning. Engineering Experiment Station Report No. EC-51-g-1, Utah State University, Logan, Utah. 47 p. (multi.)

Bear, J. 1961. On the tensor form of dispersion in porous media. Journal of Geophysical Research 66:1185-1197.

Beer, Lawrence Peter. 1967. Ground water hydrology of Southern Cache Valley, Utah. Information Bulletin No. 19, Utah State Engineer, Salt Lake City, Utah. 119 p.

Biggar, J. W. and D. R. Nielsen. 1960. Miscible displacement in saturated and unsaturated soils. 7th International Congress of Soil Science, Madison, Wisconsin. pp. 147-152.

Biggar, J. W. and D. R. Nielsen. 1962. Miscible displacement: II. Behavior of tracers. Proceedings, Soil Science Society of America 26(2):125-128.

Biggar, J. W. and D. R. Nielsen. 1963. Miscible displacement: V. Exchange process. Proceedings, Soil Science Society of America 27(6):623-627.

Biggar, J. W. and D. R. Nielsen. 1964. Chloride-36 diffusion during stable and unstable flow through glass beads. Proceedings, Soil Science Society of America 29(5):591-595.

Bittinger, Morton W. 1968. Simulation and analysis of stream-aquifer systems. Ph.D. Dissertation. Utah State University Library, Logan, Utah. 107 p.

Bjorklund, L. J. and L. J. McGreevy. 1970. Ground-water resources of Cache Valley, Utah and Idaho. U.S. Geological Survey Water Supply Paper. (In preparation)

Bower, C. A. 1962. Prediction of the effects of irrigation waters on soils. Proceedings of the UNESCO Arid Zone Symposium, Tehran, Iran. pp. 215-222.

Bower, C. A., W. R. Gardner, and J. O. Goertzen. 1957. Dynamics of cation exchange in soil columns. Proceedings, Soil Science Society of America 21:20-24.

Brooks, R. H., J. O. Goertzen, and C. A. Bower. 1958. Prediction of changes in the composition of the dissolved and exchangeable cations in soils upon irrigation with high-sodium water. Proceedings, Soil Science Society of America 22:122-124.

Carlson, Enos J. 1968. Removal of saline water from aquifers. U.S. Department of Interior, Bureau of Reclamation Research Report 13. 43 p.

Christiansen, J. E. 1966. Estimating pan evaporation and evapotranspiration from climatic data. ASCE Irrigation and Drainage Specialty Conference, Las Vegas, Nevada. November 2-4, pp. 193-234.

Cohen, J. B. and R. L. O'Connell. 1963. The analog computer as an aid to stream self purification computations. Journal of Water Pollution Control Federation 35(8):951-962.

Crawford, N. H. and R. K. Linsley. 1966. Digital simulation hydrology: Stanford watershed model IV. Technical Report No. 39. Department of Civil Engineering, Stanford University, Stanford, California. 210 p.

Day, P. R. 1956. Dispersion of moving salt-water boundary advancing through saturated sand. Trans. American Geophysical Union 37: 595-601.

Dixon, Neal P., David W. Hendricks, A. Leon Huber, and Jay M. Bagley. 1970. Developing a hydro-quality simulation model. PRWG67-1, Utah Water Research Laboratory, Utah State University, Logan, Utah. 193 p.

Doneen, L. D. 1954. Salinization of soils by salts in the irrigation water. Trans. American Geophysical Union 35:943-950.

Dutt, G. R. 1962a. Quality of percolating waters. No. 1. Development of a computer program for calculating the ionic composition of percolating waters. Berkeley: University of California Water Resources Center Contribution No. 50. 35 p.

Dutt, G. R. 1962b. Prediction of the concentration of solutes in soil solutions for soil systems containing gypsum and exchangeable Ca and Mg. Proceedings, Soil Science Society of America 26:341-343.

Dutt, G. R. 1964. Effects of small amounts of gypsum in soils on the solutes in the effluents. Proceedings, Soil Science Society of America 28(6):754-757.

Dutt, G. R. and L. D. Doneen. 1963. Predicting the solute composition of the saturation extract from soil undergoing salinization. Proceedings, Soil Science Society of America 27:627-630.

Dutt, G. R. and K. K. Tanji. 1962. Predicting concentrations of solutes in water percolated through a column of soil. Journal of Geophysical Research 67:3437-3439.

Dyer, Kenneth Lee. 1967. Effect of CO_2 on the chemical equilibrium of soil solution and groundwater. Ph.D. Dissertation, University of Arizona, Tucson, Arizona. 140 p.

Eaton, F. M. 1950. Significance of carbonates in irrigation waters. Soil Science 69:123-133.

Erickson, F. 1952. Cation exchange equilibrium on clay minerals. Soil Science 74:103-113.

Falk, Lloyd L. 1962. Analog computer--a modern tool in water pollution control. Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers 88(SA6):31-59.

Federal Water Pollution Control Administration. 1967. Fitting the Red River of the North basin to the general river basin simulation program. Division of Technical Control, Comprehensive Planning and Programs. 23 p.

Gapon, E. N. 1933. Theory of exchange adsorption in soils. Journal of General Chemistry, U.S.S.R. 3:144-152.

Glasstone S. 1946. Textbook of physical chemistry. New York: D. Van Nostrand Co., Inc. 1320 p.

Glover, Robert E. 1960. Ground water-surface water relationships. Western Resources Conference, August 24, Boulder, Colorado. 11 p.

Glover, R. E. 1965. The mechanism of aquifer sweetening. Presented at the American Society of Civil Engineers Hydraulics Division Conference, Tucson, Arizona. August 25-27. (Original not seen; cited by Carlson, 1968.)

Hanks, R. J. and E. Bresler. 1969. Numerical method for estimating simultaneous flow of water and salt in unsaturated soils. Proceedings, Soil Science Society of America 33:827-837.

Hansen, Keith. 1969. Water commissioner's report on the Little Bear River system. Logan, Utah. (Mimeo.)

Haws, Frank W. 1969. Water related land use in the Bear River drainage area. PRWG40-2, Utah Water Research Laboratory, Utah State University, Logan, Utah.

Hem, John D. 1959. Study and interpretation of the chemical characteristics of natural waters. United States Geological Water Supply Paper 1473. 269 p.

Hufschmidt, M. M. and M. B. Fiering. 1966. Simulation techniques for design of water-resource systems. Harvard University Press, Cambridge, Massachusetts. 212 p.

Hurley, Patrick A. 1968. Predicting return flows from irrigation. Journal of Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers 94(IR1):41-48.

Hutchins, Wells A. and Dallin W. Jensen. 1965. The Utah law of water rights. State Engineer of Utah, Salt Lake City, Utah. 84 p.

Hyatt, M. Leon, J. Paul Riley, M. Lynn McKee, and Eugene K. Israelsen. 1970. Computer simulation of the hydro-salinity flow system in the Upper Colorado River Basin. PRWG54-1, Utah Water Research Laboratory, Utah State University, Logan, Utah.

Israelsen, E. K. and J. Paul Riley. 1968. Application of an electric analog computer to a study of water resources management. International Association of Scientific Hydrology-Symposium at Tucson, Arizona. pp. 49-56.

Keller, Jack and Jose F. Alfaro. 1966. Effect of water application rate on leaching. Soil Science 102(2):107-114.

Krishnamoorthy, C. L., E. Davis, and R. Overstreet. 1949. Ionic exchange equations derived from statistical thermodynamics. Soil Science 108:439-440.

Longenbaugh, Robert A. 1967. Mathematical simulation of a stream-aquifer system. Presented at the Third American Water Resources Conference in San Francisco, California. 9

Maasland, D. E. L. 1965. Quality change of drain effluent. Ph.D. Dissertation. Colorado State University Library. Fort Collins, Colorado. 170 p.

Maass, A. M., M. Hufschmidt, R. Dorfman, H. A. Thomas, Jr., S. A. Marglin, and G. M. Fair. 1966. Design of water-resource systems. Harvard University Press, Cambridge, Massachusetts. 620 p.

Maletic, J. T. 1962. Supporting investigations, Shadehill Unit, Missouri River Basin. Definite Plan Report. U.S. Bureau of Reclamation. (Original not seen; cited by Maletic, 1969.)

Maletic, J. T. 1969. Chief Land Resources Branch, U.S. Bureau of Reclamation, Denver, Colorado. Personal communication.

Margheim, Gary Alec. 1967. Predicting the quality of irrigation return flows. Unpublished M.S. Thesis. Colorado State University Library. Fort Collins, Colorado. 57 p.

Morris, W. J. 1970. Hybrid computer system added to UWRL research capabilities. Aquarius, Utah Water Research Laboratory Newsletter, Vol. 1, No. 2.

Mullens, Thomas, E., and Glen A. Izett. 1964. Geology of Paradise quadrangle, Cache County, Utah. U.S. Geological Survey Bulletin 1181-S. 32 p.

Nielsen, D. R. and J. W. Biggar. 1961. Miscible displacement in soils: I. Experimental information. Proceedings, Soil Science Society of America 25(1):1-5.

Nielsen, D. R. and J. W. Biggar. 1962. Miscible displacement: III. Theoretical considerations. Proceedings, Soil Science Society of America 26(3):216-221.

Nielsen, D. R. and J. W. Biggar. 1963. Miscible displacement: IV. Mixing in glass beads. Proceedings, Soil Science Society of America 27(1):10-13.

Orlob, G. T. and P. C. Woods. 1964. Lost River System--a water quality management study. Journal of Hydraulics Division, Proceedings of the American Society of Civil Engineers HY2:1-22.

Orlob, Gerald T. and Philip C. Woods. 1967. Water quality management in irrigation systems. Journal of Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers IR2:49-66.

Paul, J. L., K. K. Tanji, and W. D. Anderson. 1966. Estimating soil and saturation extract composition by a computer method. Proceedings, Soil Science Society of America 30:15-18.

Peterson, William. 1946. Ground-water supply in Cache Valley, Utah, available for domestic use and irrigation. Utah State Agricultural College Extension Service NS 133. 101 p.

Pisano, W. L. 1968. River basin simulation program. Federal Water Pollution Control Administration, Washington, D. C. 296 p.

Poe, Stephen H. 1970. Chief, Technical and Foreign Services Branch, U.S. Bureau of Reclamation, Denver, Colorado. Personal communication. May 20.

Rennerfelt, J. G. W. 1964. An analog computer for oxygen sag calculations. Advances in water pollution research. Proceedings of the International Conference held in London, September 1962. The Macmillan Company, New York. pp. 79-87.

Ricks, Joel E. (Editor) 1956. The history of valley, Cache Valley, Utah-Idaho. Deseret News Publishing Company, Salt Lake City, Utah. 650 p.

Riley, J. Paul. 1970. Computer simulation of water resource systems at Utah State University. Occasional Paper 5, Utah Water Research Laboratory, Utah State University, Logan, Utah. 20 p.

Riley, J. Paul and Duane G. Chadwick. 1967. Application of an electronic analog computer to the problems of river basin hydrology. Utah Water Research Laboratory, Utah State University, Logan, Utah. 199 p.

Riley, J. Paul, Duane G. Chadwick, and Jay M. Bagley. 1966. Application of an electronic analog computer to solution of hydrologic and river-basin-planning problems: Utah simulation model II. PRWG32-1, Utah Water Research Laboratory, Utah State University, Logan, Utah.

Sallam, Abdel-Wahhab M. Hamza. 1966. Leaching and reclamation equations for saline soil. Ph.D. Dissertation, Utah State University, Logan, Utah. 97 p.

Sawyer, Clair N. and Perry L. McCarty. 1967. Chemistry for sanitary engineers. McGraw-Hill Company. New York. 518 p.

Scheidegger, A. E. 1954. Statistical hydrodynamics in porous media. Journal of Applied Physics 25:994-1001.

Scofield, C. S. 1940. Salt balance in irrigated areas. Journal of Agriculture Research 61:17-39.

Shen, John. 1965. Use of analog models in the analysis of flood runoff. U.S. Geological Survey Professional Paper 506-A. 24 p.

Shubik, Martin. 1960. Simulation of the industry and the firm. American Economic Review L(5):909.

Skogerboe, Gaylord V. 1967. Operation and maintenance of the Paradise project irrigation distribution system. Division of Water Resources, Department of Natural Resources, Salt Lake City, Utah. 14 p.

Soil Conservation Service. 1964. Irrigation water requirements. Engineering Division, Salt Lake City, Utah, USDA, Technical Release No. 21. April.

Soil Conservation Service. [ca. 1966]. Soil survey Cache area, Utah. Unpublished manuscript. Office of Soil Conservation Service, Logan, Utah. (Mimeo.)

Sylvester, Robert O. and Robert W. Seabloom, Jr. 1963. Quality and significance of irrigation return flow. Journal of the Irrigation and Drainage Division, ASCE 89(IR3):1-27.

Tanji, Kenneth K. 1970. Associate Specialist, Department of Water Science and Engineering, University of California, Davis. Personal Communication, January 15.

Tanji, K. K. and L. D. Doneen. 1966. A computer technique for prediction of $CaCO_3$ precipitation in HCO_3^- salt solutions. Proceedings, Soil Science Society of America 30:53-56.

Tanji, K. K., L. D. Doneen, and J. L. Paul. 1967. Quality of percolating waters. III. The quality of waters percolating through stratified substrata, as predicted by computer analysis. Hilgardia 38(9):307-318.

Tanji, K. K., G. R. Dutt, J. L. Paul, and L. D. Doneen. 1967. Quality of percolating waters. II. A computer method for predicting salt concentrations in soils at variable moisture content. Hilgardia 38(9):307-318.

Thorne, D. W. and J. P. Thorne. 1954. Changes in composition of irrigated soils as related to the quality of irrigation waters. Proceedings, Soil Science Society of America 18:92-97.

Utah State University Foundation. 1969. The characteristics and pollution problems of irrigation return flow. Research Contract No. 14-12-408. Federal Water Pollution Control Administration, U.S. Department of Interior. 237 p.

Vanselow, A. P. 1932. Equilibria of the base reactions of bentonites, permutites, soil colloids, and the zeolites. Soil Science 33:95-113.

Von Seggern, M. E. 1962. Forecasting the quality of irrigation return flows. Presented at the Mid-Continent Irrigation and Drainage Conference, Kansas City, Missouri. 27 p.

Water Resources Council. 1968. The nations water resources. Washington, D.C.

Williams, J. S. 1958. Geological atlas of Utah, Cache County. Utah Geological and Mineralogical Survey Bulletin No. 64. 32 p.

Wilcox, L. V., George Y. Blair, and C. A. Bower. 1954. Effects of bicarbonates on the suitability of water for irrigation. Soil Science 77:259-266.

Woods, Philip C. 1967. Management of hydrologic systems for water quality control. Berkeley: University of California Water Resources Center Contribution No. 121. 121 p.

APPENDICES

APPENDIX A

Description of the Little Bear River Basin

The theoretical model described in Chapters III and IV requires rather extensive input data, which may be measured or estimated. Measured data are preferred, of course, and the prototype system selected for modeling was the Little Bear River in Cache Valley, northern Utah, a basin which was extensively monitored for a previous study at the Utah Water Research Laboratory. Following is a description of this physical system.

Location and geography

The portion of the Little Bear River basin modeled in this study encompasses 203 square miles of drainage area in the southern end of Cache Valley, Utah (Figure 1), near the eastern boundary of the Great Basin physiographic province. The Little Bear River is a tributary of the Bear River which drains into the Great Salt Lake near Brigham City, Utah. Basin topography is characterized by rugged high mountain peaks, rolling foothills, and a nearly flat valley floor. Elevations range from 4600 feet near Hyrum to 9445 feet at the summit of James Peak.

Geology

Cache Valley, of which the valley floor area of the Little Bear River is a part, is probably a graben or down-faulted block surrounded by rugged upstanding mountains (Williams, 1958). Devonian, Mississippian, and Pennsylvanian sediments crop out in the Bear River Range, and Tertiary and Quanternary sedimentary rocks crop out in Cache Valley. Tertiary and Quanternary rocks were deposited in a continental environment. Most Paleozoic rocks were deposited in a marine environment, but some of the oldest Devonian rocks were probably deposited in a continental or marginal marine environment (Mullens and Izett, 1964).

The bedrock consists of Precambrian, Paleozoic, and Tertiary rocks of limestone, dolomite, shale, sandstone, conglomerate, quartzite, phyllite, and volcanic tuff.

The valley fill is composed of unconsolidated sediments of the quanternary system derived from old Lake Bonneville. The Alpine and Bonneville Formations consist of evenly bedded light-colored calcareous siltstone deposited on a gently sloping lake bottom with sand and gravel terrace features near the shoreline, formed when the lake level ranged from 5100 feet to 5160 feet. Sediments deposited at an altitude of about 4840 feet are assigned to the Provo Formation which consists of deltas composed of irregularly interbedded poorly consolidated sand, gravel, and silt (Mullens and Izett, 1964). The extensive flat between Paradise and Hyrum rests on rocks of the Provo Formation.

Alluvium occurs along East Fork and Little Bear Rivers, and along the lower reaches of West Canyon, Hyrum Canyon, Davenport Creek, and Paradise Dry Canyon. It consists of silty and sandy poorly consolidated clay with sand and gravel lenses. On East Fork River and West Canyon alluvium is restricted to the present flood plain. Along Little Bear River, alluvium is present in terraces 10-20 feet above the current flood plain. The towns of Paradise and Avon are located on alluvial fans.

A typical geological cross-section of the Little Bear River Valley approximately one mile south of Paradise is shown in Figure 25.

Climate and hydrology

The climate of this area is temperate, seasonal, and semi-arid. Winter is cold, wet, and long; spring is warm and quite wet; summer is rather short, with warm, dry days, and cool nights; and autumn is cool and fairly wet. (See Figure 26.) The high mountainous areas are, of course, wetter and cooler than the valley floor. Mountains receive up to twice the precipitation that the valleys received, most of which occurs as snow during the winter. Snow accumulates from October to March and melts during the spring (April to June) when most of the annual runoff is observed, Figure 27. The protective action of the mountains usually prevents extended periods of severe heat or cold in the inhabited parts of the valley. In the valley areas used for agriculture annual evaporation greatly exceeds precipitation, particularly in the growing season months. Thus irrigation water, available from the mountainous watershed, is required for successful agriculture.

Cultural development

The first white men to visit Cache Valley were trappers, mountaineers, surveyors, and adventurers such as Bridger, Fremont, and Stansbury. The first permanent settlement, Wellsville, was established by Mormon pioneers led by Peter Maughan in 1855. Other towns were founded throughout the valley in the ensuing 20 years.
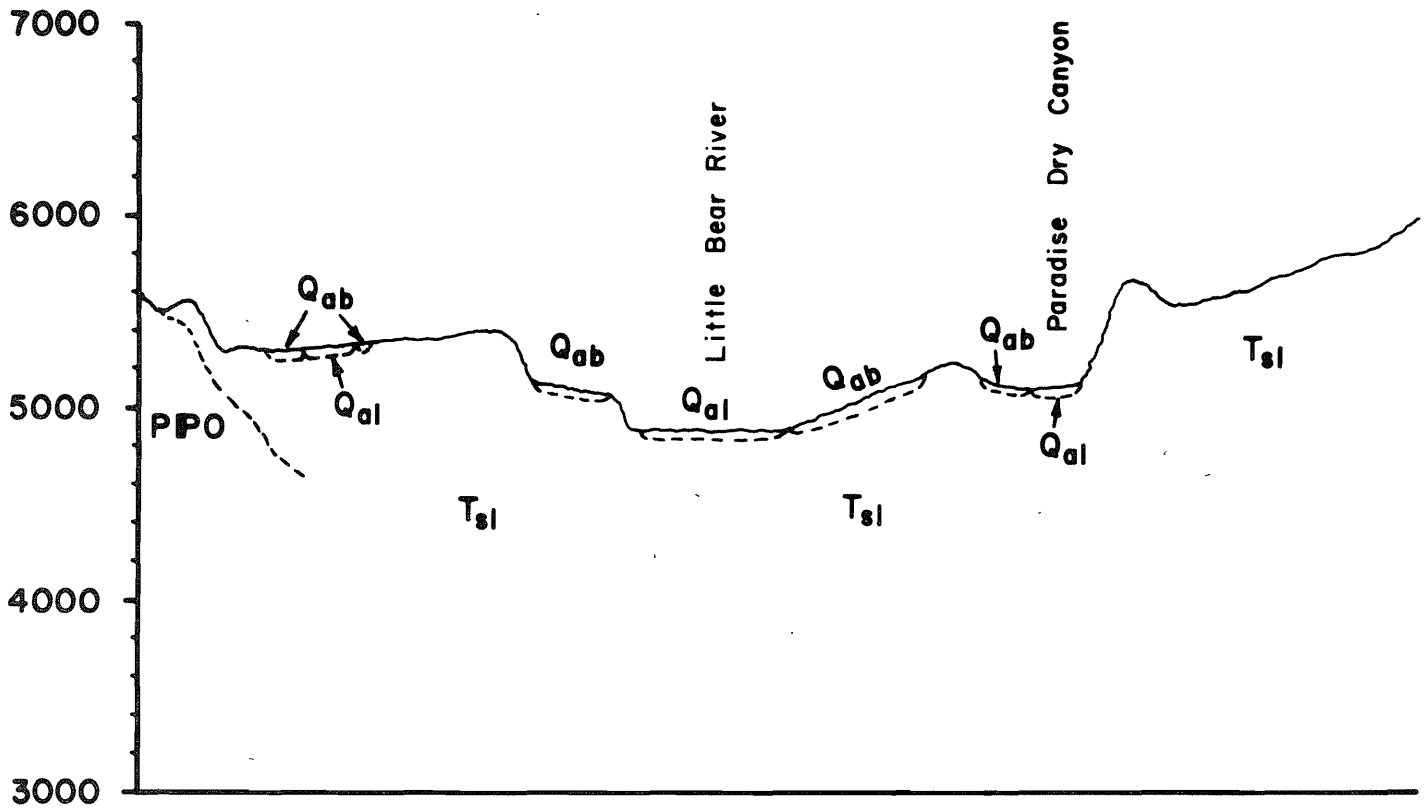
63

Figure 25. Geological cross-section of the Little Bear River Basin near Paradise.

The early settlers were quick to take advantage of the abundant water supply of Cache Valley to irrigate their crops. One group of pioneers settled at East Canyon near the present site of Avon, April 18, 1860. Ricks (1956) reports that: "They raised good crops the first year using the springs near the settlement to irrigate the grain." These settlers were forced to move because of the Indian threat and subsequently established the permanent town of Paradise in 1868.

Irrigation development continued as the population of the area increased. Paradise and Hyrum canals were constructed early to convey water from the upper reaches of the watershed to the agricultural land. Construction of Hyrum Reservoir began in 1934. Porcupine Reservoir and Highline canal were constructed during 1961 and 1962, to provide water for the sprinkler irrigation of the rolling bench lands on the east side of the valley between Avon and Blacksmith Fork River. Irrigated agriculture has always been, and continues to be, the main industry of the area. Major activities are cattle and sheep ranching and dairy farming with nearby supporting industries such as milling, meat packing, and cheese making.

Crops and land use

Agricultural land use is naturally oriented to support the principal farming activities previously mentioned. Most land is used for the production of livestock food, either directly for pasture or indirectly for alfalfa, hay, and small grain. Haws (1969) conducted an extensive land use survey of the entire Bear River drainage area, including the Little Bear River. Each field was visually inspected, identified on ASCS-USDA aerial photographs, and labeled according to the type of vegetation or land use existing at the time of the survey (1966). The photographs were later projected onto base maps with a scale of 1 inch equals 1000 feet to form a composite land use map of the area. Acreages of each land use were summarized for each section of land, thereby giving a detailed and reliable picture of the existing land use. Table 3 summarizes land use in the Little Bear River model area as compiled from Haws (1969).

Soils

The soils of the Little Bear River area were formed from limestone, sandstone, and quartzite rocks, usually in

Daily Max.

Daily Mean

Daily Min.

Avg. Monthly Temp.

100
90
80
70
60
50
40
30
20
10
0

|OCT | NOV|DEC | JAN | FEB|MAR| APR|MAY|JUNE|JULY AUG |SEP|

Logan, U. S. U. (1957 thru 1968)

Avg. Monthly Precip.

2

1

0

1.41" 1.56" 1.55" 1.67" 1.39" 1.81" 2.11" 1.86" 1.26" .39" .74" .89"

Mean Annual = 16.64"

| OCT | NOV|DEC | JAN |FEB |MAR | APR|MAY |JUNE|JULY AUG |SEP |

Logan, U. S. U. (1939 thru 1968)
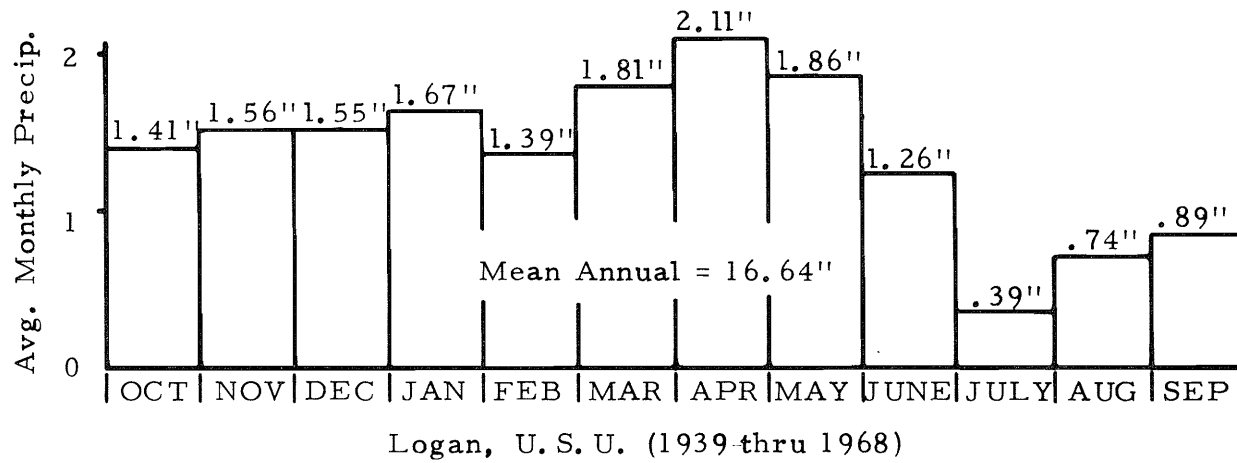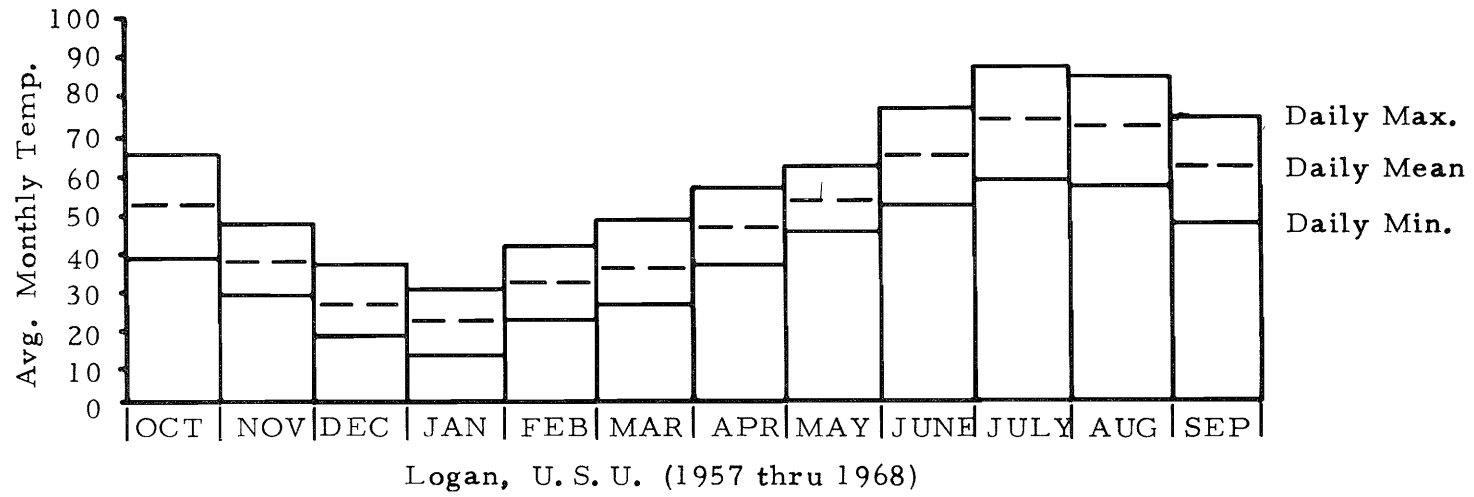
Figure 26. Average monthly precipitation and temperature at Logan USU weather station.
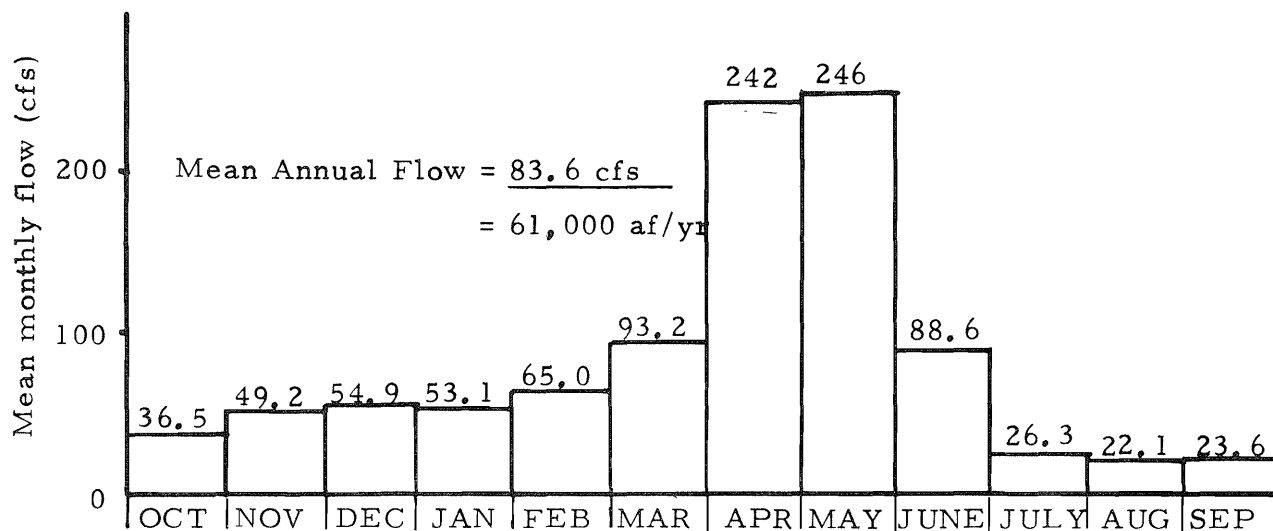
Figure 27. Mean monthly runoff of Little Bear River.

mixed lake, alluvium, and deltic sediments. Except for flat areas near the stream, the soils are generally well drained. They range in texture from fine to medium, are fairly deep, absorb water readily, and are fairly productive if well watered. Chemically, the soils present no special problems. Lime is generally abundant in most soils, although it has been leached from the surface layers in some places.

Information in Table 4, which lists specific properties of some soils in the Little Bear River model area, and the following general descriptions of the major soils were obtained from a recent soils survey of Cache County (Soil Conservation Service, 1966). Figure 14 is a map showing the areal extent of the dominant soil series.

McMurdie series (MC). The soils of this series are deep, well-drained, and fine textured. They occur on high lake terraces at elevations from 4800 to 5150 feet. Slopes range from 0 to 20 percent. The surface soil is dark grayish-brown, neutral, silt loam with moderate organic matter content. The subsoil is brown, neutral silty clay with prismatic structure. The substratum is pale-brown, mildly alkaline, loam or silt loam to silty clay loam and is massive and strongly calcareous. Permeability is moderately slow but drainage is adequate. The soil holds 10 to 12 inches of available water in a 5 foot root zone. Most of the acreage is irrigated for the production of alfalfa, small grains, and some sugar beets.

Ricks series (Bg). Soils of the Ricks series are somewhat excessively drained, gravelly moderately coarse textured soil that are moderately deep over gravel and sand. They occur on lake terraces at elevations of 4500 to 5700

feet. Slopes range from 0 to 10 percent. The surface soil is brown, mildly alkaline, gravelly loam with low organic matter content. The subsoil is brown, mildly alkaline, gravelly light loam or gravelly heavy sandy loam with weak subangular blocky structure. The substratum is pale-brown, very gravelly and cobby sand. Carbonates have generally been leached from the top soil. The presence of gravel promotes a rather high permeability and a water holding capacity of only about 3.5 inches of available water in a 5 foot profile. The soil is used about equally for dry land and irrigated farming. Principal crops are alfalfa and small grains.

Parleys series (Pr). Parleys soils are deep, well-drained, with moderately fine texture. They occur on high lake terraces at elevations of 4500 to 5100 feet. Slopes range from 0 to 10 percent. The surface soil is dark grayish-brown, neutral, silt loam. The subsoil is brown, neutral, clay loam with prismatic or blocky structure. The substratum is pale-brown or light brown, mildly alkaline, strongly calcareous, silt loam to silty clay loam. These soils are generally well-drained and permeability is moderately slow. They hold 10 to 12 inches of water in a 5 foot profile. About 80 percent of the acreage is irrigated for the production of alfalfa, small grains, and row crops. The remaining land is dry cropped with alfalfa and small grain.

Winn-Provo complex (Mb, WN). This unit occurs in the flood plain of the Little Bear River and on low lake terraces. Winn soils are deep, somewhat poorly drained, and medium textured. Slopes range from 0 to 3 percent. The surface soil is dark-gray, mildly alkaline, silt loam. The subsoil is dark-gray or grayish-brown, mildly alkaline loam or silt loam. Gravelly sandy loam is present below 36

Table 3. Land use in Little Bear River model area (From Haws, 1969).

Symbol	Land Use	Acres
A	Irrigated Cropland	
A1	Alfalfa	1,081
A2	Pasture	691
A3	Other hay	167
A4	Small grain	919
A5	Corn	110
A6	Sugar beets	51
A7	Small truck	85
A8	Idle	46
Total A		3,150
C	Non-cropped Vegetated Area	
C1	Phreatophytes-high water table marshes, tules, cattails, etc.	113
C2	Phreatophytes-high water table grasses, willows, cottonwoods, etc.	600
C3	Phreatophytes-medium water table grasses-medium density trees	375
C4	Phreatophytes-low water table grasses-light density trees	139
Total C		1,227
D	Urban areas-yards, roads, etc.	476
E	Dry (non-irrigated) farmland	
E1	Grains	2,138
E2	Alfalfa	266
E3	Grasses	617
E4	Fallow	133
Total E		3,154

Table 4. Properties of selected soils in the Little Bear River Valley.

Soil series	Available water in 5 ft profile (inches)	Depth (inches)	Moisture held at 15 atmospheres (%)	pH sat.	pH 1:5	Electrical conductivity (millimhos/cm)	CaCO₃ equivalent (%)	Cation exchange capacity (meg/100gm)	Sodium (meg/100gm)	Exchangeable sodium (%)	Moisture at saturation (%)
McMurdie silt loam	10-12	0-7	12.3	7.2	8.1	.44	1.2	31.7	.2	1	43
		7-14	17.8	7.1	8.0	.46	--	26.8	.3	1	44
McMurdie Hill Field complex		14-25	27.7	6.8	8.0	.35	--	34.2	.3	1	65
		25-33	23.7	6.7	8.0	.37	--	38.0	.3	1	68
		33-43	17.2	7.2	8.4	.44	25.9	25.8	.4	2	53
		43-50	10.4	7.4	8.6	.53	31.4	17.9	.4	2	39
		50-58	7.4	7.5	8.7	.56	27.8	12.3	.3	3	30
Parleys silt loam	10-12	0-8	9.0	6.8	7.6	.72	--	20.5	.37	90	35
		8-12	11.7	6.8	7.8	.50	--	20.0	.33	90	39
		12-19	12.9	6.9	7.8	.37	--	22.2	.36	87	43
		19-31	14.2	6.6	7.6	.35	--	26.9	.41	87	49
		31-36	9.5	7.4	8.3	.49	17.3	16.7	.28	--	41
		36-52	7.3	7.6	8.6	.43	28.4	10.9	.35	--	35
		52-68	6.3	7.7	8.8	.56	27.0	10.5	.12	--	34
		68-83+	--	7.7	8.8	.55	20.4	13.3	.33	--	35
Provo gravelly loam	3-5	0-2	59.8	7.8	9.0	2.0	25.3	50.2	1.68	--	--
		2-7	16.0	7.8	8.6	0.8	4.9	26.2	.98	--	--
		7-13	13.8	7.6	8.4	0.6	5.4	22.5	--	--	--
		13-19	11.2	7.6	8.6	0.7	22.5	12.8	--	--	--
		19-27	8.3	7.6	8.6	0.8	30.4	6.1	--	--	--
		27-34+	--	-	-	--	39.4	4.3	--	--	--
Hendricks silt loam	10-12	0-5	11.0	6.8	7.5	1.0	--	22.2	.25	1	39
		5-15	11.9	6.4	7.3	.38	--	21.6	.36	2	38
		15-27	13.1	6.2	7.5	.35	--	18.4	.35	2	36
		27-48	12.6	6.4	7.3	.37	--	17.6	.42	2	38
		48-66+	12.9	6.3	7.3	.39	--	26.2	.37	1	49

inches. Provo soils are similar to Winn soils but generally have a higher gravel content. Permeability is moderate except in the gravelly layers where it is rapid. Water holding capacity is 8 to 10 inches in a 5 foot profile, but the water table is often within 3 to 5 feet of the surface. These soils are used mostly for irrigated pasture, small grains, corn, and sugar beets.

Groundwater

Groundwater occurs under water table conditions in a highly permeable but relatively thin alluvial gravel on top of sediments of low permeability. The gravel is generally less than 30 feet thick; consequently the potentiometer gradient is controlled mostly by the natural slope of the land. Water levels on the Avon-Paradise-Hyrum benchlands slope northwest at approximately 40 feet per mile. This benchland area is covered with a veneer of highly permeable gravel and sand that is 10 to 20 feet thick and about half saturated with water. A series of springs along the edge of the bluff below the benchland and above the river drains the aquifer and prevents water logging. Transmissivity of the aquifer is generally less than 15,000 cfs/ft/day because of the shallowness of the gravel; the gravel itself is very permeable. The aquifer is recharged mostly from canal seepage and deep percolation from irrigation. Wells are generally of low yield and utilized principally

along the edge of the bluff below the benchland and above the river drains the aquifer and prevents water logging. Transmissivity of the aquifer is generally less than 15,000 cfs/ft/day because of the shallowness of the gravel; the gravel itself is very permeable. The aquifer is recharged mostly from canal seepage and deep percolation from irrigation. Wells are generally of low yield and utilized principally for domestic and stock use. Quality of groundwater is good, with total dissolved solids generally less than 500 mg/l. Figure 28 furnished by the U.S. Geological Survey (Bjorklund and McGreevy, 1970), indicates the depth to groundwater in the valley.

An additional parameter was introduced into the salinity model to account for apparent "natural inbasin salinity contributions." They assumed that a given stream was influent (contributing to the groundwater aquifer) in the upper reaches and effluent (receiving water from the groundwater aquifer) in reaches farther downstream. Since groundwater is generally higher in dissolved solids content than surface water, the salinity level of a surface stream is increased by this interchange or recirculation. The rate of recirculation was related to the rate of water flow in the surface channels by the empirical equation:

The DO loop ending with statement 222 is the heart of the hydrologic simulation, and in addition produces the quantities needed for the quality calculations. After monthly values of the pertinent quantities are read in, the variables A, B, C, and D are assigned values to be transferred to the analog: A is the snowmelt computed from Equation (3.7); B is the potential evapotranspiration, computed from the modified Blaney-Criddle formula, divided by the critical soil moisture, FMES; C is the diversions to the land; and D is the measured streamflow at a correlation station. All four values are calculated in inches and scaled for transfer to the analog. (Only numbers less than 1.00 can be transferred.)
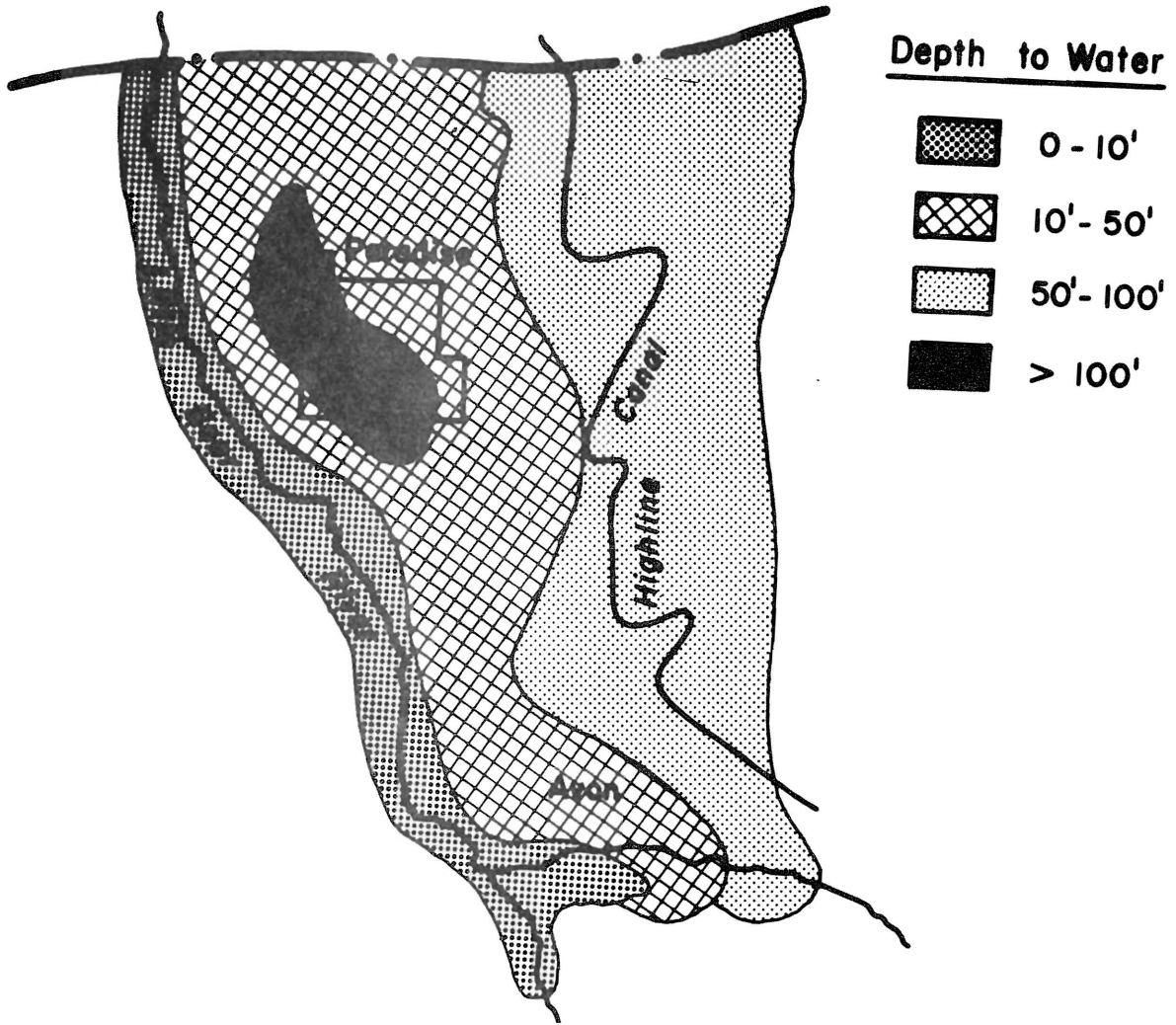
Figure 28. Depth to groundwater in the Little Bear River Valley.

```
      COMMON/BLK1/SCA(24,5),SMG(24,5),SNA(24,5),SSO4(24,5),SCL(24,5),
     1STRC2(24),SUBSRF(24),GWRF(24),SFLBRU(24),EFLBRU(24),SUMOUT(24),
     1EFCA(24),EFMG(24),EFNA(24),EFSO4(24),EFCL(24),EFHCO3(24),SFCA(24),
     1SFMG(24),SFNA(24),SFSO4(24),SFCL(24),SFHCO3(24),OCA(24),OMG(24),
     1SHCO3(24,5),CO(5),AB(9),ZE(18)
      COMMON/BLK2/OP(24),DAL(24),SRF(24),SNPC(24),STRC1(24),
     1DNA(24),DSO4(24),DCL(24),DHCO3(24),XLIME(18),TA(16),TE(18),TS(18),
     1TH(18), TW(18), TCASO(18), TF(18), TC(18), TSA(18), TXX(18),
     1TG(18),TD(18),TDA(18),TB(18),CCA(70),CMG(70),CNA(70),
     1CSO4(70),CCL(70),CHCO3(70),OILF(24)
      CALL OSHYIN (IERR,580)
      CALL OSC(1,IERR)
      PAUSE 1
      READ(6,100) NMO, NS, IK, N1, N2
  100 FORMAT(6I3)
      READ(6,102) SNO,FMES,AREA,SMC,PAR,XXK,ALPHA,BETA,SPC
  102 FORMAT(9F8.2)
      CALL OSSFCN (IERR)
      CALL OSULY (5)
      CALL OSIC (IERR)
  105 FORMAT(72  HMO TEIP    PPT SNMLT   QDIV EVAPT PHREA SOILM   DPER QBASE
     1 QOUT  QMEAS DIF /)
 1004 FORMAT(72HMO     SRF SUBSRF   GWRF    SNPC   STRC1   STRC2    SFL   E
     1FL    DOT SUMOUT    /)
      GO TO (350,351), IK
  350 WRITE(N1,105)
      WRITE(5,1004)
  351 YDIFF = 0.0
      SUMO = 0.0
      SUMM = 0.0
      YSQR = 0.0
      YSUM = 0.0
      DO 222 I=1, NMO
      READ (6,101) TEMP, PRE, PDH, XKC, PKC, QINPOR, QINLBR
      READ(6,101) OMEAS, DHYR, DHYL, DPAR, DOTH, ST1, ST2
  101 FORMAT (7F10.4)
      IF(TEMP .GT. 32.) GO TO 606
      SNO = SNO + PRE
      PSM = 0.0
      GO TO 605
  606 WS = SNO * EXP(SMC*(TEMP - 32.))
      FNR = SNO - WS
      SNO = WS
      PSM = PRE + FNR
  605 SP = PSM
      A = SP/20.
      B = XKC * (.0173*TEMP - .314) * TEMP * PDH/(5.*FMES)
      C = ((ALPHA*DHYL + DPAR) + DOTH)/44.) *12./AREA
      D=ST1*12./(3250.*50.)
C     TRANSFER DATA FROM DIGITAL TO ANALOG
      CALL OWJDAP(A,00,IERR)
      CALL OWJDAP(B,01,IERR)
      CALL OWJDAP(C,02,IERR)
      CALL OWJDAP(D,03,IERR)
  611 CALL OPLSP(ITEST,IERR)
      IF(ITEST.EQ.1240) GO TO 611
```

71

```
  612 CALL QRLBB(ITEST,IERR)
      IF (ITEST.NE.'200) GO TO 612
      CALL QSOP(IERR)
  613 CALL QRLBB(ITEST,IERR)
      IF(ITEST.EQ.'200) GO TO 613
      CALL QSH(IERR)
C     TRANSFER DATA FROM ANALOG TO DIGITAL
      CALL QRBADR(A8,0,9,IERR)
      DP(I)=20.*A8(1)
      EVT=20.*A8(2)
      SM=-20.*A8(3)
      DAL(I)=20.*A8(4)
      SRF(I)=-20.*A8(5)
      SNPC(I)=-20.*SPC*A8(6)*3250./AREA
      STRC1(I)=-20.*A8(7)*3250./AREA
      SUBSRF(I)=20.*A8(8)
      GWBF(I)=20.*A8(9)*3250./AREA
      STRC2(I) = XXK*ST2*12./AREA
      C1 = PKC*(.0173*TEMP-.314) *TEMP * PDH
      TEMQ1 = SRF(I) +SUBSRF(I) + SNPC(I) + STRC1(I) + STRC2(I)
     1 + GWBF(I)
      QMEASI = QMEAS*12./AREA
      SFLBRU(I) = QINLBR - DHYR*(1.0-BETA)
      EFLBRU(I) = QINPOR - DHYL - DPAR
      SUMOUT(I)= TEMQ1 + (SFLBRU(I)+EFLBRU(I)-DOTH)*12./AREA-C1*PAR
      QQOUT=SUMOUT(I)*AREA/12.
      DILF(I)=FNR+PRE+DAL(I)-EVT
      QBF = GWBF(I)+SUBSRF(I)
      DIV = 40.*C
      SFL=SFLBRU(I)*12./AREA
      EFL=EFLBRU(I)*12./AREA
      DOT=DOTH*12./AREA
  107 FORMAT(I2,9F7.2,F7.0)
      SUMC = SUMC + SUMOUT(I)
      SUMM = SUMM + QMEASI
      YSQR = YSQR + QMEASI * QMEASI
      DIFF = QMEASI - SUMOUT(I)
      YSUM = YSUM + QMEASI
      YDIFF = YDIFF + DIFF*DIFF
      GO TO (800,222) , IK
  800 WRITE(N1,103) I, TEMP, PRE, FNR, DIV, EVT, C1, SM, DP(I), QBF,
     1 SUMOUT(I),QMEASI,DIFF
      WRITE(5,107)I,SRF(I),SUBSRF(I),GWBF(I),SNPC(I),STRC1(I),
     1 STRC2(I),SFL,EFL,DOT,QQOUT
  103 FORMAT(I2,F5.1,10F6.2,F4.1)
  222 CONTINUE
      XNO = NMO
      X=YSQR-YSUM*YSUM/XNO
      RR = (X-YDIFF)/X
      R = SQRT(RR)
      SUMM=SUMM*AREA/12.
      SUMC=SUMC*AREA/12.
      WRITE(N1,1103) RR,R,SUMM,SUMC
      PAUSE 2
```

```
C        ENTER CYCLE TO CALCULATE QUALITY OF PERCOLATING WATER
C        READ CONCENTRATIONS OF IONS IN APPLIED WATER
C        SFCA, SFMG = SOUTH FORK STATION 1047
C        EFCA, EFMG = EAST FORK STATION 1049
    447 READ (6,1055) (SFCA(I), SFMG(I), SFNA(I), SFSO4(I),
       1SFCL(I), SFHCO3(I), I=1, NMO)
        READ(6,1055) (EFCA(I),EFMG(I),EFNA(I),EFSO4(I),
       1EFCL(I), EFHCO3(I), I=1, NMO)
        READ(6,3010) (CO(I),I=1,NS)
   3010 FORMAT(10F6.2)
        DO 3000 JJ=1,NS
C        READ NO. OF SOIL LAYERS, PORE VOLUME
        READ(6,1003)M,PV
   1003 FORMAT(I2,F6.2,I2)
   1055 FORMAT (6E12.3)
C        READ SOIL CHARACTERISTICS
        READ (6,104) (TA(I), TF(I), TS(I), TG(I), TH(I), TW(I),
       1TCASO(I),TE(I),TC(I),TSA(I),TXX(I),TD(I),TDA(I),TB(I), I=1,M)
    104 FORMAT (7E10.3)
C        READ LIME CONCENTRATION
        READ(6,1055) (XLIME(J),J=1,M)
        CF1=1000.
        CF2=2000.
        DDP=0.0
        XM=M
        KK=0
        L=0
C        IS LIME PRESENT
        DO 448 J=1,M
        ZF(J)=2.E-8
        IF(XLIME(J).EQ.0.) GO TO 448
        U=SQRT(2.*(TA(J)+TF(J)+TG(J))+.5*(TS(J)+TH(J)+TW(J)))
        ZE(J)=TA(J)*TF(J)**2*EXP(-2.341*U/(1.+U))
    448 CONTINUE
    200 L=L+1
        IF(L-NMO) 2005,2005,933
   2005 ACA=0.
        AMG=0.
        ANA=0.
        ASO4=0.
        ACL=0.
        AHCO3=0.
        DDP=DDP+DP(L)
        XM=DDP/PV
C        XM=NO. OF PORE VOLUMES OF DEEP PERCOLATION MONTH L
        YK=1./XM
        IF(XK.LE.XM) GO TO 274
   2006 IF(DAL(L).LE.0.0) GO TO 2031
        RO=DAL(L)*XM/PV
        TA(1)=TA(1)+EFCA(L)*RO
        TF(1)=TF(1)+EFMG(L)*RO
        TS(1)=TS(1)+EFNA(L)*RO
        TG(1)=TG(1)+EFSO4(L)*RO
        TH(1)=TH(1)+EFCL(L)*RO
```

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```
      TW(1)=TW(1)+EFHCO3(L)*RQ
      GO TO 200
2031  IF(DILF(L).GT.0.0) GO TO 2032
      DILF(L)=ABS(DILF(L))
      CCF=DILF(L)*XM/PV
      IF(CCF.LT.1.0) CCF=1.0
      GO TO 2033
2032   CCF=PV/(XM*DILF(L))
      IF(CCF.GT.1.0) CCF=1.0
2033  TA(1)=TA(1)*CCF
      TF(1)=TF(1)*CCF
      TS(1)=TS(1)*CCF
      TG(1)=TG(1)*CCF
      TH(1)=TH(1)*CCF
2034  TW(1)=TW(1)*CCF
      GO TO 200
 204  DDP=0.0
 203  FK=0.0
 201  J=0
      IF(DAL(L).LE..01) GO TO 2111
      FF=DP(L)/DAL(L)
       A=EFCA(L)/FF
      F=EFMG(L)/FF
      S=EFNA(L)/FF
       G=EFSO4(L)/FF
       H=FFCL(L)/FF
       W=EFHCO3(L)/FF
      GO TO 2027
2111  A=0.
      F=0.
      H=0.
      G=0.
      S=0.
      W=0.
2027   CASO=0.
 202  J=J+1
      II=2
      IF(XLIME(J).LE..00001) II=1
      KC3=0
      B=TB(J)
      DA= TDA(J)
      D=TD(J)
      A=(A+TA(J))/2.
      F=(F+TF(J))/2.
      S=(S+TS(J))/2.
      G=(G+TG(J))/2.
      H=(H+TH(J))/2.
       W=(W+TW(J))/2.
      CASO=(CASO+TCASO(J))/2.
      ET=TE(J)
      CT=TC(J)
      SAT=TSA(J)
      XXT=TXX(J)
 24  A1=A
```

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```
      KC1=0
      KC2=0
      IF (XYT)4,4,26
    4 U=SORT(2.*(A+F+G)+.5*(S+H+W))
      AA=EXP(-0.366*U/(U+1.))
      IF(2.4E-5-A*G*AA)26,18,18
   26 X=.0
      U=SORT(2.*(A+F+G)+.5*(S+H+W))
      BB=A+G
      EX=(0.366*U)/(U+1.)
      CC=A*G-(2.4E-5)*EXP(EX)
      R=SORT(BB*BB-4.*CC)
      X=(-BB+R)/2.
      CAS1=4.0E-3-CASO
      DEL=R*YXT-CAS1
      IF(DEL-X)27,28,28
   27 X=XYT*R
      YXT=.0
      CAS1=0.0
      A=A+X
      G=G+X
      U=SORT(2.*(A+F+G)+.5*(S+H+W))
      AA=EXP(-0.366*U/(U+1.))
    7 BB=-(4.0E-3+AA*A+AA*G)
      CC=AA*A*G-4.0E-3*CASO
      X1=(-BB-SORT(BB*BB-4.*AA*CC))/(2.*AA)
      CASO=CASO+X1
      A=A-X1
      G=G-X1
      GO TO 44
   18 IF(G)1,1,6
    6 IF (A)1,1,7
    1 IF(CASO)44,44,7
   28 A=A+X
      G=G+X
      XYT=XYT-X/R
      CASO=CASO+CAS1
      YXT=XYT-CAS1/R
   44 A2=A
      IF(A-F)45,46,46
   45 IJ=1
      A2=A
      A=F
      F=A2
      CT2=CT
      CT=FT
      FT=CT2
      DA2=DA
      DA=DA*D
      GO TO 5
   46 IJ=2
    5 Z=1.0E-6
      EX=EXP((-2.341*U)/(U+1.))
      AA=-2.*H*D
      AAA=1.5*FT+1.5*CT+SAT
```

```
      BB=4.*B*B*AAA-2.*B*(ET*B+S)+4.*B*DA*EX
      CC=4.*B*(ET*B+S)*AAA-.5*S*(S+4.*ET*B)-4.*DA*EX*(B*SAT+A)
      DD=S*(S+4.*ET*B)*AAA-.5*S*S*ET+B*SAT*SAT*EX*DA+4.*EX*DA*SAT*A
      EE=S*S*ET*AAA-SAT*SAT*EX*DA*A
   15 ZZ=-((((AA*Z+BB)*Z+CC)*Z+DD)*Z+EE)
      ZZZ=(((4.*AA*Z+3.*BB)*Z+2.*CC)*Z+DD)*Z
      ZZ=ZZ/ZZZ
      Z=Z*(ZZ+1.)
      KC1=KC1+1
      IF(KC1.GT.50) TYPE 505
      IF(ZZ+1.E-3)15,15,16
   16 IF(ZZ-1.E-3)23,23,15
   23 A=A-B*Z
      S=S+2.*D*Z
      ET=ET+Z
      SAT=SAT-2.*Z
      GO TO (17,13),IJ
   17 AZ=A
      A=F
      F=AZ
      CTZ=CT
      CT=ET
      ET=CTZ
      DA=DAZ     —
   13 A3=A
      BB=A+B*(CT+D*ET)+D*F
      AA=B*(1.-D)
      CC=(A*CT-D*F*ET)
      R=SQRT(BB*BB-4.*AA*CC)
      Y=(-BB+R)/(2.*AA)
      IF(1.-D)3,2,3
    2 Y=-(A+CT-D*ET*F)/BB
    3 A=A+B*Y
      F=F-B*Y
      ET=ET-Y
      CT=CT+Y
      A4=A
C     LIME CALCULATION
  399 GO TO (500,400),II
  400 AA=4.
      BB=4.*W+A
      CC=W*W+4.*A*W
      DD=A*W*W-ZF(J)*EXP(2.341*U/(1.+U))
      Z=-W/4.
      IF(W.GT.A) Z=-A/2.
      Z1=Z
  402 FXF=-(AA*Z**3+BB*Z*Z+CC*Z+DD)
      FPRIME=3.*AA*Z*Z+2.*BB*Z+CC
      EPSLON=FXF/FPRIME
      Z=Z+EPSLON
      KC2=KC2+1
      IF(KC2.GT.50) TYPE 506
      IF(ABS(EPSLON).GT. 1.E-5) GO TO 402
      A=A+Z
```

```
      W=W+2.*Z
      IF(W.LE.0.0) GO TO 403
      IF(A.GT.0.0) GO TO 404
  403 W=W-2.*Z
      A=A-Z
      Z=-Z1
      GO TO 402
  404 XLIME(J)=XLIME(J)-Z
  500 ZX=A*W*W*EXP(-2.341*U/(1.+U))
      IF(ZX.GE.ZE(J)) II=2
      KC3=KC3+1
      IF(KC3.GT.100) TYPE 507,J
      DEL=A-A1
      IF(ABS(DEL).GT.1.E-5) GO TO 24
      DEL=A-A2
      IF(ABS(DEL).GT.1.E-5) GO TO 24
      DEL=A-A3
      IF(ABS(DEL).GT.1.E-5) GO TO 24
      DEL=A-A4
      IF(ABS(DEL).GT.1.E-5) GO TO 24
    8 TA(J)=A
      TF(J)=F
      TS(J)=S
      TG(J)=G
      TH(J)=H
      TCASO(J)=CASO
      TE(J)=ET
      TW(J)=W
      TC(J)=CT
      TSA(J)=SAT
      TXX(J)=XXT
   77 IF(J-M)202,10,10
   10 KK=KK+1
C     KK COUNTS NUMBER OF FRACTIONAL PORE VOLUMES OF EFFLUENT
 5099 FORMAT(24HDIMENSION OVERFLOW KK =  ,I3)
      IF(KK.GT.70) TYPE 5099,KK
      CCA(KK)=TA(J)*CF2
      CMG(KK)=TF(J)*CF2
      CNA(KK)=TS(J)*CF1
      CSO4(KK)=TG(J)*CF2
      CCL(KK)=TH(J)*CF1
      CHCO3(KK)=TW(J)*CF1
C     FK COUNTS THE NUMBER OF FRACTIONAL PORE VOLUMES OF DEEP
C     PERCOLATION MONTH L
      FK=FK+1./XM
      IF(FK-YN)221,334,334
  334 IF(L-NMO)222,933,933
C     XNN = NUMBER OF FRACTIONAL PORE VOLUMES OF SUBSURFACE RETURN FLOW
C     MONTH I
  933 XNN=0.0
      NLOW=1
      WRITE(N1,5003)
 5003 FORMAT(//30HQUALITY OF PERCOLATED EFFLUENT)
      WRITE(N1,5111)
 5111 FORMAT(/5HMONTH,5H    CA,6X,2HMG,6X,2HNA,5X,3HSO4,6X,2HCL,4X,4HHCO3
     15X,3HTDS,5X,4HSOIL/)
C     CALCULATION OF AVERAGE QUALITY OF IRRIGATION RETURN FLOW MONTH I
      DO 5500 I=1,NMO
      XNN=XNN+XM*SUBSRF(I)/PV
      IF(XNN.LT..50) GO TO 5535
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77

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10  30.,
.62E-2,  .562E-2,  .164E-2,  .74E-3,  .639E-2,  .219E-2,
.725E-4,  .46E-4,  .109E-5,  .0E0,  .7E0,  7.1E0,  20.E2,
.446E-2,  .214E-2,  .202E-2,  .301E-2,  .20E-2,  .108E-1,  .736E-3,
.828E-4,  .278E-4,  .158E-5,  .0E0,  .7E0,  7.1E0,  25.E2,
.204E-2,  .123E-2,  .112E-3,  .158E-4,  .116E-3,  .648E-2,  .281E-5,
.611E-4,  .258E-4,  .931E-7,  .0E0,  .7E0,  7.1E0,  20.E2,
1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  25.E2,
1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  25.E2,
1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  25.E2,
1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  25.E2,
1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
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1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  25.E2,
1.7E-3,  .63E-3,  .15E-3,  .13E-3,  .21E-3,  4.33E-3,  0.0E0,
0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  0.E0,  25.E2,
1.E0,  1.E0,  1.E0,  1.E0,  1.E0,   1.E0,
1.E0,  1.E0,  1.E0,  1.E0,
```

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18 70., 1
.563E-2, .351E-2, .176E-2, .321E-2, .155E-2, .12E-1, .885E-3,
.689E-4, .300E-4, .107E-5, .0E0, .7E0, 7.1E0, 23.E2,
.359E-2, .255E-2, .27E-2, .439E-2, .103E-2, .516E-2, .886E-3,
.57E-4, .284E-4, .171E-5, .0E0, .7E0, 7.1E0, 16.7E2,
1.3E-3, 1.15E-3, .15E-3, .19E-3, .26E-3, 4.4E-3,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,  .
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
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.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
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.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
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.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.119E-2, .591E-3, .515E-2, .506E-4, .115E-3, .851E-2, .515E-5,
.624E-4, .217E-4, .567-5, .0E0, .7E0, 7.1E0, 20.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.119E-2, .591E-3, .515E-2, .506E-4, .115E-3, .851E-2, .515E-5,
.624E-4, .217E-4, .567-5, .0E0, .7E0, 7.1E0, 20.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
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.95E-3, 1.50E-3, .22E-3, .19E-3, .26E-3, 4.34E-3, 0.0E0,
0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 0.E0, 25.E2,
1.E0, 1.E0, 1.E0, 1.E0, 1.E0, 1.E0,
1.E0, 1.E0, 1.E0, 1.E0, 1.E0, 1.E0,
1.E0, 1.E0, 1.E0, 1.E0, 1.E0, 1.E0,
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