WATERLOGGING CONTROL FOR IMPROVED WATER AND LAND USE EFFICIENCIES: A SYSTEMATIC ANALYSIS

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by

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ABSTRACT

The problems of waterlogging and salinization are often associated with irrigated agriculture. Both these problems exist in the San Luis Valley, in southern Colorado. This study considers a 500 square mile study area south of the Rio Grande River in the San Luis Valley. Many thousands of acres of the study area are subject to waterlogging each year. A Fortran IV computer simulation model of the stream-aquifer-irrigation system in the study areas was developed. The computer simulation model is used to investigate two alternative management strategies and to compare effects with past water management programs (the "historic strategy"). These strategies aim to lower the water table in the waterlogged area to enable the growing of crops using center-pivot sprinkler irrigation.

The report is divided into two main parts. The first part describes the study area and the components and interactions considered in the development of the hydrologic computer model, including a detailed description of the actual computer program.

The second part of the report concerns an analysis of the management strategies aimed at reducing the waterlogging problem. The historic strategy and two alternative management strategies were subject to analysis. The first alternative management strategy involves a 16 square mile well field called the La Jara Creek well field development. The second alternative strategy is the 10 square mile Rock Creek well field development. A comparison of the effects of the historic management strategy and the two alternative well field development strategies is provided.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Chapter Page

II DESCRIPTION OF COMPONENTS AND INTERACTIONS (continued)

PHYSICAL COMPONENTS OF THE SYSTEM (continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

Chapter Page

APPENDIX (continued)

RECOMMENDED RECLAMATION TREATMENTS (continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF SYMBOLS

Symbol	
A	irrigated area
A_r	area through which water which is not available to plants percolates
D_{af}	total quantity of water from all sources made available at the farm headgate
D_{ap}	total quantity of water from all three sources made available to the plant
D^*_{ap}	optimal quantity of irrigation water to be made available to the plant
D_{apr}	quantity of water made available to the plant which deep percolates to the unconfined aquifer
D_{cgaf}	confined groundwater quantity made available to the farm
D_{cgap}	confined groundwater quantity made available to the plant
D_{cgd}	confined groundwater quantity draining overland to downslope areas
D_{cgnap}	confined groundwater not made available to the plant
D_{cgr}	confined groundwater quantity recharging the unconfined aquifer
D_d	quantity draining overland to downslope areas
D_n	quantity of irrigation water needed by the plant (or crop need)
D_{nup}	quantity of water not used by the plant
D_r	total quantity of recharge to the unconfined aquifer
D_{saf}	surface water available at the farm headgate
D_{sap}	surface water quantity made available to the plant
D_{sd}	surface water quantity draining overland to downslope area and then deep percolating
D_{snap}	surface water not made available to the plant

LIST OF SYMBOLS (Continued)

Symbol	
D_{sr}	surface water quantity recharging the unconfined aquifer
D_u	quantity of water required by the plant to satisfy consumptive use
D_{ugaf}	unconfined groundwater quantity made available to the farm
D_{ugap}	unconfined groundwater quantity made available to the plant
D_{ugnap}	unconfined groundwater not made available to the plant
D_{ugr}	unconfined groundwater pumped quantity recharging the unconfined aquifer
D_{up}	quantity of water used by plant to satisfy crop need
e	saturated thickness of the unconfined aquifer
E_c	efficiency of the canal
E_{cgf}	efficiency of the application of confined groundwater available to the farm
E_p	plant extraction efficiency
E_{sf}	efficiency of the application of surface water available at the farm headgate
E_{ugf}	efficiency of application of unconfined groundwater available to farm
f_{cgr}	fraction of confined groundwater not made available to the plant which recharges the unconfined aquifer
f_{sr}	fraction of the surface water not made available to the plant which recharges the unconfined aquifer by deep percolation
f_{ugr}	fraction of unconfined groundwater not made available to the plant which recharges the unconfined aquifer
K	weighted spatial and temporal hydraulic conductivity of fields, canals, and ditches
L	length of reach
n	time period of calculation
P_e	effective precipitation

LIST OF SYMBOLS (Continued)

Symbol	
q	discharge
QMAFD	monthly quantity made available for surface water diversion from Rio Grande according to water right priority system
$Q_\pi(l)$	volume pumped at grid cell π during time period l
RCOM	annual quantity of water required to be supplied to the Rio Grande Compact agreement based on RGPRED inflow at Del Norte
RGCUR	percentage curtailment of Rio Grande at Del Norte streamflow to go to meet the Rio Grande Compact agreement
RGINF	streamflow at Del Norte gaging station on the Rio Grande which has occurred so far in the previous months of this year
RGPRED	expected inflow at Del Norte gaging station on the Rio Grande for the following year
$S_{19}(l)$	drawdown in aquifer at river reach cell 19 at end of period l
$S_w(n)$	drawdown in aquifer at grid cell w (observation cell or river reach) at end of period n
SACT	stream quantity delivered to meet the Rio Grande Compact agreement so far in the previous months of this year
SI,SI(i)	monthly streamflow for Rio Grande at Del Norte, for month i
SO(i)	monthly streamflow quantity, outflow of the Rio Grande from the study area in month i
s_{wd}	surface water diversion from the stream to the irrigation canal based on water rights
T	aquifer transmissivity in region of river reach
T_a	average time to apply irrigation water
W_p	wetted perimeter
y	river stage
Γr	river reach transmissivity

LIST OF SYMBOLS (Continued)

Symbol	
$\delta_{19,\pi}(1)$	discrete kernel of drawdown response at river reach cell 19 due to a unit excitation at grid cell π
$\delta_{w,\pi}(n-v+1)$	discrete dernel of drawdown response at grid cell w (observation cell or river reach) due to a unit excitation at grid cell π
v	a summation dummy (over time-months) index
π	finite difference grid cell reference number

CHAPTER I

INTRODUCTION

IRRIGATION, WATERLOGGING, AND DRAINAGE: AN HISTORICAL PERSPECTIVE

The transition from a hunting and food collecting way of life to one based on agricultural food production affected all aspects of human existence. No less significant than this early food producing revolution is the continuing evolution of agriculture -- the development of new systems of agricultural technology, the incorporation of such systems into the framework of society, and their gradual extension to other parts of the world.

Ancient history contains numerous references to the practice of irrigation. These historical references are reinforced by the striking examples in many countries, including Egypt, Iraq, and China, of ancient irrigation works still in service. Many of these ancient works have been improved with modern technology and techniques and now are working more efficiently than when they were constructed several centuries or milleniums ago. However, there are ruins of many canals, tanks, and aqueducts which failed, fell into disrepair, or went out of production after operating for a relatively short time (Stamp, 1961).

In areas where irrigated agriculture provided the agrarian base of society, the benefit carried with it grave responsibilities. On one hand, control of water resources permits the establishment of highly productive agricultural practices and the consequent expansion of human society in regions where natural rainfall provides either an inadequate or an unreliable moisture supply. On the other hand, there are many potential adverse effects of the development of such complex irrigation systems; and, if ignored, they may lead to disaster. Eckholm (1975) identifies two factors which threaten the productivity of irrigation works. Both are of major importance but are often overlooked by those who design the dams, canals, and wells. Soil salinity, usually caused by mismanaged irrigation is undermining to varying degrees the productivity of a large proportion -- some say as much as one-third -- of the world's irrigated lands. The other factor is waterlogging -- the saturation of soils due to the water table rising into the root zone, with the consequent damage to crop production.

The demise of a number of ancient societies has been attributed to a breakdown in the social structure needed to operate, maintain, and replace their irrigation systems. One of the most notable examples occurred along the Tigris and Euphrates Rivers before the birth of Christ. There is evidence that similar disasters befell Anasazi Indian settlements in what is now the southwestern United States, as well as in portions of the Indus Basin in what is now Pakistan. In fact, an economy or culture based on irrigated agriculture that has survived over a few hundred years is more the exception than the rule (Moore, 1972).

Waterlogging is without question one of the most prevalent and serious problems associated with irrigation in arid regions of the world. In its physical aspects, the problem arises as follows: The excess of irrigation water applications over and above evapotranspiration losses will percolate below the crop root zone, eventually reaching the groundwater table. The water table will in time rise, eventually to reach the crop root zone and even, in lower lying areas, the land surface. Saturated or waterlogged soils are usually detrimental to crop yields, and the rising water table often leads to salinization, a further detriment to crop production. When water is applied to a crop, most of the moisture leaves the soil through evapotranspiration; but the salts remain in the soil. If a large enough portion of irrigation water over crop needs is applied, the soluble salts will be carried past the root zone. But if the water leaching past the root zone does not contain as much of the dissolved salts as was applied with the irrigation water, the net result is an unfavorable salt balance resulting in a salt accumulation within the soil and a loss in productivity. Since these problems are often companions, any actions, such as pumping down the water table or drainage systems which relieve waterlogging, will do much to relieve salt accumulation in soils (Luthin, 1957).

There are numerous discussions of the waterlogging problem in the technical literature.

Systematic drainage and reclamation has been tried back as early as the pre-Christian era in Greece, where a system of drainage ditches to reclaim apparently waterlogged land has been reported (FAO/UNESCO, 1973). A good technical review of the problem is provided by, among others, Aart (1974). Bouwer (1974) gives a detailed discussion of salinity control and how it is used in drainage system design. Arnon (1974) describes the history of irrigation in the Imperial Valley in California.

In contrast to the abundant technical literature in hydrology, soils, and agronomy, comprehensive legal-economic analyses of the waterlogging problem are relatively rare. A WRSIC search and our own review turned up only the following. The White House-Interior Department Panel on Waterlogging and Salinity in the Indus Basin (1965) studied the serious problems in what was then West Pakistan. Johnson (1975) analyzed the problem in the Closed Basin, San Luis Valley, Colorado, with a detailed economic model of water allocation. Due to resource limitations, his approach relied on a simplified hydrologic model. He concluded that the existing problem in the area would likely be overcome by the increased development of center pivot sprinklers using groundwater. The pumping would most probably lower the overall water table in the area he studied sufficiently to restore productivity without further drainage activities. Rigaux and Singh (1977) present an elaborate analysis of the economic feasibility of a drainage network in Manitoba, Canada. When heavy rains occur, leaving standing water on fields, the area suffers from serious crop damage which can be avoided or reduced by removing the excess water in a rapid fashion. The study was particularly noteworthy for its detailed empirical analysis of the detrimental effects of various periods of standing water on crop yield. Fitz, etal., (1980), in an innovative study, examined the economic feasibility of installing a tile drainage system in a central California irrigation district.

THE PROBLEM SETTING

The San Luis Valley is a large relatively flat area located in the highlands of south central Colorado. The valley floor itself covers an area nearly twice the size of the state of Delaware. It is bounded on the west and north by the Continental Divide, and on the east by an offshoot of the Rocky Mountains, the Sangre de Cristo Range. The valley lies in the drainage of the headwaters of the Rio Grande River, an area of about 8,000 square miles. The Rio Grande enters the valley from the west and flows south out of the valley into New Mexico.

The climate is that of a high mountain desert with an average annual precipitation of about seven inches. The desert climate makes irrigation essential for agricultural production. The short growing season of from 90 to 120 days limits the available crops to those adapted to short cool seasons, such as barley, potatoes, forage crops, lettuce, and peas.

The northern portion of the valley lies within a closed basin which is separated from the Rio Grande drainage by a low alluvial divide. The trough or sump of the closed basin is defined in general by a contour of 7,525 feet.

The groundwater in the San Luis Valley occurs in two types of aquifers -- unconfined and confined. These aquifers consist mainly of unconsolidated clay, silt, sand, and gravel. The unconfined aquifer is relatively shallow (less than 200 feet) and occurs nearly everywhere. The average depth to groundwater varies from year to year, but is usually less than ten feet. The confined or artesian aquifer occurs under nearly one-half of the San Luis Valley. The two aquifers are separated by a "clay series" or by an upper layer of volcanic rock. A summary of the thickness, physical character, and water supply charactersitics of the aquifers is given in Emery, et al., (1973).

<u>Historical Background on Water Use in the San Luis Valley</u> -- Most of the pioneer farmers of Colorado came from the humid East. Inasmuch as they were unaccustomed to farming in a region of less than ten inches of annual rainfall, they had to adjust their agricultural techniques and institutions to their new environment. However, the first farmer-settlers in the San Luis Valley were Spanish-Americans from arid New Mexico; they moved up from the Rio Grande Valley and settled on the Culebra and Conejos Rivers in the southern portion of the San Luis Valley. On April 10, 1852, these settlers began the San Luis People's Ditch, which has the distinction of being the oldest ditch in Colorado in continuous use and has the first priority of water for agriculture under Colorado's irrigation laws (Smiley, et al., 1913).

These early canals were of necessity narrow and crude affairs designed to irrigate small plots of land. Irrigating was done by means of the check and border system. Small rectangular areas were enclosed by banks of earth and the basins so formed were flooded to a depth of two to three inches.

It was not until the 1880's that the first large system for irrigation, planned upon modern principles, was started in the San Luis Valley. The great main ditch, now called the Rio Grande Canal, was on the northward side of the Rio Grande and was the largest canal in the United States at its time of construction. By 1890 the present skeleton of canals south and north of the Rio Grande had been completed (Hafen, 1948, p. 129).

Following the completion of the major canals in the late 1880's, farmers of North European stock came to settle the San Luis Valley, especially the area north of the Rio Grande River. Wheat and oats were the principal crops. To water their fields, the farmers developed a unique system of irrigation known as sub-irrigation. The technique of sub-irrigation involved bringing the groundwater table up to within 20 to 30 inches of the ground surface by massive applications of surface water during the spring runoff. Once the groundwater table was raised, it was maintained by small flows in sub-ditches. These ditches were about 18 inches deep and were spaced on 20 to 50 foot centers. Water percolated from these ditches maintaining the water table within reach of the plant roots (Hafen, 1948, p. 148).

Initial wheat yields were good -- sometimes between 40 and 60 bushels an acre -- and flour mills were built at Del Norte, Monte Vista, Hooper, Mosca, and Alamosa. However, this method of sub-irrigation soon resulted in lower lands "going to seep" and forced abandonment of many farms. The rapidity and impact of this loss of productive lands is graphically described by a consulting engineer's report.

> This process of abandonment progressed westward at a rate from one-half to one mile per year, other lands being brought under irrigation further west that formerly had been too dry to irrigate without drainage. Finally, the irrigated area extended westward to the large canals on the western edge of the valley floor, and the central portion of the valley that had formerly been beneficially irrigated was rendered unproductive by seepage. (Tipton, 1939, p. 166)

While land in the area north of the river would have perhaps had waterlogging problems in time due to the sub-irrigation practices, the fact that this area was a closed basin -- that is, an area with no natural drainage outlet -- served to hasten the eventual outcome. By 1915 most of the land around Mosca and Hooper had become waterlogged. Drainage of the irrigated lands by community effort started about 1915, when local drainage systems were constructed. Four of these systems served the land in the closed basin, only one of which led to the Rio Grande River. The others drained into the "sump." These systems, while relieving local problems, contributed to down-gradient waterlogging and simply served to pass problems on to other areas.

Proposals for a main outlet drain to carry water from the closed basin to the river began to appear in the early 1900's. The first comprehensive study for such a drain was made jointly by the United States Department of Agriculture (USDA) and the U.S. Bureau of Reclamation in 1915 and 1916. This or similar plans were reviewed periodically over the years.

The most recent plan to relieve the closed basin drainage problems is the "Closed Basin Project" proposed by the U.S. Bureau of Reclamation (now the Water and Power Resources Service). This project would drill a series of well fields directly in the sump area and then gravity flow the water to the San Luis Lake. From the lake the water would be released into the Rio Grande River as part of the Rio Grande Compact requirement.

Similar problems of waterlogging were encountered in the portion of the San Luis Valley which lies to the south of the Rio Grande, between the Rio Grande and the Conejos Rivers. Due to relatively less water per unit land being diverted into the area, and because the area benefited from better natural drainage (in the sense that there was no closed basin), the problem was longer in appearing and somewhat less severe in impact. However, with decades of upslope irrigation on these heavier soils, a severe porblem of waterlogging has developed, together with a serious soil salinization in tens of thousands of acres of otherwise potentially productive lands. It is this area to which the present study is directed.

We turn now to a description of the institutional arrangements important in managing water in the San Luis Valley.

The Rio Grande Compact -- Irrigation was initiated along the Rio Grande River in the states of Colorado and New Mexico and in the Republic of Mexico over 300 years ago. A nominal area was irrigated in New Mexico probably as early as the 16th century. Irrigation development took place rapidly in the San Luis Valley during the decade 1880 and 1890. However, no significant areas were put under irrigation in Texas until after the completion of Elephant Butte reservoir in 1916. Due to the common need of the three states of Colorado, New Mexico, and Texas, and of the Republic of Mexico, for water from the Rio Grande for irrigation, and, due to the fact that the available water supply developed by the stream is not sufficient to irrigate all of the irrigable land adjacent to the stream, disputes arose at an early date between Mexico and the United States and among the states over the uses of the water from the river.

The international difficulty was brought to a head by the occurrence in the 1890's of a cycle of extremely low runoff in the Rio Grande Basin. Finally, as a result of such controversy on December 5, 1896, an embargo was placed upon the river by the Department of the Interior which prevented the granting of rights-of-way over public lands for the construction of reservoirs on the upper Rio Grande, and a treaty was entered into with the Republic of Mexico on May 21, 1906, proclaimed by the President on January 16, 1907, ceding to that nation 60,000 acre feet of water from the Rio Grande annually in perpetuity.

To insure the fulfilling of the terms of the treaty, the United States Bureau of Reclamation constructed the Elephant Butte reservoir on the Rio Grande in the state of New Mexico. The reservoir, with a capacity of 2,600,000 acre feet, was placed in operation in 1916. The area served by the reservoir at present is about 200,000 acres, including the area irrigated in Mexico.

The placing of the embargo upon the river and the ceding to Mexico of the 60,000 acre feet from the limited common water supply accentuated the interstate controversy over the uses of the water of the river.

Colorado interests were finally able to get the embargo on the river removed in 1925, following which immediate steps were taken to finance the construction of reservoirs on the upper river. Threats of interstate litigation prevented such steps. Following a number of preliminary conferences, active compact negotiations between representatives of the states of Colorado, New Mexico, and Texas started in 1928.

Such negotiations finally culminated in a temporary compact in February, 1929, between the three states. This compact simply provided that conditions on the stream would remain status quo as far as water consumption was concerned for a five-year period. It provided, also, that negotiations should be under-taken to consummate a permanent compact. Negotiations between the commissioners of the three states were resumed in the winter of 1934.

The temporary compact was extended for a two-year period from June 1, 1935, to June 1, 1937, and later to October 1, 1937. The Rio Grande Compact was finally formulated and signed in March, 1938. The Compact was ratified by the three states' legislatures in February and March, 1939, consented to by Congress, and approved by the President on May 31, 1939 (Radosevich, Hamburg, and Swick, 1975).

Colorado's obligation to deliver water at the Colorado-New Mexico line, as set forth in the Compact, is based upon the relationship between inflow and outflow of tributary water in the San Luis Valley for the years 1928-1937, inclusive. The Compact also recognizes the potentiality of salvage of Closed Basin waters for beneficial use. However, this salvaged water is not credited to Colorado unless it meets a water quality standard. Radosevich and Hamburg quote from the Rio Grande Compact as follows:

> In event any works are constructed after 1937 for the purpose of delivering water into the Rio Grande from the Closed Basin, Colorado shall not be credited with the amount of such water delivered, unless the proportion of sodium ions shall be less than forty-five percent of the total positive ions in that water when the total dissolved solids in such water exceeds three hundred fifty parts per million.

Due to a number of circumstances Colorado did not always meet the delivery requirements of the Rio Grande Compact and through the years compiled a rather substantial deficit. This problem finally came to a head when the downstream states of New Mexico and Texas sued Colorado, claiming that Colorado was 840,000 acre feet in arrears to those states. The case eventually reached the U.S. Supreme Court, where it is now held in abeyance as long as Colorado meets it current delivery obligations under the Compact.

According to the terms of the Compact, Colorado cannot construct or operate any new reservoirs as long as it is held to be in debit status. Thus, not until Colorado has removed its deficit, will the state be able to regulate the river in such a manner as to avoid cycles of overabundance or drought.

The Present Situation -- Years of large-scale diversion of Rio Grande water into the area south of the river, combined with the practice of maintaining the water table sufficiently high for sub-irrigation have resulted in waterlogging and some salinization of tens of square miles of lower lying lands. The appropriation doctrine, as presently interpreted in Colorado, has encouraged a system where each individual considers only the results of his actions (on his farm) even though downslope impacts have become obvious. Therefore, some type of collective action, which represents a modification of the existing rules, must be sought. Institutional changes (drainage and improvement districts) and investments in conveyance and drainage facilities are required for control of the problem. The farmers in the valley are aware of the complexity of the problem, but up to this time have not had the analytical tools and the necessary data to analyze the economic implications of alternative solutions. The model developed will allow the simulation of many different activities. The results of these simulation runs will provide the local planners both economic and physical data with which they can measure the tradeoffs between different alternatives. These data will allow the planner to obtain maximum economic benefits from the water resources system.

OBJECTIVES

The overall objective of this study is to develop a systematic approach to predicting impacts of alternative procedures for management of irrigation water so as to minimize waterlogging and salinization and to improve water-use efficiency. The specific model is developed for and applied to the San Luis Valley, Colorado; but the general methodology will be applicable to other areas. To achieve the overall objective, the following specific steps will be taken:

1. Develop a computer simulation model which will enable the prediction of the impact of management and control measures on groundwater status and river flows throughout the affected area;
2. Inventory the potentially reclaimable waterlogged and salt-affected lands in the study area, according to degree of waterlogging and salinization;
3. Review the existing legal structure and formulate a set of institutional arrangements which would accomplish waterlogging control and assure adequate financing and management of the system;
4. Operate the model for a selected set of control measures, so as to predict their impact on water table and river flows.

PLAN OF THE REPORT

The remainder of the report is organized as follows: Chapter 2 describes the components and interactions considered in developing the hydrologic model. Chapter 3 describes the computer simulation model. Chapter 4 describes the management strategies evaluated with the computer model. Chapter 5 presents and discusses the results of the simulation runs, while Chapter 6 presents a summary, conclusions and recommendations for further research. Agronomic considerations are summarized in one appendix.

STUDY AREA

The study area (Figure 1) selected comprises a portion of the San Luis Valley containing a region of waterlogged land adjacent to the Rio Grande in the central to southern part of the valley.

The nearly flat San Luis Valley covers about 8,000 square miles. The average elevation of the valley floor is approximately 7,000 feet. The valley is bounded on the west and north by the Continental Divide, on the east by the Sangre de Cristo Range, and on the south by the Colorado-New Mexico state border. The physiography varies from a high mountain desert with an annual precipitation of 7.5 inches to high surrounding mountains with an annual precipitation of 45 inches.

The study area selected consists of approximately 500 square miles lying to the south of the closed basin and contains the wedge of land between the Rio Grande and the Conejos River. The northern boundary begins just downstream of Del Norte on the Rio Grande and runs almost parallel to the river in a south-easterly direction along the low lying ridge marking the hydraulic divide which separates the Rio Grande from the closed basin. The northern boundary ends close to the confluence of the Rio Grande and Conejos Rivers. From here the southern boundary runs south-westerly along the Conejos River with the San Luis Hills immediately adjacent to the south to a point upstream of Antonito, the boundary then turns directly west until intersecting La Jara Creek. The western boundary runs from La Jara Creek roughly northwards back to the beginning of the northern boundary near Del Norte.

The waterlogged area stretches from Alamosa in a south-easterly direction in a strip parallel and south of the Rio Grande towards the confluence of the Rio Grande and Conejos Rivers. This is the area of prime importance in the

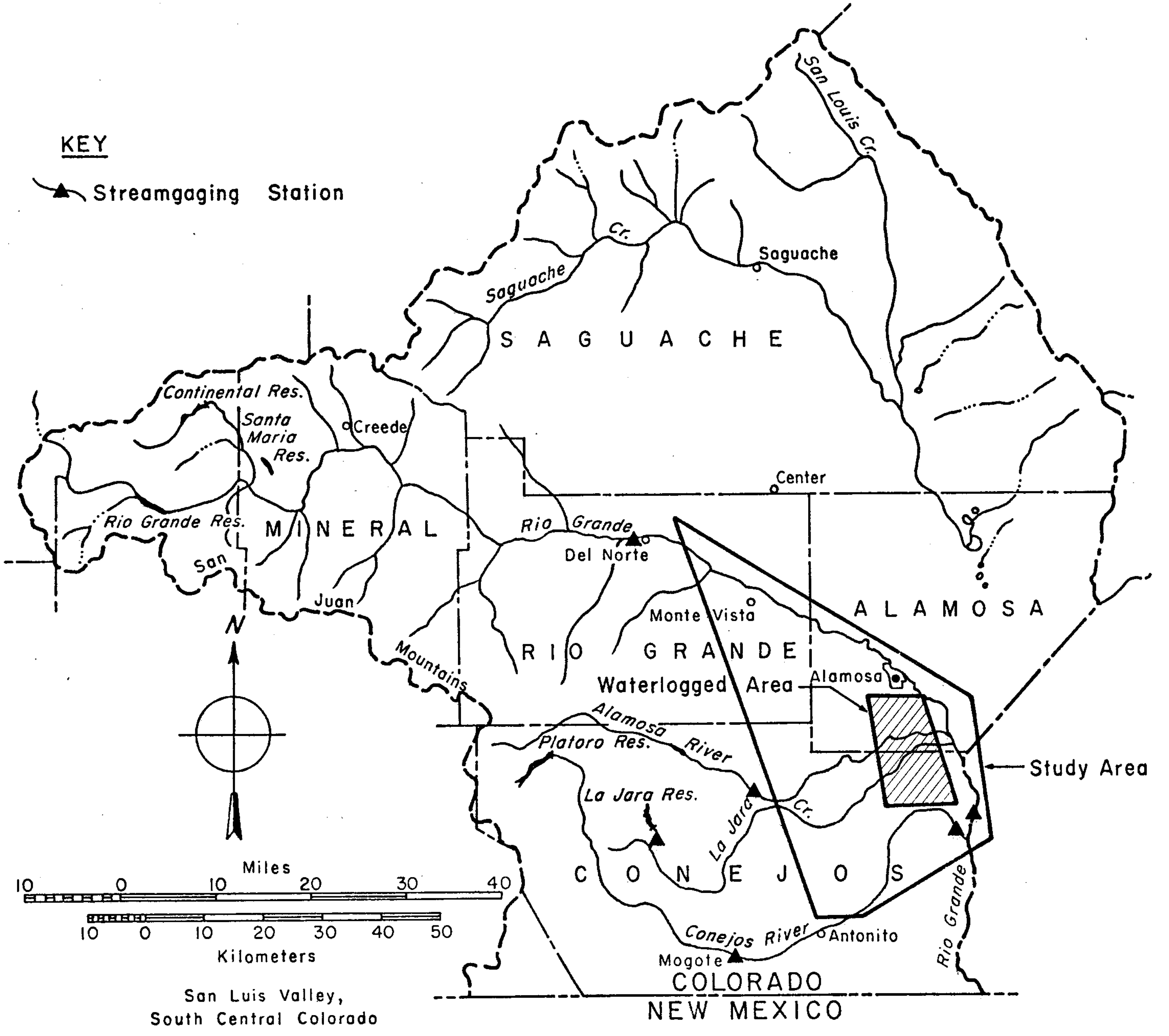


Figure 1. Location Map of Study Area, San Luis Valley, Southern Colorado

overall interdisciplinary study. The waterlogged area is also outlined in Figure 1.

CHAPTER II

DESCRIPTION OF COMPONENTS AND INTERACTIONS CONSIDERED IN DEVELOPMENT OF THE HYDROLOGIC MODEL

TYPE OF HYDROLOGIC MODEL REQUIRED

General

The type of hydrologic model required should enable the study of various management strategies and their effect on the waterlogged area. The model should be a planning or management model rather than an exact operating model. It should give an overall idea of changes which occur when various management strategies are simulated. The results from the hydrologic model are to be used as input to an economic study. Although the hydrologic model is separate from the economic model, it is influenced by economic considerations reflected through the various management strategies.

Composition of the System: The system to be studied is composed of a number of features. It includes the natural features of a stream-aquifer system along with the modifications introduced by man's engineering (canals, dams, reservoirs, wells, ditches) and agricultural practices (center pivot sprinkler irrigation, furrow irrigation) (Morel-Seytoux, 1979, p. 9). Legal, political, and economic components also affect the system.

To manage the system, each of the components must be described in a precise quantitative way in the hydrologic model (Morel-Seytoux, 1979, p. 3). However, the use of simplifying assumptions for modeling of various components which still yield reasonably realistic results from the hydrologic model should be investigated.

Modeling of the Unconfined Aquifer: Modeling of the unconfined aquifer and streams in the study area and the stream-aquifer interaction forms the basis of the hydrologic model. The already existing discrete kernel approach is used to model the unconfined aquifer. This approach conveniently provides the unconfined aquifer response both to pumping from wells and seepage flow from the river, as well as the river response to pumping from wells (Morel-Seytoux, 1975, p. i). Three types of excitation which need to be considered in the hydrologic model include upstream inflows, stream diversions, and the net aquifer withdrawals (Morel-Seytoux, 1979, p. 12).

Waterlogging: The waterlogging in the San Luis Valley is a result of the unconfined aquifer level rising to near the ground surface. Consequently, to assess the effects of various management strategies on the waterlgging, the actual evolution of the unconfined groundwater aquifer levels with time is required. One feature of the model needs to be the calculation of the unconfined aquifer level at various locations within the waterlogged area and in the surrounding irrigation areas.

Irrigation areas to the north, west, and southwest of the waterlogged area contribute to the build-up of the levels of the unconfined aquifer due to irrigation methods employed in the San Luis Valley. These irrigation areas and the methods used by farmers to manage surface water diversions from the rivers and the groundwater withdrawals will also need to be considered.

Return Flows: To model a stream-aquifer system, such as the one being considered in the San Luis Valley, the interaction between the stream and aquifer must be recognized. The term "return flow" refers to the exchange of water between the river and unconfined aquifer or vice versa. These return flows depend on the level of water in the river and the level in the unconfined groundwater aquifer in the region of the river. Consequently another feature needed in the model includes the calculation of the river stage and its subsequent variation along the river and the calculation of the unconfined aquifer level in the region of the river.

Climate: The nature of the climate in the San Luis Valley has led to the use of irrigation due to the lack of sufficient rainfall during the irrigation season. Rainfall, streamflow, and evaporation as well as crop requirements for water during the growing season are also factors that should be considered in the development of a hydrologic model of the study area.

Legal Constraints: Legal aspects affecting the conjunctive water use in the San Luis Valley were introduced in Chapter I. The Water Right Doctrine for distribution of irrigation water and the Rio Grande Compact Agreement which attempts to ensure water supply for the downstream states and Mexico will play an important role and will constrain the way in which certain quantities of water may be used. These two legal aspects are important features of the hydrologic model.

Component Interactions: Finally the interactions between various components mentioned above must be evaluated. The important interactions will be consequently included in the hydrologic model of the study area.

Time Increment and Grid Size Selection

Three important parameters need to be decided upon before considering any of the components or interactions in detail and before gathering data for the model. These are the time horizon, the time increment, and the grid size. The finite difference model utilized to generate the discrete kernels for the unconfined aquifer response partly determines the time increment and grid spacing. These aspects are discussed more fully in a later section.

Time Horizon: In order to assess the long term effects of the various management strategies a reasonable time horizon over which the hydrologic model simulates the study area is required. On the other hand the cost of a simulation run increases with time. The increase is not a straight line, but increases in slope as time goes on. Doubling the time horizon much more than doubles the cost of a run. This is a consequence of the technique used to model the unconfined aquifer, i.e., the discrete kernel approach, which will be more fully detailed in a later section. The number of calculations in any one time step using the discrete kernel technique is directly proportional to the number of time steps from the beginning of the run. Consideration of the factors mentioned above led to the selection of a time horizon of 12 years.

Time Increment: A one-month time increment is used in the hydrologic model. This is regarded as a time period which adequately reflects the seasonal variation of the system. A smaller time increment would improve the accuracy of simulation, but also would increase the cost of running the various management strategies.

The water year is from October to the following September and has been used in the hydrologic model as the basic year. Simulation runs begin in October. The frost-free season in the valley ranges from 90 to 115 days (USDA, 1969). Surface water diversions occur during April to October.

Grid System Size: To enable modeling of the study area it is necessary to overlay the study area with a grid system of finite difference calculation cells in order to apply the discrete kernel approach. The grid system enables the representation of a continuum (physical problem) by a set of points some distance apart (Peters and Morel-Seytoux, 1977, p. 33). The grid system allows the unconfined aquifer, the rivers and canals, and the irrigated areas to be modeled using a distributed approach, i.e., spatial variability can be accounted for. However, within each grid cell a lumped parameter approach is used to describe changes within the cell. The effect of pumping, the aquifer properties, or the evaporation, etc., are assumed to be uniformly distributed over the cell, i.e., the properties surrounding any one grid point but within the grid cell are assumed to be homogeneous. For example, a pumping excitation may occur at four separate wells within one of the cells, however, the hydrologic model would regard the combined effect of the wells as acting uniformly over the cell.

The first decision related to the selection of a grid system is to adopt a square grid system. The closer the grid points are to one another the more accurately the model represents the physical problem (Peters and Morel-Seytoux, 1977, p. 33). On the other hand, the greater the number of grid cells the greater the computer costs and storage requirements. Based on these computer costs and storage, along with the NASA infrared photographs which are used to determine location and size of the irrigation areas, a grid system spacing of one mile is selected. This spacing is as small as practical for using the infrared photographs (see a later section for further discussion), however, one mile is small enough so as to adequately model the study area. This grid spacing adequately represents the variation of aquifer parameters of transmissivity and porosity over an area by a single point value.

The portion of the San Luis Valley to be modeled and the grid system is shown on Figure 2. This entire grid is not used in the model. The portions used and criteria behind selection of portions is discussed in the later subsection on the moving grid system (section on Aquifers).

Units Used in the Hydrologic Model

Elevations and depths in the model are expressed in terms of feet while volumes of water are expressed in acre feet/month. Originally meters and meters

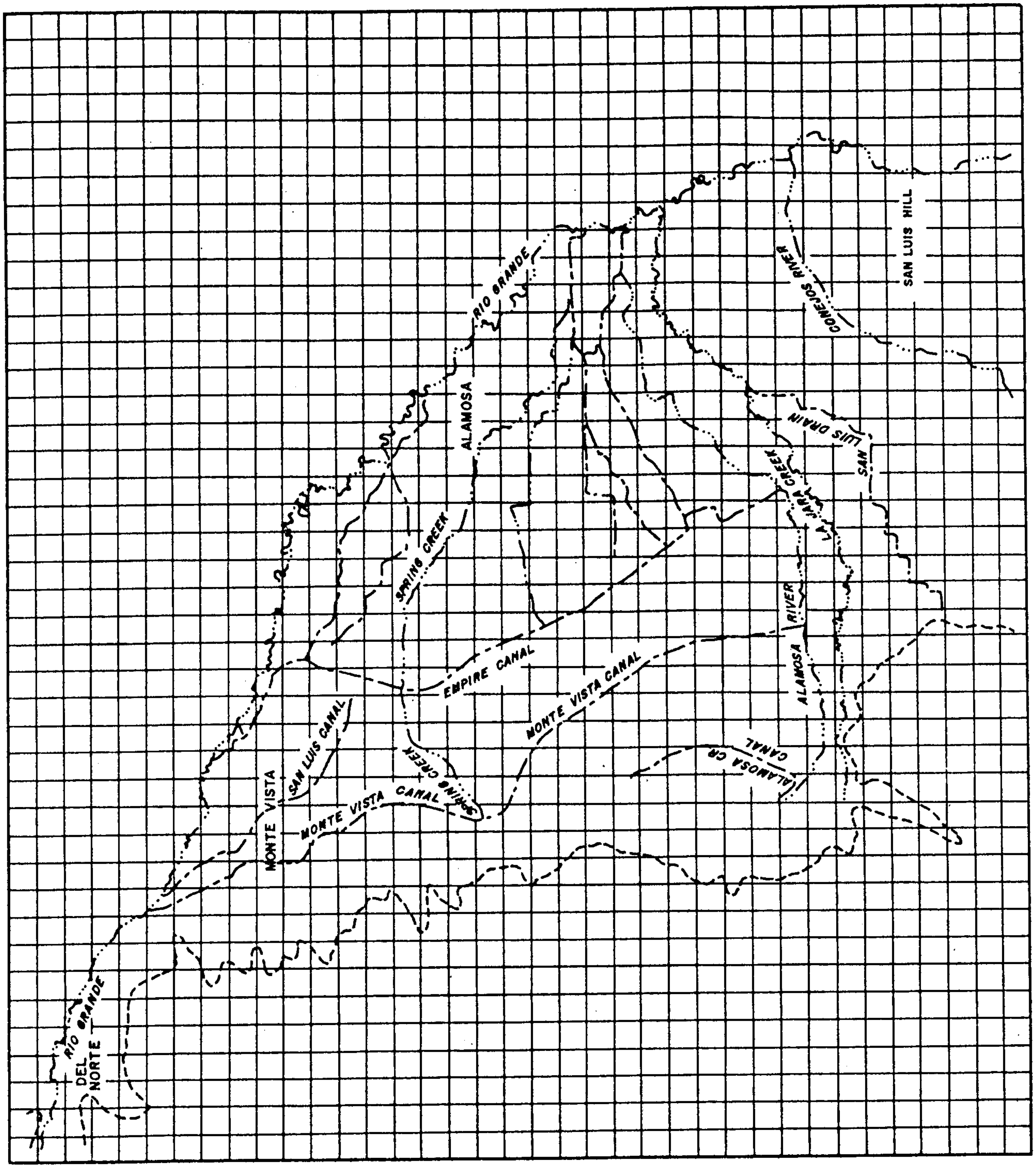


Figure 2. The Square Mile Finite Difference Grid System

cubed were used for height and volume respectively, however, it was decided to change to the Imperial System. The first reason for this change stems from the size of the grid system being selected as one square mile rather than a metric distance. Secondly, if this report is to be used by people familiar with the San Luis Valley it will be much more useful to them if presented in easily recognizable units. Volumes in meters cubed become excessively large and while millions of meters cubed is convenient, it may be difficult to attach a physical meaning to the quantity unless there is some familiarity with the metric system. However, it should be noted, metric units are used in some sections of this report summarizing work completed prior to changing to the Imperial System. Conversion of these values to Imperial is not warranted.

Output from the Model

To summarize, the output from the model needs to include the following at each monthly time step.

(i) Rio Grande and Conejos River historical inflow and outflow

(ii) Rio Grande and Conejos River predicted outflows

(iii) Water table elevations at each of the 34 calculation cells in the Observation Area

(iv) Monthly and annual quantities of

- stream diversions
- irrigation efficiency and crop use
- unconfined aquifer recharge and withdrawals
- surface runoff to down gradient areas
- pumping from confined and unconfined aquifer
- evaporation
- return flows

(v) Information relating to each channel reach including

- elevation of river surface
- average elevation of unconfined aquifer in vicinity of the river

- their difference
- transmissivity of the reach
- return flow for the reach
- diversions from the reach
- quantity of water flowing into and finally leaving the reach

PHYSICAL COMPONENTS OF THE SYSTEM

General

The physical components of the study area which are considered in the computer simulation hydrologic model include the rivers, the aquifers, the irrigation areas, the irrigation water distribution systems, and the waterlogged area. These components are each discussed in detail in following sections.

Sources of irrigation water for the study area include surface water, confined, and unconfined groundwater. The primary source of surface water inflow is derived chiefly from snowmelt. The three main supplies of surface water to the study area are the Rio Grande, the Conejos River, and the La Jara/Alamosa Rivers. Water from these sources is conveyed to the irrigation areas via man-made irrigation canals. The three major canals carrying Rio Grande water south are the Monte Vista Canal, San Luis and Rio Grande Canal, and the Empire Canal. Five major irrigation areas have been denoted depending on source of surface water supply. Appropriately these areas are the Empire irrigation area, Monte Vista irrigation area, San Luis and Rio Grande irrigation area, Conejos irrigation area, and La Jara/Alamosa irrigation area. Figure 3 shows these five major irrigation areas and the downslope drainage areas (where overland drainage from the irrigation areas finally percolates to the unconfined aquifer).

Various components and interactions within the system can be modeled to different degrees of complexity. The following sections outline the basic

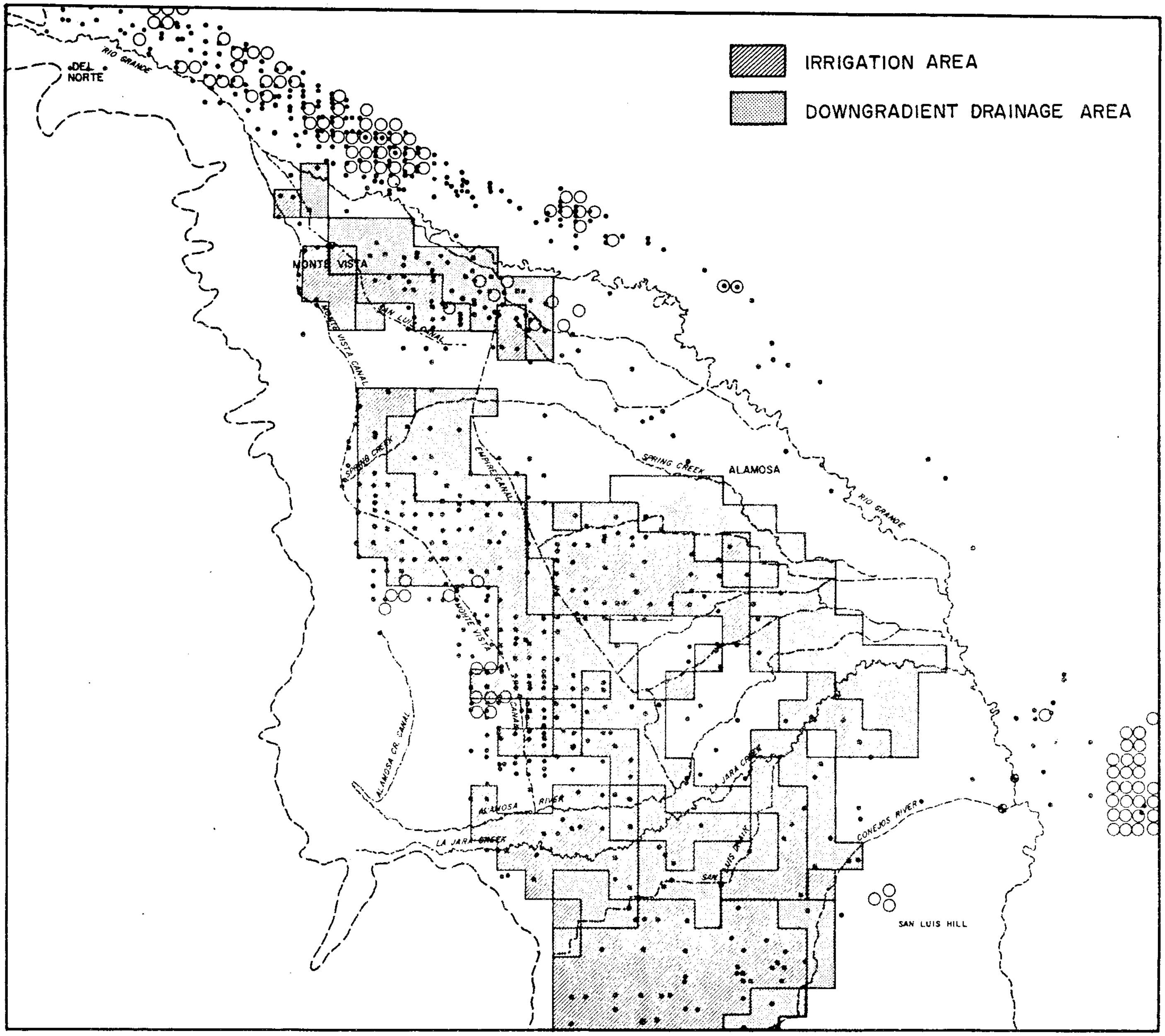


Figure 3. The Major Irrigation Areas and the Downslope Drainage Areas Within the Study Area

physical components and interactions which need to be included in the computer simulation model. The modeling technique employed in the computer model for each component and interaction is also discussed noting the degree of complexity adopted.

The Waterlogged Area

Description: The location of the waterlogged area is south and west of Alamosa. In order to evaluate various management strategies, it is necessary to know how the levels of the unconfined aquifer in the region of waterlogged area evolve with time. The unconfined aquifer elevation is calculated in each time step at 34 square mile grid cells within and close to the waterlogged area. These 34 cells are referred to as "calculation cells." The location of these 34 cells is shown in Figure 4. The calculation cells require a grid system for calculation of aquifer levels. The grid system is referred to as the observation area grid system and it is also shown in Figure 4. The grid cells at which aquifer levels are calculated are selected to include cells in the waterlogged area as well as cells in the surrounding irrigation areas and downslope drainage areas to the west of the waterlogged area.

Modeling Technique: The waterlogged area is modeled using the discrete kernel approach. (Discussed in detail in the section on Aquifers.) The approach gives a detailed account of the month by month evolution of the unconfined aquifer over time for the 34 calculation cells.

Rivers

Description: The rivers considered in the computer model which are important to the study area are the Rio Grande, Conejos River, and the La Jara Creek/Alamosa River system. The San Luis Drain which runs close to the

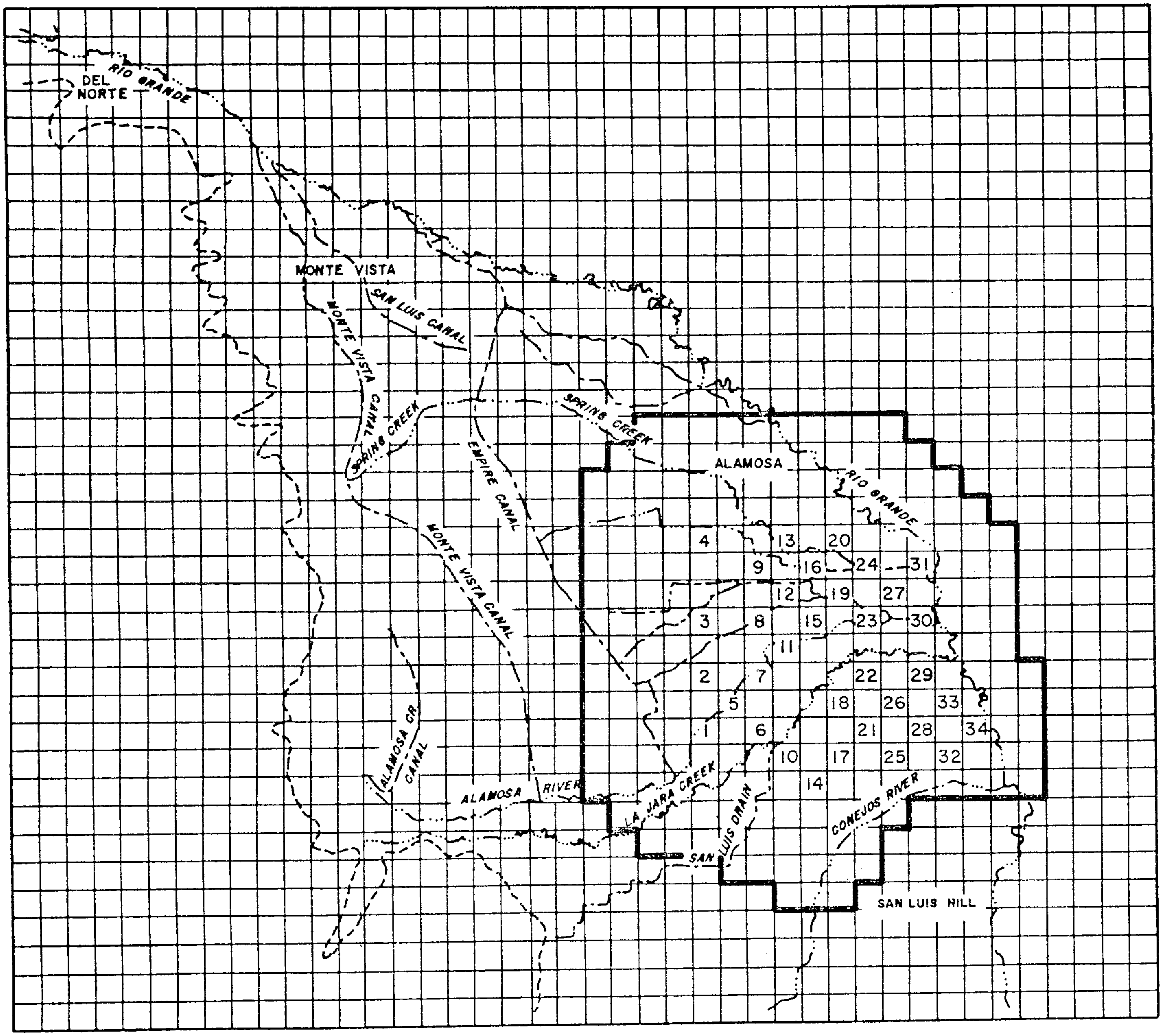


Figure 4. Observation Area Grid System and the 34 Calculation Cells

Alamosa River is also considered in detail, as it is a major channel available to carry excess water away from lower portions of the study area (see Figure 2). The drain serves a double purpose. The upper reaches collect return flow and then redistribute this water to farms further downstream while the lower parts serve as a true drain for irrigation return flow. In the lower parts the drain joins the La Jara Creek which flows into the Rio Grande.

Modeling Technique: The Rio Grande and Conejos River are modeled in detail in the simulation model. They are both assumed to be hydraulically connected to the unconfined aquifer. However, for simplicity it is assumed these channels are not affected by other channels.

On the other hand, the La Jara Creek and Alamosa River are not modeled in nearly as much detail. These two water courses only carry a small amount of water except during high spring snowmelt flows when flooding can occur and many diversions to adjacent irrigation areas are made. All the spring streamflow from the two streams, most of which is regulated by reservoirs on the La Jara Creek and Alamosa River is assumed to be diverted to the La Jara/Alamosa irrigation area which is comprised of scattered lands in the center of the study area adjacent to and west of the waterlogged area. The nearby San Luis Drain is modeled in detail and is assumed to hydraulically connected to the unconfined aquifer. Rock Creek flows through the study area but only carries flows in the spring and has been ignored in the hydrologic model.

-River reaches: The grid system overlayed on the study area divides a river into reaches. A river reach is that portion of a river contained within a square mile grid cell. River reach numbers are associated with each of the river cells beginning at the upstream end. The Rio Grande has 57 river reach cells, the Conejos River has 17 river reach cells while the San Luis

Drain has 21 river reach cells. These are also denoted in Figure 5.

-Return flows: In order to calculate the return flow between the unconfined aquifer and the river or vice versa for a particular river reach, the stage in the river reach and the average unconfined aquifer level in the river reach grid cell is required. The river stage can be obtained using a stage-discharge relationship which is described in detail in Chapter III. However, the average unconfined aquifer level requires knowledge of the excitations at adjacent and nearby grid cells to be able to calculate the effect on the aquifer level at the river reach under consideration. The result is that three separate river grid systems are required. These include a grid system for the Rio Grande, for the Conejos River, and the San Luis Drain. This enables the unconfined aquifer levels in each of the 95 river reaches to be calculated in each time step. The three grid systems and the respective river reaches are shown in Figures 6 to 8. The reasoning behind the selection of the shape of these grid systems is discussed in detail in the following section on Aquifers. Appropriate numbering systems for each of the cells within the three grid systems are used. This is not discussed in detail here. It should be noted these grid systems do overlap.

-Reach outflow computation: The outflow from a reach for a particular time period can be determined given the inflow to the reach and the diversions. Various modeling techniques can be used. A classical approach is the Muskingum method of flood routing (Morel-Seytoux, 1979, p. 23). This approach and the fluid mechanics approach for flood routing are considered to be too sophisticated with regard to the objectives of the study to warrant inclusion in the hydrologic model. Instead, a simple mass balance technique is used to model inflow and outflow for a reach. The outflow from the adjacent upstream reach

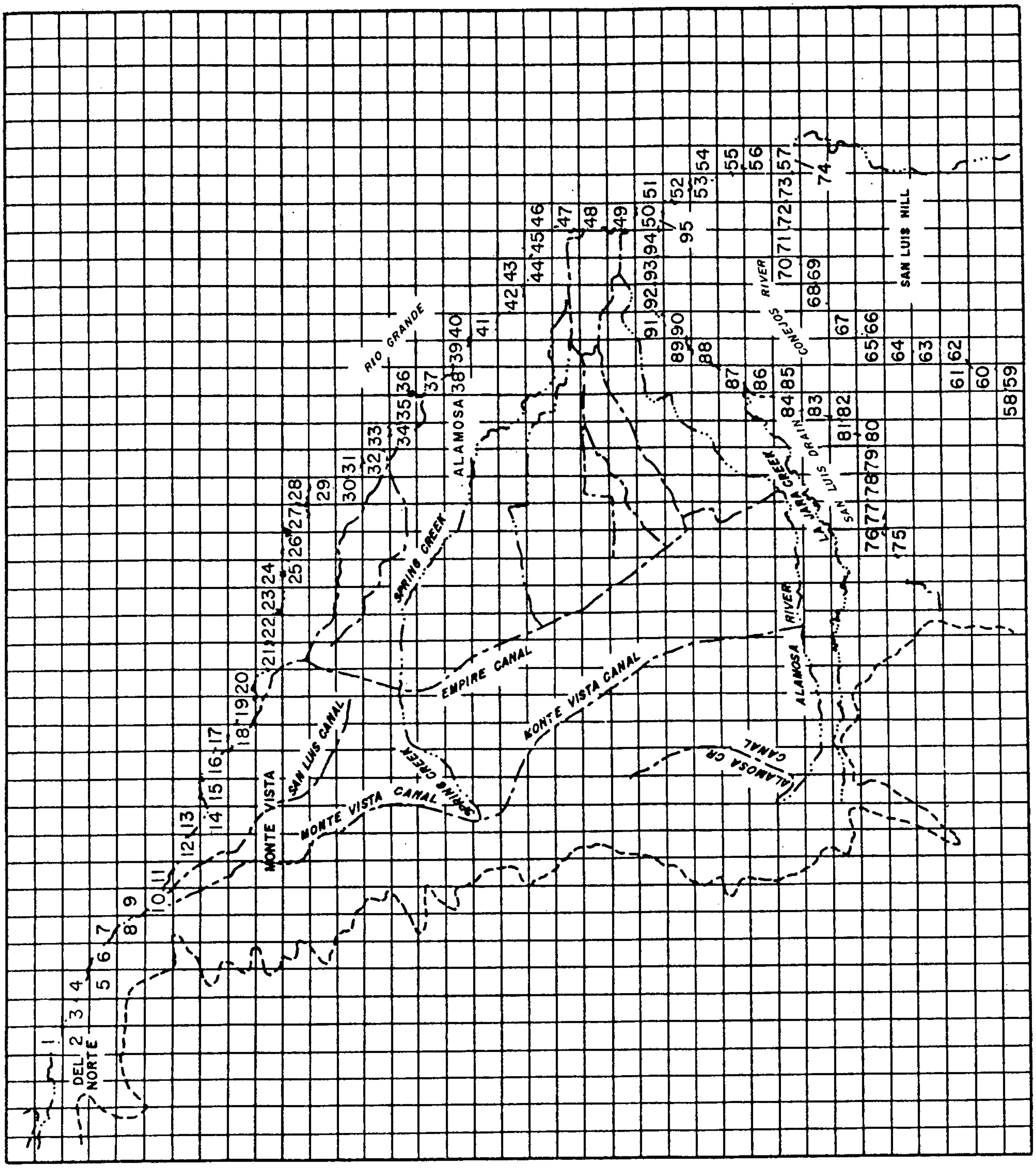


Figure 5. River Reach Cell Numbers for the Rio Grande, the Conejos River and the San Luis Drain

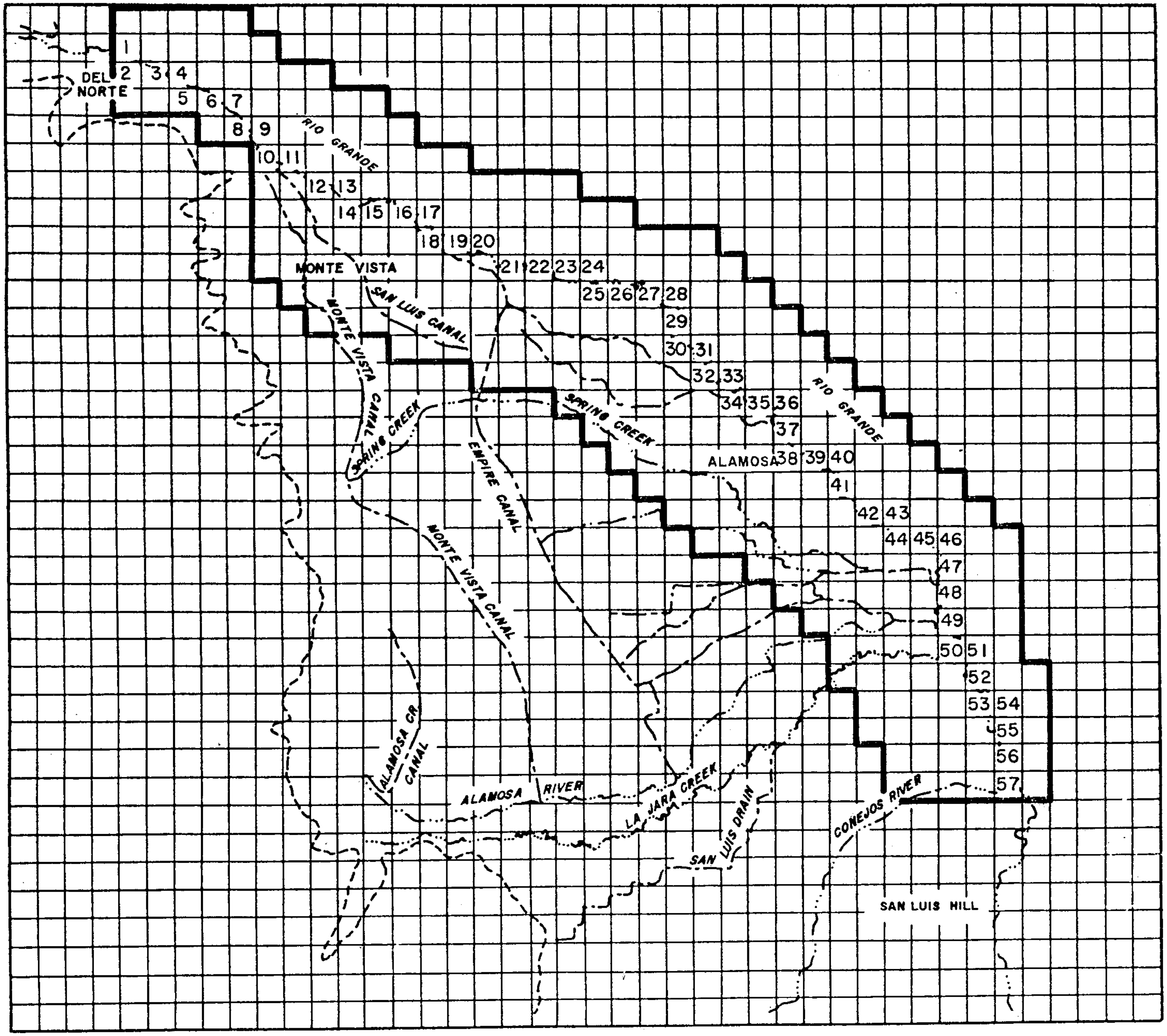


Figure 6. The Rio Grande Grid System

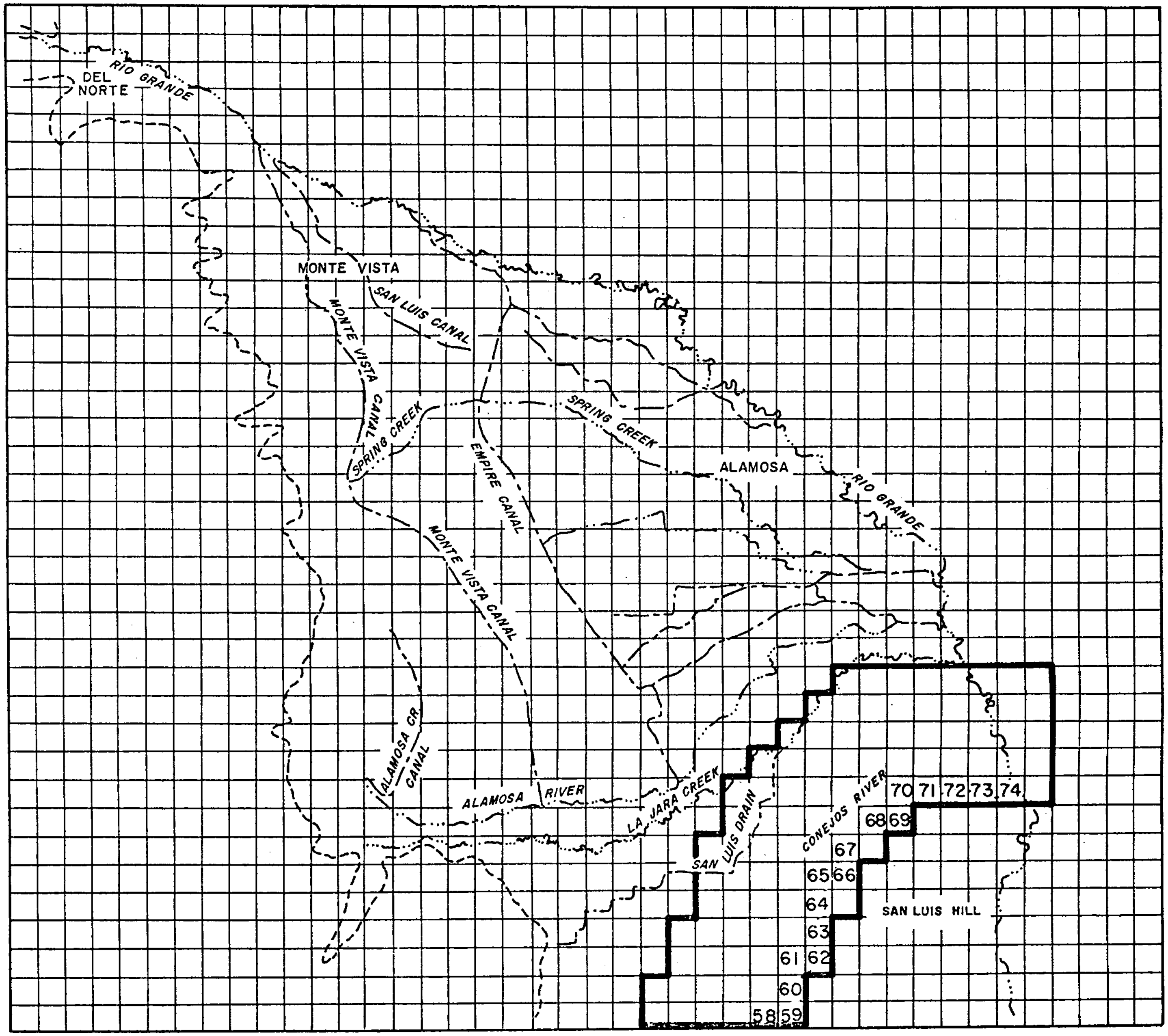


Figure 7. The Conejos River Grid System

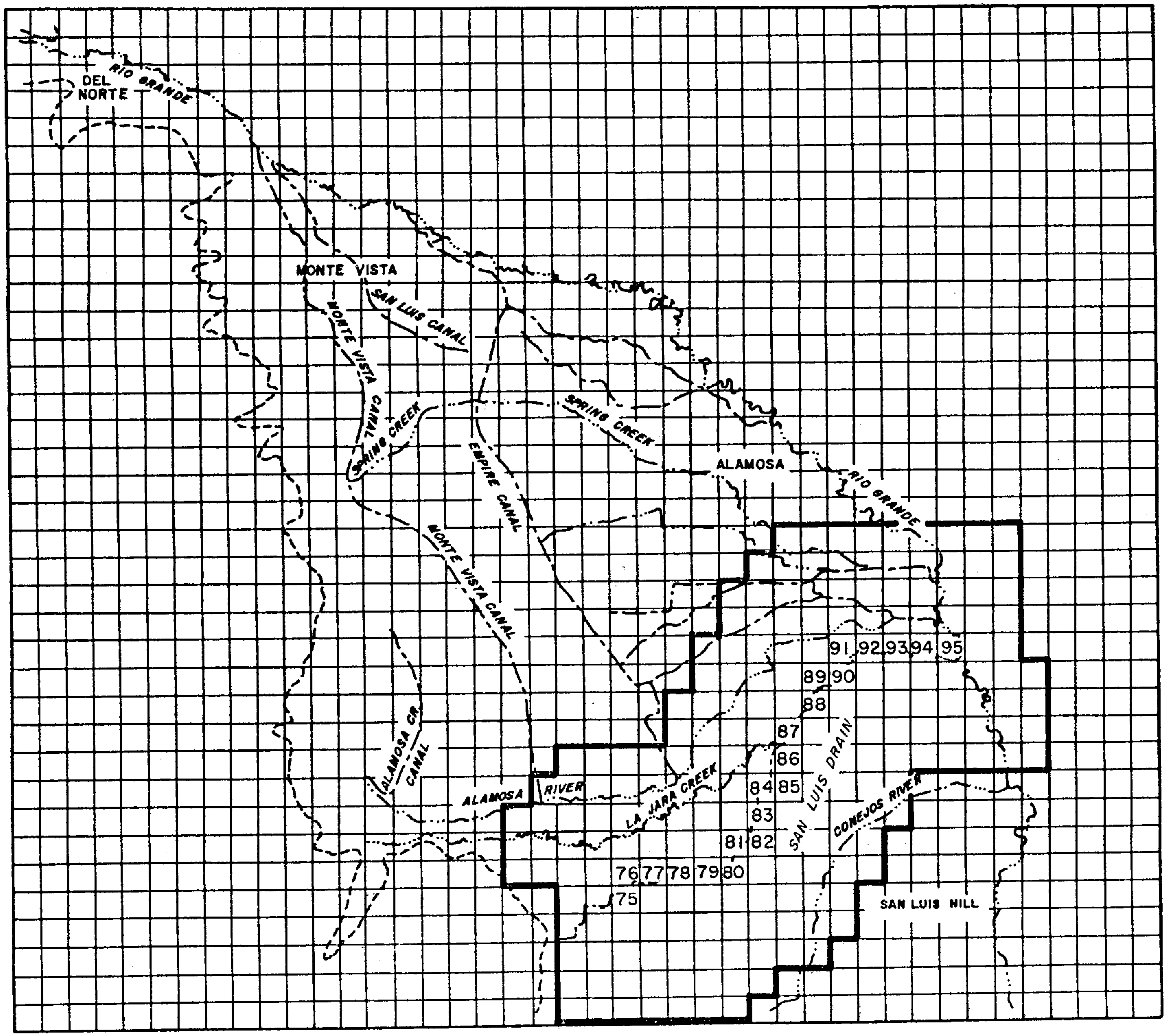


Figure 8. The San Luis Drain Grid System

becomes the inflow for this reach. Diversions to canals are subtracted from inflow while return flow is subtracted when there is flow from river to unconfined aquifer and added when flow is from unconfined aquifer to the river. The final result is the outflow for the reach.

The inflow to the first reach on the Conejos River and Rio Grande is the historic inflow; this will be discussed in detail in Chapter III. The resulting outflows predicted by the computer model for the furthermost downstream river reaches on the Rio Grande and the Conejos River both measured just above their confluence can be compared with historic measured flows to assess the model calibration.

Reservoirs

Description: A number of reservoirs are utilized for regulation of the spring runoff in the San Luis Valley. In the upper reaches of the Rio Grande, the Beaver Creek Reservoir, the Continental Reservoir, Rio Grande Reservoir, and Santa Maria Reservoir regulate streamflow. On the Conejos River, the Platoro Reservoir (60,000 acre feet) regulates flow while on the La Jara Creek the La Jara Reservoir (14,040 acre feet) regulates streamflow and on the Alamosa River, Terrace Reservoir regulates flow.

Modeling Technique: The regulating effect of the reservoirs is not modeled directly in this simulation model. The model is not supposed to be an exact operating model but rather a management model which will give a general idea of the effects of implementing various management strategies.

In Chapter III, it is shown that a 30 year average inflow is calculated for the Rio Grande and Conejos Rivers and the Alamosa River/La Jara Creek system. These 30 year averages are used as streamflow input to the computer model. Some of the reservoirs (e.g., Platoro Reservoir on the Conejos, 1951) were constructed within the period (1935-64) used to calculate the 30 year averages. The regulating effect of the reservoirs does not greatly affect the system and any effect is reflected in the 30 year average streamflows. The effect on the 30 year averages of construction of reservoirs within the period 1935-64 is assumed to be negligible.

Lack of Upstream Storage: The Rio Grande Compact has resulted in a lack of upstream storage on the Rio Grande restricting the ability to capture and fully utilize the spring runoff in the river. The Compact also places restrictions on the way some of these reservoirs are operated. There are pre- and post-Compact storages. Post-Compact storage cannot be increased.

Aquifers

Description: Groundwater occurs in two types of aquifers, unconfined and confined (Emery, et al., 1973, p. 1). The composition of these aquifers includes unconsolidated clay, silt, sand, and gravel. Clay layers and lava flows separate the unconfined aquifer from the confined aquifer. Figure 9 shows a diagrammatic section of the two aquifers in the San Luis Valley (Emery, et al., 1972, Back Cover). Unconfined groundwater occurs nearly everywhere in the valley while confined or artesian groundwater only occurs under one-half of the San Luis Valley. The confined aquifer is hydrologically connected to the unconfined aquifer. Upward leakage from the confined aquifer to the unconfined aquifer occurs through and around the clay layers. Emery, et al., 1973, p. 12, indicate this seepage may be considerable.

The unconfined aquifer is bounded hydrologically on all sides except the southern boundary where simplifying assumptions have been made. The San Juan Mountains to the west of the study area bound the unconfined aquifer. Just north and east of the Rio Grande is a hydrologic no-flow boundary as identified

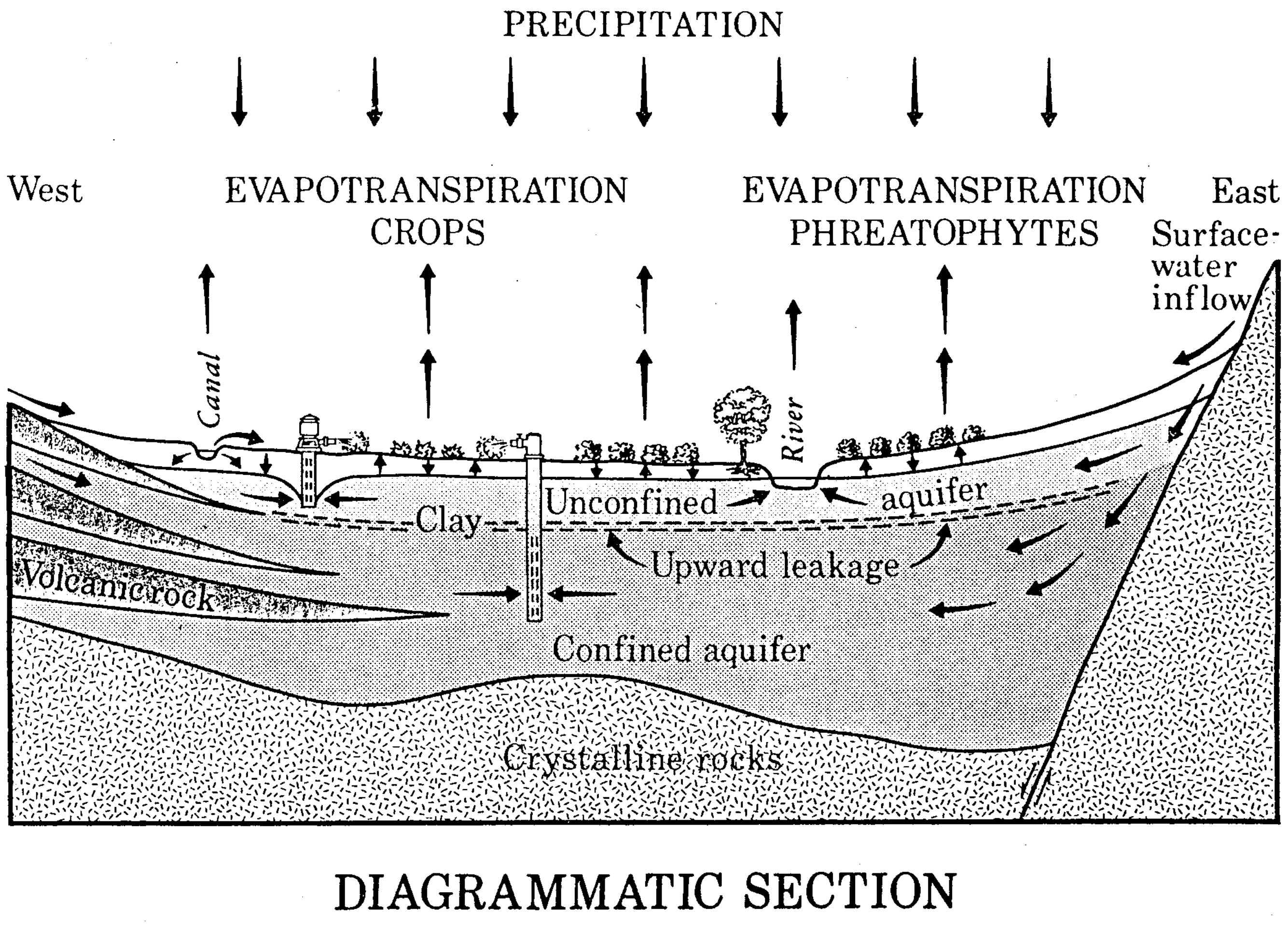


Fig. 9. Diagrammatic section of the unconfined and confined aquifers. (after Emery et al., 1972, Back Cover)

by previous studies (Emery, et al., 1972). This corresponds to the water divide between the Rio Grande and the Closed Basin. The San Luis Hills to the southeast also bound the unconfined aquifer. Only about 8 miles of the south boundary permit hydrologic flow, but this is a region where the unconfined aquifer thins out rapidly and where the proportion of water diverted to irrigation from the Conejos can be estimated.

Emery, et al., 1973, p. 14, indicates that during 1969 the depth to water below land surface was 12 feet or less over one-half the valley while Plate 1 (Emery, et al., 1973) indicates the unconfined aquifer levels in the study area are less than 6 feet below the ground surface.

Modeling Technique: The confined aquifer is modeled using essentially a black box modeling technique. The model assumes each of the five major irrigation areas has a certain total confined aquifer well capacity. This confined water is assumed to be supplied under pressure to the farms all year round. During the winter months the crop need and evapotranspiration is close to zero and consequently the confined aquifer water delivered is assumed to be apportioned between aquifer recharge and downslope drainage. Any leakage from the confined to the unconfined aquifer is ignored.

The unconfined aquifer is modeled in much more detail than the confined aquifer. A distributed approach has been adopted to describe the state of the system more closely to account for both the effect on the unconfined aquifer of rivers, canals, farms, and irrigation wells and the spatial variation of unconfined aquifer properties (Morel-Seytoux, 1979, p. 21). Excitations, i.e., net withdrawals or recharge at each of the 499 square mile grid cells, are calculated in each time step to enable calculation of the evolution of the unconfined groundwater surface as time proceeds. The discrete kernel approach for modeling the unconfined aquifer has been utilized. This approach is discussed in detail in the next section.

Discrete Kernel Approach for Modeling the Unconfined Aquifer: A major advantage of this hydrologic model for describing the stream-aquifer interaction is the use of the discrete kernel approach for modeling the unconfined aquifer. This method is both convenient and cost effective (Peters and Morel-Seytoux, 1978, p. 26). The method uses a finite difference model employing an Alternating Direction Implicit (ADI) scheme to generate the discrete kernel coefficients (Morel-Seytoux and Daly, 1975, p. 255) that describe system responses to unit excitations. Because a linearized form of the Boussinesq equation is used to describe the system, solutions can be superimposed in both time and space. In addition, unit excitations can be multiplied by actual excitations and then superimposed. The beauty of dealing with a linear system using a discrete kernel approach is that the response to many different patterns of excitations can be easily calculated by multiplying the unit excitations by the actual excitation and summing all the excitations (Peters and Morel-Seytoux, 1977, p. iv).

Once the discrete kernels are generated using the finite difference technique they are stored on a computer file and need not be calculated again. The work necessary to multiply and superimpose unit solutions is nominal compared with solving the finite difference equations and consequently the cost of simulating many different management strategies can be reduced tremendously (Peters and Morel-Seytoux, 1977, p. v.).

Moving Grid System: The cost of the generation of the discrete kernels can be reduced enormously by using the concept of a moving grid system (Peters and Morel-Seytoux, 1977, p. 27). Both the use and size of area of influence for a moving grid system is based on the nature of the aquifer transmissivity in the study area. Outside the zone of influence the discrete kernel coefficients become too small to be of any practical significance. In the case of the San Luis Valley a distance of 4 miles is selected as the maximum distance or zone of influence at which the discrete kernel coefficients are large enough to warrant inclusion in the calculation. The moving grid system produces the shapes of the river system grids in Figures 6 to 8. The final selected moving grid system size was 9 miles (east-west) by 16 miles (north-south). This was based on zone of influence and on the comparison of finite-difference and analytic solutions.

As an example of the moving grid system, consider Figure 10 showing the extent of the moving grid for the Rio Grande reaches 17, 18, and 19. The entire Rio Grande grid system shown in the figure is a result of this moving grid system concept. Reach 17 is assumed to be influenced by 76 nearby square mile cells -- numbers 42 to 118 in the Rio Grande grid system. The 9 x 16 moving grid is used in the east, west, and southerly directions, however, the northerly direction is restricted by the hydraulic boundary existing between the study area and the Closed Basin. Other boundaries which may also reduce the moving grid extent are the outer edge of the unconfined aquifer shwon by the dotted line in Figure 10 and the San Luis Hills to the south of the Conejos River. The moving grid for reach number 18 is exactly the same as for 17, however, for reach number 19 the Rio Grande grid system numbers influencing this reach are 52 to 127. The extent of the moving grid system for river reach number 19 is shown in Figure 10 by the dashed line.

The discrete kernels (deltas) are generated for the particular river reach or calculation cell within the observation area (the vicinity of the

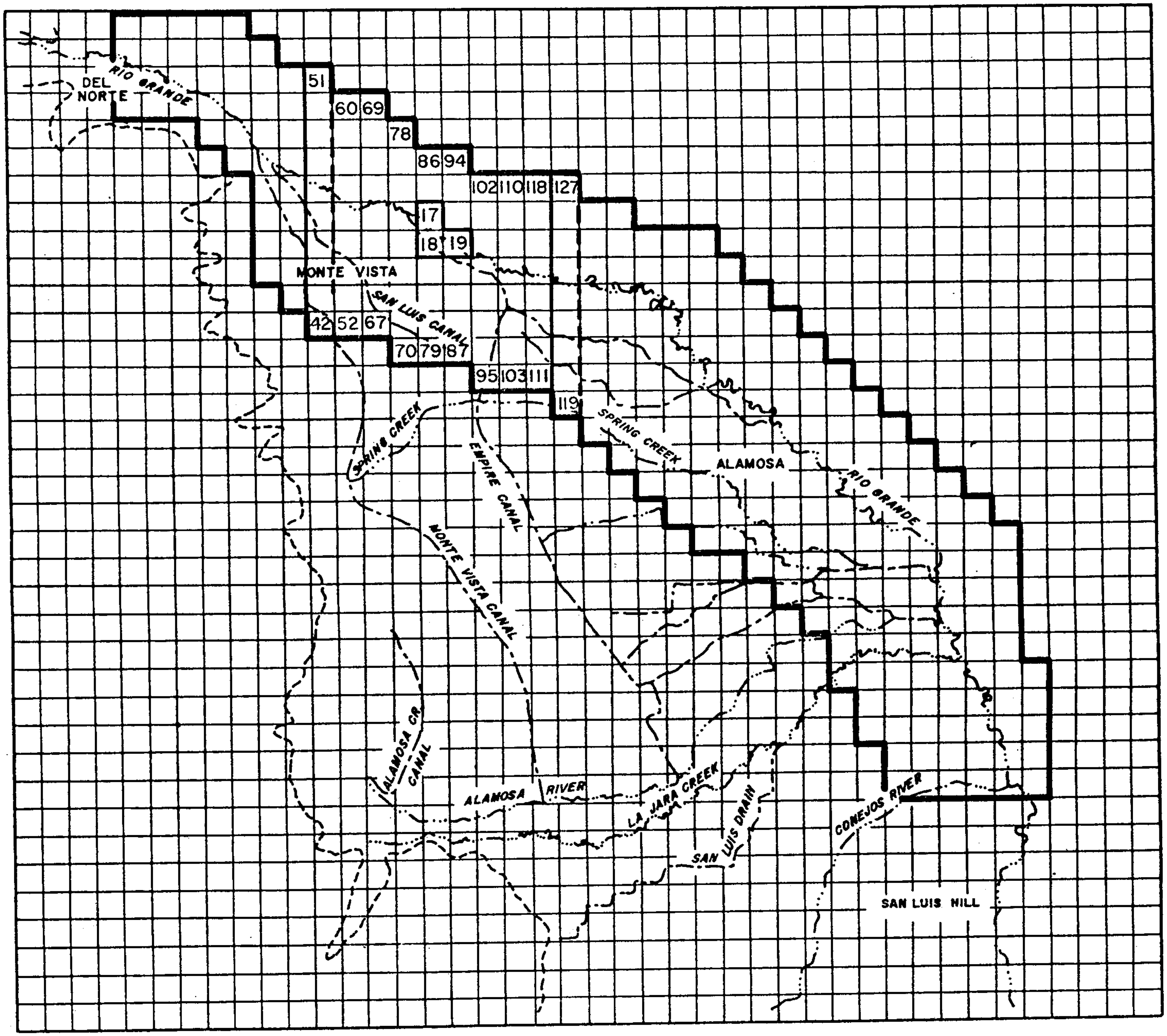


Figure 10. Moving Grid System for River Reach Numbers 17, 18, 19 Within the Rio Grande Grid System

waterlogged area which is described in detail in an earlier section) and the square mile cells within its associated moving grid system. These deltas are stored on computer file and can be recalled to calculate in turn the drawdown in the unconfined aquifer at all the river reaches and at the calculation cells in the observation area. The moving grid concept has been used to generate all the discrete kernel coefficients for the three river systems (Rio Grande, Conejos River, San Luis Drain) and the observation area which incorporates the waterlogged area.

An illustration of calculation of drawdown at reach 19 at the end of the first time period follows. The drawdown in the unconfined aquifer in the square mile cell of river reach cell 19 depends on excitations at cells (influence cells) within the defined moving grid system for reach 19. The drawdown is the sum of the product of the pumping excitations and the deltas for each influence cell. Hence

$$\begin{array}{l}\text{Drawdown in Aquifer}\\ \text{for Reach No. 19}\end{array} = S_{19}(1) = \sum_{\pi=52}^{127} \delta_{19,\pi}(1) \cdot Q_{\pi}(1)$$

where $S_{19}(1)$ = drawdown in aquifer at river reach cell 19 at end of period 1 (in general, $S_W(n)$)

$\delta_{19,\pi}(1)$ = discrete kernel of drawdown response at river reach cell 19 due to a unit excitation at grid number π (in general, $\delta_{W,\pi}(n-v+1)$)

$Q_{\pi}(1)$ = volume pumped at grid cell π during time period 1.

<u>Lumped Effect of Areas Outside the Moving Grid</u>: The effect of areas outside the moving grid system may have an influence on the drawdowns in the observation area after a long period of time. To account for this the excitations as a result of large areas outside the observation area grid, are lumped

together and assumed to act at the centroid of area. An analytic solution for drawdown at each of the 34 calculation cells in the observation area due to lumped excitations is then computed and superimposed on to the drawdown due to excitations with the observation area moving grid system. The three lumped areas considered in the hydrologic model for the analytic solution calculations are shown in Figure 11.

Modeling of the Initial Conditions: In order to utilize the discrete kernel technique an initial steady state condition is required to exist in the unconfined aquifer at the beginning of each simulation run. In the San Luis Valley the surface irrigation practices employed by the farmers have changed very little with time. Due to the current low farm efficiency irrigation practices there is a large amount of recharge of the unconfined aquifer in the irrigation areas. This recharge flows toward the rivers resulting in return flow from the unconfined aquifer to the rivers. Consequently, to enable the use of the discrete kernel approach for modeling the unconfined aquifer, the aquifer flow from the irrigation areas to the rivers is assumed to be in a condition of approximate steady state. The steady state is referred to as the initial conditions.

To determine these initial conditions the computer simulation model is run for a long period of time in an attempt to recreate the steady state flow situation. At the commencement of this simulation run the unconfined aquifer levels are assumed to be quite a distance below the ground surface. In the river reach cells the unconfined aquifer is assumed to be at average river state level. On moving perpendicularly away from the river the unconfined aquifer is assumed to be approximately flat. The irrigation system is operated from year to year, however, only surface water diversions are assumed to take

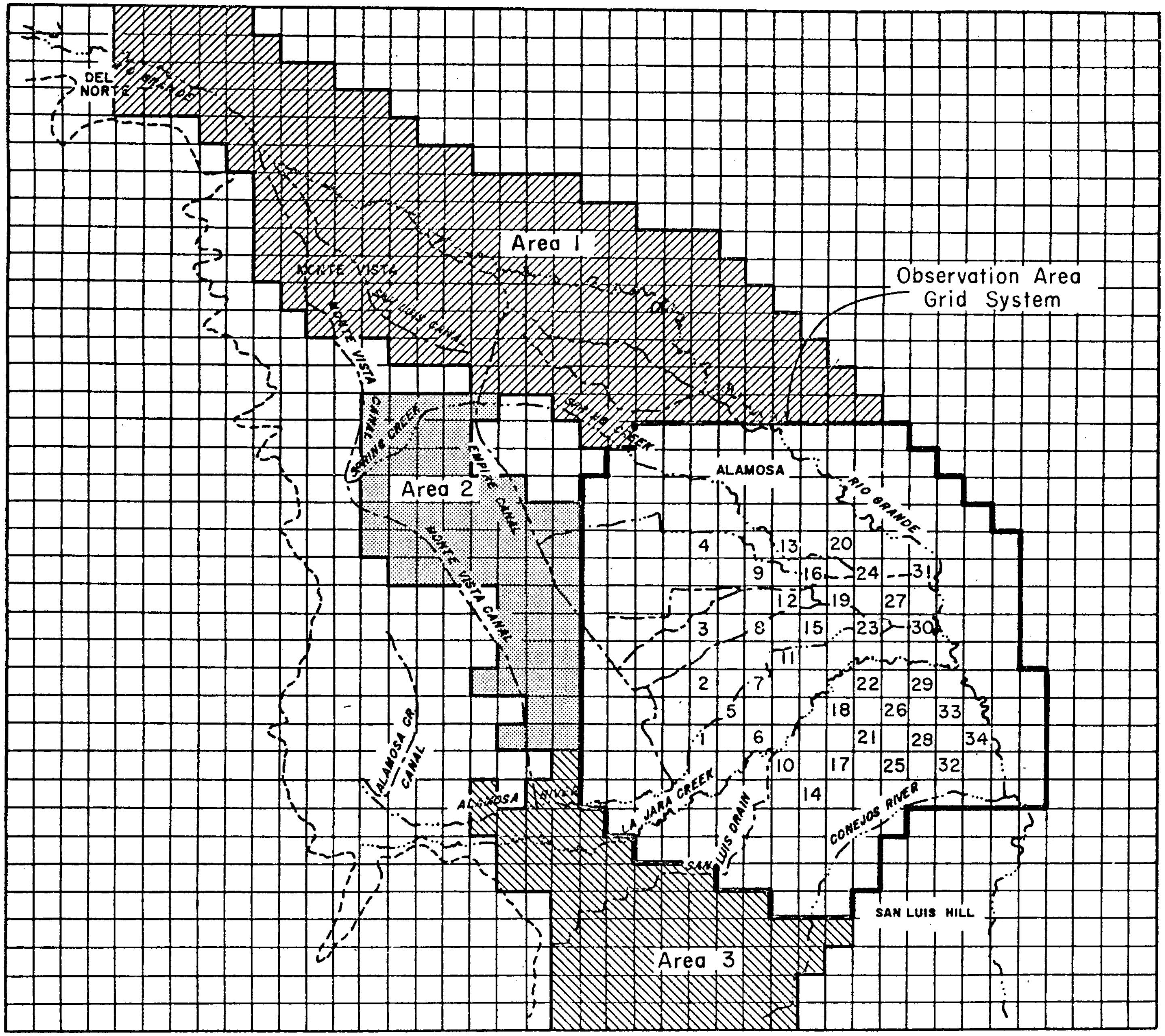


Figure 11. Lumped Areas Outside the Observation Area Used in the Analytic Solution

place. No groundwater withdrawals are made from either the unconfined or the confined aquifer.

The unconfined aquifer levels at each of the 34 calculation cells in the observation area at the end of the 12 year steady state simulation run are are used as the initial conditions for all the management strategy simulation runs.

The important feature of these initial conditions is that they reflect approximately the levels of the unconfined aquifer found in the San Luis Valley today. Consequently the various management strategies indicate the impact on the waterlogged area if various alternatives are used over the next 12 years.

Irrigation Areas

Description: Irrigated cropland is a major component of the San Luis Valley's economy. Crops grown in the valley include barley, wheat, oats, alfalfa, potatoes, vegetables, grass, and small grain hay. Cropland comprises 9.1 percent of the valley while irrigated pasture is another 4.2 percent making irrigated lands account for only 13.3 percent (624,660 acres) of total land (4,831,294 acres) of the basin, yet producing high-value grains, vegetables, hay, and pastures.

Five major irrigation areas within the study area were selected on the basis of the major sources of surface water supply. Three major canals convey water from the Rio Grande to irrigation areas. These major canals are the Empire Canal, Monte Vista Canal, and the San Luis and Rio Grande Canal. The irrigation areas are appropriately named Empire, Monte Vista, and the San Luis and Rio Grande. The other two irrigation areas are served by the Conejos River and the La Jara Creek/Alamosa River system respectively. Again these irrigation areas are named the Conejos and La Jara/Alamosa. Each irrigation area has downslope drainage areas where surface drainage runs overland from the irrigation area and then deep percolates to the unconfined aquifer.

CLIMATICALLY CONTROLLED COMPONENTS

General

The physical components of the system have been described in the previous section. The climatically controlled components which will be dealt with here are also physical components, however, they are governed by the annual cycle and consequently vary from year to year. The climatic conditions prevailing in the San Luis Valley result in the need for irrigated agriculture. The average rainfall is very low, resulting in a deficiency of moisture during the crop growing season. In turn the demand for surface water from diversions of streamflow is high.

A result of the high water table levels in the San Luis Valley is the high evapotranspiration which is a true loss of water from the system. Each of the climatically controlled variables introduced, i.e., rainfall, streamflow, evapotranspiration, and crop need, as well as the techniques used to model these components will be discussed in the following sections.

The Standardized Year: An important decision related to the use of climatic data in the hydrologic model was whether to use a 12 year historic sequence or average values for all the various climatic variables. A standardized year is established by taking this approach. This approach allows more conrol of the system because the annual cycle is repeated exactly during each of the 12 simulation years in the hydrologic model. However, the monthly fluctuations in the water budget are still retained. Consequently the changes due to the various management strategies should be more easily detectable.

The averages of the climatic variables are based on a 30 year period (1935-1964). The standard year also greatly facilitates data handling and storage requirements in the computer model.

Upstream River Inflows

Description: Streamflow resulting mainly from the spring snowmelt runoff is the source of surface water for irrigation in the San Luis Valley. As mentioned previously, these sources of surface water for the study area are the Rio Grande, the Conejos River, and the Alamosa River/La Jara Creek system. Good streamflow records for a considerable time period are available for a number of locations on each of these streams.

Modeling Technique: The Rio Grande is the major source of water supply in the study area. The modeling technique used is as follows: Some of the upstream flow into the study area for the Rio Grande is made available for diversion according to individual water rights during the irrigation season months. A certain quantity is reserved for the Rio Grande Compact Agreement. In addition, this upstream flow quantity may also be added to or removed from by return flow as it travels downstream toward the confluence of the Rio Grande and the Conejos Rivers. The location of the Rio Grande upstream inflow into the study area was selected very close to the Del Norte gage. Consequently, these gaging records are used as upstream inflow data.

The 30 year monthly average (1935-64) to form the standardized year of streamflows on the Rio Grande at Del Norte were calculated and are used as input to the hydrologic model. In each month of the simulation run of the hydrologic model, the 30 year monthly average streamflow is assumed to be the inflow to reach number 1. First, this inflow quantity is made available to satisfy the Rio Grande Compact Agreement requirements and then water rights in order of priority (only during months of irrigation season for crop need or for replenishing the unconfined aquifer storage). Return flows occur in each of the 57 Rio Grande reaches from the Del Norte gage downstream to the confluence of the Rio Grande and Conejos Rivers. The gaging station above Trinchera Creek near Los Sauses on the Rio Grande also has streamflow records available. As this gaging station is near the confluence of the Rio Grande and Conejos Rivers, the predicted monthly outflow from Reach 57 from the hydrologic model on the Rio Grande can be compared with the 30 year monthly averages for the Los Sauses gaging station. This comparison will give an indication of the calibration of the hydrologic model with the real physical situation.

The Conejos River irrigation diversions are not modeled in the same detail as for the Rio Grande. A fixed percentage of upstream inflow is reserved to satisfy the Rio Grande Compact Agreement. The existing individual Conejos River water rights are not used but rather the remaining percentage of the Conejos upstream inflow in each month is assumed to be available for irrigation (during the growing season) or for replenishment of the unconfined groundwater aquifer. Return flow is assumed to occur in each of the 17 Conejos River reach cells.

The Conejos River upstream inflow to the study area is assumed to be comprised of water from the Conejos River and the San Antonio River (a tributary of the Conejos River). The 30 year monthly average streamflows were calculated for the Mogote gaging station on the Conejos River (Rio Grande Compact Agreement index-station) and the Manassa gaging station on the San Antonio River. The Mogote gaging station is outside the study area, however, it is located on the southern edge of the entire Conejos irrigation district. There are few irrigation diversions above the Mogote gaging station on the Conejos River.

The major irrigation diversions along the Conejos River are downstream of Mogote gaging station. The confluence of the San Antonio and Conejos Rivers is inside the study area about half-way between the Mogote gaging station and the confluence of the Rio Grande and Conejos Rivers.

The Alamosa River/La Jara Creek diversions are modeled similarly to the Conejos River. Water rights are not modeled individually, instead, the total upstream inflow from the Alamosa River and the La Jara Creek is assumed to be available for irrigation. The upstream inflow for the Alamosa River is gaged just downstream of the Terrace Reservoir while for the La Jara Creek the gage is downstream of the La Jara Reservoir at Capulin. The 30 year monthly average upstream inflows for the La Jara Creek (Capulin) and Alamosa River (Terrace Reservoir) are used.

The San Luis Drain which includes the lower portion of the Alamosa River removes irrigation return flows from the Alamosa River/La Jara irrigation region delivering them back to the Rio Grande. As mentioned previously this drain is assumed to be hydraulically connected to the unconfined aquifer and consequently return flows in the 22 San Luis Drain reach cells are calculated in the hydrologic model. The upper reaches of the San Luis Drain do not have any associated streamflows.

Rainfall and Crop Needs

Description: Rainfall for the study area averages about 7.5 inches per annum. This is small and the growing season is short (90 to 120 days), however, this rainfall does meet some of crop needs. Again the 30 year basic period (1935-64) is used to compute the average monthly precipitation values. The rainfall records at Manassa and Alamosa are used to calculate these averages.

Crop needs vary according to crop type and month during the irrigation growing season (May through August). For the purposes of this study, the composition of the crops in each of the major irrigation areas is assumed to be equal amounts of alfalfa, hay, and barley. It should be noted that this type of crop pattern did not need to be assumed for the smaller irrigation areas. This results from the different technique employed to model the smaller irrigation areas compared to the On-Farm Allocation Method used to model the major areas.

Modeling Technique: Assuming the above crop composition, crop needs are calculated for the four growing season months (May to August) using Blank's Method (Blank, 1975). Blank calculated crop consumptive use data for controlled plots in Fort Collins. Blank's method is extrapolated to the San Luis Valley with a number of climatic adjustments.

Evapotranspiration

Description: The final climatically controlled variable to be considered is evapotranspiration. When the unconfined groundwater aquifer surface is within 12 feet (Emery, et al., 1979, and Figure 24 in Chapter IV) of the ground surface it is assumed evaporation will take place directly from the aquifer. Evaporation is calculated as a function of water table depth below the ground surface. This is based on the graph of annual evapotranspiration versus depth to unconfined aquifer water table below the land surface presented in the Hydrologic Investigations Atlas HA-381 by Emery, et al., (1971).

The amount of evaporation depends on the month, being low in winter and higher during the growing season for the same location of unconfined aquifer relative to ground surface. Pan evaporation rates for Alamosa (U.S.

Weather Bureau) were used to determine the 30 year averages. However, only 26 years of record (1939-64) were available rather than 30 years. Data are only available for Alamosa during the summer months; however, this is not a major problem as the majority of evaporation results in the four crop growing season months.

Modeling Technique: In the computer model the evaporation for a month is based on the location of the water table with respect to the ground surface at the end of the previous month. Due to the aquifer level falling as a result of the evaporation (especially when the unconfined aquifer is below the ground surface where the decline will be approximately 5 times the depth of evaporation due to the porosity of 0.2) the actual evaporation rate would decline as the month progressed. Consequently, the monthly evaporation is in general overestimated if only the level of the aquifer with respect to the land surface at the end of the previous month and the graph of Emery, et al., (1971) is considered. In order to correct for this effect the evaporation depth is multiplied by a fraction (F1.0) to more adequately reflect the actual evaporation from the unconfined aquifer. Selection of this fraction is also used in the calibration of the computer model. The calibrated value of the fraction is 0.7 when the aquifer is more than 6 inches above the ground surface, 0.5 when the aquifer is between zero and 6 inches above the ground surface and 0.2 when the aquifer is below the ground surface. It should be noted the evaporation rate would not always decrease as the month progressed if there was a large recharge of the unconfined aquifer during the month.

The evapotranspiration is most important in the region of the waterlogged area where the unconfined aquifer is close to the ground surface. Consequently it was decided to calculate the evaporation from the cells in the observation area only. The locations of cells at which the average elevation of the unconfined aquifer is calculated also determines where the evapotranspiration can be calculated.

To calculate the evapotranspiration in each cell the average water table elevation with respect to the ground is required. However, as noted previously, only 34 calculation cells are considered in the observation area. Consequently it is necessary to interpolate between these 34 points to estimate the evapotranspiration at all of the 245 square mile grid cells contained within the observation area. During irrigation season months when irrigation area grid cells have a consumptive use of water due to transpiration by plants the evaporation from the unconfined groundwater aquifer is not calculated.

LEGAL CONSTRAINTS

General

The two major factors which constitute the legal constraints for this study are the Rio Grande Compact Agreement and the doctrine of prior appropriation which dictates water rights in Colorado. The Rio Grande Compact Agreement resulted from the common need of Colorado, New Mexico, Texas, and the Republic of Mexico for water from the Rio Grande. The International Boundary Committee has jurisdiction over the Rio Grande Compact. Within Colorado the doctrine of prior appropriation provides that a person who first diverts and applies to a beneficial use the waters of a stream has a prior right thereto in relation to subsequent appropriators to the extent of his appropriation (Morel-Seytoux, et al., 1973, p. 59). Both of these aspects are discussed in more detail in the following sections.

Water Rights

The water rights associated with the Rio Grande can be subdivided into three categories. These include water rights for the three major irrigation areas (Monte Vista, Empire, and the San Luis and Rio Grande), for the 10 smaller irrigation areas, and for the Closed Basin. The water rights for the Closed Basin are assumed to be diverted to outside of the study area and are considered to no longer have any effect on the study area. Generally the quantity diverted to the Closed Basin is greater than the combined quantity diverted southward to the major irrigation areas and the smaller irrigation areas.

Allocation of Water for Surface Water Irrigation from the Rio Grande and the Conejos River: The quantity of surface water to be made available for diversion during the irrigation season (April to October) from the Rio Grande and the Conejos Rivers is determined by the District Engineer. He represents the State of Colorado and at present is Mr. McFadden at Alamosa in the San Luis Valley. The objectives of the District Engineer include ensuring the annual streamflow delivery requirements of the Rio Grande Compact Agreement are achieved and the proper administration of the water right priority system.

To determine the quantity of water to be made available for surface water diversion the following procedure is used by the District Engineer. In late March, prior to the beginning of the irrigation season, Mr. McFadden estimates the quantity of expected inflow for this calendar year (January to December) at the Del Norte index station on the Rio Grande. He also estimates the expected inflow for the Conejos system which involves the Mogote index station on the Conejos River and the index stations on the Los Pinos River and San Antonio River which both flow into the Conejos River. These expected inflow estimates are based on snow pack information, soil moisture conditions, stream flows in the past calendar year and the experience of the District Engineer.

Modeling of Water Rights: Individual surface water rights are modeled for the Rio Grande. The monthly quantities (acre feet/month) necessary to satisfy the water rights have been calculated from the flow rates (cfs) obtained from the State Engineer's Office.

The detailed procedure used in the hydrologic model for determining the total quantity to be made available for water right diversion from the Rio Grande is given in Simpson, et al., (1980). Each of the water rights is satisfied in priority sequence until this quantity (QMAFD) has been fully distributed. Lower priority surface water rights are not satisfied.

As explained previously, individual water rights are not modeled on the Conejos River system. A percentage curtailment for the Conejos River system inflow to meet the Rio Grande Compact Agreement is also calculated similarly to the steps outlined above for the Rio Grande. A certain quantity of water is then made available for diversion and is applied uniformly as irrigation surface water to the Conejos irrigation district. A similar procedure is followed to model the La Jara Creek/Alamosa River system.

Rio Grande Compact Agreement

Description: As mentioned previously, this compact attempts to reserve water for downstream states and the Republic of Mexico. In the early years after the Compact came into effect Colorado did not allow enough water from the Rio Grande and the Conejos River to flow downstream. Consequently a huge alleged debt resulted (700,000 acre feet). Limitations on the construction and operation of upstream storages were imposed until Colorado makes up this alleged deficit.

Modeling Techniques: The requirements of the Rio Grande Compact Agreement are based on the annual flow past the Del Norte index station on the Rio Grande and the Mogote index station (including San Antonio streamflow) on the Conejos River. As the 30 year average annual flows at the index stations are used as input to the model during each of the 12 years of simulation, the annual quantity which is supposed to be reserved for the Rio Grande Compact Agreement can be determined. The technique used by the District Engineer in the San Luis Valley to ensure water is reserved to go to meet the Rio Grande Compact Agreement is detailed in the section above on Water Rights.

INTERACTIONS BETWEEN COMPONENTS

General

To model the complex system in the San Luis Valley the behavior of various components has been studied and understood. Previous sections have presented these components and the approach adopted to model them in the hydrologic simulation model.

The next step is to consider the way in which these components interact. The components can be of the same type (i.e., both physical, like a stream and an aquifer) or of a different type like legal constraints and the aquifer (Morel-Seytoux, 1979, p. 12). Of the many interactions which exist the ones that will be described include the stream-aquifer interaction, stream-legal interaction, and the interaction between irrigation areas and the unconfined aquifer.

Stream-Aquifer Interaction (Return Flows)

Description: The three water courses which are considered to be hydraulically connected to the unconfined aquifer include the Rio Grande, the Conejos

River, and the San Luis Drain. Return flow occurs in each of the river reaches and as mentioned previously, depends on the relative levels of the water in the river reach and the level in the unconfined aquifer in the region of the river. The return flow is directly proportional to this elevation difference.

The coefficient of proportionality relating the return flow and the elevation difference between the level in the unconfined aquifer surrounding the river and the water level in the river depends on the aquifer characteristics and the shape of the stream cross-section (Morel-Seytoux, 1964; Bouwer, 1969). This constant of proportionality is the "reach transmissivity" (Morel-Seytoux, et al., 1979, p. 1). The definition of reach transmissivity in terms of aquifer properties and streambed characteristics will be presented in Chapter III.

Unlike pumping from the unconfined aquifer, which is a decision variable, the discharge from the river to the aquifer or vice versa (return flow) is a state variable. In other words, the return flow is not susceptible to man's control (Morel-Seytoux and Daly, 1975, p. 254). However, decisions concerning irrigation recharge and pumping from the unconfined aquifer do have an effect on the return flow even though it cannot be controlled directly. In areas of low precipitation this baseflow depends to a great degree on how the system is managed and does not depend solely on storage characteristics (Morel-Seytoux, et al., 1979).

Modeling Technique: In order to determine the return flows during one time period at all 95 reaches, the solution involves solving for 95 unknowns simultaneously. As an approximation to simplify the hydrologic model without sacrificing accuracy, each river reach return flow is solved for individually.

The return flows at other reaches for the previous time period are used as estimates of return flow for this time period. The return flow for a particular reach is then calculated based on streamflow and diversion information for this month as well as excitations for pumping, canal losses, and irrigation recharge during this time period. However, return flows in upstream and downstream reaches for the previous time period are used as an approximation.

Stream-Legal Interaction

This interaction involves the effect of legal constraints (which include the water rights and the Rio Grande Compact Agreement) on the quantity of water in the stream. This interaction has already been presented in detail in the section on Legal Constraints but it is important to recognize this as an interaction.

Irrigation Areas-Unconfined Aquifer Interaction

This is the final interaction which is discussed. There are numerous other interactions between various components.

Water distribution methods which are practiced by the farmer will determine the recharge of the unconfined aquifer in the region of the irrigation areas where the water was applied. These methods will also influence recharge of downgradient areas by surface runoff from the irrigation areas. This interaction has been one of the major factors contributing to the waterlogging problems in the San Luis Valley.

CHAPTER III

THE COMPUTER SIMULATION MODEL OF THE HYDROLOGIC SYSTEM

DATA REQUIREMENTS

Data requirements for the hydrologic model can be subdivided into four major categories:

- (i) Natural physical components. These include the rivers and aquifers.
- (ii) Man-made physical components. Irrigation areas and canals are examples of these.
- (iii) Climatically controlled components such as streamflow and evaporation.
- (iv) Legal constraints which include the water rights and the Rio Grande Compact.

Simpson, et al., (1980, Chapter III) describes and presents the data which are assembled and utilized in the hydrologic model to simulate the study area in the San Luis Valley. Some of the sources of data for this study include:

USGS (1960, 1961, 1962, 1963, 1964) Records of Surface Water of the United States
NASA Infrared Photographs (Department of Natural Resources, Colorado State University)
7 ½ Minute Series Topographic Maps (U.S. Geological Survey)
Unconfined Aquifer Transmissivity Map (U.S. Geological Survey)
Colorado Water Resources Circular 18, Plate 3 (Emery, et al., 1973)
Colorado Water Resources Basic Data Release No. 22 (Emery, et al., 1972)
Rainfall and Evaporation Data (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service)
State Engineer's Office, Denver
Measurements taken on site

The remainder of the chapter describes the sequence of computations which take place in the computer simulation model of the hydrologic system for the study area in the San Luis Valley. The individual components and interactions incorporated in the hydrologic model are discussed in detail in Chapter II.

In the following sections the actual workings and subroutines of the computer model are described.

The hydrologic computer model can be divided into the following sections (in sequence of calculation):

(i) Input data
(ii) Title page - printout
(iii) Surface water availability to the study area
(iv) Distribution of irrigation water to the farms
(v) Calculation of river grid system excitations
(vi) Return flows
(vii) Calculation of observation area grid system excitations
(viii) Excitations for the analytic solution calculation
(ix) Unconfined aquifer drawdowns at the 34 calculation cells in the observation area
(x) Summary of results - printout

Sections (i) and (ii) are only carried out once, at the beginning of the simulation run. However, sections (iii) to (x) are carried out during every month of the simulation run. Each of these sections is discussed in detail below.

THE INPUT DATA

General

The areas within the computer program where the input data is read include the main program SANLUIS and Subroutine READ.

A distinction is made between two forms of input data used in the computer model of the hydrologic system. The first form of input data is read from computer cards at the beginning of the program prior to commencement of the simulation run. This input data is stored in variables and arrays within the program and is passed between subroutines using COMMON. The other form of input data involves the discrete kernels of drawdown. These are stored on permanent files and are read from the file for use in calculations in each month of simulation. These permanent files are rewound after the calculations for each month are completed.

Data Read at the Beginning of the Simulation Run

The length of the simulation run in months (NMON) and the management strategy alternative (denoted by a flag (MSTRAT)) are set in SANLUIS. The input data is read from a computer storage file called SANDAT in subroutine READ. A complete description of input data, Fortran variables, and card format is available in a User's Manual for the SANLUIS computer program.

Discrete Kernels Read from Permanent File

The total number of discrete kernel coefficients (deltas) for the three river grid systems and the observation area grid system is so large it is not possible to store them all in arrays within the program. Instead these deltas are stored on permanent file. When the deltas are required for unconfined aquifer drawdown calculation in a particular month they are read from the permanent file. When all computations for a particular month are complete, the permanent files are rewound in preparation for use in the next month.

The permanent files storing the deltas are as follows:

(i) RFILE1, Rio Grande grid system deltas
(ii) CFILE, Conejos River grid system deltas
(iii) SFILE, San Luis Drain grid system deltas
(iv) WFILE, Observation area grid system deltas

TITLE PAGE PRINTOUT

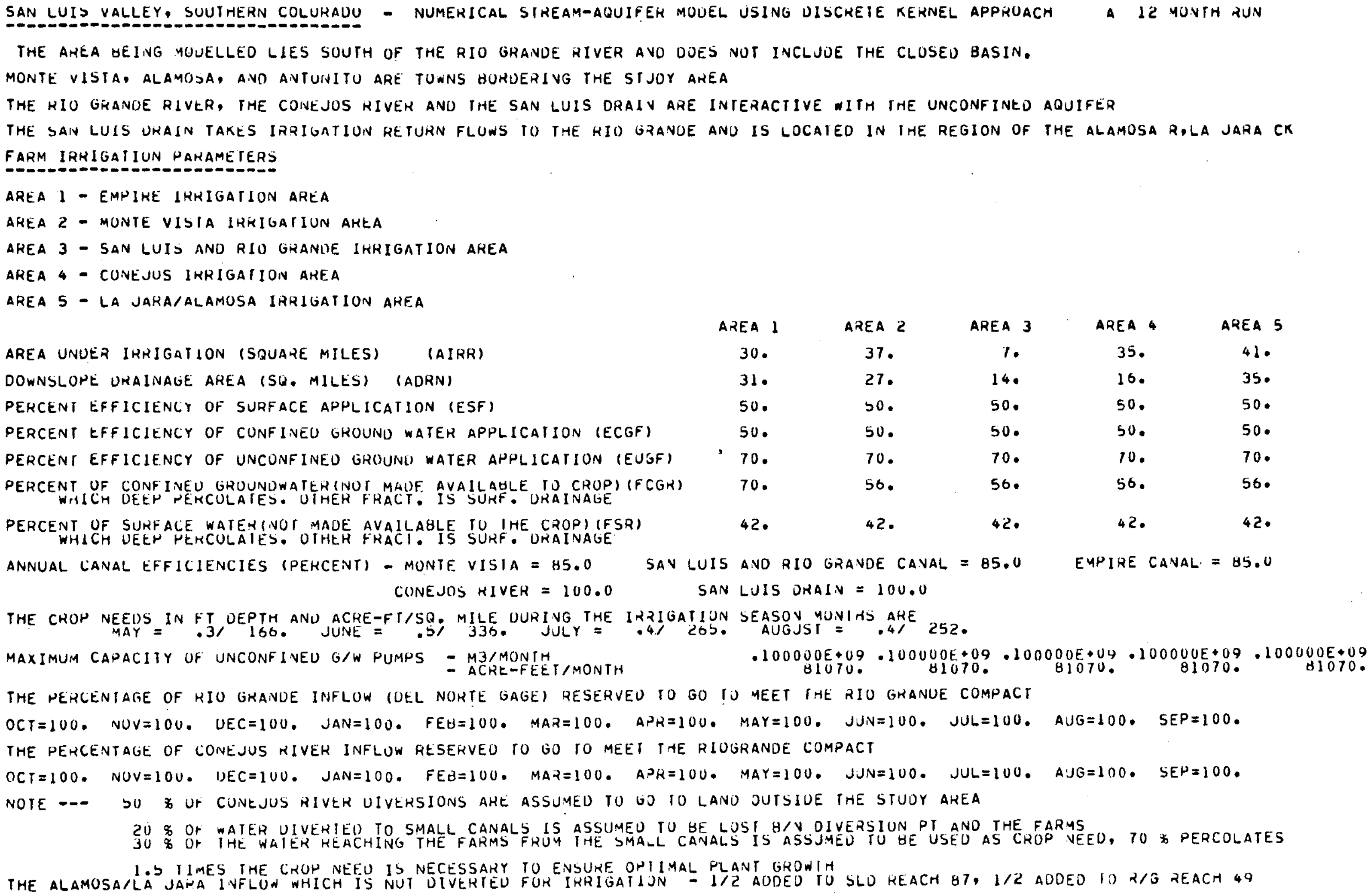
Subroutine PRIFACE prints the face sheet and includes all important input data information used in the hydrologic model.

An example of the title page is shown in Figure 12. The information printed out includes input data variables which may be altered for the different management strategies. Data which remains constant no matter which strategy is being investigated is not printed out.

SURFACE WATER AVAILABILITY

Subroutine AVAILAB calculates the surface water availablity from the Rio Grande to the major irrigation areas (5), the smaller irrigation areas (10), and the Closed Basin irrigation areas. The surface water availability is also calculated for the Conejos River and Alamosa River/La Jara Creek irrigation systems. Subroutine AVAILAB is only used in months during which surface water diversions are made from the rivers. That is, in growing season months or months prior to or just following the irrigation season when surface water is used to replenish the groundwater unconfined aquifer storage.

The surface water to be made available for diversion to satisfy irrigation requirements is calculated in this routine. The percentage curtailment of the Rio Grande and Conejos River system inflow is determined so as to meet the requirements of the Rio Grande Compact Agreement. The details of the curtailment calculation are given in the section on Legal Constraints in Chapter II. As a result a certain quantity of water is made available for diversion from both the Rio Grande and the Conejos River. The quantity of water available from the Rio Grande is distributed according to water right priorities. If the aquifer level is within 6 inches below the ground surface or above the ground surface in a major irrigation area in a growing season month, then sub-irrigation is used. The monthly surface water diversion to the major irrigation area is reduced to 60 percent. This percentage was determined by calibration. A percentage of 100 percent was used initially, however, the



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SAN LUIS VALLEY, SOUTHERN COLORADO  -  NUMERICAL STREAM-AQUIFER MODEL USING DISCRETE KERNEL APPROACH     A  12 MONTH RUN
----------------------------------
 THE AREA BEING MODELLED LIES SOUTH OF THE RIO GRANDE RIVER AND DOES NOT INCLUDE THE CLOSED BASIN.
MONTE VISTA, ALAMOSA, AND ANTONITO ARE TOWNS BORDERING THE STUDY AREA
THE RIO GRANDE RIVER, THE CONEJOS RIVER AND THE SAN LUIS DRAIN ARE INTERACTIVE WITH THE UNCONFINED AQUIFER
THE SAN LUIS DRAIN TAKES IRRIGATION RETURN FLOWS TO THE RIO GRANDE AND IS LOCATED IN THE REGION OF THE ALAMOSA R,LA JARA CK
FARM IRRIGATION PARAMETERS
--------------------------
AREA 1 - EMPIRE IRRIGATION AREA
AREA 2 - MONTE VISTA IRRIGATION AREA
AREA 3 - SAN LUIS AND RIO GRANDE IRRIGATION AREA
AREA 4 - CONEJOS IRRIGATION AREA
AREA 5 - LA JARA/ALAMOSA IRRIGATION AREA
                                                                        AREA 1     AREA 2     AREA 3     AREA 4     AREA 5
AREA UNDER IRRIGATION (SQUARE MILES)     (AIRR)                          30.        37.         7.        35.        41.
DOWNSLOPE DRAINAGE AREA (SQ. MILES)   (ADRN)                             31.        27.        14.        16.        35.
PERCENT EFFICIENCY OF SURFACE APPLICATION (ESF)                          50.        50.        50.        50.        50.
PERCENT EFFICIENCY OF CONFINED GROUND WATER APPLICATION (ECGF)           50.        50.        50.        50.        50.
PERCENT EFFICIENCY OF UNCONFINED GROUND WATER APPLICATION (EUGF)         70.        70.        70.        70.        70.
PERCENT OF CONFINED GROUNDWATER(NOT MADE AVAILABLE TO CROP)(FCGR)        70.        56.        56.        56.        56.
     WHICH DEEP PERCOLATES. OTHER FRACT. IS SURF. DRAINAGE
PERCENT OF SURFACE WATER(NOT MADE AVAILABLE TO THE CROP)(FSR)            42.        42.        42.        42.        42.
     WHICH DEEP PERCOLATES. OTHER FRACT. IS SURF. DRAINAGE
ANNUAL CANAL EFFICIENCIES (PERCENT) - MONTE VISTA = 85.0     SAN LUIS AND RIO GRANDE CANAL = 85.0     EMPIRE CANAL = 85.0
                                             CONEJOS RIVER = 100.0        SAN LUIS DRAIN = 100.0
THE CROP NEEDS IN FT DEPTH AND ACRE-FT/SQ. MILE DURING THE IRRIGATION SEASON MONTHS ARE
          MAY =   .3/  166.    JUNE =   .5/  336.    JULY =   .4/  265.    AUGUST =   .4/  252.
MAXIMUM CAPACITY OF UNCONFINED G/W PUMPS  - M3/MONTH                    .100000E+09 .100000E+09 .100000E+09 .100000E+09 .100000E+09
                                          - ACRE-FEET/MONTH                 81070.      81070.      81070.      81070.      81070.
THE PERCENTAGE OF RIO GRANDE INFLOW (DEL NORTE GAGE) RESERVED TO GO TO MEET THE RIO GRANDE COMPACT
OCT=100.  NOV=100.  DEC=100.  JAN=100.  FEB=100.  MAR=100.  APR=100.  MAY=100.  JUN=100.  JUL=100.  AUG=100.  SEP=100.
THE PERCENTAGE OF CONEJOS RIVER INFLOW RESERVED TO GO TO MEET THE RIOGRANDE COMPACT
OCT=100.  NOV=100.  DEC=100.  JAN=100.  FEB=100.  MAR=100.  APR=100.  MAY=100.  JUN=100.  JUL=100.  AUG=100.  SEP=100.
NOTE ---    50  % OF CONEJOS RIVER DIVERSIONS ARE ASSUMED TO GO TO LAND OUTSIDE THE STUDY AREA
          20 % OF WATER DIVERTED TO SMALL CANALS IS ASSUMED TO BE LOST B/N DIVERSION PT AND THE FARMS
          30 % OF THE WATER REACHING THE FARMS FROM THE SMALL CANALS IS ASSUMED TO BE USED AS CROP NEED, 70 % PERCOLATES
          1.5 TIMES THE CROP NEED IS NECESSARY TO ENSURE OPTIMAL PLANT GROWTH
THE ALAMOSA/LA JARA INFLOW WHICH IS NOT DIVERTED FOR IRRIGATION  - 1/2 ADDED TO SLD REACH 87, 1/2 ADDED TO R/G REACH 49
```

Fig. 12. Face sheet of the computer model printout of results.

aquifer level was found to rise to between 1 and 2 feet above the ground surface. The total amount of water received by each of the five major irrigation areas and 10 smaller irrigation areas is then calculated.

DISTRIBUTION OF IRRIGATION WATER TO THE FARMS

Subroutine IRRGATE calculates the distribution of surface water diversions, confined and unconfined aquifer water withdrawals for each of the five major irrigation areas. Again, as for Subroutine AVAILAB, this subroutine is only used in months during which surface water diversions are taken from the rivers. In other months Subroutine NONIRR is used.

The On-Farm Water Allocation Method is utilized in Subroutine IRRGATE. Some of the smaller irrigation areas overlap the major irrigation areas. Consequently, the water available to these smaller areas is added to the appropriate diversions to the major irrigation areas. The total surface water quantities available to the three Rio Grande supplied irrigation areas are then adjusted to account for transmission losses in the unlined canals. A certain quantity of water is then available to the farms in each of the five major irrigation areas and is adjusted by a fraction to account for a proportion of water which will not be within reach of the plant root zone. This is referred to as the irrigation efficiency, E_{sf}. A set quantity of confined groundwater is also available to each of the five major irrigation areas.

The total crop need for the month is determined (if the month is in the growing season) and compared with the total surface and groundwater available to the plant. If there is a deficiency, water from the unconfined groundwater aquifer is pumped. The upper limit for pumping is the maximum capacity of the pumps. If the aquifer level is within 6 inches of the ground surface subirrigation is used. The crop consumptive use is assumed to be met in the following way. Unconfined aquifer water in the soil profile provides 50 percent while surface water and confined aquifer deliveries provide 50 percent. The plant efficiency is then calculated.

The irrigation water applied to the farms in excess of crop need either ends up as deep percolation to the unconfined aquifer or surface drainage to downgradient areas where it then deep percolates. Subroutine IRRGATE keeps track of the water and ensures mass balance is maintained in each of the five major irrigation areas.

In months when no surface water diversions are made from the rivers, Subroutine NONIRR is used in place of Subroutine AVAILAB and Subroutine IRRGATE. Even in months of no surface water diversions, confined groundwater wells are still assumed to deliver water to the farms. The purpose of Subroutine NONIRR is to distribute the confined groundwater deliveries in non-growing season months.

RIVER GRID SYSTEM EXCITATIONS

The excitations are calculated at each of the 460 unique square mile grid cells for the Rio Grande, Conejos River, and the San Luis Drain grid systems in Subroutine SPACE. These excitations are used to calculate the average aquifer drawdowns at each of the 95 river reach cells in Subroutine HYDRO.

The various types of individual excitations which can contribute to the overall square mile grid cell excitation include:

(i) deep percolation to the unconfined aquifer in the five major irrigation area grid cells (On-Farm Water Allocation Method)

(ii) deep percolation of irrigation water which runs off from the major irrigation areas and deep percolates to the unconfined aquifer in the downgradient drainage areas

(iii) deep percolation to the unconfined aquifer in the 10 smaller irrigation areas (70 percent of the water reaching the farm headgate)

(iv) canal losses from the three major canals within the study area (Monte Vista, Empire, San Luis and Rio Grande)

(v) evapotranspiration at each of the grid cells in the region of the waterlogged area. The evaporation is based on interpolation between unconfined aquifer levels for last month at the 34 calculation cells in the observation area

(vi) return flow excitations at each of the 95 river reach cells.

On completion of calculation of the monthly excitations at each of the 460 unique grid cells within the three river grid systems, the excitations at the remaining 169 overlapping cells of the total 629 river grid system cells are assigned. Excitations have now been determined at all the grid cells in the three river grid systems.

RETURN FLOWS

The return flows for each of the 95 river reaches are calculated in Subroutine HYDRO.

Firstly, the excitations calculated in Subroutine SPACE are used to determine the unconfined aquifer average drawdowns in each of the 95 river reach grid cells by the discrete kernel technique. All the past monthly excitations are also used in the discrete kernel calculations. Secondly, the stage-discharge relationships are used to determine the average river stage in each of the 95 river reaches, in Subroutine STAGE.

To determine the values of the return flows in each of the river reaches a set of simultaneous equations would need to be solved. To simplify the computations in this hydrologic model it is assumed for the calculation of return flow at one particular river reach, that the return flows at all other river reaches are the same as last month's return flows. This approximation should produce only very minor errors. Each of the return flows in the 95 river reaches is solved for individually in turn in Subroutine HYDRO.

Once the return flows are known, the final quantity of water in each reach is found by applying mass balance beginning at the furthest upstream reaches on the Rio Grande, the Conejos River, and the San Luis Drain and proceeding downstream adjusting for return flows and diversions in each reach.

OBSERVATION AREA EXCITATIONS

The excitations for calculation of the average unconfined aquifer drawdowns at each of the 34 calculation cells in the observation area are determined in Subroutine NRESEC.

Many of the observation area grid cells overlap with the Rio Grande and San Luis Drain grid system. The 206 overlapping grid cell excitations are assigned the same values as calculated in Subroutine SPACE. For the remaining 39 unique square mile grid cells in the observation area of the total 245 grid cells, the excitations are calculated in Subroutine NRESEC taking into account the various types of excitations discussed in the previous section in River Grid System Excitations.

ANALYTIC SOLUTION EXCITATIONS

The lumped excitations for the three major areas of influence outside the observation area are calculated in Subroutine NRESEC. These excitations are used to calculate analytically the effect on the drawdown at each of the 34 calculation cells in the observation area due to these three lumped areas.

WATERLOGGED AREA DRAWDOWNS

The average unconfined aquifer drawdowns at each of the 34 calculation cells in the observation area are calculated in Subroutine DRAWD. Again, the discrete kernel approach is used to calculate aquifer drawdown similar to the average unconfined aquifer drawdown calculation at each of the 95 river reaches. The drawdown effect at each of the 34 calculation cells resulting from the three lumped areas is also evaluated using the analytic solution in Subroutine ANALYT. Subroutine EXI is for the calculation of the exponential integral and is utilized in Subroutine ANALYT. The analytic drawdowns are superimposed on the discrete kernel drawdowns to give total drawdowns of the unconfined aquifer at each of the 34 calculation cells (square mile grid cells) within the observation area.

RESULTS SUMMARY

When all the computations for a particular month have been completed a monthly summary is printed out. An annual summary is also prepared and printed out at the end of each water year (ends September).

Figures 13 to 15 show the typical output summary for a month. Firstly, the month number in the simulation run and the month within the water year is printed out. Whether the month is a growing season month (May through August) or not is also noted. The remaining output can be subdivided into four sections. These include the river summary, the river reach summary, the calculation cell drawdown summary, and the irrigation water use summary. These are discussed below.

River Summary

For both the Rio Grande and Conejos Rivers the following are output:

- upstream inflows
- total diversions
- Rio Grande Compact Agreement quantities reserved
- total return flow

```
IRRIGATION SEASON MONTH      JULY          MONTH =     10           MONTH OF IRRIGATION YEAR =  10

HISTORICAL      RIOGRANDE    HISTORICAL          CALC.      CONEJOS         RIOGRANDE       CONEJOS       CONEJOS            ALAMOSA/LA JARA
INFLOW RG       COMPACT QTY  OUTFLOW RG          OUTFLOW    HISTORIC        COMPACT QTY     HISTORIC      CALCULATED           INFLOW
(ACRE-FT/MON)   RESERVED                                    INFLOW          RESERVED        OUTFLOW       OUTFLOW
 78877.          11831.         12112.           32648.      26800.          20569.           7301.        22[illegible]83.        11659.

                                            MASS BALANCE ESTIMATES  -  ACRE-FEET/MONTH
      TOTAL                 TOTAL                   TOTAL              TOTAL            TOTAL R/G        UNSATISFIED R/G      TOTAL R/G
      RETURN FLOW           RETURN FLOW             RETURN FLOW        RETURN FLOW      DIVERSIONS       DIVERSIONS           DIVERSIONS
      RIO GRANDE            CONEJOS RIVER           SAN LUIS DRAIN     ALL REACHES      ALLOCATED                             MADE
         -692.                  2314.                  1275.             2897.            71469.                0.               55556.

      TOTAL CONEJOS       TOTAL ALAMOSA/LA JARA
      DIVERSIONS          DIVERSIONS
      MADE                MADE
         3116.                2915.

                                                                                                                          WATER
RIVER   RIVER   DISTANCE ABOVE  AQ. LEVEL   AQ. LEVEL   ELEVATION   CHANGE  TRANSMISS Y  CALCULATED     LEAVING         IRRIGATION
NUMBER  STAGE    LOW DATUM       ABOVE       ABOVE      DIFFERENCE  FROM    ACRE-FEET    RETURN FLOW    RIVER REACH     DIVERSION
                WATER IN RIVER  LOW DATUM   GROUND                  LAST    PER                                         ACRE-FEET
NR      SIGMA   (ZB-SIGMA)       (SP1)                  (ZB-SIGMA)  MONTH   FEET         QRR(NR)        QACNOW(NR)      SWDE(NR)

        (FEET)     (FEET)       (FEET)      (FEET)      (FEET)      (FEET)               (ACRE-FEET)    (ACRE-FEET/MONTH)
RIO GRANDE RIVER
  1      1.9       345.3        331.9       -18.1       -13.4        .9       76.         -1016.        53245.          24616.
  2      1.8       338.7        327.8       -15.7       -10.9       1.2       61.          -667.        51865.            712.
  3      1.8       322.3        322.5        -4.6          .2        .3      456.            94.        51331.            528.
  4      1.8       305.9        305.2        -5.4         -.7        .4      183.          -121.        51029.            181.
  5      1.8       296.0        290.3       -10.5        -5.7       1.1       61.          -346.        50681.              0.
  6      1.8       279.6        280.3        -4.1          .7        .5      200.           139.        50320.              0.
  7      1.8       269.8        268.3        -6.3        -1.5        .5      167.          -245.        46450.           2125.
  8      1.7       259.9        259.3        -5.4         -.6        .8       88.           -50.        44219.            181.
  9      2.6       251.0        249.0        -5.9        -2.0        .7      194.          -386.        47833.              0.
 10      2.4       231.0        230.8        -4.4         -.2        .8      202.           -42.        37114.          10676.
 11      2.4       221.2        221.7        -3.7          .5       1.3       62.            33.        37105.             42.
 12      2.3       198.2        199.3        -3.1         1.1       1.2      105.           115.        36809.            411.
 13      2.3       185.1        185.2        -4.1          .2       1.3       50.             8.        36195.            622.
 14      2.3       181.8        181.9        -4.1          .1       1.5       64.             7.        35960.            242.
 15      2.3       168.6        168.7        -4.2          .0       1.1      102.             2.        35745.            217.
 16      2.3       155.5        155.9        -3.9          .3        .9      144.            45.        35793.              0.
 17      2.3       145.7        145.0        -4.9         -.6       1.2       30.           -19.        35212.            562.
 18      2.3       142.4        142.9        -3.7          .5        .9      160.            85.        35298.              0.
 19      2.2       132.5        133.0        -3.8          .6       1.0      111.            62.        32375.           2984.
 20      2.1       122.5        125.2        -1.7         2.8       1.6       26.            72.        27472.           4975.
 21      2.1       112.6        114.4        -2.7         1.8        .9      217.           394.        27865.              0.
 22      2.1       100.1        106.6        -3.9          .5        .5      332.           179.        28045.              0.
 23      2.0        99.4        100.2        -3.8          .7        .9      130.            95.        24873.           3256.
 24      2.0        92.9         93.0        -3.8          .7       1.0       92.            69.        24942.              0.
 25      2.0        89.6         90.6        -3.5         1.0       1.0      110.           115.        25057.              0.
 26      2.0        86.3         86.8        -4.1          .4        .7      187.            83.        25140.              0.
 27      2.0        79.8         80.2        -4.1          .5        .5      320.           152.        25293.              0.
 28      2.0        79.8         80.3        -4.1          .5       1.1       83.            42.        25335.              0.
 29      2.0        76.5         77.0        -4.1          .5        .7      202.           101.        25436.              0.
 30      2.0        76.5         76.9        -4.2          .4        .8      118.            44.        25480.              0.
 31      2.0        69.9         70.5        -4.0          .6        .8      147.            82.        25562.              0.
 32      2.0        69.9         70.2        -4.3          .3        .8      124.            36.        25599.              0.
 33      3.8        65.2         65.4        -2.5          .3       1.0      149.            40.        25638.              0.
 34      3.8        65.1         65.3        -2.6          .1        .8      198.            27.        24989.            676.
 35      3.8        58.6         58.8        -2.5          .3        .9      175.            46.        25037.              0.
 36      3.8        55.3         54.9        -3.2         -.4       1.4       59.           -25.        25010.              0.
 37      3.8        52.0         52.0        -2.8          .0       1.2       99.             2.        25012.              0.
 38      3.8        52.0         50.4        -4.4        -1.7       1.6       33.           -54.        24958.              0.
 39      3.7        48.7         48.3        -3.2         -.4       1.1      114.           -43.        24253.            652.
 40      3.7        42.1         42.0        -3.0         -.2       1.2       69.           -15.        24247.              0.
 41      3.7        38.8         39.0        -2.7          .2        .9      204.            35.        22583.           1594.
 42      3.7        32.2         32.0        -3.1         -.2       1.4       68.           -14.        22674.              0.
 43      3.7        32.2         27.7        -7.4        -4.5       1.8       13.           -59.        22516.              0.
 44      3.7        28.9         27.5        -4.4        -1.5       1.8       37.           -51.        22371.            193.
 45      3.6        28.9         27.9        -4.0        -1.1       1.6       51.           -54.        22317.              0.
 46      3.6        25.6         21.0        -7.5        -4.5       1.9       12.           -55.        22262.              0.
 47      3.6        22.4         21.4        -3.8         -.9       1.6       45.           -43.        22219.              0.
 48      3.6        22.4         21.3        -3.9        -1.0       1.6       50.           -51.        22168.              0.
 49      3.8        19.3         19.2        -2.8         -.1       1.4       75.            -7.        26533.              0.
 50      4.1        19.5         19.7        -2.3          .2        .7      215.            35.        32215.              0.
 51      4.1        19.5         18.2        -3.8        -1.3       1.6       48.           -64.        32152.              0.
 52      4.1        16.2         16.4        -2.3          .1        .8      227.            32.        32183.              0.
 53      4.1        13.0         13.2        -2.3          .2       1.2      110.            22.        32205.              0.
 54      4.1        13.0         13.1        -2.3          .2       1.2      120.            26.        32225.              0.
 55      4.1        13.0         13.0        -2.5         -.0       1.1      134.            -0.        32225.              0.
 56      4.1         9.7         10.2        -1.9          .5        .9      180.            94.        32320.              0.
 57      4.1         9.7         13.1          .9         3.6        .9       97.           375.        32648.          11831.
```

Figure 13. Hydrologic Computer Model Results Summary (Part 1).

```
CONEJOS RIVER
 58        2.4          158.9      158.6        -1.1        -.3       .4      249.          -65.       20504.
 59        2.4          155.6      151.5        -5.0       -4.1      1.6       23.          -35.       20469.
 60        2.4          139.2      139.7         -.4         .5       .4      231.          140.       20549.
 61        2.4          126.1      126.0        -1.0        -.1       .6       55.           -7.       20542.
 62        2.4          119.5      121.8         1.4        2.2      1.0       65.          146.       20685.
 63        2.4          109.7      110.5         -.1         .8       .3      299.          227.       20915.
 64        2.4           99.9      100.8          .1        1.0       .4      234.          227.       21142.
 65        2.4           90.0       90.1         -.8         .0       .4      208.            9.       21151.
 66        2.4           83.5       84.3         -.1         .8       .8      106.           82.       21233.
 67        2.4           73.6       74.9          .4        1.2       .4      221.          272.       21505.
 68        2.4           60.5       60.9         -.5         .4       .6      166.           67.       21572.
 69        2.5           50.7       52.4          .9        1.7       .5      211.          368.       21940.
 70        2.5           47.4       45.2        -3.1       -2.2      1.4       25.          -56.       21884.
 71        2.5           37.6       38.4         -.0         .8       .5      243.          193.       22077.
 72        2.5           27.7       29.1          .6        1.4       .6      183.          252.       22329.
 73        2.5           17.9       19.6          .9        1.7       .5      195.          324.       22652.
 74        2.5           11.4       13.0          .8        1.6       .6      145.          231.       22883.
SAN LUIS DRAIN
 75         .0          140.1      142.8         -.6        2.7       .0       41.          110.         110.
 76         .0          127.0      127.2        -3.0         .2      -.5       51.           11.         121.
 77         .0          117.2      118.2        -2.2        1.0      -.2      295.          296.         417.
 78         .1          110.7      111.4        -2.4         .7      -.1      298.          215.         632.
 79         .2          110.7      111.1        -2.8         .4      -.1      259.           97.         729.
 80         .2           97.6       97.7        -3.0         .1      -.2      224.           28.         757.
 81         .2           94.3       94.8        -2.7         .4      -.1      158.           70.         827.
 82         .2           91.1       91.6        -2.6         .5      -.1      146.           72.         899.
 83         .2           81.2       81.9        -2.4         .6      -.1      199.          127.        1025.
 84         .2           78.0       77.5        -3.6        -.5      -.2      145.          -73.         953.
 85         .2           74.7       74.0        -3.7        -.6      -.2      142.          -91.         862.
 86         .2           68.1       68.4        -2.6         .3      -.1      221.           68.         929.
 87         .7           62.1       62.4        -2.3         .3       .1      371.          123.        5424.
 88         .7           55.5       55.2        -2.8        -.3       .1      434.         -112.        5312.
 89         .7           52.2       51.4        -3.4        -.8       .1      126.         -105.        5206.
 90         .7           45.6       45.9        -2.4         .2       .1      404.           99.        5305.
 91         .7           42.4       42.7        -2.3         .3       .2      212.           66.        5372.
 92         .7           39.1       39.2        -2.5         .1       .1      494.           43.        5415.
 93         .7           32.5       32.6        -2.5         .1       .1      481.           40.        5455.
 94         .7           22.7       22.9        -2.4         .2       .2      410.           81.        5536.
 95         .7           19.4       19.7        -2.3         .3       .2      439.          111.        5547.

SATISFIED WATER RIGHT = 1. NON-SATISFIED = 0     1-132, 1ST LINE     133-228, 2ND LINE
111111111111111111111111111111111111111111111111111111111111111111111111111100000000000000000000000000000000000000000000000000000000

000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000

PROPORTION OF WATER RIGHTS ON THE RIO GRANDE SATISIFIED =  .33

 DRAWDOWNS IN WATERLOGGED AREA          --IF DISTANCE ABOVE GROUND SURFACE IS POSITIVE, THIS HAS BEEN CALCULATED FROM
              FEET                                  0.2X(DIST. ABOVE GROUND SURFACE MINUS LAND SURFACE ELEVATION)

    WELL ID.      AQUIFER        LAND SURFACE       DISTANCE ABOVE  CHANGE FROM   DRAWDOWN DUE            EVAP
                  LEVEL           ABOVE LOW DATUM   GROUND SURFACE  LAST MONTH    ANALYTIC SOLUTION       FT DEPTH
       1           76.9              81.               -4.2            .2         .16402E-12               0.0
       2           73.0              81.               -8.1            .0         .88966E-18               0.0
       3           69.7              76.               -8.1           -.1         .13051E-15               0.0
       4           58.6              61.               -2.8            .5         .22296E-15                .0
       5           64.9              71.               -6.3            .2         .26494E-18               0.0
       6           69.3              74.               -5.2            .1         .16158E-19               0.0
       7           54.0              58.               -4.1            .4         .50116E-25               0.0
       8           57.2              65.               -7.4           -.7         .23962E-23               0.0
       9           44.3              52.               -7.2           -.4         .45826E-23               0.0
      10           68.4              71.               -2.8           -.1         .37967E-15                .0
      11           49.2              55.               -5.6            .5         .25274E-29               0.0
      12           43.3              52.               -8.2            .5         .90485E-28               0.0
      13           37.7              45.               -7.2            .6         .90885E-28               0.0
      14           69.9              74.               -4.6            .2         .20120E-15               0.0
      15           38.5              45.               -6.5            .7         .68355E-33               0.0
      16           33.9              42.               -7.8            .6         .14701E-32               0.0
      17           54.0              65.              -10.6            .0         .99150E-22               0.0
      18           47.5              55.               -7.3           -.7         .89809E-30               0.0
      19           31.5              42.              -10.2            .5         .84784E-39               0.0
      20           30.5              38.               -7.9            .6         .84784E-39               0.0
      21           43.9              55.              -10.9          -1.0         .37724E-30               0.0
      22           37.2              42.               -4.5            .9         .52251E-39               0.0
      23           27.3              38.              -11.1            .4         .35031E-45               0.0
      24           23.3              35.              -11.6            .3         .20907E-44               0.0
      25           35.2              45.               -9.8            .4         .27100E-31               0.0
      26           32.8              42.               -8.9            .4         .19474E-39               0.0
      27           19.9              32.              -12.0            .3         .21881E-50               0.0
      28           21.4              32.              -10.5            .3         .35667E-41               0.0
      29           16.4              25.               -8.9            .7         .63986E-50               0.0
      30           16.8              29.              -11.8            .4         .47025E-58               0.0
      31           19.1              32.              -12.7            .3         .35517E-57               0.0
      32           16.3              25.               -9.0            .5         .60103E-43               0.0
      33           12.4              25.              -12.9            .3         .68843E-51               0.0
      34            7.6              15.               -7.9            .7         .75546E-54               0.0
```

Figure 14. Hydrologic Computer Model Results Summary (Part 2).

```
                                                                                         IRRIGATION AREAS
 UNITS - (1) ACRE-FEET/MONTH (2)FT/MONTH                 EMPIRE        MONTE VISTA   SANLUIS/RIOGRANDE     CONEJOS          ALAMOSA/LA JARA
AREA OF IRRIGATION REGION    (SQUARE MILES)               30.             37.               7.               35.                 41.
                                                       ACRE-FT/  FT
TOTAL WATER QUANTITY DIVERTED FROM RIVER VIA CAN       2984./  .2       1995./  .1        325./  .1       3116./  .1         2915./  .1
   SWD                                                  R/G RCH 19     R/G RCH 10       R/G RCH 10     .12XCONEJOS INF    ALL SLD INF

MAJOR CANAL DIVERSION AVAIL. TO FARMS                  2537./  .1       1696./  .1        276./  .1       3116./  .1         2915./  .1
      (SWD X EC)
TOTAL VOLUME OF SURFACE WATER AVAIL. TO FARMS          3382./  .2       2706./  .1        918./  .2       3116./  .1         2915./  .1
      (DSAF) - MAJOR CANALS AND SMALL CANALS
TOTAL SURFACE WATER AVAIL. TO PLANTS                   1691./  .1       1353./  .1        459./. .1       1558./  .1         1457./  .1
      (DSAP)
TOT. VOL. OF CONFINED G/W AVAIL. TO FARMS              3681./  .2       6729./  .3        284./  .1       4556./  .2         5715./  .2
      (DCGAF)
VOL. OF CONFINED G/W AVAIL. PLANTS                     1840./  .1       3364./  .1        142./  .0       2278./  .1         2858./  .1
      (DCGAP)
TOTAL SURF. AND CONF. WATER AVAIL. TO PLANT            3532./  .2       4717./  .2        601./  .1       3836./  .2         4315./  .2
      (DSAP + DCGAP)
VOL. OF WATER SUPPLEMENT REQ. BY PLANTS               11911./  .6      14691./  .6       2779./  .6      13897./  .6        16279./  .6
      (DN X 1.5) FOR OPTIMAL PLANT GROWTH
TOTAL PUMPING CAPACITY OF UNCONFINED WELLS            81070./ 4.2      81070./ 3.4      81070./18.1      81070./ 3.6        81070./ 3.1
      (TCUGW)
UNCONFINED AQUIFER WATER PUMPED TO                    11971./  .6      14247./  .6       3112./  .7      14373./  .6        17091./  .7
MAKE UP CROP NEED (DUGAF)
VOL. OF UNCONF. G/W PUMPED TO MAKE UP CROP NEED        8380./  .4       9973./  .4       2176./  .5      10061./  .4        11964./  .5
      AVAIL. TO PLANTS  (DUGAP)
TOT. SURFACE, CONF, UNCONF G/W AVAIL. TO PLANTS       11911./  .6      14691./  .6       2779./  .6      13897./  .6        16279./  .6
      (DAP)
PLANT EFFICIENCY                                              .56              .66              .66              .56                .66
      (EP)
CONSUMPTIVE USE BY PLANTS                              7838./  .4       9667./  .4       1829./  .4       9144./  .4        10712./  .4
      CUSE
TOTAL VOLUME OF WATER DEFICIT                            0./ 0.0          0./ 0.0          0./ 0.0          0./ 0.0            0./ 0.0

IRRIGATION WATER RECHARGING AQUIFER (DR)               9148./  .5      11260./  .5       2137./  .5      10675./  .5        12507./  .5
IRRIGATION WATER DRAINING TO ADJACENT AREAS (DD)       2048./  .1       2736./  .2        348./  .0       2225./  .2         2503./  .1

DEPTH OF WATER REMOVED - NORTH SIDE PUMPING=   .2 FT

MAJOR CANAL DIVERSIONS =            5304. ACRE-FT  10. % OF THE DIVERSIONS
SMALL CANAL DIVERSIONS =           19580. ACRE-FT  35. % OF TOTAL DIVERSIONS
CLOSED BASIN DIVERSIONS =          30672. ACRE-FT  55. %  OF TOTAL DIVERSIONS

SMALL CANAL DIVERSIONS                                                               ACRE-FT/ACRE          TOT. VOL.(ACRE-FT)

          AREA 1 - 12 SQ.MI. ON STH OF R/G UPSTREAM OF MV CANAL OFFTAKE, REACH 1           .2                     1509.
          AREA 2 - 15 SQ.MI. ON NTH OF R/G STRETCHING EAST FROM DEL NORTE, REACH 1         .1                     1051.
          AREA 3 - 13 SQ.MI. STH OF R/G ALONG 1ST SECT. OF MV CANAL, REACH 10             1.2                     9654.
          AREA 4 - 6 SQ.MI. ON NTH OF R/G JUST EAST OF MV CANAL. REACH 12                  .1                      411.
          AREA 5 - 13 SQ.MI. STH OF R/G JUST EAST OF MV CANAL OFFTAKE, REACH 13            .1                      459.
          AREA 6 - 4 SQ.MI. STH OF R/G NR EMPIRE CANAL OFFTAKE, REACH 19                  1.9                     4975.
          AREA 7 - 5 SQ.MI. NTH OF R/G - COSTILLA CANAL, REACH 28                         0.0                        0.
          AREA 8 - 6 SQ.MI. NTH OF R/G NTH OF ALAMOSA, REACH 34                            .2                      676.
          AREA 9 - 5 SQ.MI. STH OF R/G JUST EAST OF ALAMOSA, REACH 39                      .2                      652.
          AREA 10 - 5 SQ.MI. STH OF R/G JUST NTH OF LA JARA CONFLUENCE, REACH 44           .1                      193.
```

Figure 15. Hydrologic Computer Model Results Summary (Part 3).

- downstream outflows (predicted)
- historic downstream outflows for comparison with predicted outflows.

While for the Alamosa River/La Jara Creek system the following are output:

- upstream inflows
- total diversions to irrigation areas
- total return flow for the San Luis Drain.

River Reach Summary

For each of the three major systems hydraulically connected to the aquifer (Rio Grande, Conejos River, San Luis Drain) the following are output in the summary:

(i) River reach number
(ii) Average stage in the river reach
(iii) Average elevation of the river surface with respect to the low datum
(iv) Average unconfined aquifer elevation in the river reach grid cell with respect to the low datum
(v) Difference in level between (iii) and (iv)
(vi) Change in the difference of level (v) from last month
(vii) The reach transmissivity
(viii) The calculated return flow
(ix) The water leaving the reach (which becomes the inflow for the reach immediately downstream)
(x) The surface water irrigation diversion from the reach (for the Rio Grande only).

Waterlogged Area Summary

For each of the 34 calculation cells in the observation area the following information is included in the output summary:

(i) Calculation cell identification number
(ii) Average unconfined aquifer elevation in the square mile grid cell for the calculation cell

(iii) The average land surface elevation in the square mile grid cell for the calculation cell

(iv) The average distance the unconfined groundwater aquifer lies above or below the land surface in the square mile grid cell of the calculation cell

(v) The change of the average distance above or below the ground surface (iv) from last month

(vi) The drawdown at the calculation cell resulting from the effect of the three lumped areas outside the observation area calculated using an analytic solution

(vii) The average depth of evaporation from the square mile calculation point grid cell.

Irrigation Water Use

On-Farm Water Allocation: For each of the five major irrigation areas a summary of irrigation water use is output in the irrigation season months. The following items are included in the output for each of the five major irrigation areas:

(i) Area under irrigation (square miles) and area of downgradient runoff

(ii) Total volume of surface water (acre feet) made available for diversion from the river to the farms via the canals

(iii) The volume of surface water (acre feet) arriving at farm headgate depleted by canal losses

(iv) The total volume of water (acre feet) available to the farm ((iii) + overlapping smaller irrigation areas surface water diversions)

(v) The total volume of surface water (acre feet) available to the plants -- some of the water available to the farm will be out of reach of the plant root zones

(vi) Total volume of confined groundwater (acre feet) available to the farms and consequently to the plants -- again some water is out of reach of the root zone

(vii) Total volume of surface water (acre feet) and confined groundwater available to the plants

(viii) Total volume of water supplement (acre feet) required by the plants for optimal plant growth (crop need)

(ix) Total volume of unconfined aquifer well pumping capacity (acre feet)

(x) Total volume of unconfined aquifer water (acre feet) pumped to meet any water deficit due to the surface water diversions and the confined groundwater deliveries (vii) not meeting the crop need

(xi) Plant efficiency expressed as a decimal fraction

(xii) Volume of consumptive use (acre feet) by the plants

(xiii) Total volume (acre feet) of water deficit. The water deficit is the difference between the volume of irrigation water required for optimal plant growth and the amount of water actually supplied to the crops

(xiv) Total volume of irrigation water (acre feet) recharging the unconfined aquifer beneath the irrigation areas.

(xv) Total volume of irrigation water (acre feet) which runs off overland to downgradient drainage areas and then deep percolates to the unconfined aquifer.

The surface water rights satisfied in the particular month and the proportion of surface water rights satisfied (out of 228) are also printed out.

Northside Pumping: The depth of water (feet) assumed to be removed or recharging the square mile grid cells of the Northside Pumping Area is also output in the monthly summary.

Rio Grande Surface Water Diversions: The total surface water diversions (all expressed as volumes in acre feet) from the Rio Grande are subdivided into:

(i) diversions to the major irrigation areas (3) -- Empire, Monte Vista, San Luis and Rio Grande

(ii) diversions to the 10 smaller irrigation areas

(iii) diversions to the Closed Basin.

These are included in the output summary.

Smaller Irrigation Areas Water Use: For each of the 10 smaller irrigation areas the following items are output:

(i) the number of the irrigation area

(ii) land area (square miles) included in the irrigation area

(iii) depth of surface irrigation water applied (feet)

(iv) total volume (acre feet) of surface irrigation water made avail-for diversion to the irrigation area from the Rio Grande River.

Annual Summary

This section of the printout which is carried out at the end of each September includes the following sections (all water quantities are expressed as volumes in acre feet):

(i) Water resources available over the past year (surface water, confined groundwater, unconfined groundwater)

(ii) Overall Annual Utilization of Water Resources -- surface water diversions, river return flows, Rio Grande Compact Agreement, water requirements for optimal growth, water consumption by the crops, water deficit, total unconfined aquifer recharge, and the total evaporation loss

(iii) Annual Utilization of Rio Grande Water Resources -- inflow, quantity reserved for Rio Grande Compact Agreement, quantity required to meet Compact, predicted outflow, historic outflow, return flow, surface water diversions from the river, diversions allocated but not satisfied, breakdown of surface water diversions to major irrigation areas, smaller irrigation areas, and the Closed Basin

(iv) Utilization of Conejos River Water Resources -- items printed out are similar to (iii)

(v) Utilization of Alamosa River/La Jara Creek Water Resources -- inflow, streamflow diverted for surface water irrigation, the return flow for the San Luis Drain, and the outflow from the San Luis Drain to the Rio Grande.

CHAPTER IV

THE MANAGEMENT STRATEGIES

GENERAL

The description of the management strategies is presented in this chapter while the results of the simulation runs of the various strategies are compared in Chapter V. For management strategies no. 1 and 2, the effect on the study area due to the development of the well fields to alleviate waterlogging is assessed.

The management strategies investigated in this study are as follows:

(i) Historic strategy
(ii) Management strategy no. 1 - La Jara Creek well field development
(iii) Management strategy no. 2 - Rock Creek well field development

THE HISTORIC STRATEGY

This strategy reflects the way in which irrigation practices are carried out in the study area in the San Luis Valley at the present time. Results from the run of the computer simulation model using the historic management strategy enable a check to be made of the calibration of the model.

The historic strategy has been described in detail in preceding chapters. The important feature of the strategy is the downgradient drainage, both underground and overland, from the irrigation areas (especially Empire and Alamosa/La Jara irrigation areas) which contribute to the waterlogging of downslope areas. Excessive application of surface water and uncontrolled flow from the confined aquifer wells are causes of the waterlogging problem.

MANAGEMENT STRATEGY NO. 1 - LA JARA CREEK WELL FIELD DEVELOPMENT

Description of Strategy

Location: This strategy involves a well field in the region of the La Jara Creek/Alamosa River and Rio Grande confluence. Sixteen square miles of land are included in the well field. Figure 16 shows the location of the well field. The center pivot pumps in the well field are used to lower the water table of this waterlogged area. Water for leaching and irrigation requirements is also provided by these pumps after dewatering of the aquifer is completed.

Soil Types: According to soil studies carried out by Franklin (1978, p. 2), three groups of soils are found in the waterlogged area in the San Luis Valley. The subdivision is based on salinity, exchangeable sodium, and water table depth. The following discussion is based on the information presented in Franklin's 1978 report. The three soil groups are wet meadow soils, salt meadow soils, and salt flat soils.

The wet meadow soils are non-saline to slightly salinized but no gypsum or leaching is necessary before cropping. These soils consist of level to nearly level, low flood plains along the Rio Grande, Alamosa River, La Jara Creek, and Rock Creek that are flooded periodically during spring runoff. These soils produce native hay, as well as furnishing pasture for livestock.

Salt meadow soils are salinized and waterlogged soils requiring drainage and leaching water applications before cropping. These soils are at slightly higher elevation than wet meadow soils and are subject to occasional flooding only when runoff is much higher than normal. Crop cultivation is limited by both salinity and high water table.

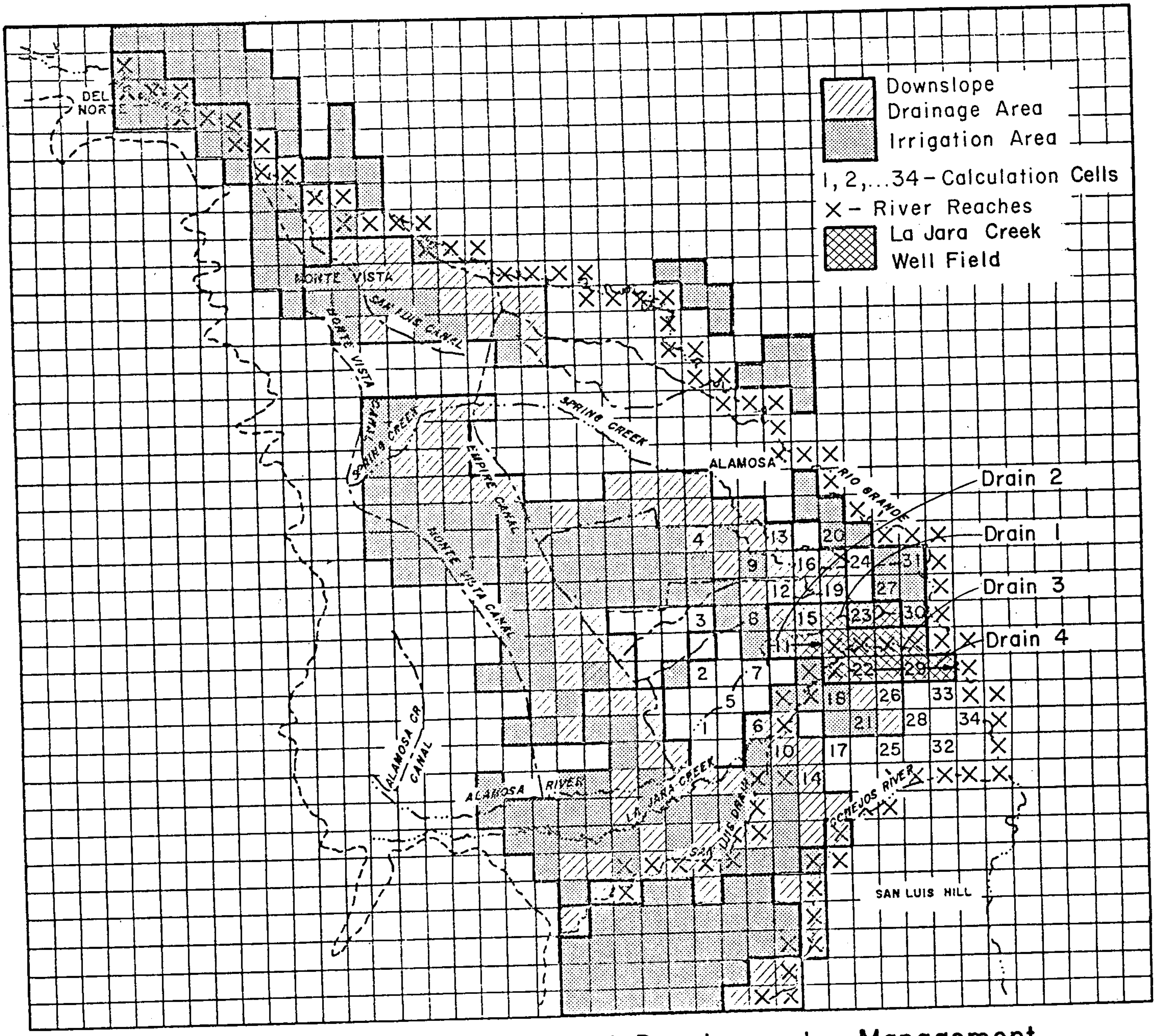

Figure 16 The La Jara Creek Well Field Development - Management Strategy No. 1

Salt flat soils are saline and sodic requiring drainage, gypsum, and leaching water for reclamation before establishing crops. These soils occupy gently sloping low terrace positions somewhat higher than the other two soil types. These soils are seldom flooded. Vegetation has a limited grazing value for livestock. The salt flat soils are subject to a fluctuating water table. The La Jara Creek well field contains a mixture of wet meadow soils and salt meadow soils.

Lowering the Water Table: The well field consists of center pivot sprinklers located 4 per square mile to irrigate 135 acres each. The capacity of the 4 wells in a square mile needs to be 608 acre feet/month each to meet the optimal growth water requirement in the highest water deficit month (June). However, for purposes of lowering the water table the 4 pumps are assumed to deliver 500 acre feet/month in the computer model. Franklin (see Appendix) suggests the water table be lowered to 8 to 10 feet below the ground surface. To lower the water table, water is pumped into drainage ditches spaced one mile apart.

Within the computer model four drains were assumed to drain water from the fields to the streams when dewatering pumping is carried out. These drains are indicated on Figure 16. Drain 1 incorporates the Alamosa River and serves cells running east-west from calculation cell 8 to calculation cell 30 into the Rio Grande. Drain 2 begins in cell 11 and extends to the La Jara Creek. Both these drains carry pumped unconfined aquifer water and Empire downslope drainage water. Drain 3 includes the La Jara Creek (San Luis Drain) running from the cell above calculation cell 18 to the cell above calculation cell 29. Finally drain 4 runs from calculation cell 22 through calculation cell 29 into the Rio Grande.

Leaching: The wet meadow areas within the La Jara Creek well field require no leaching, however, the salt meadow soils require about two acre feet/acre of leaching water to reduce salt to an acceptable level before planting a crop. The La Jara Creek well field appears to be approximately half wet meadow and half salt meadow. Consequently a leaching volume of 10,240 acre feet is required to be pumped. The leaching has no direct bearing on the computer model as the water pumped percolates back to the aquifer. Consequently, there is no net effect on the aquifer level.

Flood Control: Franklin (see Appendix) suggests construction of dikes or levees along the Alamosa River and La Jara Creek. To develop the La Jara Creek well field it is assumed these flood control structures are built.

Aquifer Recharge: Due to the consumptive use of the crops in the La Jara Creek well field, after full development it is necessary to recharge the aquifer. To accomplish this recharge is it possible to use the drains which are constructed to carry the excess water away from the well field when the aquifer is lowered. These drains can be checked in order to recharge the aquifer with downslope drainage water from the Empire and Alamosa/ La Jara irrigation areas.

Timing of the Strategy: In the computer model it is assumed the drains, flood control works, and pumps are installed to be ready to operate from October of the first year onwards. Pumping in November and December is used to lower the water table. Leaching and clearing is carried out in the irrigation season of the first year (April to October). It is then assumed crops are planted and grown in each year from the second year onwards (month 20, May onwards). If the average water level in the well field (excluding the San Luis Drain river reach cells) is less than six feet below the ground surface the pumping field is activated in the computer model in March to dewater the aquifer and consequently lower the water table. The crop composition in the La Jara Creek well field is assumed to be exactly the same as for the five major irrigation areas.

MANAGEMENT STRATEGY NO. 2 - ROCK CREEK WELL FIELD DEVELOPMENT

Description of the Strategy

Location: This strategy involves a well field as in management strategy no. 1. The well field is in the vicinity of Rock Creek and is north of the La Jara Creek well field. Ten square miles are included in this well field as shown in Figure 17. The center pivot pump arrangement is the same for the Rock Creek well field as for management strategy no. 1. This area contains some salt flat soils which require gypsum treatment prior to leaching. The cost of the process is more than for the preparation of the land in the first management strategy, however, less flood control works are necessary for this strategy.

Lowering the Water Table: Drainage ditches are constructed to drain the pumped unconfined water to the streams. After the water table is lowered and crop production commences, these drains are then used to recharge the unconfined aquifer with downslope drainage water from the Empire irrigation area. In the computer model three drains are assumed to run through the Rock Creek field and into the Rio Grande. Drain 1 runs from calculation cell 13 through calculation cell 20 to the Rio Grande (see Figure 17). Drain 2 runs from calculation cell 9 through cells 16 and 24 to the Rio Grande. Finally, drain 3 runs from calculation cell 12 through cells 19 and 27 to the Rio Grande.

Leaching: Salt meadow and salt flat soils are included within the Rock Creek well field area. Salt flat soils require more leaching water than salt

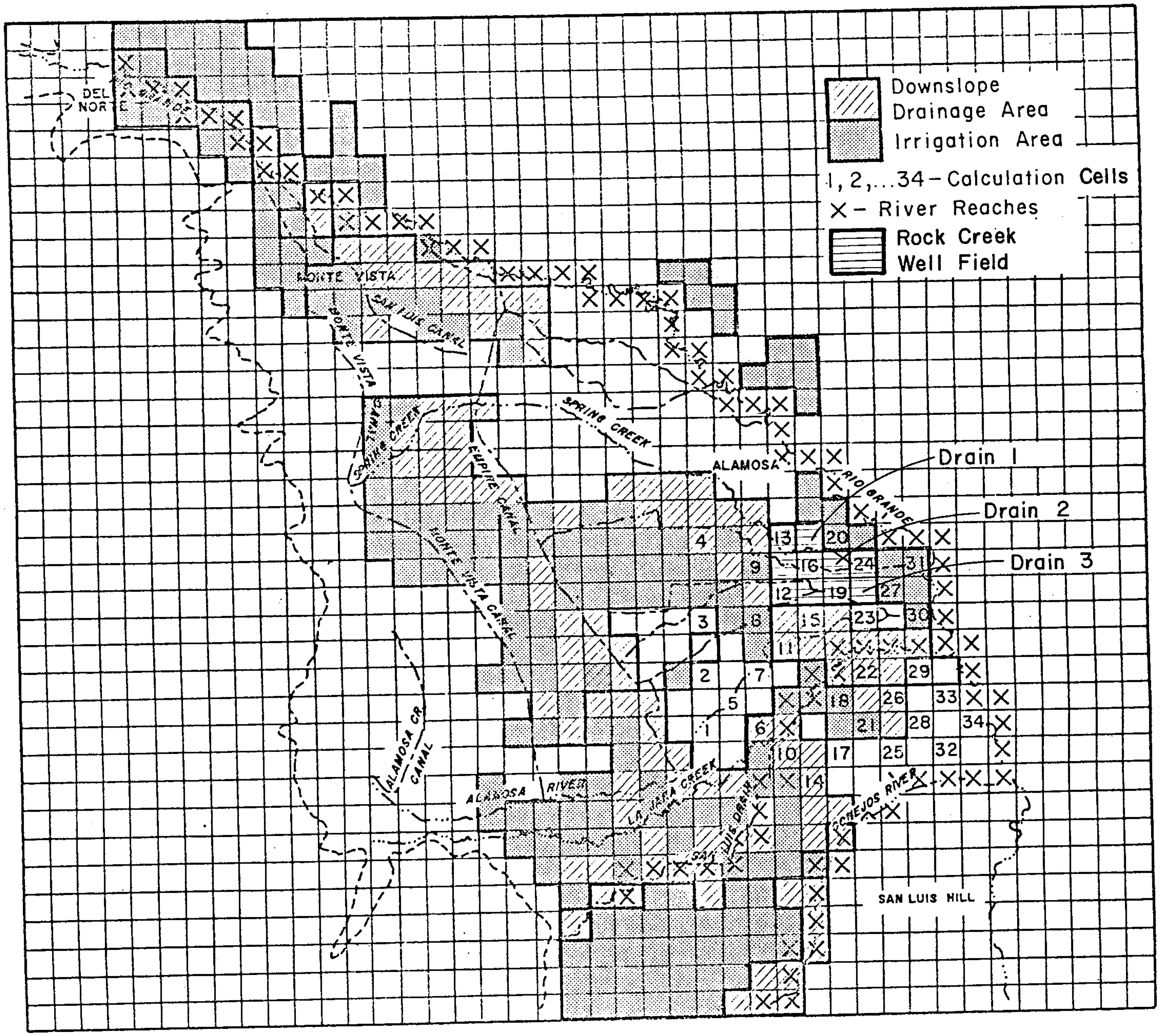

Figure 17 The Rock Creek Well Field Development-Management Strategy No. 2

meadow soils because water is required to dissolve native soil gypsum or commercial gypsum. In general 4 to 5 acre feet/acre of water is required to reduce exchangeable sodium to less than 10 percent in the 0 to 1 foot depth before a crop is planted (Franklin, 1978, p. 9). Assuming approximately one-half of Rock Creek well field is salt meadow soil and one-half is salt flat soil then 22,400 acre feet of leaching water is required.

Timing of the Strategy: The timing of the strategy is exactly the same as the timing used in management strategy no. 1. Drains and pumps are installed and operate by the first month of simulation. Pumping in November and December in the Rock Creek well field lowers the water table and the leaching of salts is carried out during the first irrigation season (April-October). Crops are planted from the second irrigation season onwards beginning in May (month 20). Pumping to lower the water table is carried out in March if the average aquifer depth is less than six feet below the surface in the well field. Again the crop composition is assumed to be the same as that of the five major irrigation areas.

CHAPTER V

ANALYSIS OF THE MANAGEMENT STRATEGIES

MODEL CALIBRATION

Monthly Streamflows

Figure 18 shows the Rio Grande monthly streamflows for the 12 year time horizon. The inflow to the study area (Rio Grande at Del Norte) together with the predicted and historic outflows from the study area (Rio Grande above Trinchera Creek) are shown for the historic management strategy. The predicted and historic monthly outflows compare reasonably well.

Figure 19 shows the Conejos River monthly streamflows. The inflow to the study area includes Conejos at Mogote plus San Antonio River inflow to the Conejos River. The outflows are determined near the mouth of the Conejos River at the confluence of the Rio Grande and Conejos Rivers. Again, the predicted and historic outflows compare reasonably well.

COMPARISON OF THE STRATEGIES

Simpson, et al., (1980) present the detailed results for each of the three management strategies. It is the purpose of this chapter to compare pertinent annual quantities and the variation of calculation cell aquifer levels from the computer model simulation runs for management strategy no. 1 and no. 2 with the historic management strategy. Only the quantities for management strategy no. 1 and no. 2 showing a noticeable difference from the historic strategy quantities will be addressed in this chapter.

The comparison of the strategies presented in this chapter is subdivided into four categories. They include:

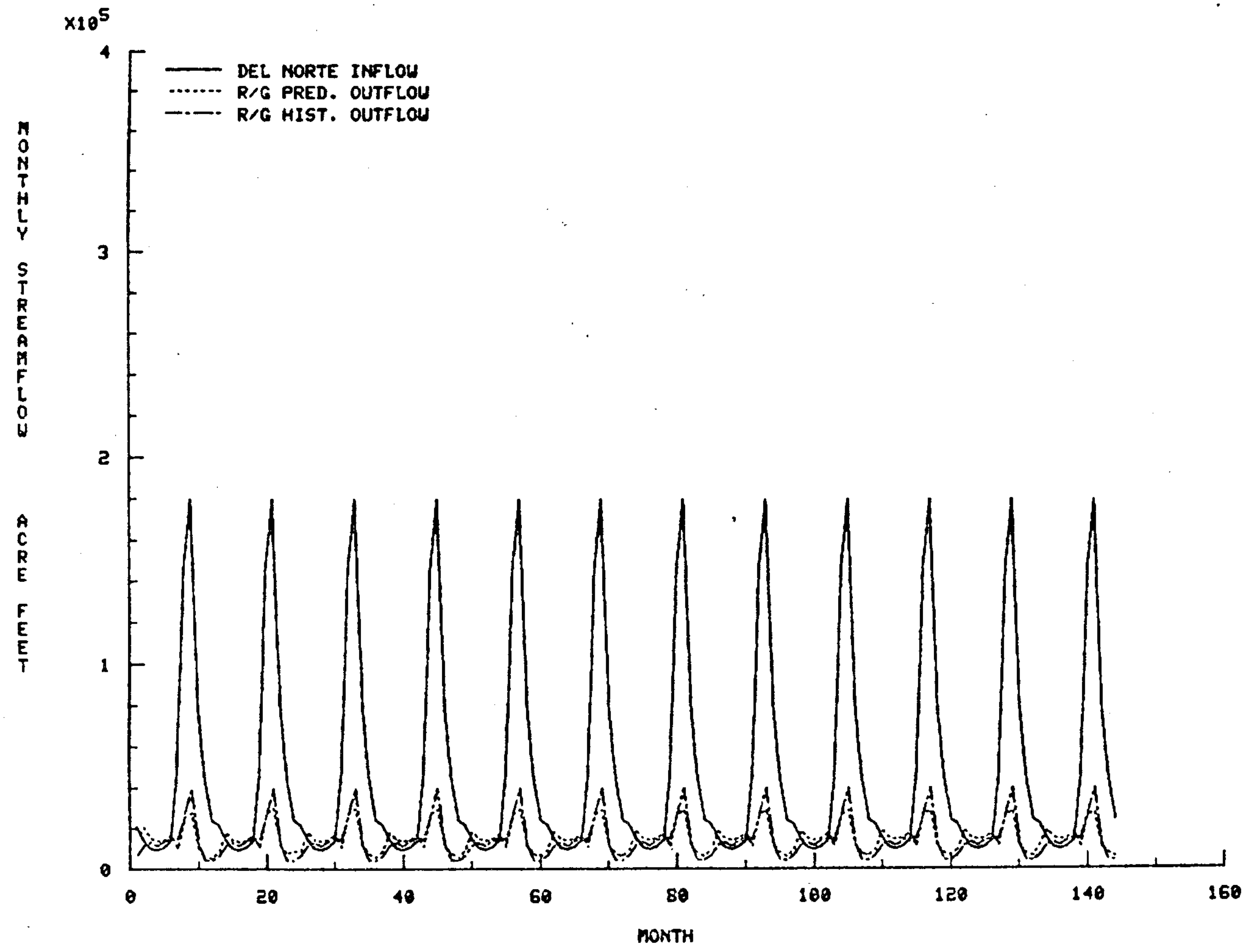

FIG. 18. RIO GRANDE MONTHLY STREAMFLOWS - HIST. STRAT.

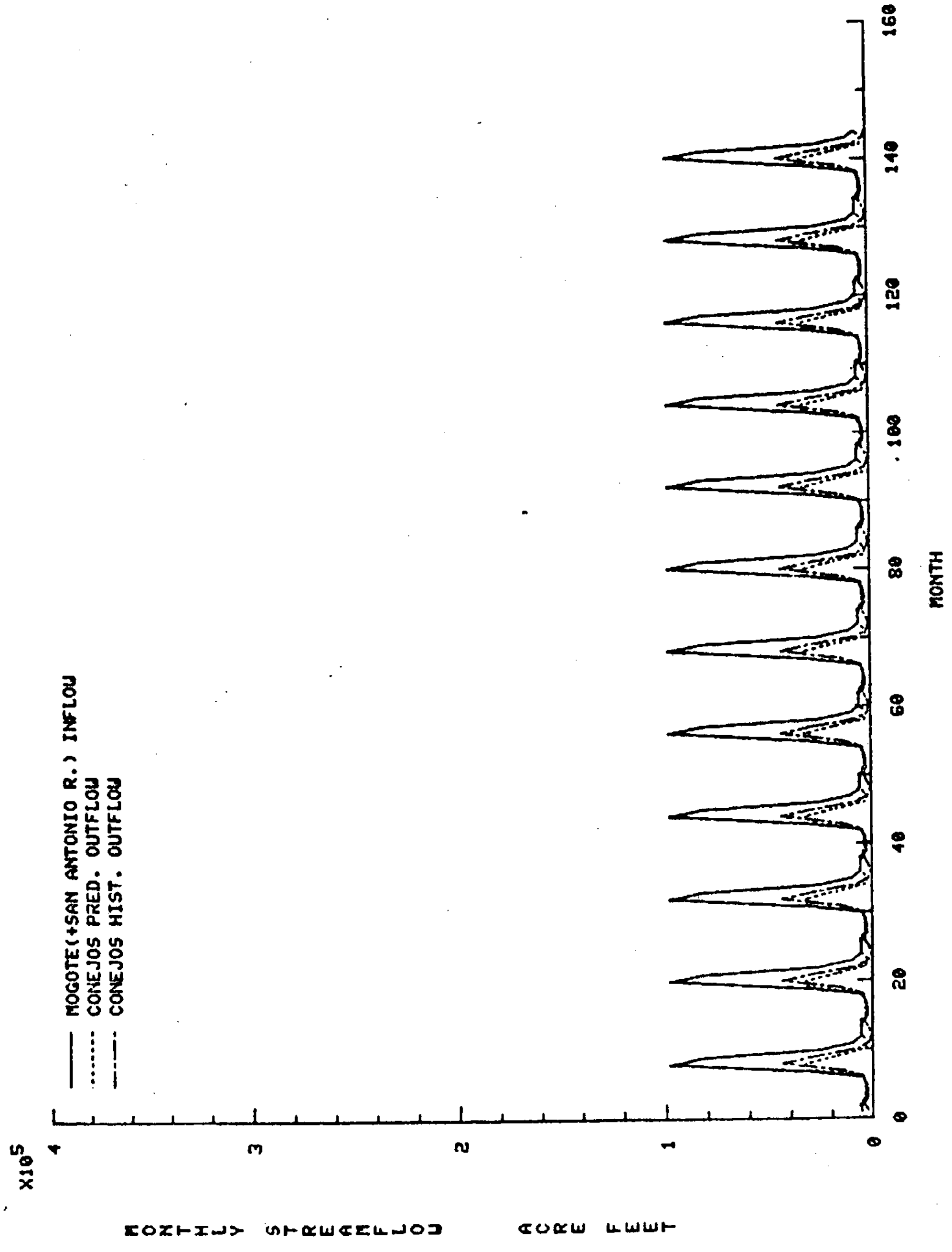

FIG. 19 CONEJOS RIVER MONTHLY STREAMFLOWS - HIST. STRAT.

(i) Comparison of the behavior of the river systems within the study area for the three strategies

(ii) Comparison of evaporation and unconfined aquifer excitations (from the observation area (245 square miles) and the study area (499 square miles)) for the three categories

(iii) Comparison of the calculation cell aquifer levels for management strategy no. 1 with the historic strategy

(iv) Comparison of the calculation cell aquifer levels for management strategy no. 2 with the historic strategy.

RIVER SYSTEMS

Overall System Behavior

Total System Return Flow: The comparison of the total system return flow for management strategy no. 1 and no. 2 against the historic strategy is shown in Figure 20. Management strategy no. 1 has approximately 50,000 acre feet return flow per year in comparison to the historic strategy, with a total return flow of approximately 68,000 acre feet per year. The majority of this decrease is a result of the reduction in San Luis Drain return flow while the remaining decrease is in Rio Grande return flow. Further discussion on return flows is presented in following sections. The Conejos River return flow is the same for both strategies.

The total system return flow for management strategy no. 2 is similar to the historic strategy values in each of the 12 simulation years. There is a slight deviation below the historic values due to the pumping from the Rock Creek well field. The reduction in return flow due to the well field is partly compensated for by recharge of the aquifer from the Rock Creek well field drains located between the well field and the Rio Grande.

Rio Grande

Rio Grande Return Flow: Figure 21 shows the Rio Grande annual return flow quantities for the three management strategies. The average Rio Grande

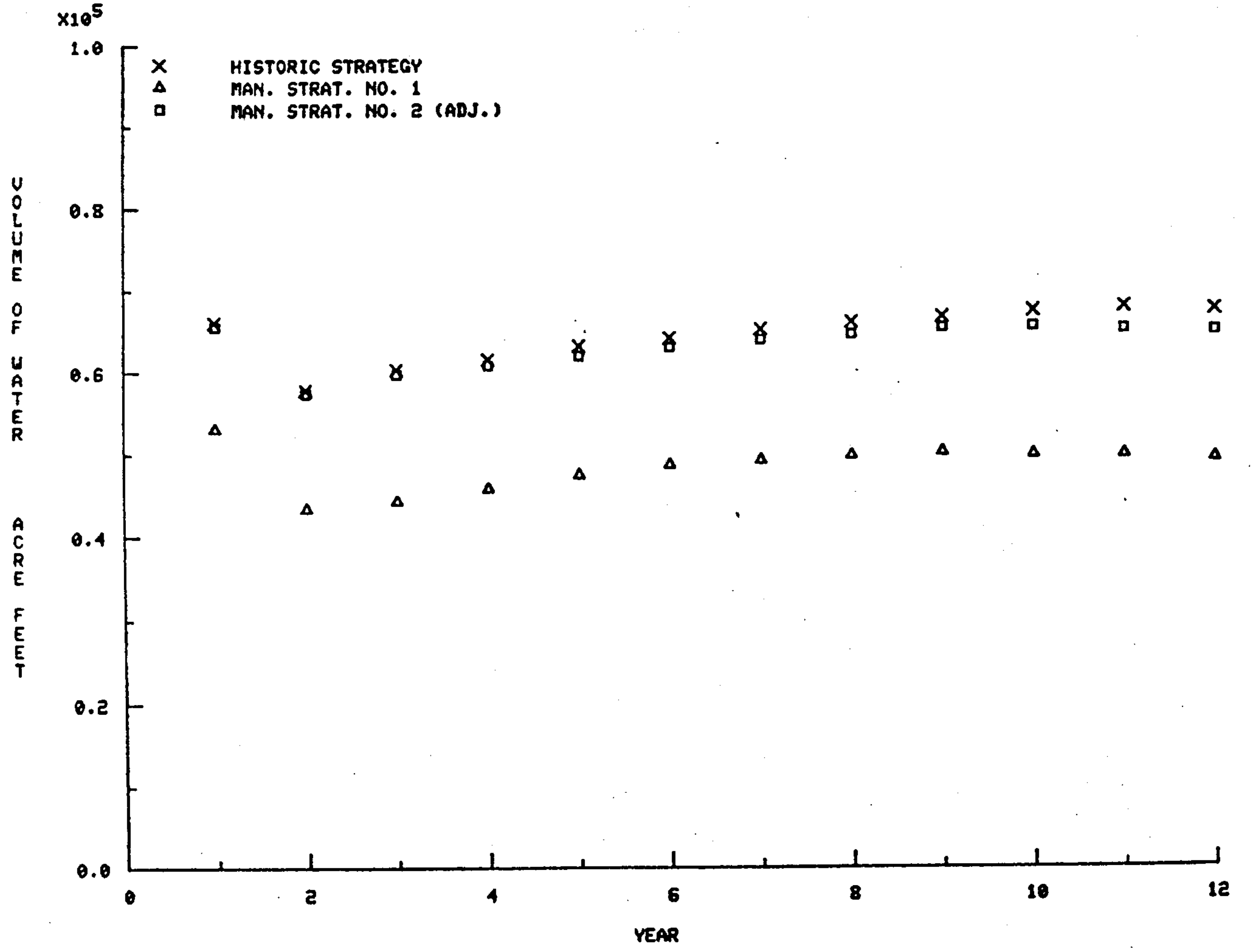

FIG. 20 COMPARISON OF STRATEGIES - ANNUAL TOTAL STUDY AREA RETURN FLOW

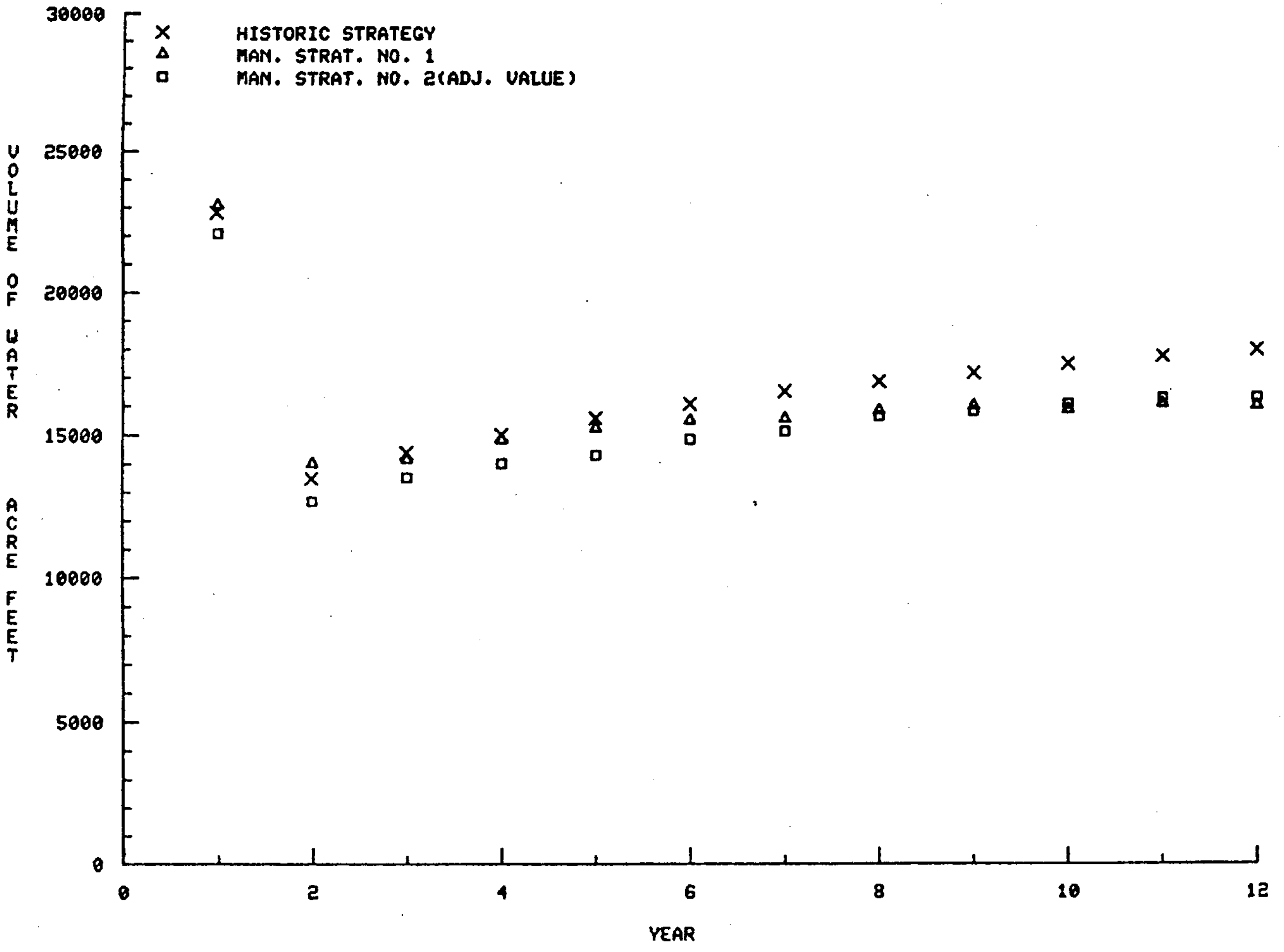

FIG. 21 COMPARISON OF STRATEGIES - RIO GRANDE RETURN FLOW

annual return flow for management strategy no. 1 compared to the historic value is reduced by approximately 2,000 acre feet. This decrease is a result of pumping from the unconfined aquifer in the La Jara Creek well field. The annual return flow in years 1 and 2 for management strategy no. 1 is slightly greater than for the historic strategy. This is caused by the underestimation of the evaporation at a few of the observation area grid cells. An adjustment of the return flows for management strategy no. 1 to account for the evaporation underestimation is not made. The adjustment is small.

The annual return flows for management strategy no. 2 are less than the corresponding historic values. The return flows for management strategy no. 2 are adjusted values to account for the underestimation of evaporation at 19 grid cells above the Rock Creek well field. The reduction in return flow is a result of the pumping of unconfined aquifer water from the 10 square mile Rock Creek well field.

San Luis Drain Return Flow and Outflow

Figure 22 compares the San Luis Drain annual return flows for the three strategies. For management strategy no. 1 the return flow is reduced compared to the historic strategy. This is a result of the San Luis Drain reaches which are part of the La Jara Creek well field. Pumping for crop consumptive use from these reaches reduces the positive return flow. However, the San Luis Drain annual outflows for management strategy no. 1 are similar to the historic strategy outflows (Figure 23). Both downgradient drainage from irrigation areas and water pumped from the La Jara Creek well field into the San Luis Drain compensate for the reduction in return flow.

The San Luis Drain return flows for management strategy no. 2 and the

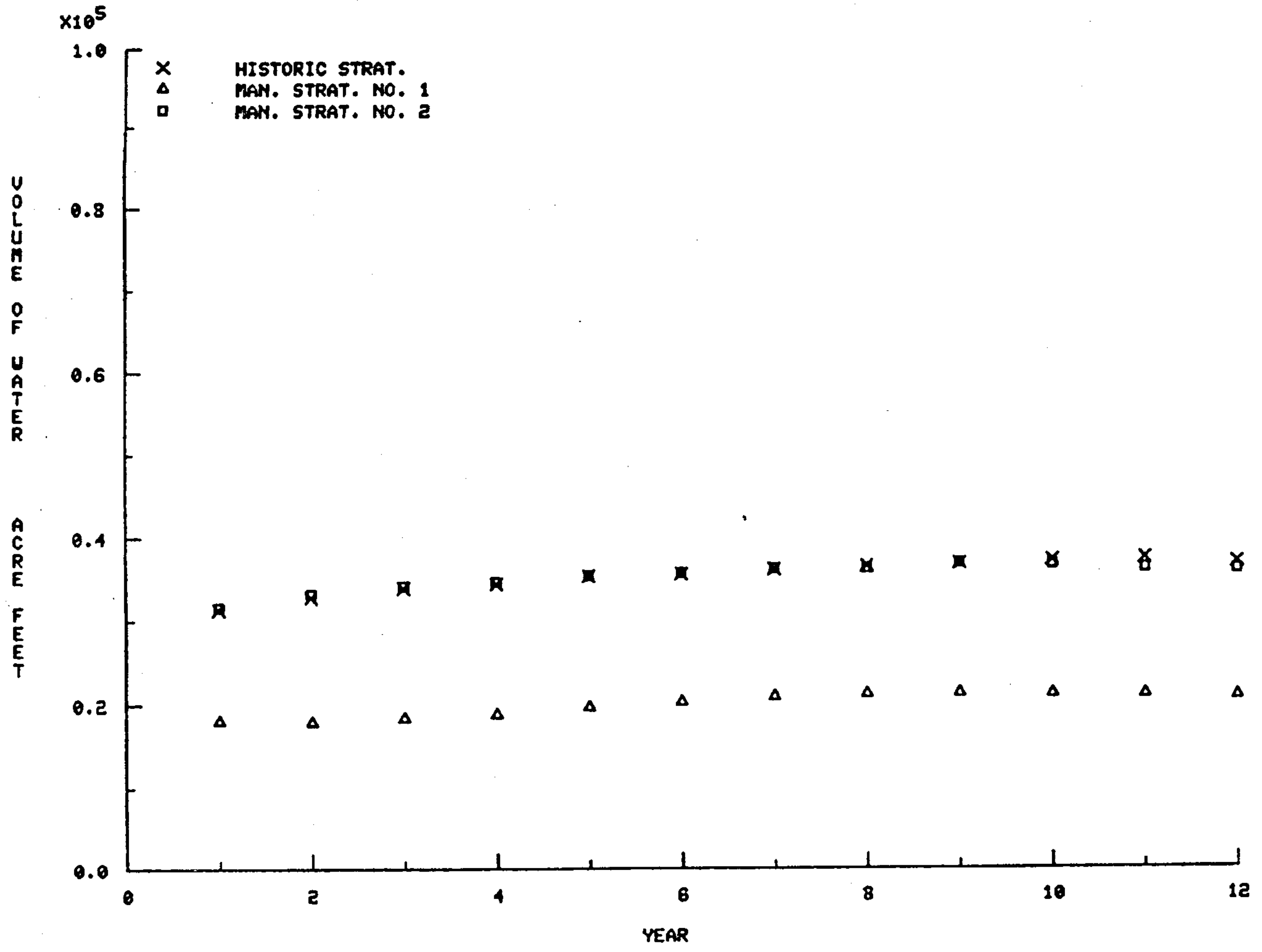

FIG. 22 COMPARISON OF STRATEGIES - SLD ANNUAL RETURN FLOW

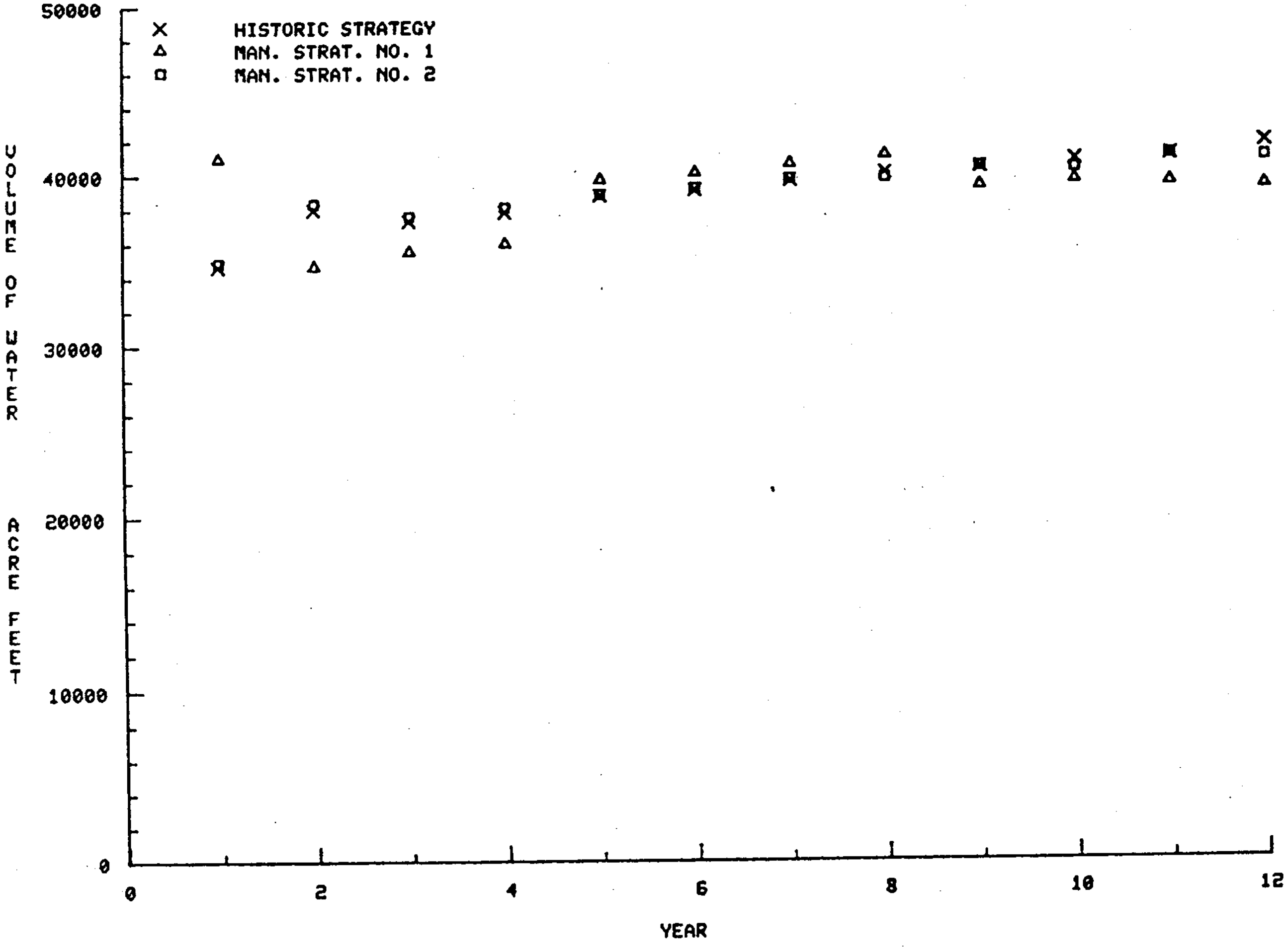

FIG. 23 COMPARISON OF STRATEGIES - SAN LUIS DRAIN OUTFLOW TO RIO GRANDE

historic strategy compare closely. The pumping from Rock Creek well field decreases the return flow for management strategy no. 2. The decrease is small.

EVAPORATION AND UNCONFINED AQUIFER EXCITATION

Evaporation

The comparison for the three management strategies of the annual evaporation from the unconfined aquifer in the 245 square mile observation area is presented in Figure 24. The annual evaporation for management strategy no. 1 is less than for the historic strategy. Consequently, the evaporation can be reduced if the water table in the waterlogged areas in the San Luis Valley is lowered. This reduction represents a "true" water gain for the system and makes more water available for crop production.

The annual evaporation for management strategy no. 2 is also less than the historic strategy. This decrease is a result of the lowering of the water table in the Rock Creek well field.

Study Area Unconfined Aquifer Pumping

The annual pumping from the unconfined aquifer to meet irrigation requirements within the 5 major irrigation areas and well field developments is shown for the 3 strategies in Figure 25. The development of center pivot sprinkler well fields in management strategies no. 1 and no. 2 result in the increase in pumping compared with the historic strategy.

Net Excitation of the Observation Area Unconfined Aquifer

The net unconfined aquifer excitation for the 245 square mile observation area for the 3 management strategies are compared in Figure 26. The consumptive use of the La Jara Creek well field in management strategy no. 1

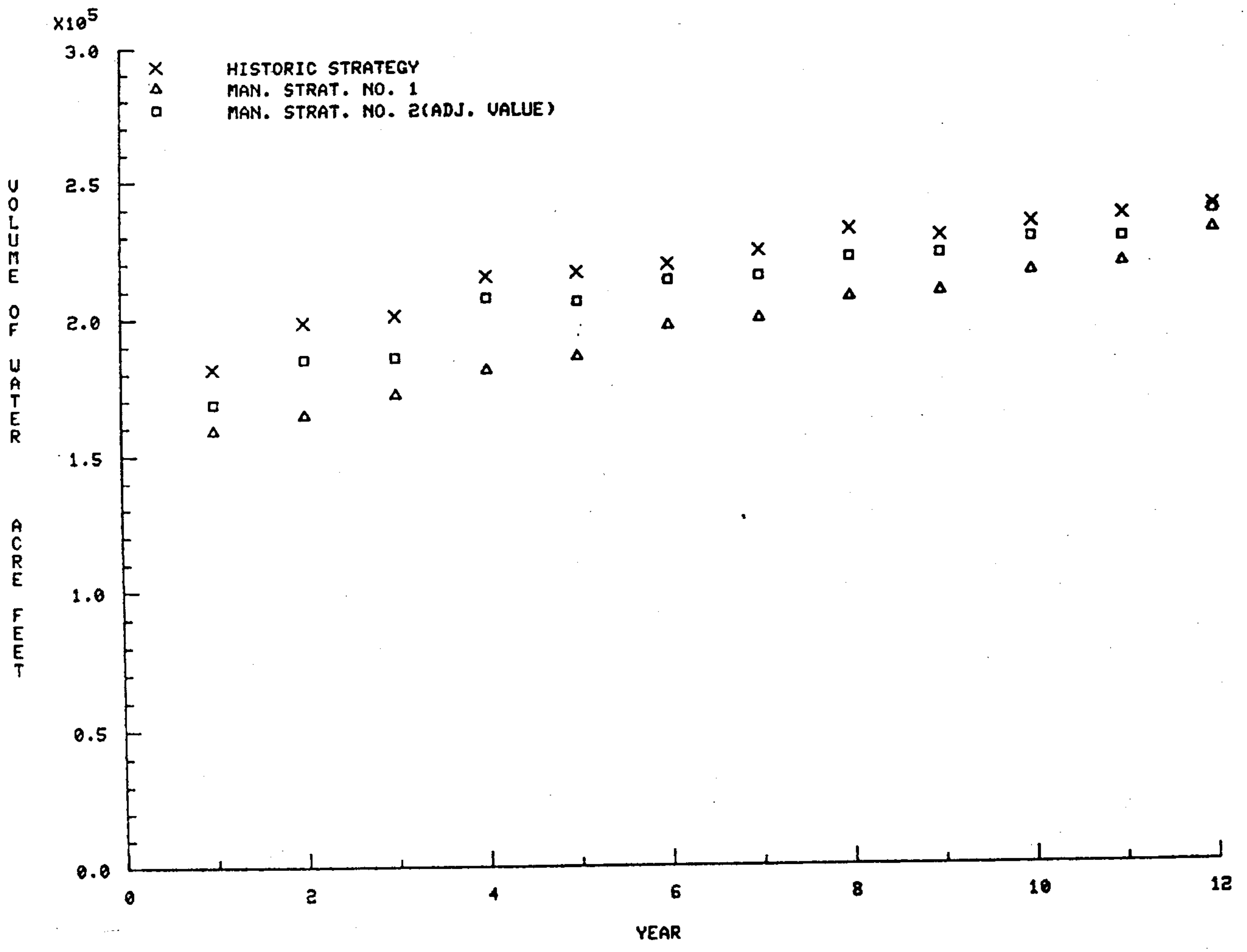

FIG. 24 COMPARISON OF STRATEGIES - EVAPORATION FROM OBS. AREA

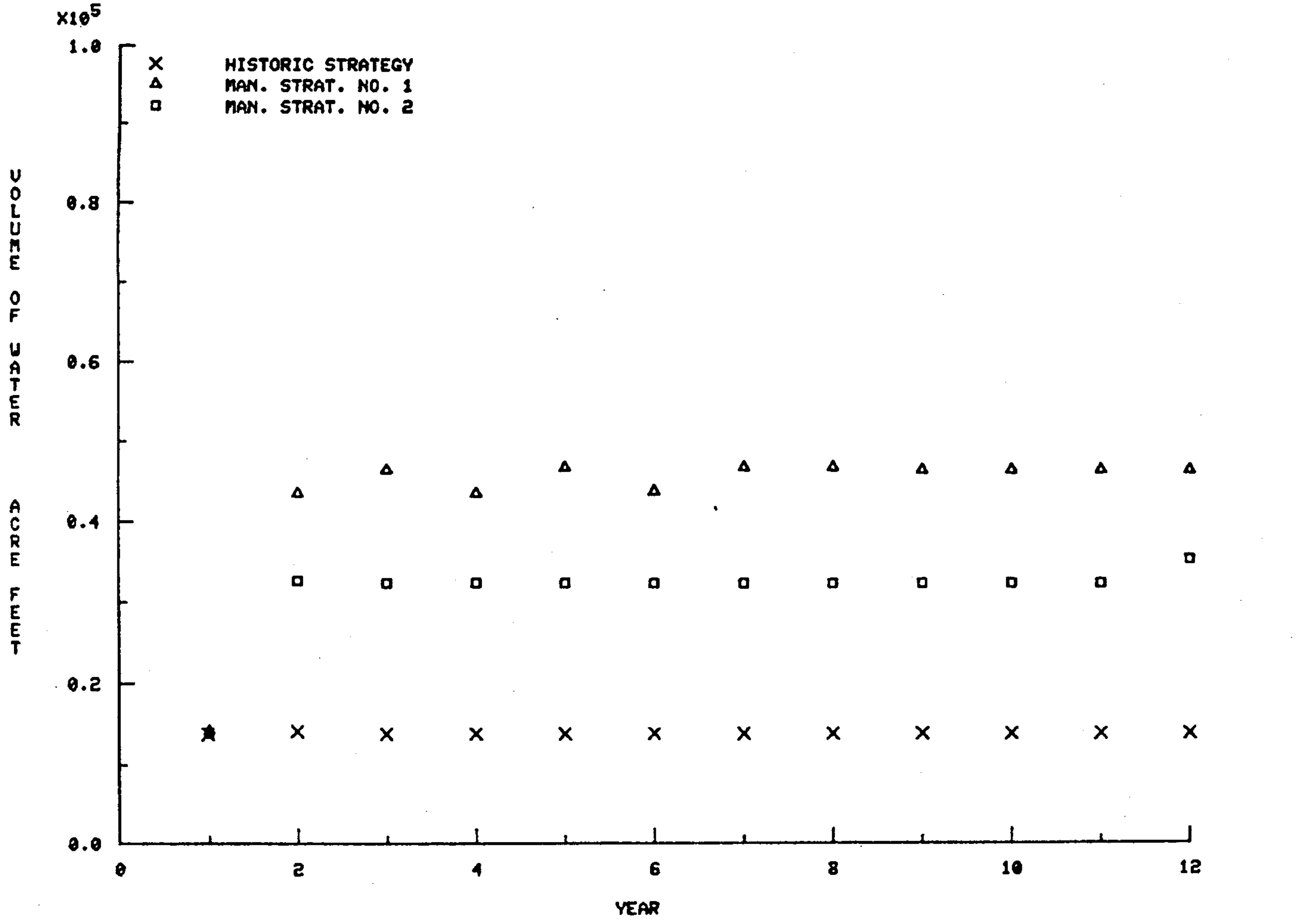

FIG. 25 COMPARISON OF STRATEGIES - TOTAL UNCONFINED AQUIFER PUMPING

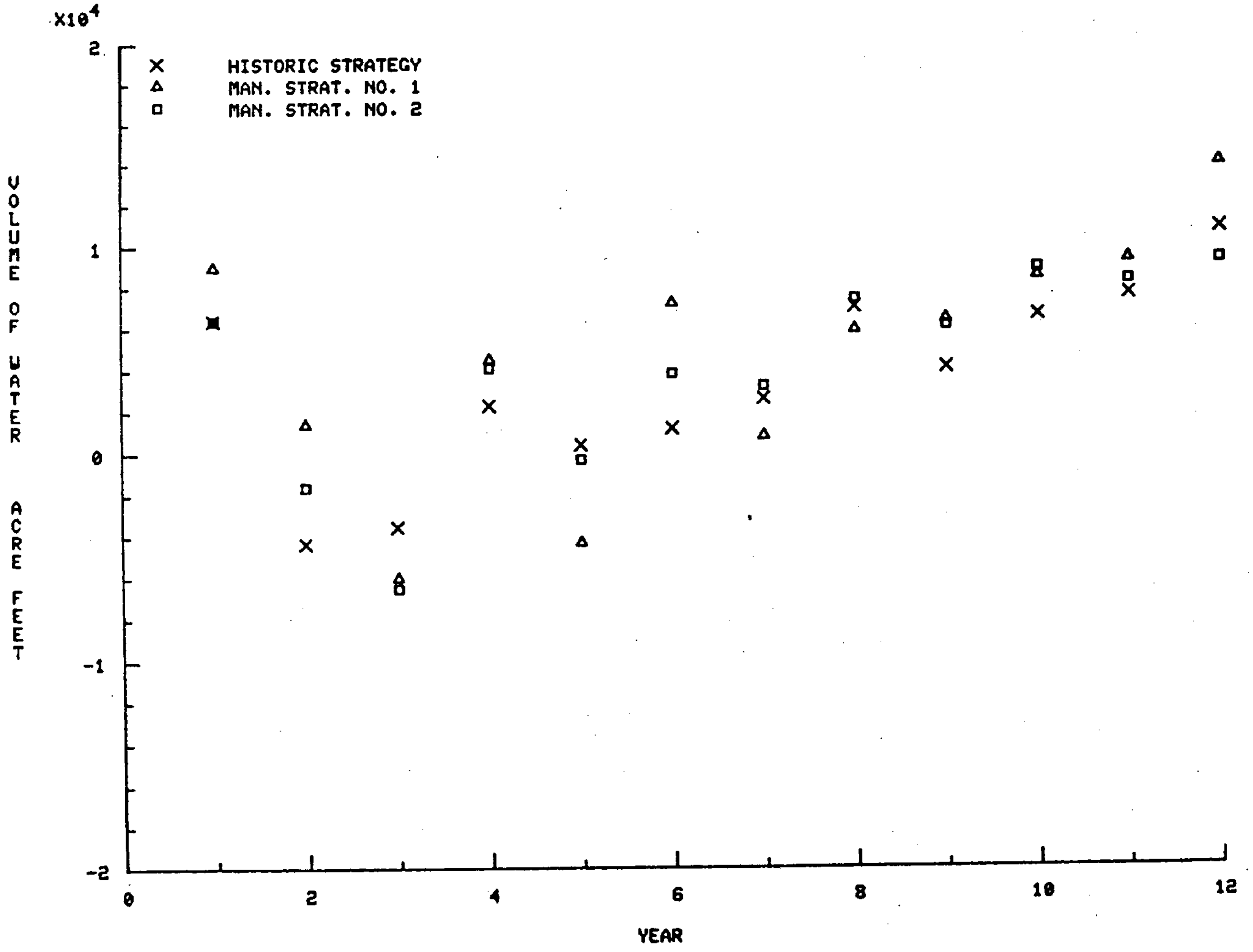

FIG. 26 COMPARISON OF STRATEGIES - NET AQUIFER EXCITATION IN OBS. AREA

is 13,600 acre feet per year from year 2 onwards, while for the Rock Creek well field in management strategy no. 2 the consumptive use is 8,500 acre feet per year. Despite these additional withdrawals from the aquifer the net excitations of the observation area for the three strategies are similar, especially in the later years. The consumptive use in these well fields is compensated for by the decrease in evaporation. Consequently, development of these well fields does not dramatically alter the distribution of irrigation water for existing users.

COMPARISON OF CALCULATION CELL AQUIFER LEVELS FOR MANAGEMENT STRATEGY NO. 1 AND THE HISTORIC STRATEGY

Introduction

Calculation cells within the La Jara Creek well field include cells 11, 15, 22, 23, and 29. The monthly variation of aquifer level at these calculation cells for management strategy no. 1 are compared to the historic strategy results in the following section. The effect of the La Jara Creek well field on the study area is assessed. The behavior of the aquifer level for a cell (calculation cell 30) which is a part of the La Jara Creek well field drain to the Rio Grande is also compared.

Calculation Cells Within the La Jara Creek Well Field

Figures 27 to 30 show the comparison of the aquifer levels for the 3 management strategies at calculation cells 11, 15, 22, 23, and 29, respectively. It is evident from Figures 27, 28, and 30 for calculation cells 11, 15, and 23 the aquifer levels for these cells in management strategy no. 1 stabilize at approximately 6 to 9 feet below the ground surface compared to the historic strategy where levels are closer to ground surface. Cells 11 and 15 waterlogged in the historic strategy. These cells are located on the north

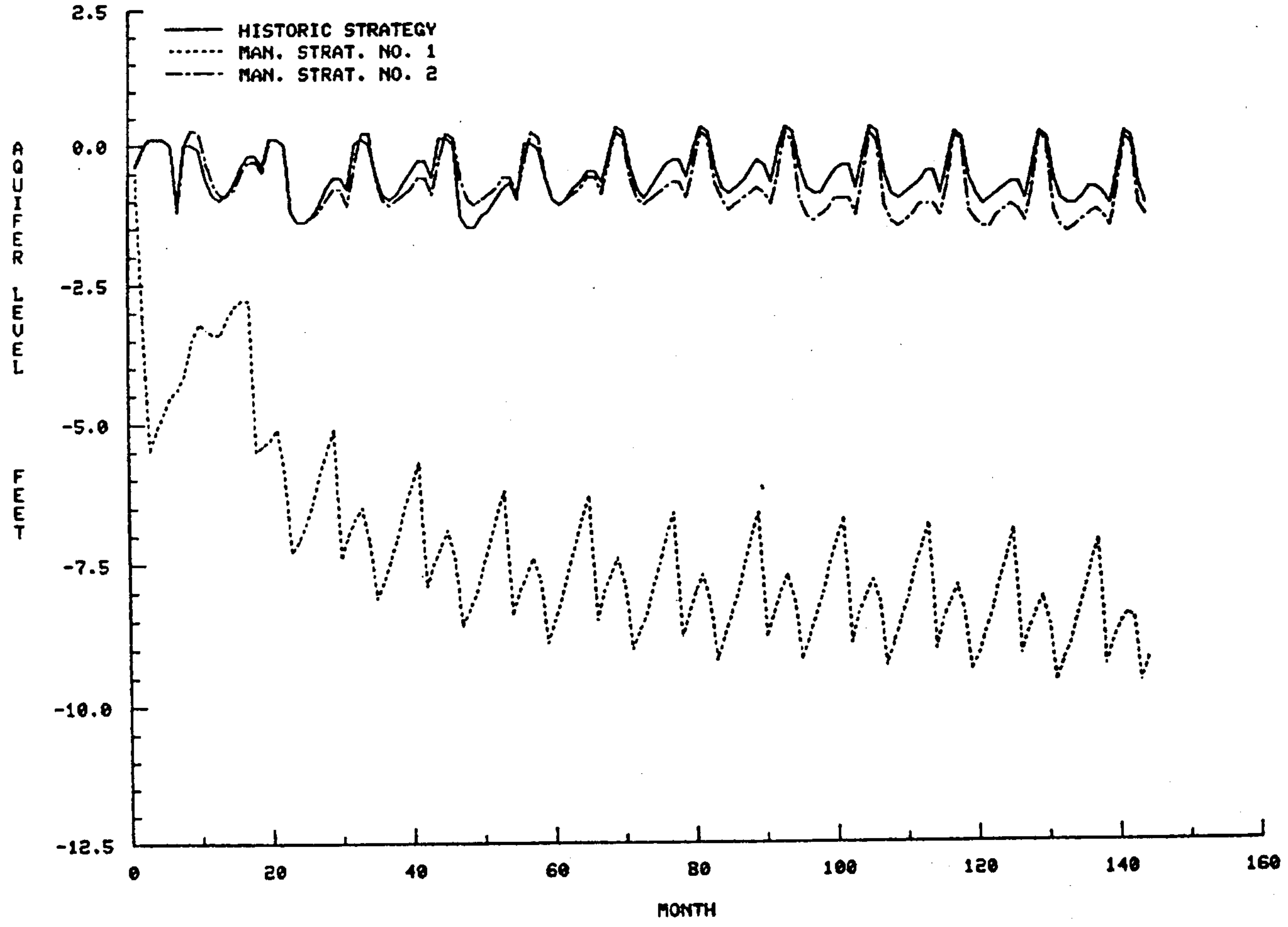

FIG. 27 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 11

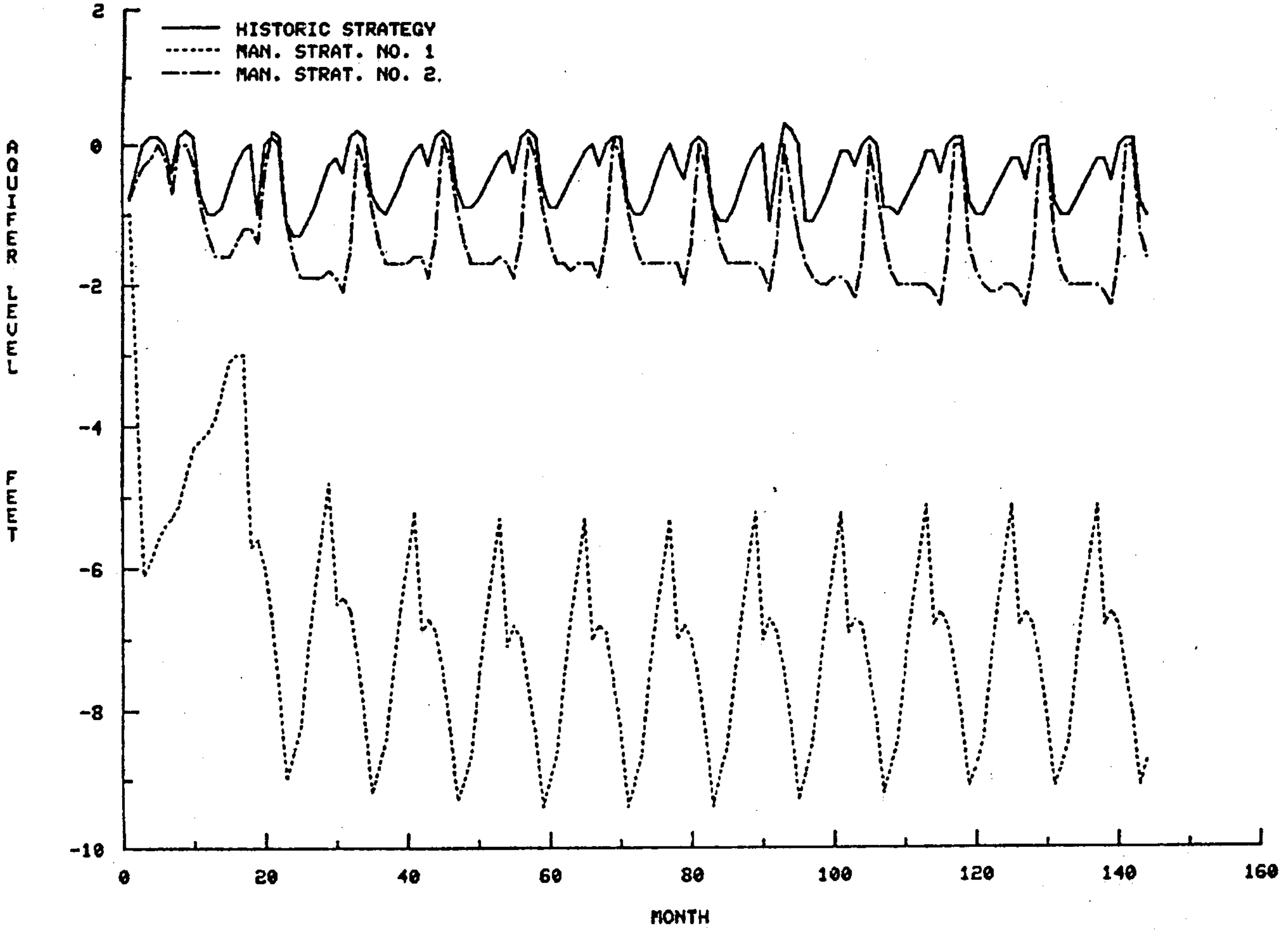

FIG. 28 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 15

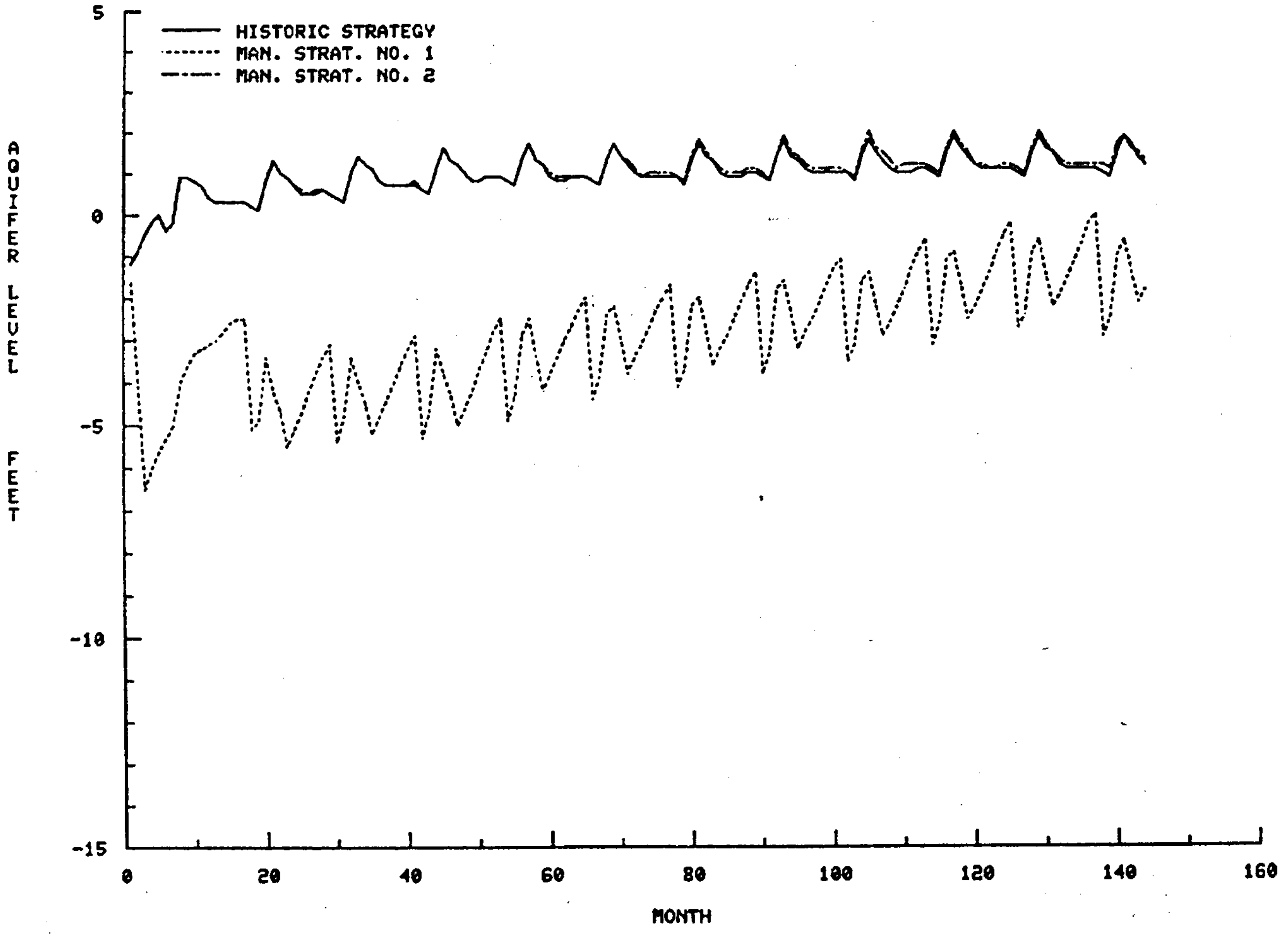

FIG. 29 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 22

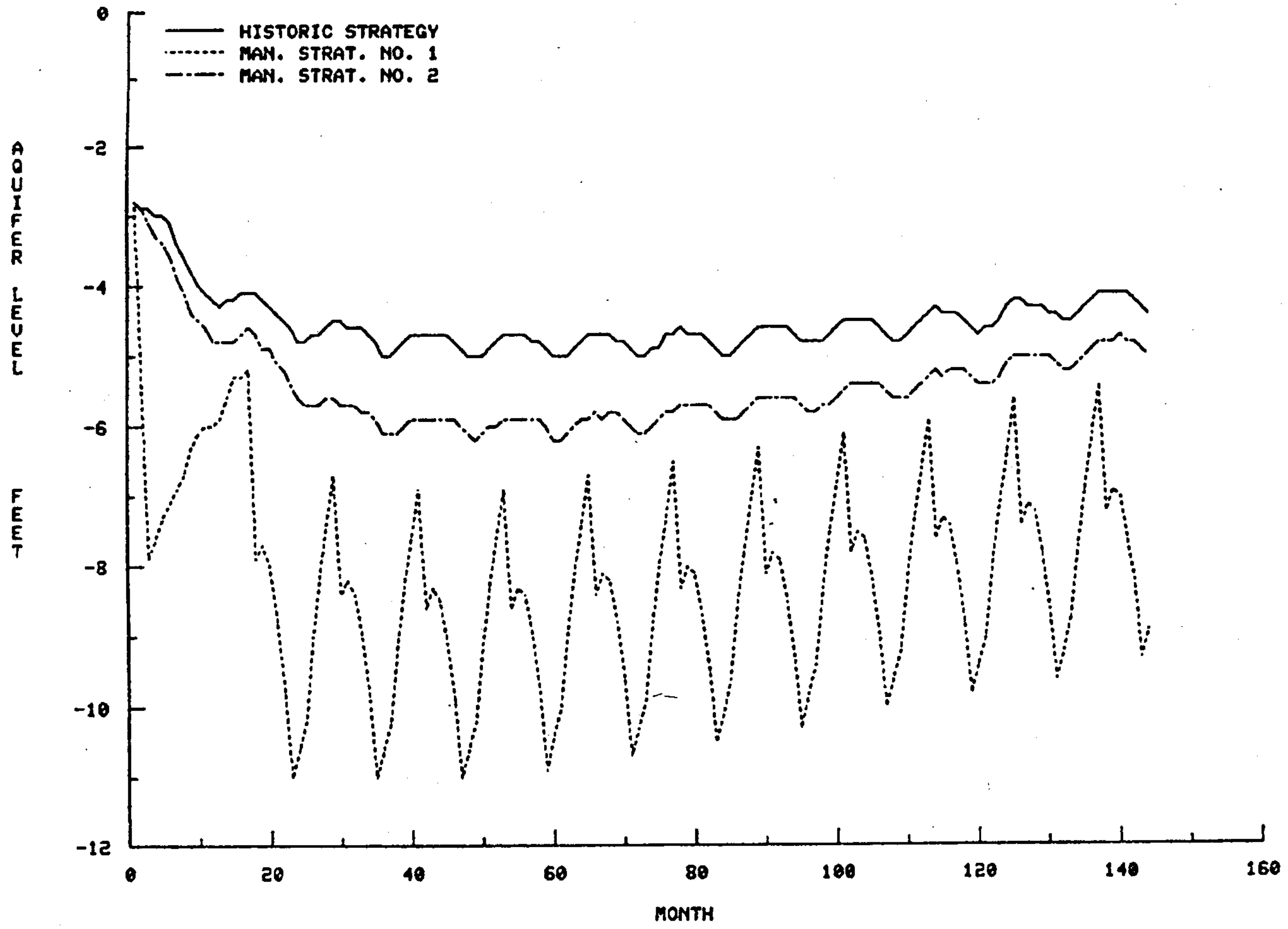

FIG. 30 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 23

side of the San Luis Drain. These plots indicate the operation of the La Jara Creek well field is successful in the vicinity of these three calculation cells. The crop consumptive use is balanced by the recharge from the downgradient drainage from the upslope irrigation areas.

The calculation cells 22 and 29 (Figures 29 and 31) are located south of the San Luis Drain. The aquifer level for calculation cell 29 in management strategy no. 1 does stabilize after being drawn down but does rise slightly with time. However, the aquifer level for calculation cell 22 does not stabilize and eventually waterlogs despite the crop consumptive use. Cell 22 waterlogged severely in the historic strategy. The recharge from the downgradient drainage and the severe waterlogging of adjacent grid cells in management strategy no. 1 cause the aquifer level at cell 22 to rise with time. This situation is not satisfactory for the successful operation of La Jara Creek well field in this region. Additional measures, including further drainage, would need to be considered to prevent this problem from occurring.

Calculation Cell 30 Within La Jara Well Field Drain

The comparison of the aquifer levels for the 3 strategies for calculation cell no. 30 is shown in Figure 32. In management strategy no. 1 calculation cell 30 is a part of one of the recharge drains for the La Jara Creek well field. In the historic strategy the aquifer level stabilizes at three to four feet below the ground surface. The formation of a mound of water in management strategy no. 1 at calculation cell 30 is evident from Figure 32. Water from this mound both recharges the aquifer beneath the La Jara Creek well field and also contributes positive return flow to the Rio Grande.

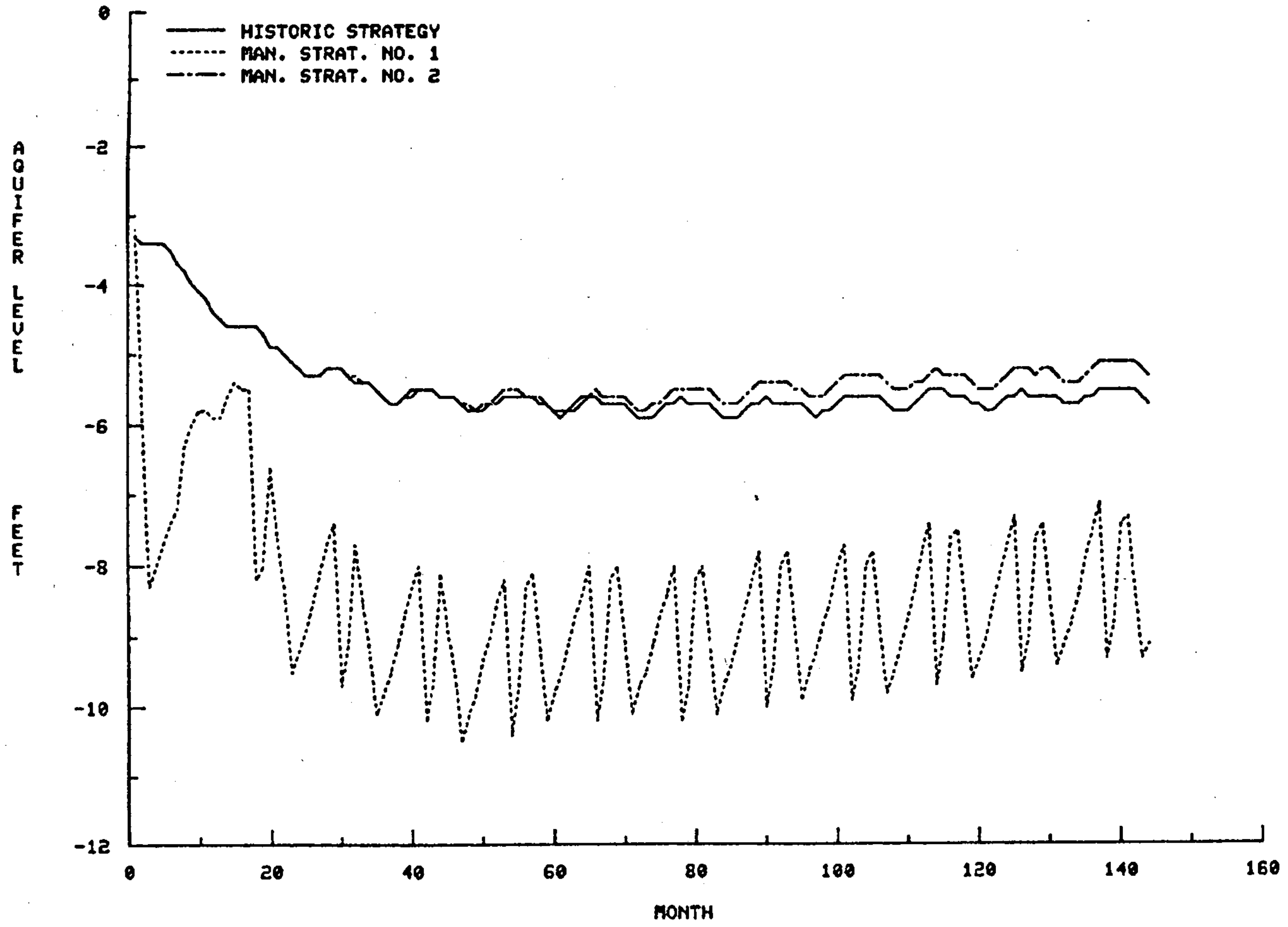

FIG. 31 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 29

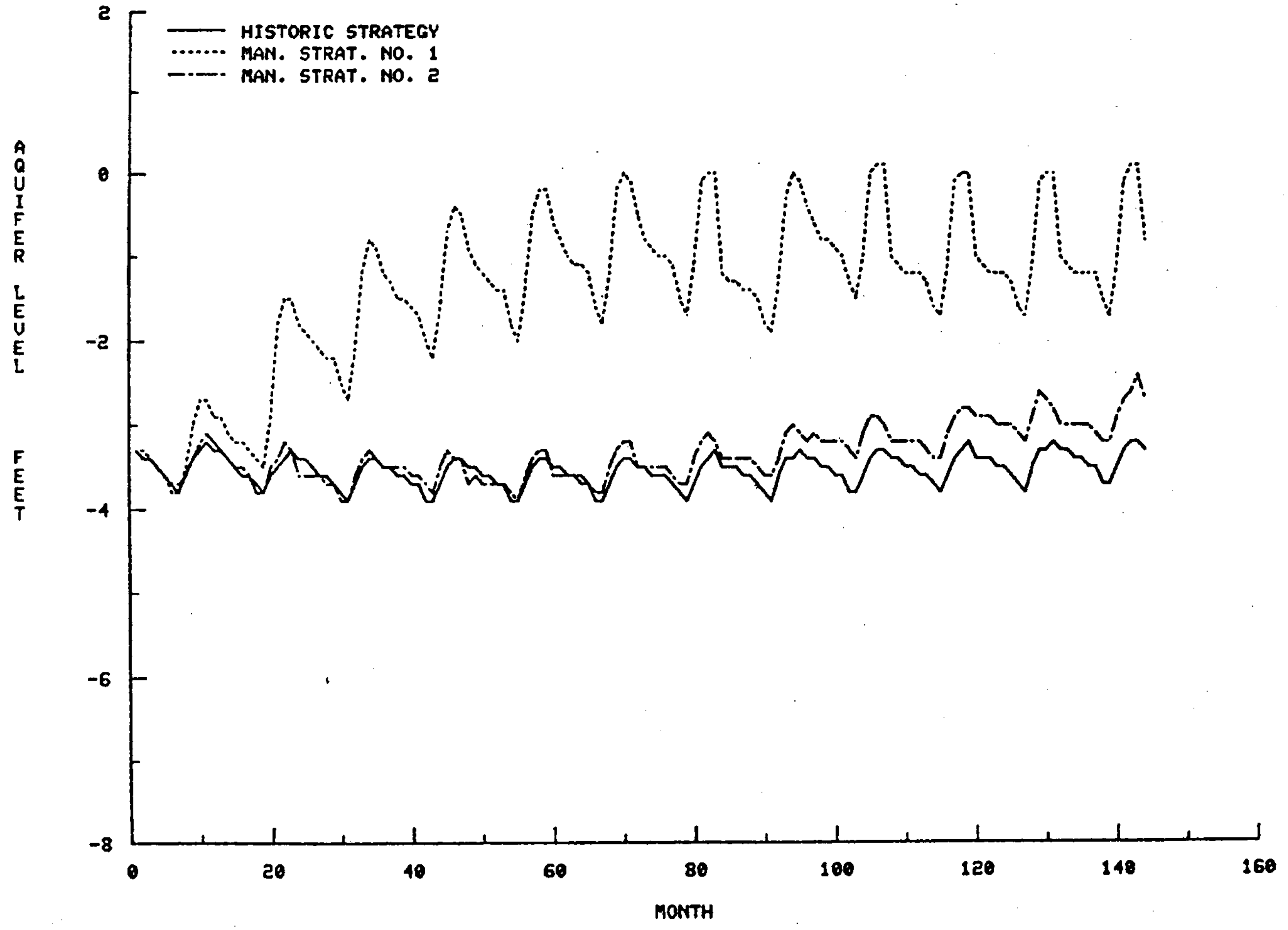

FIG. 32 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 30

COMPARISON OF CALCULATION CELL AQUIFER LEVELS FOR MANAGEMENT STRATEGY NO. 2 AND THE HISTORIC STRATEGY

Introduction

The Rock Creek well field for management strategy no. 2 incorporates calculation cell numbers 12, 13, 16, 19, and 24. The aquifer levels at these calculation cells for management strategy no. 2 are compared to the historic strategy behavior in the following section. The effect of the Rock Creek well field on the study is assessed. Calculation cells 20, 27, and 31 are located between the Rock Creek well field and the Rio Grande. These cells are part of the recharge drain from the well field to the Rio Grande. The behavior of the aquifer levels at these cells for management strategy no. 2 and the historic strategy are compared in a section below. Finally, the aquifer level for an irrigation area calculation cell (no. 9) adjacent to the Rock Creek well field is compared for the 2 strategies.

Calculation Cells Within the Rock Creek Well Field

The aquifer levels for the 3 management strategies at cells 12, 13, 16, 19, and 24 are shown in Figures 33 to 37. All these figures indicate the aquifer levels in the Rock Creek well field for management strategy no. 2 stabilize at a level far below the ground surface to ensure satisfactory operation of the Rock Creek well field. This compares to the waterlogging behavior at these cells in the historic strategy. In fact, the aquifer levels at these cells in management strategy no. 2 are still falling slightly with time after 12 years. The aquifer recharge from both downgradient drainage and cells adjacent to the Rock Creek field will eventually balance the crop consumptive use.

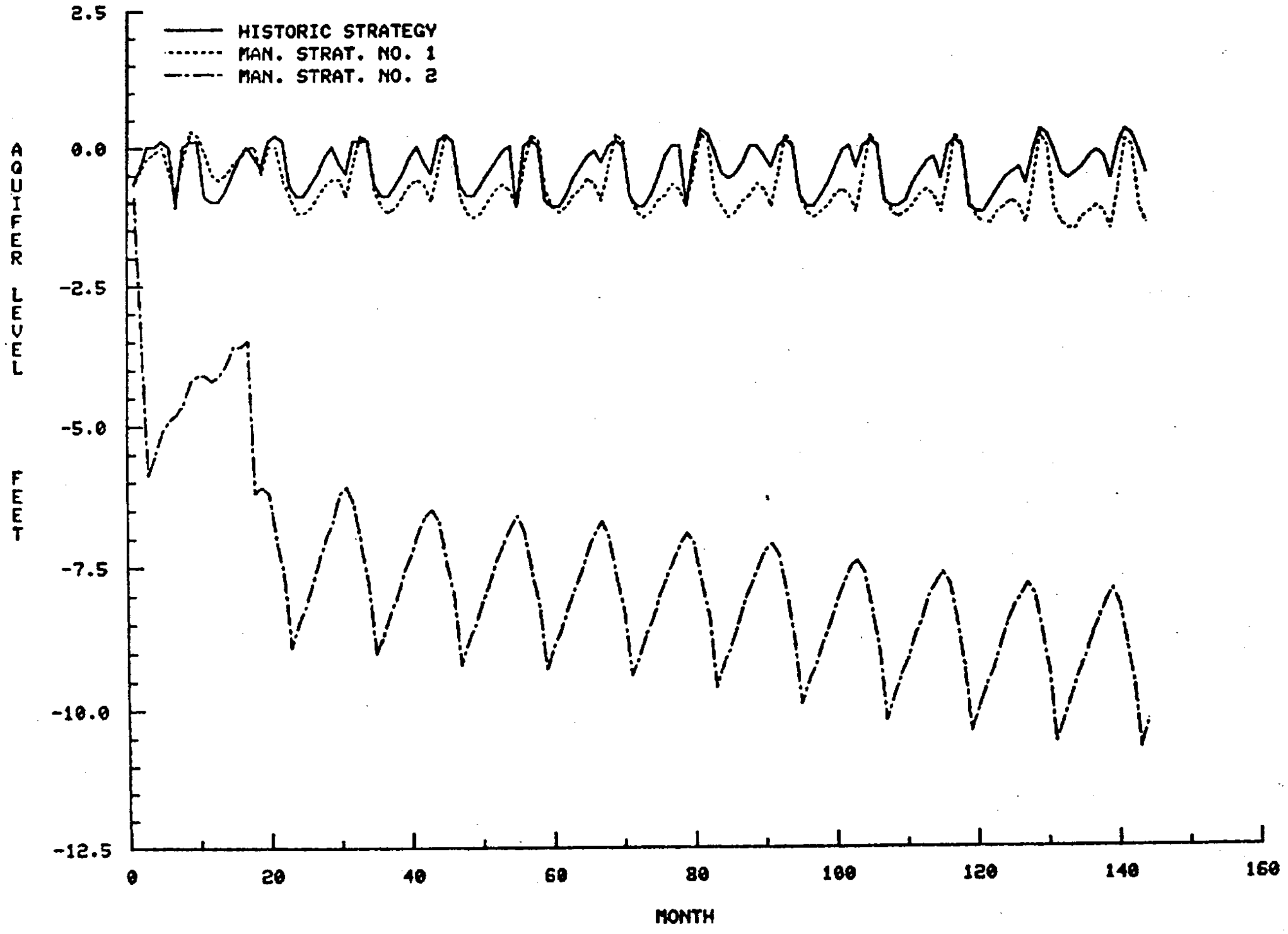

FIG. 33 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 12

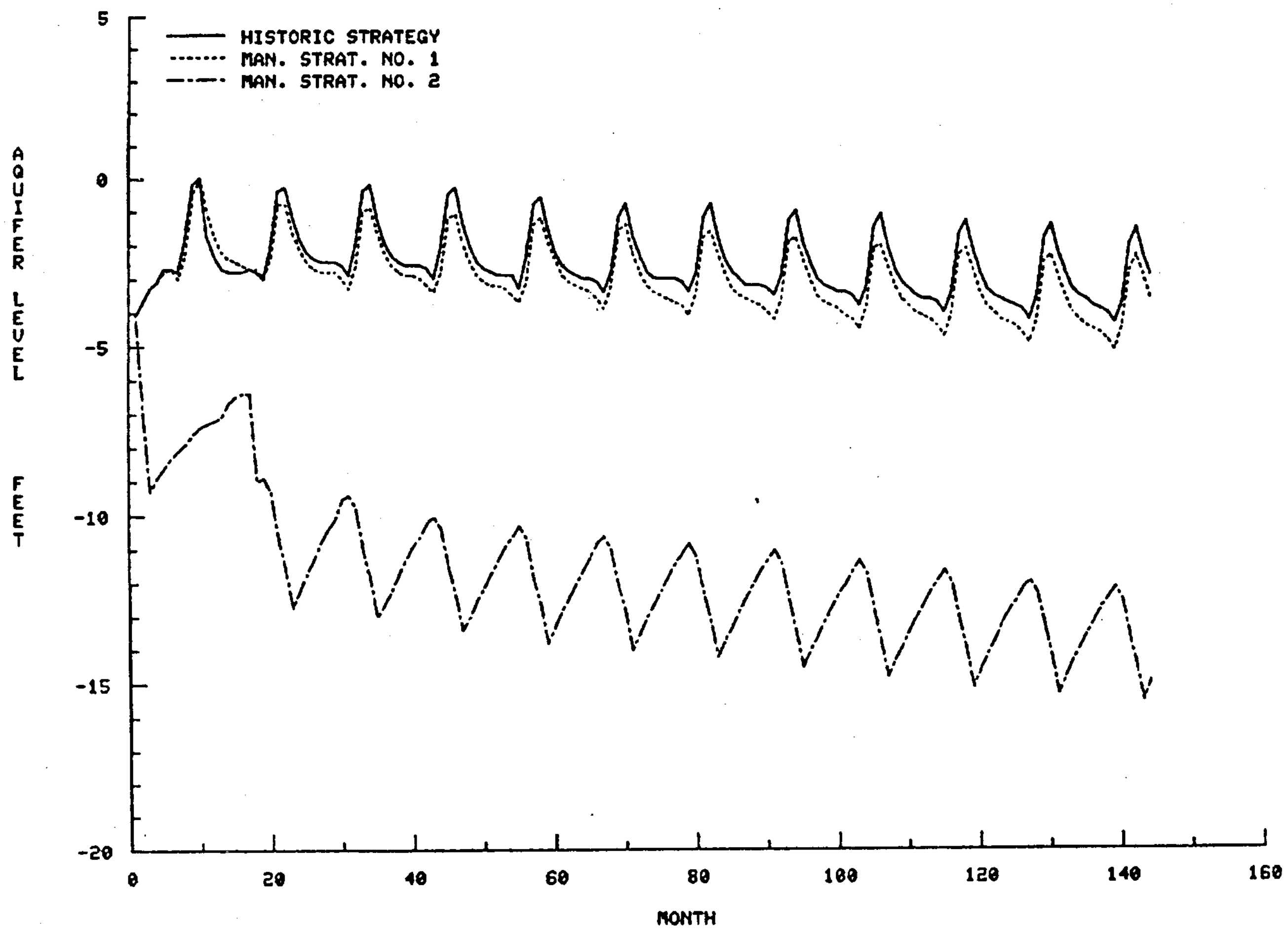

FIG. 34 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 13

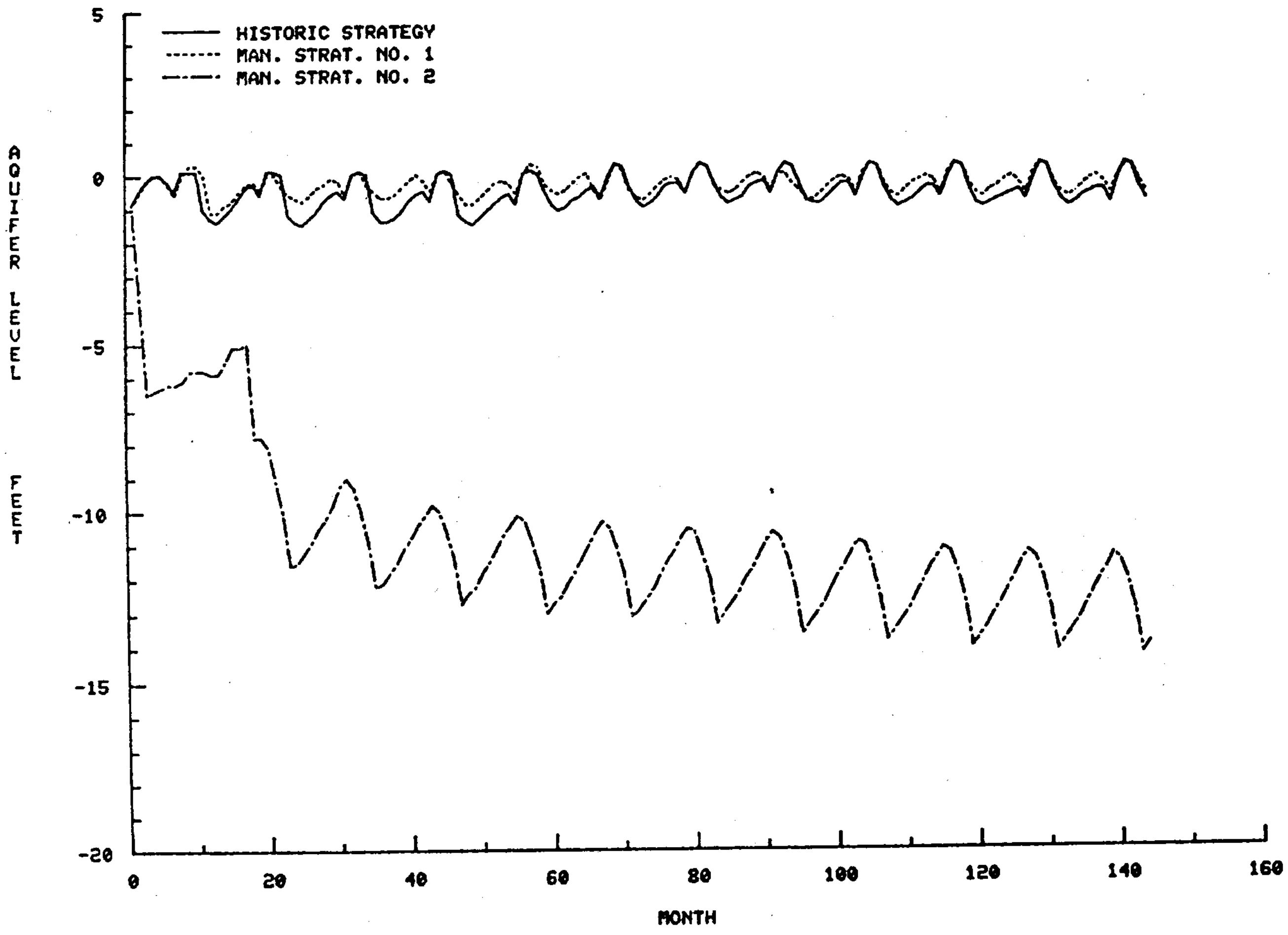

FIG. 35 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 16

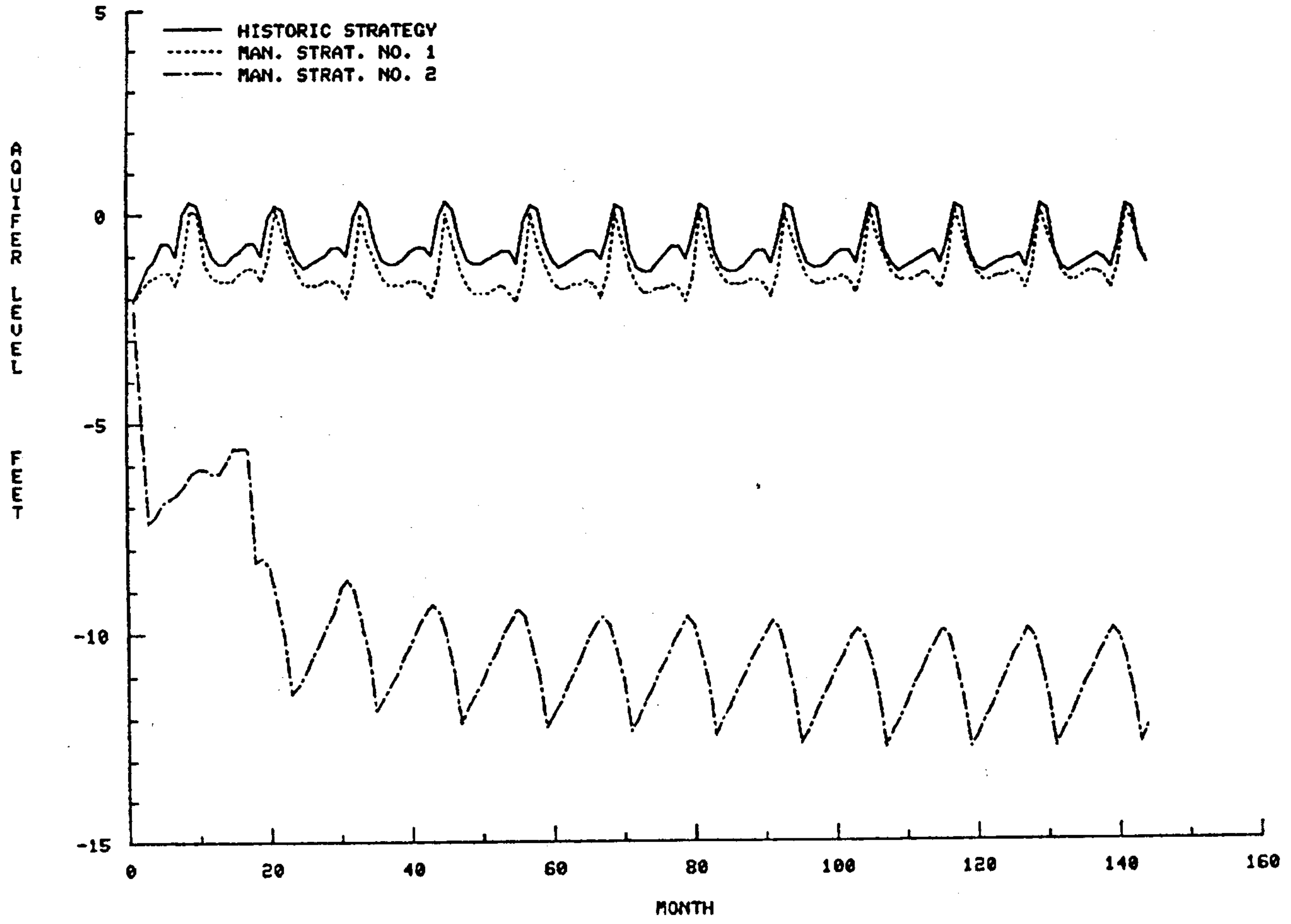

FIG. 36 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL 19

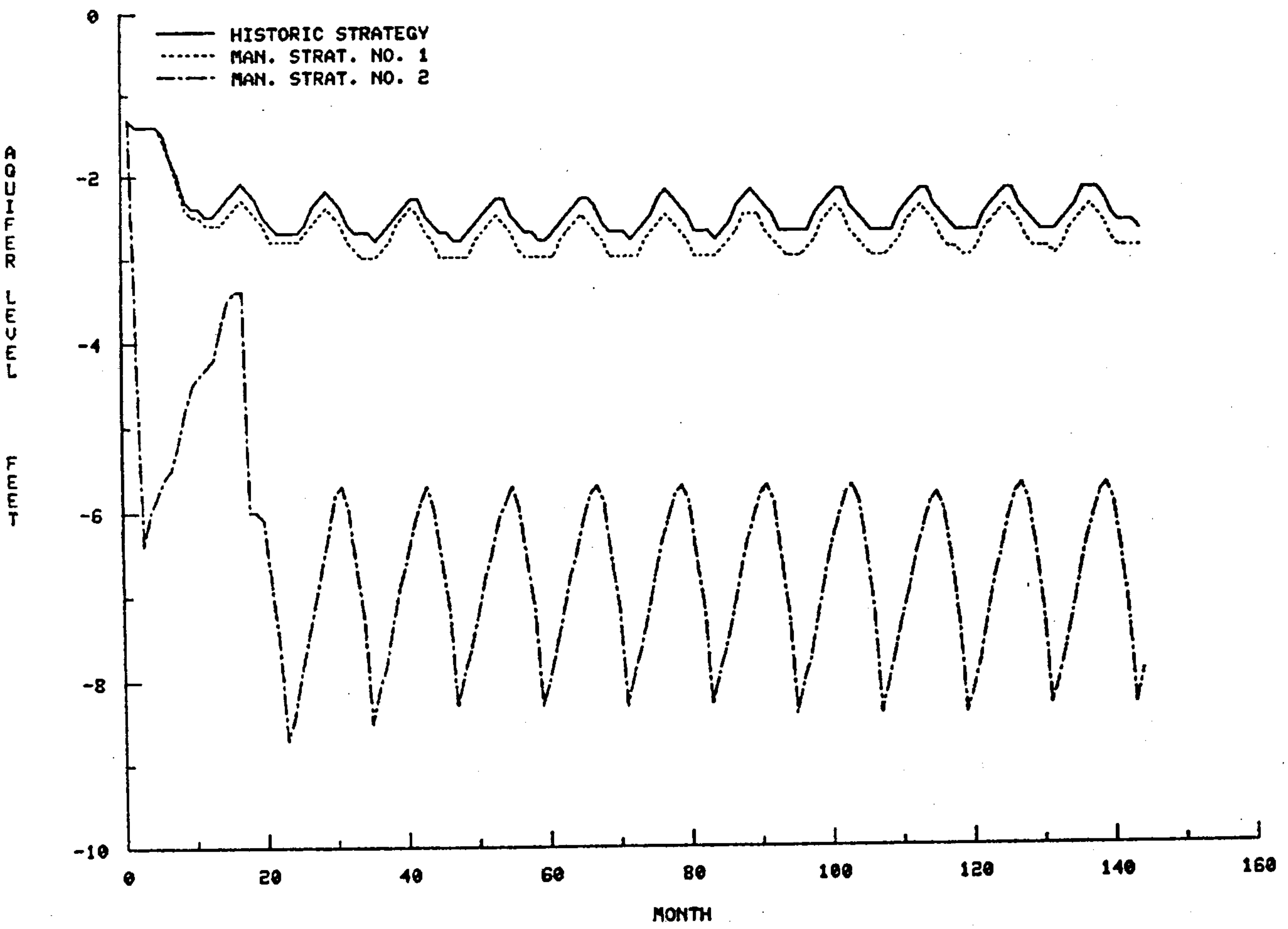

FIG. 37 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 24

Calculation Cells Within Rock Creek Well Field Drains

Figures 38 to 40 show the comparison of the aquifer levels for the 3 strategies for calculation cell numbers 20, 27, and 31. Calculation cell 20 aquifer level variation in management strategy no. 2 exhibits similar behavior to the historic strategy except the variation of the level for strategy no. 2 is larger. The plots for calculation cells 27 and 31 (Figures 39 and 40) indicate the aquifer levels for management strategy no. 2 are closer to the surface than for the historic strategy. This is a result of the formation of a mound of water between the Rock Creek well field and the Rio Grande due to seepage from Rock Creek well field recharge drains.

Calculation Cell No. 9 Adjacent to the Rock Creek Well Field

The aquifer level variation for the 3 management strategies at calculation cell no. 9 is shown in Figure 41. The aquifer level for management strategy no. 2 is drawn down compared to the historic strategy. The lower aquifer level in the Rock Creek well field adjacent to cell no. 9 causes the aquifer level at this cell to decline with time. Consequently a result of the Rock Creek well field is that aquifer levels at adjacent cells may be drawn down. In addition, the use of sub-irrigation techniques may not be possible in these adjacent cells due to the lower aquifer levels.

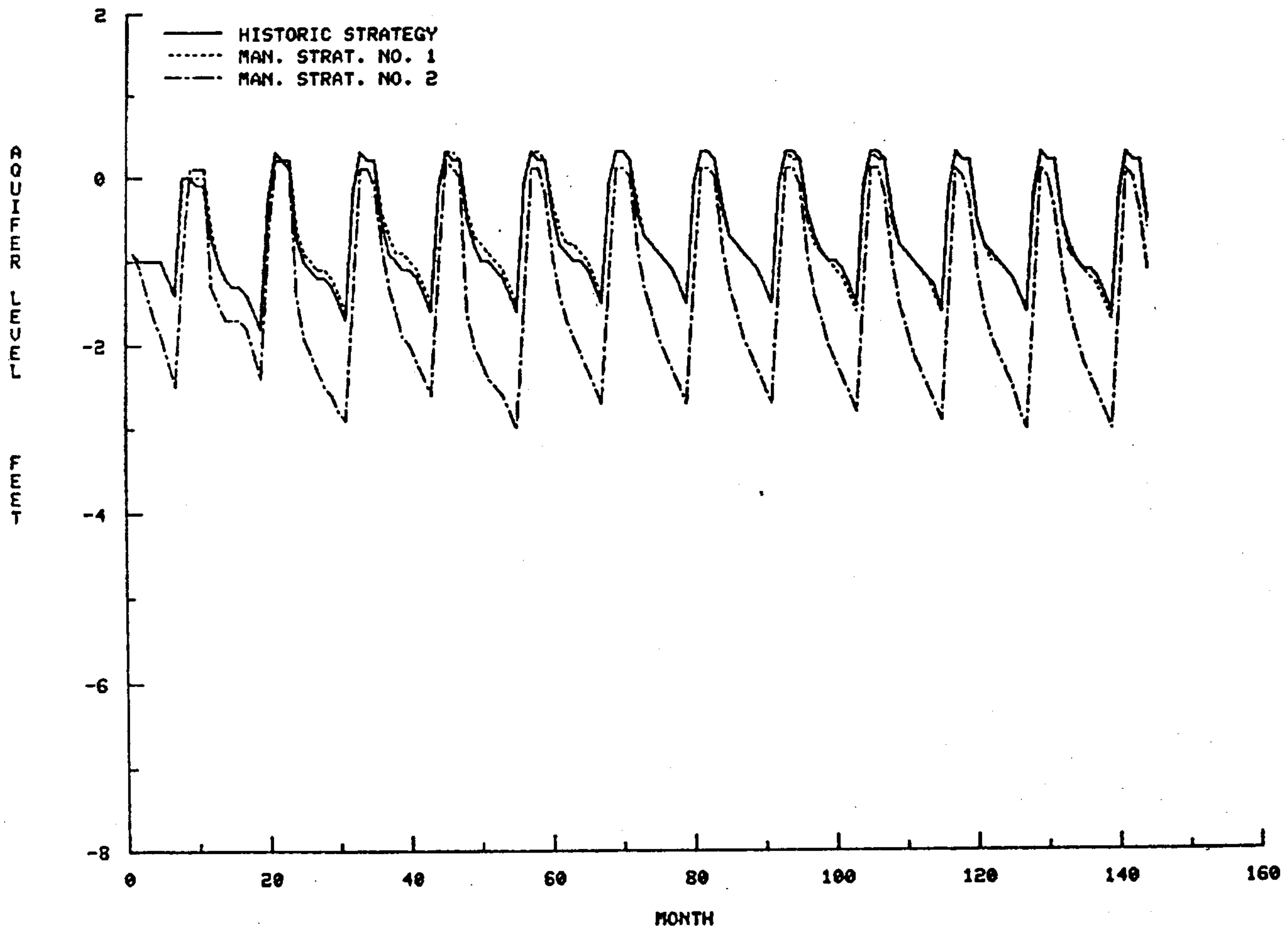

FIG. 38 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 20

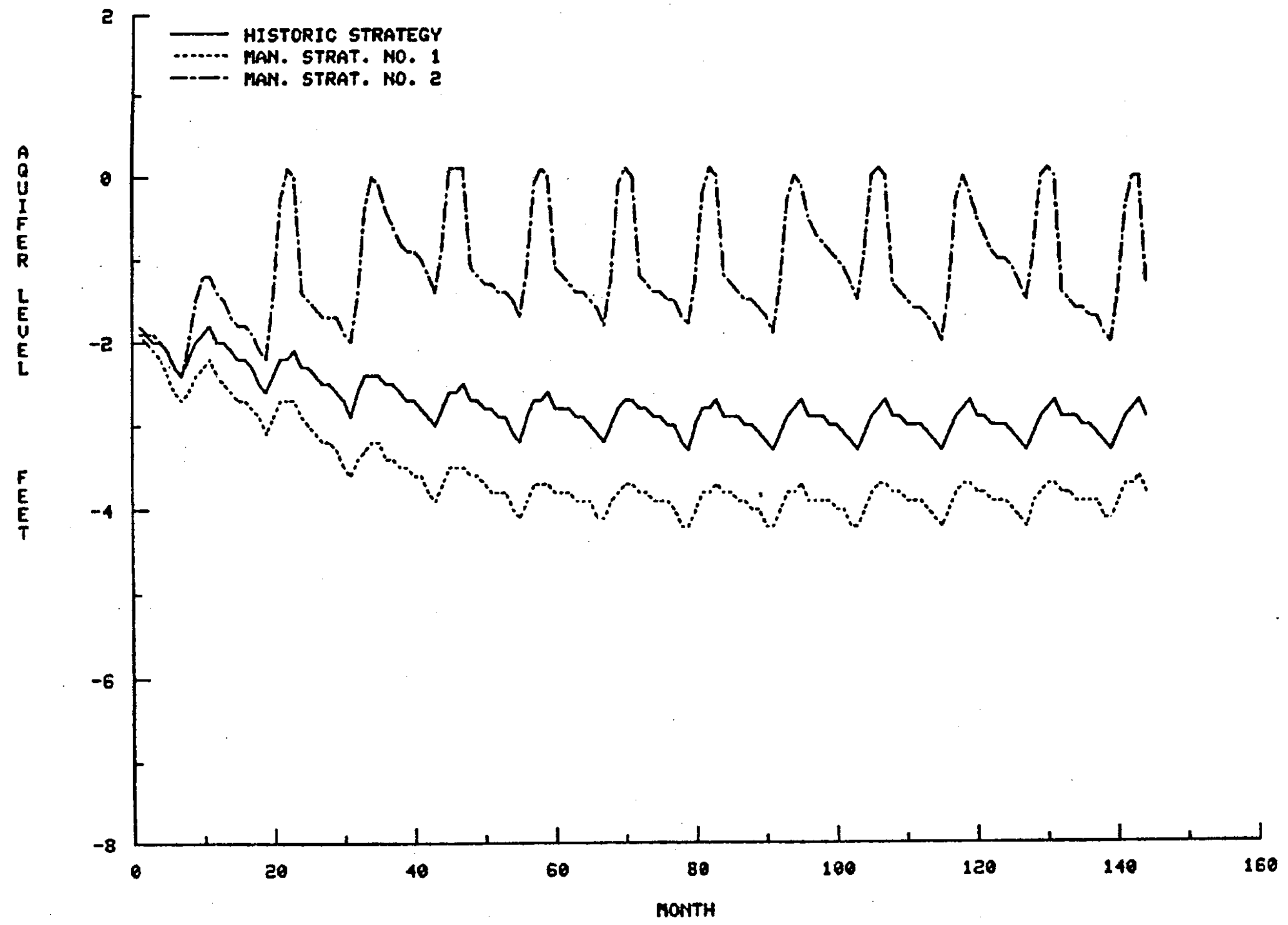

FIG. 39 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 27

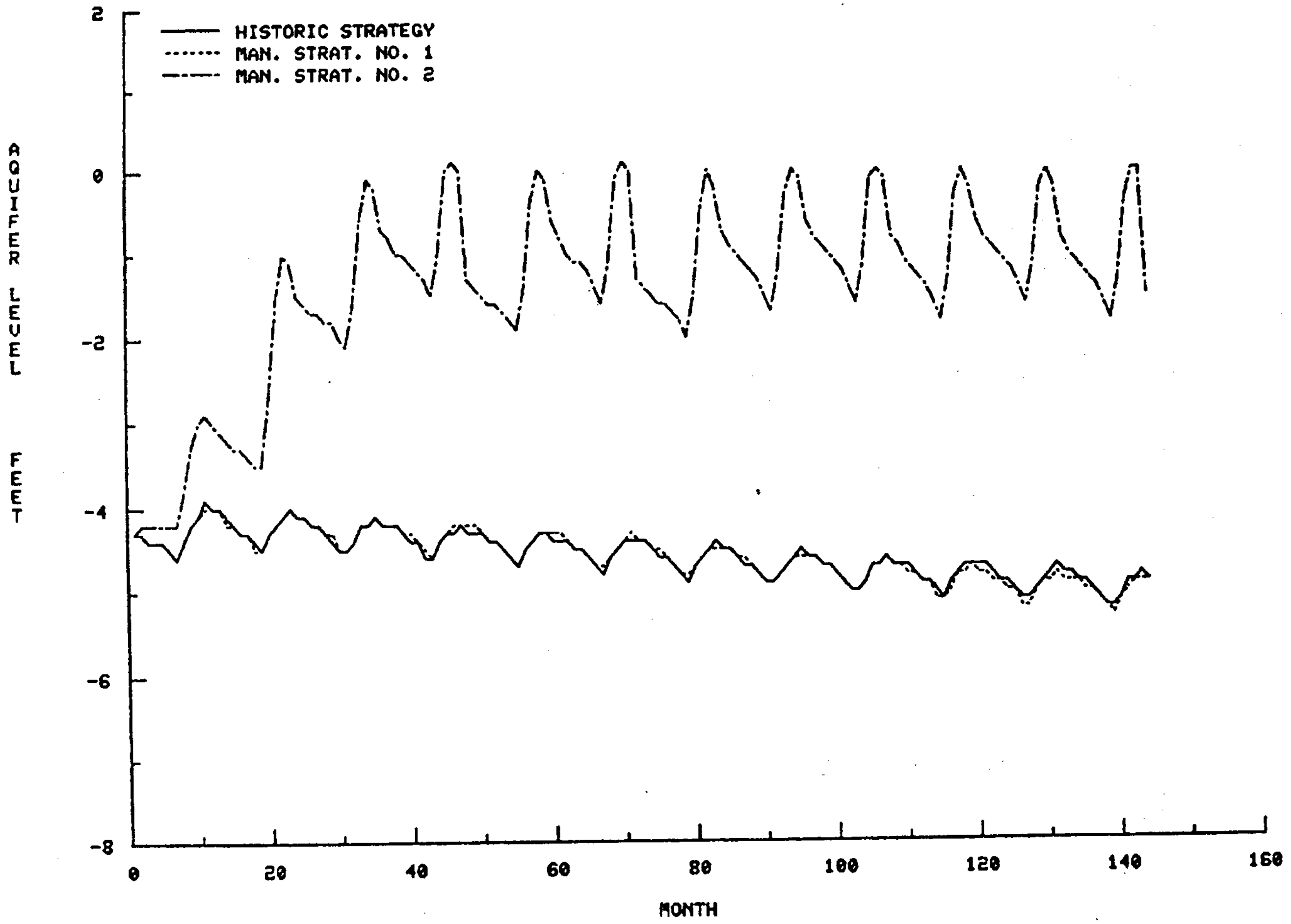

FIG. 40 COMPARISON OF STRATEGIES - AQUIFER LEVEL AT CALN. CELL NO. 31

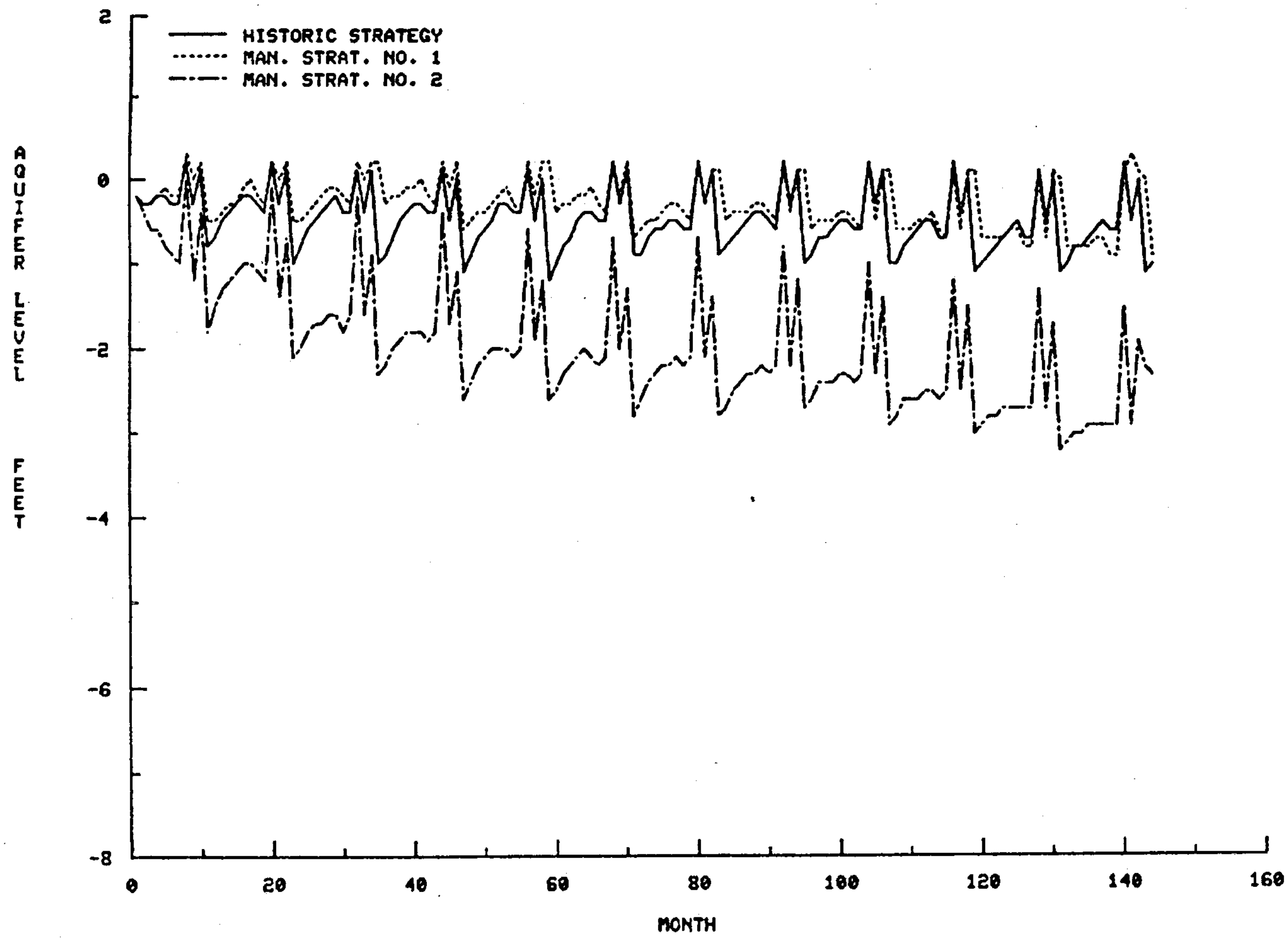

FIG. 41 COMPARISON OF STRATEGIES - AQUIFER LEVEL OF CALN. CELL NO. 9

CHAPTER VI

CONCLUSIONS

General. The 500 square mile study area in the San Luis Valley is a complex system made up of many components and interactions between the various components. A computer simulation model of this stream-aquifer-irrigation system has been developed in this study to investigate various management strategies. This report is a first step in the process of investigating the waterlogging problems of the study area in the San Luis Valley. Two alternative management strategies are considered in this study; however, many other possible strategies exist and could be investigated in future studies. The results of these strategies indicate the value of computer models for investigating various strategies for improving the conjunctive use of surface and groundwater.

Chapters II through V of this report present the details of the computer model and development of the model of the stream-aquifer-irrigation system in the study area within the San Luis Valley. Chapter II describes the components and interactions considered in the development of the hydrologic model. The modeling techniques adopted in the computer model for various components and interactions along with degree of complexity of the technique are presented. Chapter III presents the details of the actual computer program. Chapter IV and V address the solution of the waterlogging problems in the San Luis Valley. Chapter IV describes the historic management strategy and the 2 alternative management strategies, while Chapter V compares the results for the 3 management strategies.

It is the intent of this chapter to summarize the conclusions related to the results for the historic management strategy and the 2 alternative management strategies. Some of the conclusions for this study have been mentioned previously.

The Historic Management Strategy. The historic strategy is used as a base run against which 2 well field development management strategies can be compared. The change in both water volume and aquifer level variation at calculation cells in the management strategies compared with the historic strategy is more important than the actual numerical value of these quantities. The comparison of the results for the strategies is presented in Chapter V. The computer model is an adequate representation if the water volume quantities are reasonable approximations of the existing situation in the San Luis Valley.

In the historic strategy the major sources of irrigation water supplied to the study area are surface water diversions and confined aquifer deliveries. The utilization of low-efficiency irrigation techniques, including sub-irrigation, results in a great deal of drainage from the irrigation areas to downslope areas both by overland flow and by aquifer flow. The result is the continued waterlogging of these downslope areas near the rivers within the study area. Flooding along the Alamosa/La Jara system also contributes to waterlogging, however, the major waterlogging mechanism is the downgradient water movement from irrigation areas.

The results in Chapter V for the historic strategy suggest that the computer model is reasonably calibrated with the existing situation in the San Luis Valley. The predicted monthly outflows for both the Rio Grande and Conejos Rivers agree fairly well with historic outflows (Figures 18 and

19). The Rio Grande compact is also satisfied in each of the 12 years of simulation. The total return flow for the system is approximately 65,000 acre-feet per year while the evaporation from the observation area increases from 180,000 acre-feet in year 1 to 240,000 acre-feet per year in year 12. Waterlogging of the downslope areas between the irrigation areas and the rivers is predicted by the model for the historic strategy. This coincides with knowledge of waterlogging which exists presently in the San Luis Valley.

Management Strategy No. 1. The purpose of the first management strategy (La Jara Creek well field development) is to lower the water table in a 16 square mile area. This would enable leaching of salts, land preparation and planting of crops. A development of 4 center-pivot sprinklers per square mile is assumed in both this management strategy no. 1 and for management strategy no. 2. Both these alternative strategies serve as examples of the effect of a well field development on the study area.

From the comparison of results in Chapter V it is concluded that the strategy for development of the La Jara Creek well field is only partially successful. The intent of this strategy is to permanently lower the water table to 8 to 10 feet below the ground surface. The lowering of the aquifer level is achieved for drains 1 and 2 (calculation cells 11, 15, 23, and 30 -- Figures 27, 28, 30, and 32, respectively) in the La Jara well field. The recharge of these well field drains balances the consumptive use of the crops grown in this section of the La Jara Creek well field. The net excitation for the recharge drains in the La Jara Creek well field except for the San Luis Drain is positive indicating aquifer inflow from adjacent areas must occur for the aquifer level to stabilize. This strategy is not successful for the section of the La Jara Creek well field incorporating San Luis Drain cells and cells to the south of the San Luis Drain. The lowering of the aquifer level to 8 to 10 feet below the ground surface is not achieved for drain 3 comparised of the San Luis Drain cells. The aquifer level varies between 3 and 5 feet below the ground surface due to aquifer recharge from the San Luis Drain. Adequate leaching and drainage may be difficult to achieve with aquifer levels close to the surface. In addition, the upper end of drain 4 located south of the San Luis Drain (cell 22 -- Figure 29) becomes waterlogged with time despite the consumptive use of crops and dewatering pumping each March. This waterlogging is caused by the downgradient drainage from the Alamosa/La Jara irrigation area to cells south of drain 4. Consequantly, further drainage measures would be necessary in this strategy to prevent this waterlogging. Drains from the downslope drainage areas to the Rio Grande or additional dewatering pumping from the La Jara Creek well field would solve this problem.

In this management strategy dewatering pumping is carried out each March in the La Jara Creek well field to lower the aquifer level. The quantity of pumping would be reduced if the amount of recharge of downgradient drainage in the well field drains is reduced. Leaving the drains unchecked for a portion of the year would achieve this goal.

Lowering the water table in the La Jara creek well field area reduces the evaporation from the 245 square mile observation area compared with the evaporation for the historic strategy (Figure 24). This reduction represents a true gain of water for the stream-aquifer system.

The total system return flow is considerably less for this strategy compared to the historic strategy (Figure 20). The Rio Grande return flow is reduced by approximately 2,000 acre-feet per year as a result of this strategy compared with the historic strategy (Figure 21). This is a result of lowering the water table in the La Jara Creek well field, however, the effect on the Rio Grande return flow is not a significant change. The return flows to the San Luis Drain are reduced in this strategy compared with the historic values by approximately 16,000 acre-feet per year (Figure 22), however, the outflow from the drain to the Rio Grande is similar in both cases (Figure 23). The decrease in San Luis Drain return flow is compensated for by both the downslope drainage from irrigation areas and dewatering pumping in March to the drain. Drainage from the well field to the Rio Grande contributes to the Rio Grande Compact agreement and consequently, additional diversions from the Rio Grande take place in this management strategy compared with the historic strategy.

Management Strategy No. 2. The purpose of the second management strategy is to lower the water table in a 10 square mile area (Rock Creek well field) to enable the growing of crops using a center-pivot sprinkler irrigation system. From the comparison of strategies in Chapter V it is concluded this strategy is reasonably successful. Permanent lowering of the aquifer level to 8 feet or further below the ground surface occurs at all cells within the well field (calculation cells 12, 13, 16, 19, and 24 -- Figures 33 to 37). Recharge of the well field aquifer approaches a balance with the consumptive use of the crops grown in the Rock Creek well field. As in the first management strategy, the annual net excitation at cells in the well field area is positive indicating aquifer flow from adjacent areas must also contribute to recharge of the aquifer below the Rock Creek well field. An effect of lowering the aquifer adjacent to the well field may be to prevent the use of sub-irrigation techniques.

As a result of the permanent lowering of the aquifer levels at least 6 feet below the ground surface, dewatering pumping (March) to lower the aquifer level is not necessary from year 3 onwards in the Rock Creek well field strategy. This result contrasts with the first management strategy.

Evaporation from the 245 square mile observation area is also reduced in this strategy as in management strategy no. 1 (Figure 24) as a result of the lowering of the water table in the Rock Creek well field area. A net gain of water results for the study area. Consequently, the irrigation water for consumptive use requirements of the crops in the Rock Creek well field is made available without adversely affecting existing water users.

The total return flow for the system decreases for this management strategy compared with the historic management strategy (Figure 20). The return flows for the Conejos River and San Luis Drain (Figure 22) are similar for both strategies. The decrease in total return flow results from the decrease in Rio Grande return flow. The lowering of the water table in the Rock Creek well field reduces the return flow from the unconfined aquifer to the Rio Grande.

Finally, the impact of the Rock Creek well field on other irrigators in the study area has both advantages and disadvantages. Water deliveries to the Rio Grande from the Rock Creek well field drains go to meet the Rio Grande Compact agreement, and consequently more surface water diversions are available from the Rio Grande in this strategy compared with the historic strategy. Waterlogged areas adjacent to the Rock Creek well field may also become reclaimable as a result of the lowering of the water table in the region of the Rock Creek well field. A detrimental effect of the Rock Creek well field scheme is the drawdown of the aquifer in irrigation areas adjacent to the Rock Creek well field. Sub-irrigation may be eliminated in these areas as a result of the lower water table. The net quantity of water available to users in the study area does not decrease as a result of this management strategy. The decrease in evaporation compensates for the consumptive use of the crops in the Rock Creek well field development.

Suggestions for Further Research

In economic terms, waterlogging is an "externality" (an unintended uncompensated side effect of normal production activities). Normal market processes fail to account for external effects, and institutional adjustments are usually called for. Control of waterlogging, as seen above, can be physically accomplished by reducing irrigation losses and/or by drainage of affected lands, and investments in conveyance and drainage facilities are required for control of the problem.

The next steps in the research program will call for assignment of economic costs and benefits of the drainage activities, so as to measure the private and social rates of return to the community groundwater management institutions designed to control waterlogging.

APPENDIX

APPENDIX

INVENTORY OF POTENTIALLY RECLAIMABLE, WATERLOGGED AND SALT-AFFECTED LANDS IN LOWER SAN LUIS VALLEY[1]

OBJECTIVES

The objectives of this phase of the study were to delineate and inventory waterlogged and salt-affected soils in the study area that could be reclaimed and put into crop production if the water table was lowered and if improved irrigation management practices were followed thereafter.

PROCEDURES

The general location of the study area is south and west of the Rio Grande and north of the Conejos River, extending between Monte Vista and Alamosa. The area encompasses parts of Alamosa, Rio Grande, and Conejos counties.

Soil surveys of Alamosa, Rio Grande, and Conejos counties and U.S. Geological Survey topographic maps (1:24,000 scale) of the study area were obtained. Soil samples of major soil series lying to the south and west of Alamosa (described in Table A-4) were generously provided by Soil Conservation Service and CSU Extension Service personnel.[2]

One reason for analyzing soil samples was to determine whether or not the salt and sodium contents of major soil series were significantly different

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[1] Prepared by Professor William T. Franklin, Department of Agronomy, Colorado State University. Appreciation is expressed to John Olsen for analysis of soil samples and to Wayne Jensen for making map overlays and determining land acreages.

[2] Mike Peterson, SCS, USDA, and Abe Relyea, Area Agronomist, Colorado State University Extension Service, Alamosa, Colorado.

for analytical results obtained several years ago and reported in Soil Survey of Alamosa Area, Colorado (1973). Saturated paste extracts of the soil samples were analyzed to determine salt ($ECx10^3$) and sodium-absorption-ratio (SAR). The gypsum content of each soil sample was measured also. The salt and sodium contents of the samples fell within the expected range as reported by the Soil Survey of Alamosa Area, Colorado (1973).

Overlays of soil series, delineated on aerial photos, were superimposed on the 1:24,000 scale USGS topographic maps. Blocks of land that were farmed, predominately, and Wildlife Refuge land were eliminated from the "potentially reclaimable" category. Waterlogged and/or salt-affected soil series were then segregated into two different general areas (Figure A-1) that are potentially reclaimable.

The soils within the two general areas were then subdivided into three groups on the basis of salinity, exchangeable sodium, and water table depth, as follows:

1. Wet Meadow Soils (Group I) - Non-saline to slightly salinized waterlogged soils needing drainage but no gypsum or leaching water before cropping.
2. Salt Meadow Soils (Group II) - Salinized and waterlogged soils requiring drainage and leaching water applications before cropping.
3. Salt Flat Soils (Group III) - Saline and sodic soils requiring drainage, gypsum, and leaching water for reclamation before establishing crops.
    IIIA - Soils containing gypsum within the profile.
    IIIB - Soils containing no gypsum requiring application of commercial amendment.

Necessary treatments or procedures for reclaiming each group of soils were proposed and the time to accomplish complete reclamation and achieve full crop production was estimated. Production capabilities of each group

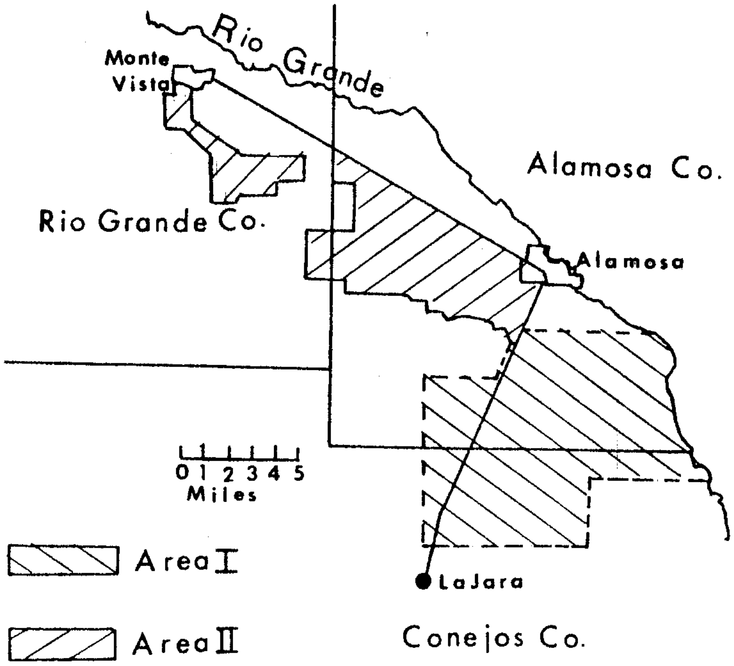

Fig. A-1. Areas of Potentially Reclaimable Land Studied South of the Rio Grande in the San Luis Valley.

were estimated under present conditions and under completely reclaimed conditions with a high level of management.

SOIL ANALYTICAL RESULTS AND GROUPINGS OF SOILS

The analytical results on soil samples taken by series lying generally south of Alamosa are shown in Table A-1. The soils can be placed into three broad groups with respect to severity of waterlogging and salt and sodium contents.

Wet Meadow Soils (Group I) - Non-Saline to Slightly Saline Soils

The Alamosa and Vastine series (Table A-1) are representative of the first group. Other soils falling within this group are the La Jara series, Sandy and Loamy Alluvial Land, and Marsh areas. The above soils consist of level to nearly level, low flood plain areas along the Rio Grande, Alamosa Creek, La Jara Creek, and Rock Creek that are flooded periodically during spring runoff. The water table is about one foot from the soil surface during much of the growing season but may drop to four feet or lower during fall and winter months. The frequent surface flooding prevents accumulation of salts at the soil surface. Thus, crop cultivation is mainly limited by the high water table and wet conditions.

Vegetation consists of water-tolerant species, such as sedges, rushes, slough grass, alkali sacaton, and salt grass. The soils produce native hay, as well as furnishing pasture for livestock. Willows and cottonwoods occur along river and stream banks in some places.

Salt Meadow Soils (Group II) - Saline, Non-Sodic Soils

The Acacio (1) and Zinzer (1) samples in Table A-1 are representative of this group. Other series in this group are parts of the Alamosa,

Table A-1. San Luis Valley Soil Sample Analyses for Salinity Assessment.

Sample	Depth in	Saturation %	ECX10^3 mmhos/cm	Ca	Mg me/l	Na	SAR	Gypsum me/100g
Alamosa	0-12	49	2.7	14.2	3.0	15.2	5.2	0
	12-24	51	2.6	7.5	1.6	20.0	9.4	0
	24-36	30	1.7	4.6	2.9	17.0	8.8	0
Vastine (A)	0-12	47	5.8	30.4	17.3	33.5	6.9	30.9
	12-24	55	5.0	28.5	13.7	25.0	5.4	13.1
	24-36	47	3.9	28.1	9.6	16.0	3.7	4.6
Vastine (B)	0-12	46	1.9	11.0	4.1	7.0	2.6	0
	12-24	51	1.9	12.3	4.2	9.2	3.2	0
	24-36	59	1.4	9.4	3.6	4.8	1.9	0
Vastine (C)	0-12	53	2.0	14.5	5.3	7.5	2.4	0
	12-24	45	1.7	10.4	5.5	7.2	2.6	0
	24-36	37	0.8	4.2	2.3	3.4	1.9	0
Zinzer (1)	0-12	37	6.8	35.1	14.1	34.0	6.9	6.4
	12-24	29	4.0	31.2	7.2	15.4	3.5	2.0
	24-36	23	3.3	24.9	6.5	11.0	2.8	1.9
Zinzer (2)	0-12	42	24.3	62.3	13.6	262	42.6	27.5
	12-24	33	20.9	60.4	13.9	180	29.5	28.5
	24-36	30	12.9	46.3	13.5	102	18.7	28.2
Acacio (1)	0-12	35	20.2	31.0	294.2	92.0	7.2	15.0
	12-24	48	4.8	39.2	17.1	16.0	3.0	30.7
	24-36	36	3.2	34.7	5.6	10.0	2.4	31.0
Acacio (2)	0-12	63	21.7	7.8	6.2	270	66.1	0
	12-24	69	15.2	3.6	5.2	175	83.4	0
	24-36	38	22.5	27.4	9.9	270	62.5	25.2
Lasauses (A)	0-12	47	30.4	50.0	128.7	290	30.7	5.0
	12-24	38	25.3	40.9	100.0	263	31.3	13.4
	24-36	47	15.6	31.4	47.5	148	23.6	30.1
Lasauses (B)	0-12	38	30.4	39.9	71.2	350	47.0	1.1
	12-24	49	24.3	30.0	47.5	290	46.6	20.5
	24-36	43	22.5	24.1	45.4	323	54.7	25.7
Lasauses (C)	0-12	37	26.4	28.4	77.0	315	43.4	16.0
	12-24	37	19.6	28.2	57.1	218	33.3	20.7
	24-36	27	9.1	25.8	26.4	76	14.9	21.8

Nortonville, San Acacio, Hooper, Mosca, McGinty, Villa Grove series and Wet Alluvial Land. These soils consist of nearly level flood plain areas of the valley floor that are slightly higher in elevation than the wet meadow soils and are subject to occasional flooding only when runoff is much higher than normal. In some places these soils form a band between the wet meadow and drier soils. The salt meadow soils have a seasonal high water table at about two to two and one-half feet from the surface resulting from irrigation seepage from creeks or the Rio Grande. Crop cultivation is limited by both salinity and high water table.

Vegetation is variable from site to site but usually consists mainly of alkali sacaton, alkali cordgrass, slender wheatgrass, saltgrass, wirerush, sedges, and perennial forbs. Scattered greasewood and rabbitbrush occur on some of the drier sites. The vegetation is harvested as native hay and used for pasture in most areas.

Salt Flat Soils (Group III) - Saline and Sodic Soils

The Acacio (2), Zinzer (2), and Lasauses samples in Table A-1 are representative of Group IIIA, saline-sodic soils containing gypsum. Other series falling in this group within the study area are saline phases of San Acacio, Nortonville, and Villa Grove. Soil series in Group IIIB, saline-sodic soils that generally do not contain gypsum, are Corlett, Gunbarrel, Hapney, Hooper, Laney, McGinty, Mosca, and San Luis. All these soils occupy gently sloping low terrace positions adjacent to salt meadow and wet meadow soils along the Rio Grande and various creeks and are somewhat higher than salt meadow and wet meadow soils. These soils are seldom, if ever, flooded under natural conditions. However, the salt flat soils are subject to a fluctuating water table that is three feet from the surface during most of the cropping season and may fall to as low as six feet during fall and winter months. Crop cultivation is limited by excess salt and sodium, by lack of precipitation, and by the high water table.

Vegetation is generally a mixture of salt-tolerant grasses and shrubs consisting of alkali sacaton, alkali cordgrass, western wheatgrass, blue grama, four-wing saltbush, saltgrass, greasewood, rabbitbrush. The vegetation has a limited grazing value for livestock.

ACREAGES OF POTENTIALLY RECLAIMABLE AREAS AND GROUPS

The acreage of potentially reclaimable land falling into each area and each group were measured on color-coded overlays of soil series. These measurements are as follows:

Group	Area I	Area II	
Wet Meadow (I)	14,810A		
Salt Meadow (II)	20,260A		
Salt Flat (IIIA)	23,730A	6,860A	(no gypsum needed)
(IIIB)		27,460A	(2,700 need 10-12 T/A gypsum)
Total Reclaimable	58,800A	34,320A	(24,000 need 5-6 T/A gypsum)
Farmed	-------	5,120A	
Total Land	58,800A	39,440A	

The "farmed land" category in Area I could not be determined in an unambiguous way from the aerial photos used because native hay is harvested from wet meadow and some salt meadow soils. Thus, difference between land harvested for native hay and land planted with grain, for example, were not easily discernible. Estimates do not include land necessary for drain ditches, irrigation ditches, roads, and farmsteads.

RECOMMENDED RECLAMATION TECHNIQUES

Requirements for putting waterlogged and salinized land into normal agricultural production include part or all of the following treatments.

Flood Control, Drainage, and Aquifer Recharge

Flood control is necessary to prevent periodic inundations of wet meadow and salt meadow soils adjacent to Alamosa, La Jara, and Rock Creeks, and the Rio Grande. Putting up and stabilizing dikes or levees along these bodies of water are probably the most feasible treatments. Stabilization of dikes would probably consist of facing the earthen dike with rocks and establishing permanent vegetative cover. This would be necessary mainly in Area I (Figure A-1).

Drainage would best be maintained by pumping from wells. The water table should be lowered eight to ten feet from soil surface for most efficient salt leaching. The unconfined aquifer has a specific yield coefficient of about 0.2 (Emery, et al., 1972). Thus, the water table would drop about five feet for each foot of water pumped and removed from the area. Some drain ditches would still be necessary for removal of excess water. This would be applicable to both Area I and Area II. Open drain ditches, spaced one mile apart at a minimum, would be essential and vital for recharge of the unconfined aquifer also.

Brush Eradication

Some "brush" eradication may be necessary on all three groups of soils. Removal of willows and trees (on smaller areas) would be helpful immediately adjacent to the Rio Grande, the various creeks, and drainage ways leading into the river and creeks. These appear only on wet meadow soils (Group I) and constitute only relatively small acreages within this group.

Some drier sites in the salt meadow group (Group II) have scattered greasewood and rabbitbrush. This vegetation could be cleared with a bulldozer blade, piled, and burned after the water table is lowered.

The salt flat soils generally have a cover of greasewood, rabbitbrush, and saltbrush varying in density. Removal can be accomplished in several ways but the simplest means is uprooting the brush with railroad ties pulled behind a track-type tractor, piling the brush, and burning it when dry.

Land Leveling and Irrigation Systems

Land leveling is necessary in both areas and on all three soil types. The land, for the most part, is realtively flat, sloping 0-1 percent toward the east and northeast. Land leveling requirements are best described as "light." Small areas of wet meadow land near the Rio Grande contain hummocks which would result in variable leveling requirements and would have somewhat higher than average leveling costs. Small dunes occur in some drier soil sites, making leveling costs variable in other areas also. Land leveling costs would be somewhat less for areas which could be sprinkler irrigated.

Sprinkler irrigation would be recommended for about 70 percent of Area II, or 27,500 acres in the western part of this area. This part of Area II consists predominantly of coarse-textured loamy sand soil. Approximately 3,000 acres of coarse-textured land south of La Jara Creek near the Rio Grande in Area I would be best suited for sprinkler irrigation also. All other soils, which are generally in the medium-textured class, could be irrigated satisfactorily by flood or furrow irrigation. The available moisture in the top 0-2 foot depth of medium-textured soil is about 4.2 inches of water and about 3.3 inches in the 2-4 foot depth, totaling 7.5

inches. In comparison, total available moisture in the 0-4 foot depth of the coarse-textured soil is about 3 inches. Permeability of the medium-textured soil in Area I generally ranges between moderately slow (.2-.8 in/hr) and moderate (.8-2.5 in/hr), whereas the permeability of coarse-textured soils generally ranges between moderately rapid (2.5-5 in/hr) and rapid (5-10 in/hr). Thus, because the permeability of the medium-textured soils is relatively slow compared with the coarse-textured soils and the moisture-holding capacity is relatively high, the medium-textured soils should be well-suited to flood or furrow irrigation.

Even though the medium-textured soils are suitable for flood or furrow irrigation, difficulties in obtaining reliable labor in the San Luis Valley may make sprinkler irrigation actually more feasible than flood.

Amendments, Subsoil Tillage, and Leaching

The wet meadow and salt meadow soils in Area I are non-sodic (ESP 15) and, therefore, need no amendment. The salt flat soils in both Area I and Area II are sodic (ESP 15). The salt flat soils in Area I contain substantial amounts of native soil gypsum, more than enough to reduce exchangeable sodium to acceptable levels in the majority of cases (Table A-2). However, the native gypsum does not extend to soil surface in some cases (Acacio, Sample 2, Table A-1). It is estimated that about 4,500 acres of such land exists in Area I, or about 20 percent of salt flat soils. Plowing to a depth of two and one-half to three feet with a moldboard plow would bring the necessary gypsum to the soil surface in the majority of the cases. The cost of deep-plowing is estimated to be $55 per acre.

About 15 percent of the salt flat soils in Area II (about 5,000 acres) contain substantial amounts of native soil gypsum. A commercial amendment

Table A-2. San Luis Valley soil reclamation requirements

Sample	Depth	Leaching Water Required to Reduce EC to <4 mmhos	Gypsum Required to Reduce ESP to 10		Gypsum Deficit	Leaching Water Required[1/] to Reduce ESP to 10
	in		me/100 g	T/A	T/A	A-ft/A
Alamosa	0-36	None	None	None	None	None
Vastine (A)	0-24	6 A-in/A	None	None	None	None
Vastine (B)	0-36	None	None	None	None	None
Vastine (C)	0-36	None	None	None	None	None
Zinzer (1)	0-12	4 A-in/A	None	None	None	None
Zinzer (2)	0-12	-	6.0	10.5	None	6
	12-24	-	2.9	5.1	None	3
	24-36	-	1.2	2.1	None	1
	0-36	-	10.1	17.7	None	10
Acacio (1)	0-12	2 A-ft/A	None	None	None	None
Acacio (2)	0-12	-	17.9	31.4	31.4	18
	12-24	-	20.3	35.4	35.4	20
	24-36	-	8.5	14.8	None	8.5
	0-36	-	46.7	81.7	21.5*	46.5
Lasauses (A)	0-12	-	4.8	8.4	None	5
	12-24	-	3.8	6.7	None	4
	24-36	-	3.0	5.3	None	3
	0-36	-	11.6	20.4	None	12
Lasauses (B)	0-12	-	6.0	10.5	4.9	6
	12-24	-	8.0	14.0	None	8
	24-36	-	8.7	15.2	None	9
	0-36	-	22.7	39.7	None*	23
Lasauses (C)	0-12	-	5.6	9.8	None	5.5
	12-24	-	3.9	6.8	None	4
	24-36	-	.9	1.6	None	1
	0-36	-	10.4	18.2	None	10.5

[1/] One A-ft of water passing through a 1-ft soil depth will dissolve about 1.75 tons of native soil gypsum (equal to 1 me/100g)

* Assuming soil was moldboard plowed to bring gypsum to soil surface.

would have to be applied to remove excessive exchangeable sodium on the remaining 85 percent. About 27,600 acres of land in Area II consist of coarse-textured loamy sand and sandy loam soils. Chiseling (subsoil tillage) would be beneficial for improving the uniformity of water infiltration and improving plant root development on the coarse-textured soils. On the average, this land would require an application of 4 to 5 T/A of gypsum to reduce exchangeable sodium to a desirable level (ESP 10). The application could be reduced by about 1 T/A if a high Ca groundwater was used for leaching. Information about groundwater quality within both Areas I and II is very sketchy, however. Medium-textured soils (loam to clay loam) exist on about 6,700 acres in Area II. Most of this land would require 40 to 80 T/A.

The wet meadow soils would not require leaching water for salt or sodium removal, in general. Salt meadow soils would require about two acre feet per acre of leaching water before planting a crop to reduce salt to an acceptably low level (Table A-2). The salt flat soils would require more leaching water than salt meadow soils because water is required to dissolve native soil gypsum but will dissolve only 1.25 to 1.5 T/A of commercial gypsum. In general, less commercial gypsum is dissolved than native soil gypsum because it is concentrated at the soil surface and generally has a larger particle size than native soil gypsum. In general, 4 to 5 acre feet per acre of water will be required to reduce the ESP to less than 10 percent in the 0-1 foot depth before the crop is planted (Table A-2). Reducing the ESP before cropping is much more critical for the medium-textured soils than for coarse-textured soils. Applications of water totaling more than 10 acre feet per acre are needed to reduce the ESP to less than 10 percent in the 0-3 foot foot zone depth (Table A-2).

ADJUSTED ACREAGES OF POTENTIALLY RECLAIMABLE LAND IN AREA I

The net total acreage of potentially reclaimable land in Area I after adjustment for flood control, ditches, roads, and farmsteads is broken down as shown in Table A-3.

Table A-3. Net acreage after adjustment for flood control, ditches, roads, and farmsteads.

Group	Adjustment	Adjusted Acreage
Wet Meadow	14,810 - 1,455 of flooding	13,355
Salt Meadow	20,260	20,260
Salt Flat	23,730	23,730
	58,800	57,345
	57,345 - 2,000 of roads and drains	55,345
	55,345 - 3,345 of farm roads, irrigation structures, farmsteads (6 percent)	
Net Acreage		52,000

Table A-4. Location of soil samples taken from Study Area I in the fall of 1977.

Soil	Location
Alamosa	2,100 ft. E and 500 ft. S of NW corner, Sec. 2, T37N, R 10E
Vastine (A)	800 ft. E and 200 ft. N of SW corner, Sec. 15, T36N, R 10E
Vastine (B)	1,500 ft. N and 200 ft. W of SE corner, Sec. 13, T36N, R 10E
Vastine (C)	2,500 ft. S and 500 ft. W of NE corner, Sec. 1, T36N, R 10E
(Shown as La Jara on survey map)	
Zinzer (1)	100 ft. W and 100 ft. N of SE corner, Sec. 4, T36N, R 10E
Zinzer (2)	1,800 ft. W and 100 ft. S of NE corner, Sec. 3, T36N, R 10E
Acacio (1)	900 ft. W and 500 ft. N of SE corner, Sec. 4, T36N, R 10E
Acacio (2)	100 ft. W and 1,200 ft. N of SE corner, Sec. 4, T36N, R 10E
Lasauses (A)	350 ft. W and 100 ft. N of SE corner, Sec. 9, T36N, R 10E
Lasauses (B)	500 ft. S and 250 ft. W of NE corner, Sec. 12, T36N, R 10E
Lasauses (C)	1,000 ft. S and 1,000 ft. E of NW corner, Sec. 7, T36N, R 10E

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