A SALINITY MANAGEMENT STRATEGY FOR STREAM-AQUIFER SYSTEMS

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LIST OF SYMBOLS

C = Concentration of total dissolved solids (TDS) in water $[M/L^3]$

C_i = Concentration of water from Section i applied for irrigation or artificial recharge $[M/L^3]$

C_{dj} = Average concentration of drainage water over a model period $[M/L^3]$

C_{mj} = Upper bound on concentration of drainage water $[M/L^3]$

C_{gj} = Average concentration of groundwater over a model period $[M/L^3]$

c_{ij} = Cost of transporting 1 unit of water from section or source i to section j $[\$/L^3]$

D_{ij} = Second order dispersivity tensor $[L^2/T]$

D_L = Longitudinal dispersion coefficient $[L^2/T]$

D_T = Transverse dispersion coefficient $[L^2/T]$

D_w = Depth of applied irrigation water [L]

DCON = Artificial decision variable corresponding to difference between the maximum concentration of drainage water C_{mj} and the groundwater C_{gj}, for section j $[M/L^3]$

d_i = Demand for water at section i $[L^3/T]$

EC = Electroconductivity [micromhos/L^2]

EC_w = Electroconductivity of irrigation water [microhos/L^2]

EC_{dw} = Electroconductivity of drainage water [microhos/L^2]

ET = Evapotranspiration or consumptive use [L]

ET_i = Evapotranspiration at section i $[L^3/T]$

ϵ_L = Longitudinal dispersivity [L]

ϵ_T = Transverse dispersivity [L]

h = Piezometric surface above some datum [L]

M = Mass flux of the source or sink $[M/L^3T]$

NR_i = Natural recharge in section i $[L^3/T]$

q_{ij} = Amount of water transferred from section or source i to section j $[L^3/T]$

q^*_{ij} = Optimal amount of water transferred from section or source i to section j $[L^3/T]$

S = Specific yield or storage coefficient

s_i = Total water available from section or source i $[L^3/T]$

T_{ij} = Second order transmissivity tensor $[L^2/T]$

TDS = Total dissolved solids

t = Time [T]

x,y = Spatial cartesian coordinates [L]

v_i = Seepage velocity [L/T]

W = The volume flux per unit area [L/T]

ΔC = Basin wide change in TDS concentration $[M/L^3]$

ΔS = Basin wide change in salt mass [M/T]

ΔW_k = Change in water quantity balance in section k $[L^3/T]$

ΔW = Change in basin-wide water quantity balance $[L^3/T]$

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This research is part of a continuing cooperative effort involving Colorado State University and several agencies at the federal, state, and local levels. From the United States Geological Survey, the writers wish to acknowledge Joe Moreland, who did the initial water quantity modeling in the San Luis Rey Basin; Jim Skrivan, who was later assigned to the project; and Leonard Konikow, who gave unselfishly of his time in explaining the simulation model which he developed and permitted the authors to use in this research. Thanks are also extended to Glenn Twitchell, of the California State Water Resources Control Board, and Col. A. C. Bowen, general chairman of the Santa Margarita-San Luis Rey Watershed Planning Agency, for their cooperation and support. The research leading to this report was supported by the Office of Water Research and Technology, Department of the Interior, (Grant No. 14-31-0001-5229 (C-6301)), and the State of California, with funds from the latter administered through the Santa Margarita-San Luis Rey Watershed Planning Agency.

ABSTRACT

A Salinity Management Strategy for
Stream-Aquifer Systems

One of the pressing problems facing the irrigation intensive areas of the world is the increasing salinity of groundwater. Currently proposed solutions, such as agricultural sewering and desalinization, require large capital investment. There appear to be few available alternatives which are both low cost and effective in controlling aquifer degradation from irrigation drainage. The ultimate result in many areas may be abandonment of the groundwater resource and increasing dependence on more expensive imported water.

Presented herein is a cost-effective salinity management technique which may be feasible for many stream-aquifer systems. The basic idea is to encourage application of pumped water downstream of the well from which it is pumped, rather than within its vicinity. In this way, a mechanism is established for accelerating the downstream transport of salts in the groundwater at a more rapid rate than would occur naturally through convection and dispersion, while still satisfying irrigation demands. The strategy is therefore referred to as the Accelerated Salt TRANsport (ASTRAN) Method. Salt accumulation can be controlled in this manner, while taking care that salt problems are not simply transferred downstream.

A management algorithm is developed for implementing the ASTRAN method which combines a screening or optimizing model with a detailed quantity-quality simulation model. The optimizing model generates least-cost alternatives for distributing water over the basin. These alternatives are subsequently examined by the simulation model as to their effectiveness in controlling the salt balance. A parameter in the optimizing model can be adjusted so as to produce a desired degree of salinity control.

The management algorithm has been applied to Bonsall Subbasin in the Lan Luis Rey River Basin in order to test its effectiveness. An 11 year historical period including a wide range of climatic variation was used for this purpose. The simulation model of the Subbasin was based on a previous modeling effort carried out by the United States Geological Survey in the area.

Results of the case study indicate that the ASTRAN method (1) is truly cost-effective, requiring roughly 10% of the cost of tiling for this area, (2) encourages balanced conjunctive use of surface water and groundwater, and (3) is flexible enough to respond to future management needs.

Chapter I
INTRODUCTION

A. Groundwater Basin Degradation

The potential for, or reality of, degradation of groundwater basins in irrigation intensive areas around the world is a pressing problem facing water planners and managers at all levels of government. Agricultural production in these areas is highly dependent on the availability of low cost water of suitable quality. Consequently, improperly managed river basins, where land and water are allowed to deteriorate by salt accumulation, might seriously impair a nation's food supply. Increasing urbanization intensifies this problem by not only taking prime agricultural land out of production, but also creating expanding urban populations needing additional food which must be produced on the remaining productive land. Therefore, not only must nations conserve presently available arable land, but they must attempt to reclaim land now considered lost to agricultural production. Production loss may be due to salt accumulation in land, groundwater (if a reliable supply of good quality surface water is not available), or both.

Hall [7], in a plea to recognize this issue, has written:

> "Salt problems are particularly insidious. They do not come charging at you with trumpets blowing and battle flags flying, a sight to set stirring the hearts of activists in any century. Rather, they slip in almost unnoticed. They invariably seem to promise to step aside and behave themselves in return for small additional concessions. Then one day, as witnessed by many dead civilizations, they assert their supreme command of the situation. Time is of no concern, for they are supremely confident of their ultimate victory. History is on their side, as are the laws of physics, and chemistry, and biology. They have quietly destroyed, without fuss or fanfare, more civilization than all of the mighty armies of the world.
>
> "Today, every arid land region of the world is in some intermediate or final stage of this process, and nowhere, it would seem, has there been established a genuine detente with these deceptively simple destroyers of man's vaunted accomplishments."

In support of this argument, Yaron [25] estimates that one-fifth of the irrigated land in the United States and one-third of the irrigated land in the world is plagued by salt accumulation. Often, salt accumulation in land and salt accumulation in groundwater go hand in hand. The emphasis in this research is the groundwater degradation problem, which is particularly compounded by its invisible nature. The aphorism, *out of sight; out of mind* is all too applicable to salt build-up in groundwater basins. In spite of the danger, Hall fears that the necessary research and application will not be marshalled in time to effectively combat salt problems. Hopefully, however, the future will not substantiate this fear.

Salts contributing to aquifer degradation can occur from many sources, such as combined and storm sewer discharges, precipitation infiltrating through solid waste landfills, animal feed lots, dairy farms, sewage settling basins, and irrigation return flows. Perhaps the most difficult to control are the nonpoint sources such as drainage water from irrigation. Certainly, they seem to be the least visible.

In this report, the terms *salt accumulation*, *aquifer degradation*, and *salinity problems* will be used interchangeable to denote groundwater degradation. The term *groundwater* refers to water in the saturated zone. The term *salt* includes all of the dissolved solids found in the water, which correctly implies that this research is considering aquifer salinity from an aggregated perspective.

In an era of environmental awareness, it may surprise some that groundwater quality has not received more attention. It is important to arrive at priorities in addressing environmental problems, because they are corrected at great cost, and those problems that may be irreversible or most harmful must be corrected first. The relative abundance of water in the United States has, perhaps, contributed to the low priority given to groundwater quality in this country. Since, however, over 97% of the earth's fresh water exists underground, unpolluted aquifers are an extremely important natural resource. Furthermore, most water resources engineers agree that integrated, conjunctive use of surface and groundwater is the most efficient way to utilize the total water resource. Hence, a fundamental motivation for this research has been a belief that the groundwater resource must be preserved and protected if it is to be utilized by man in the most beneficial way.

Briefly, the objectives of the research leading to this report were to develop a low capital investment management strategy with the potential of retarding, and even halting, aquifer degradation, and then test it with a well respected, commonly used stream-aquifer model simulating a real-world situation. The San Luis Rey River Basin in Southern California was chosen as the case study area, under cooperative agreement with certain interested federal, state, and local agencies. Once the validity of the general management strategy had been confirmed, the goal was to devise an algorithm for implementing the strategy in the most economical way. The encouraging results of these studies are reported herein.

B. Current Approaches to Groundwater Quality Management

A description of the state-of-the-art in water quality planning and management is given by Maletic [12], and listed in Table I-1. At first glance, it might appear that water planners and managers have a vast number of alternatives from which to choose for controlling water quality in river basins. Upon closer examination, however, some of the alternatives are either infeasible, or of questionable effectiveness. Notice, for example, that two of the Categories list desalting, which is still prohibitively expensive. Under Category III, *Irrigation Sources*, improved irrigation methods are listed as possible alternatives. These approaches tend to encourage the temporary storage of salts in the unsaturated zone, thereby controlling their release to the saturated zone. A high degree of control is required for the success of this approach, however, and considerably more research is needed. Dilution is also mentioned as an alternative in this list, but it presupposes the availability of an adequate supply of good quality surface water, which might not be the case.

The management technique presented herein would appear to fall under Category III(3), *Groundwater Management*, since it involves selective pumping and application of groundwater. It might also be classified under Category IV, *River System Management*. This technique is not presented as the ultimate solution to groundwater salinity problems, but a potentially viable alternative for consideration among the many other alternatives. The challenge to water planners and managers is to find the optimal mix of alternatives that will meet water quality goals in the most beneficial way.

TABLE I-1

MAJOR CATEGORIES OF SALINITY CONTROL

I. POINT SOURCES

    1. Desalt
    2. Divert/Evaporate
    3. Divert/Special Use
    4. Plug Wells
    5. Deep Injection

II. NATURAL DIFFUSE SOURCES

    1. Collect/Desalt
    2. Collect/Evaporate
    3. Collect/Special Use
    4. Watershed Management
        a. Vegetative conversions
        b. Forest management
        c. Structural measures
        d. Water harvesting
        e. Reduced sediment production
    5. Phreatophyte Control
        a. Control of spread
        b. Replacement vegetation
        c. Antitranspirants

III. IRRIGATION SOURCES

    1. Improved On-Farm Irrigation Use
        a. Irrigation scheduling
        b. Improved farm irrigation systems
            1) Pipes and Lining
            2) Automation
            3) Advanced systems
    2. Improved Water Conveyance Systems
        a. Piles, lining
    3. Groundwater Management
        a. Water table control (drainage)
        b. Selective pumping
        c. Groundwater recharge
    4. Return Flow Management
        a. Collect/desalt
        b. Collect/sepcial use
    5. Evaporation Suppression

IV. RIVER SYSTEM MANAGEMENT

    1. Alteration of Time Pattern of Streamflow
    2. Alteration of Time Pattern of Saline Discharges

V. DILUTION

    1. Augmentation
        a. Weather modification
        b. Geothermal resources
        c. Desalting
        d. Wastewater reclamation
        e. Conservation practices
    2. Importation

There are four river basins around the world which appear to be receiving the most attention in the area of stream-aquifer system water quality management. They are: the Colorado River Basin, the Santa Ana and San Luis Rey River Basins in California, and the Murray River Basin in Australia. The Lower San Luis Rey River Basin is the area focused upon for this study. This basin is a nearly ideal stream-aquifer system for quality management research since there have been previous studies which lay a foundation for the research, and considerable data are available which aid in evaluating management schemes. In addition, the Santa Margarita-San Luis Rey Watershed Planning Agency (WPA) is highly oriented toward solving the salinity problems in the area, which makes the implementation of a total management plan more probable. Recent studies by the WPA are instructive as an example of applying the state-of-the-art in controlling aquifer degradation.

Table I-2 lists the control measures considered by the WPA to halt aquifer degradation in the San Luis Rey Basin [21]. Of the nine measures listed in Table I-2, only measures IV, VII, and IX were considered economical. Even is measures III and VI were adopted, which center around the tiling of irrigated lands, the salt accumulation would only be slightly decreased, as shown in Figure I-1 [22].

TABLE I-2

WATER QUALITY CONTROL MEASURES TO MEET THE FEASIBLE WATER QUALITY OBJECTIVES

I. Improvement of Source Water Quality
II. Export of Municipal Waters
III. Export of Agricultural Waters
IV. Storm Water Conservation
V. Demineralization and Exportation of Salts
VI. Extraction and Exportation of Salts
VII. Land Use Control
VIII. Weather Modification
IX. Sea Water Intrusion Control

For example, the *Comprehensive Water Quality Management Study (CWQMS)* for the San Luis Rey Basin concluded that:

> "Gradual degradation of the groundwater would be permitted in all basins except Warner Basin and the confined aquifers of the Murrieta-Tamecula groundwater area. The more sensitive quality oriented uses will be progressively eliminated from reliance on the groundwater supplies and will be forced to turn to the purchase of imported water. This process will satisfy all beneficial uses but through economic allocation of local groundwater or imported supplies.

"The groundwater basins will become reservoirs of brackish water which will serve only the most salt tolerant beneficial uses. When the economics of cost of production of desalted water crosses the ascending line of cost of comparable imported water, it will be feasible and practical to extract and demineralize the groundwater, exporting the salts to the ocean, and reduce the quantity of water imported" [21].

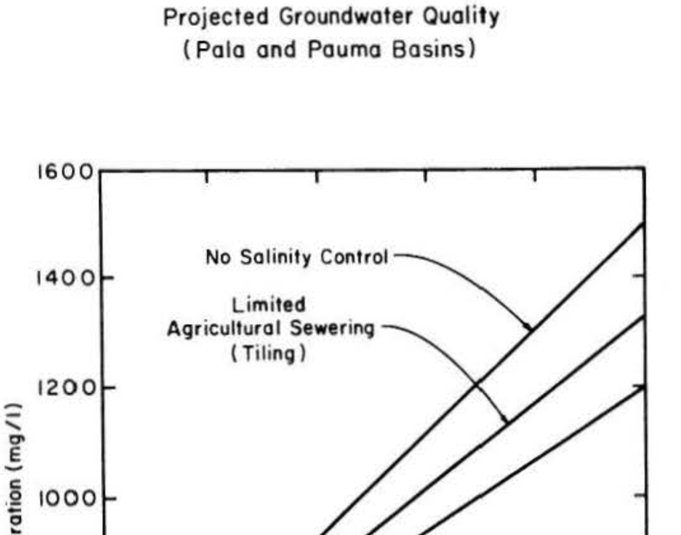


Figure I-1. Projected Degradation of Pala and Pauma Aquifers

Computer modeling studies on the upper Santa Ana River Basin by Water Resources Engineers, Inc. [23] were apparently some of the first efforts at studying the total river basin management problem; i.e., including groundwater and surface water quantity and quality. Though these studies did not investigate feasible control measures, they did suggest some positive actions, such as the exportaion of salts and irrigation management. Most of the present plans consider desalting as a main corrective and hope that some of the various desalinization methods will become economical in the near future. This may happen, but a dependence on it as the main corrective seems dangerously optimistic.

Another example of large-scale planning is the combination of methods being considered for halting the degradation of the Colorado River. Table I-3 itemizes these methods. It is important to note, however, that the emphasis on this list is surface water. The item *Source control* probably involves storing salts underground in the saturated and unsaturated zones, which solves the surface water quality problem only to create another; i.e., eventual degration of the aquifers. Moreover, note the reliance on desalting costs, and other speculative salt control schemes. All in all, the technical picture is not encouraging; and as yet, the political and institutional obstacles have received little consideration.

TABLE I-3

PROJECTED SALINITY REDUCTIONS: COLORADO RIVER AT IMPERIAL DAM (mg/1)

	1970	1980	1990	2000
Estimated salinity level	850	930	1100	1200
Anticipated range*	(730-1030)	(800-1340)	(950-1340)	(1040-1460)
Source control	---	(-54)	(-130)	(-130)
Vegetation management	---	0	(-20)	(-40)
Desalting	---	(-0)	(-40)	(-90)
Weather modification	---	(-20)	(-40)	(-90)
Other practices	---	(-6)	(-20)	(-20)
Total reduction	---	-80	-250	-350
Estimated salinity level range**	(730-1030)	(730-1030)	(730-1030)	(730-1030)

*Without salinity control programs
**With salinity control programs

To summarize this section on *Current Approaches*, though regulation of groundwater quantity is rather advanced technically, the same cannot be said for groundwater quality. There are pumping, importation, and artificial recharge schemes that have been in use for some time in quantity management. Salinity management, on the other hand, is much more difficult. The solutions that are usually proposed are tiling (which depends upon having high quality water available), or desalinization (which also is expensive and technically infeasible on a large scale, at the present time). Of course, point source pollution is the most obvious and is the easiest to control technically. It is the problem of nonpoint sources, particularly irrigation drainage, that is addressed here. Again, the control of irrigation applications in such a way as to *store* salts in the unsaturated zone, thereby preventing them, at least for a time, from reaching the water table, is under heavy study. Despite these, and other management techniques, it must be concluded that there is a dearth of effective and economical solutions to the problem of aquifer degradation.

C. *Accelerated Salt TRANsport (ASTRAN) Method*

Many stream-aquifer systems may be conducive to application of a potentially cost-effective salinity management technique referred to as the *Accelerated Salt TRANsport (ASTRAN) Method*. The basic ideas leading to the development of this approach originated with Warren A. Hall, in conjunction with the Irrigation Management Practices (IMP) committee of the Council on International Development (CID), formerly named the Council of U. S. Universities for Soil and Water in Arid and Sub-Humid Areas (CUSUSWASH).

The usual irrigation practice is to apply groundwater on fields near the well supplying the water. The ASTRAN method, however, encourages the application of groundwater on downstream fields (via canals or pipes) instead of on nearby fields. That is, fields proximate to a pumping well should be irrigated, to at least some extent, by water from upstream wells. Salts in the pumped water can therefore be transported downstream at a faster rate than would occur naturally through flow in the saturated zone; hence, the name *Accelerated Salt TRANsport (ASTRAN) Method*. The slow movement of groundwater tends to cause an accumulation of salts from normal irrigation practice, since drainage water adds salt to the aquifer at a faster rate than it can be naturally transported downstream. The idea behind this technique is to simply augment the natural process by transporting pumped water downstream via a surface distribution system of some kind.

The management technique is illustrated in Figure I-2. This diagram depicts an increasing salt concentration downstream, since many stream-aquifer systems have this characteristic. Such a condition, however, would not seem to be necessary for successful application of the ASTRAN method. It is, however, required for application of the management algorithm presented in this report. Appropriate modification of the algorithm could be carried out, in case this condition does not exist.

It should be noted that if irrigation water quality is the same as the groundwater quality, then by the time it drains through the root zone and reaches the water table, it is generally of lower quality than the groundwater. This is due to (a) transpiration of pure water by crops, leaving water with a higher concentration, and (b) addition of salts which have accumulated in the unsaturated zone due to past irrigations and/or the chemical composition and geologic characteristics of the porous media. Of course, many complex chemical interactions can take place between the water and soil. It is difficult to model these interactions, however, because of (i) the complexity of the interactive processes, and (ii) lack of field data for verifying a model.

What this points to is that even if extremely good quality water is always applied for irrigation purposes, aquifer degradation can still occur. Other methods are therefore needed for controlling degradation. The ASTRAN method offers a simple, straightforward way of achieving control.

From this preliminary discussion, some very general inferences about the basic requirements for successful application of the ASTRAN method can be drawn.

1. Perhaps the most obvious requirement is that the combined average transport rates of pumped water being moved downstream, applied, and drained back down to the saturated zone, should be considerably greater than the natural transport by convection and dispersion.

2. Since the emphasis is on transporting salts downstream, in addition to meeting irrigation demands, it may be necessary to pump and transport more water than is needed for irrigation, in order to control degradation. This may (or may not) require: (a) drilling additional wells; (b) providing additional artificial recharge facilities; (c) augmenting the surface water distribution system. The cost-effectiveness of the ASTRAN method will be highly dependent on the costs and potential capacities of these works. In situations where large quantities of salt are known to exist in the unsaturated zone (e.g., in the salt shale of Grand Valley, Colorado), the ASTRAN method would have to be applied with great care since increased drainage might accelerate the degradation process.

3. Since upstream groundwater is applied downstream, it is apparent that at least some water of reasonable quality, in addition to the groundwater in the basin, will be required for upstream lands. This might be: (a) local surface water; (b) imported water; (c) groundwater farther upstream of the basin of interest; (d) or a mixture of these. It would seem that if the groundwater in the basin were of a usable quality, then less of this additional water would be required. If, on the other hand, the groundwater were of marginal, or even unusable, quality, then much more of this additional water would be needed to improve the situation.

4. In order to prevent salt problems from simply being transferred downstream, it seems clear that implementation of the ASTRAN method requires a total basin scope for its maximum effectiveness. It is assumed that there is some way of ultimately removing salts from the basin, either by pumping downstream groundwater into an outfall or into a natural channel leading to the ocean. If the basin is closed, then a salt sink area must be identified.

5. Finally, it is obvious that considerable cooperation would be required of water users in the basin. It would probably be necessary to create some kind of basin-wide management authority for implementing the ASTRAN method.

These deductions are admittedly vague. They do, however, represent general guidelines for identifying stream-aquifer systems that would be candidates for successful application of the ASTRAN method.

It is important to emphasize once again that the ASTRAN method has not been designed to operate alone, but rather in conjunction with other methods so as to produce the most economical mix of schemes to totally manage the stream-aquifer system. For example, tiling a downstream constriction in a basin might increase the discharge rate of poor quality rising water in order to increase salt export. Mixing imported water with the pumped groundwater or spatially varying their applications might also help. Or, it might be possible to use improved irrigation methods to store salts in the unsaturated zone until the irrigation season is over. Then, they can be leached out and sent to the ocean as a *slug* of poor quality water, or they could be pumped to an outfall.

D. Objectives

The research leading to this report was conduced to investigate the validity of the ASTRAN method as a legitimate salinity management strategy for irrigated stream-aquifer systems. More specifically, the objectives were to:

1. Test the technical feasibility of the ASTRAN method for controlling groundwater basin degradation by selecting a typical stream-aquifer system and simulating its hydrological and hydrochemical response under the ASTRAN method.

2. Construct a management algorithm which could be used to answer specific questions as to the importation, pumping, and application policies necessary to implement the ASTRAN method in the most cost-effective manner.

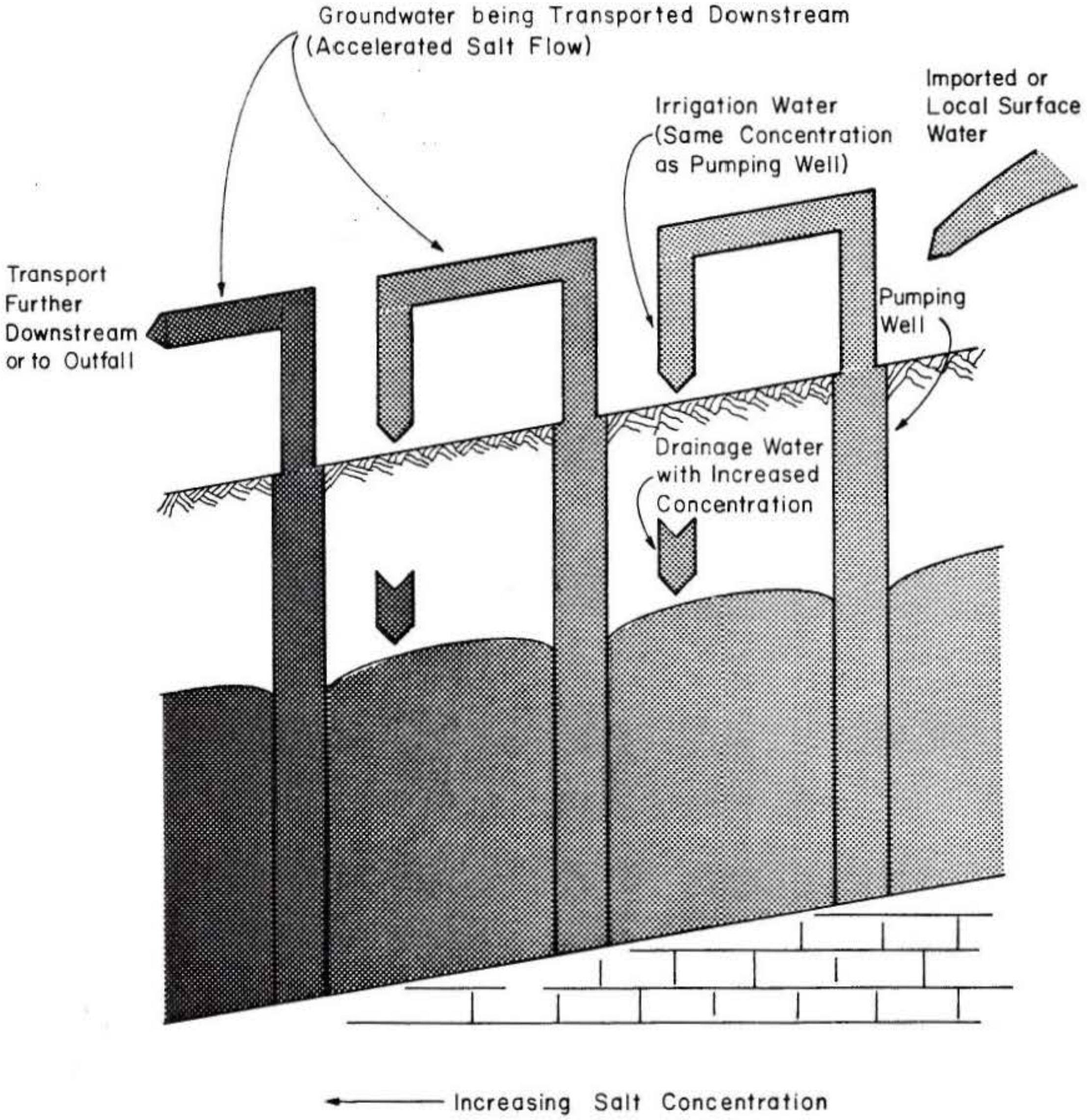


Figure I-2. A Schematic Diagram of the Accelerated Salt TRANsport (ASTRAN) Method

As far as the authors are aware, a combined groundwater quantity and quality simulation model has only been applied to two areas: the Santa Ana River Basin [23] and a segment of the Arkansas River [9]. As mentioned earlier, the Lower San Luis Rey River Basin in San Diego County, California, was chosen for studying the ASTRAN method. A portion of this study area, Bonsall Subbasin, was selected for initial investigation. To reiterate, this selection was advantageous for several reasons: (i) water quantity models for the area had already been calibrated and tested by the United States Geological Survey (USGS), so that after some modifications, all that was required was the addition of a water quality model; (ii) considerable historical quantity and quality data are available; and (iii) a high degree of cooperation appears to exist among water users in the basin.

The second objective of developing a management algorithm, for cost effective implementation of the ASTRAN method, represents an attempt to blend simulation and optimization into a workable framework. An optimizing model is developed to *screen out* uneconomical alternatives. The remaining alternatives are then tested by the quantity-quality simulation model as to their effectiveness in controlling groundwater degradation. An iterative process is designed which involves sequential solution of the optimizing model and simulation model until an adequate range of cost-effective policies are determined.

These objectives have been pursued in view of political, social, legal, and other intangible constraints that might arise. Though beyond the scope of the work reported herein, the eventual goal of this continuing research is to apply the ASTRAN method to the entire Lower San Luis Rey River Basin.

E. Summary of Chapters

The report continues with Chapter II, which describes the study area and gives a brief introduction to its geography, geology, hydrology, water quality, and existing water-related institutions. Chapter III introduces the modeling methods used and compares them with the current state-of-the-art. A condensed outline of the basis for the water quantity-quality simulation model is presented. This includes a description of the way existing quantity and quality models were adapted and calibrated for purposes of this study. Chapter IV presents the management algorithm by which the ASTRAN method can be applied. The use of a screening (optimizing) model, in conjunction with the simulation model, is the crux of the algorithm. Chapter V gives the results of the study, including the computational experience of integrating the simulation model into the overall management algorithm. Chapter VI considers the nonquantitative factors influencing the implementation of the ASTRAN method in the San Luis Rey River Basin. The legal, political, and sociological constraints are evaluated. Chapter VII gives some general conclusions and recommendations for future research. Though the ASTRAN method has been applied to a particular river basin as a case study, it is hoped that the experience gained here will facilitate its consideration in other areas as a viable salt balance management alternative.

Chapter II
DESCRIPTION OF THE STUDY AREA

A. Geography

The San Luis Rey River Basin is located in Southern California between San Diego and Los Angeles, as shown in Figure II-1. Figure II-2 depicts the Lower San Luis Rey River Basin in more detail. The Lower Basin includes the westerly four subbasins, which are separated from the Upper Basin by an earth dam. The entire river basin is composed of five subbasins which are named (proceeding from east to the Ocean) Warner, Pauma, Pala, Bonsall, and Mission, (see Figure II-2). The total watershed is 565 square miles in area. County road 76 runs from Oceanside to Lake Henshaw and various roads branch off to Fallbrook and other small settlements. The famous Palomar Observatory is near the boundary of the basin and several Indian reservations are located within the watershed.

The area is largely unsettled or rural and most of the crops are citrus, avocadoes, grains, dairy farms, etc. Scrub trees and native bushes are found throughout the valley. The basin was divided into three subunits (3A, 3B, and 3C) in the *Comprehensive Water Quality Management Study (CWQMS)* [21]. These three subunits comprise the San Luis Rey River Basin, while the rest of the subunits are the other watersheds adjacent to the San Luis Rey River Basin. The areas of the subunits are:

3A	(Mission and Bonsall)	186 mi^2
3B	(Pauma and Pala)	171 mi^2
3C	(Warner)	208 mi^2

This study, as indicated, comprises the Lower San Luis Rey River Basin which includes subunits 3A and 3B. Table II-1 gives further land use information on this area.

B. Geology of the San Luis Rey River Basin

The area of the San Luis River Basin has an interesting geologic history [22]. From the Triassic Period the area was composed of pre-batholithic rocks, probably sandstones and shales. These were subjected to tectonic forces which resulted in folding, faulting, and metamorphism. From a body of molten granitic rock, many separate injections occurred along zones of structural weakness. Some of the existing rocks were intruded and assimilated by encroaching magma and now occur as roof pendants or inclusions of hybrid gneisses and schists.

After emplacement of batholith, uplift occurred and allowed most of the overlying rocks to be removed by erosion. During the Tertiary Period, the sea alternately covered the area and receded. Uplift occurred later, causing the then level deposits to produce a rougher relief. During recent geologic time, crystalline materials have been weathering to form the present terrain.

There is a complex system of nearly parallel faults which result in earthquake activity. Almost 20 earthquakes of magnitude 4-Richter have occurred within a 50 mile radius of the north middle boundary of the river basin, with most of the epicenters along the San Jacinto Fault Zone.

The floor of the valley is composed of alluvium and valley fill of the late Pleistocene Epoch. Beneath this are plutonic igneous rocks, some of which break through the alluvium. The northern boundary of the basin is formed by the Agua Tibia Mountains which reach elevations of 6,000 feet and are about 20 miles long and eight miles wide. There are many fans, especially along the southwestern base of the Agua Tibia Mountains. The Agua Tibia fan in the Pala area probably built up so rapidly during the Late Pleistocene Epoch that it dammed the San Luis Rey River and caused the fine-grained lacustrine deposits which appear on many of the well logs of the Pauma Subbasin. Most of the valley fill in the various subbasins consists of recent alluvium. This alluvium is made up of sand, gravel, and silt, with occasional boulders.

C. Surface and Groundwater Hydrology

Taking a look first at the surface water hydrology, the San Luis Rey River runs about 35 miles from the Lake Henshaw Dam to the Ocean. The main channel originates in the northern part of the Warner Basin about 15 miles above Lake Henshaw. There are numerous creeks that flow into the main river all along its course. Some of these have been gauged at various times, but most are seasonal creeks. The two largest are Keys and Moosa Creeks.

About ten miles west of Henshaw Dam there is a diversion structure for the Escondido Canal. The water remaining in the river just after this diversion averages 1,487 acre feet per year. Four miles downstream, due to inflows, this average flow increases to 3,736 acre feet per year. There is a gauging station at the Monserate Narrows, which separates the Pala and the Bonsall Subbasins. The gauging station has been in operation since about the middle 1930's.

To indicate the overall rainfall and runoff relationships in the Basin, Figure II-3 shows precipitation at Lake Henshaw superimposed over runoff as measured near the Bonsall Narrows. Figure II-4 gives the monthly stream flows for the station at Monserate Narrows over a two-year period, and Figure II-5 shows the monthly stream flows for the station at Bonsall Narrows.

As is common in stream-aquifer systems, the quality of the groundwater decreases toward the downstream end. The characteristics of the four main subbasins are given in Table II-2. The aquifer characteristics of the four subbasins are similar, with the hydraulic conductivity ranging from 20 to 2,000 gpd/ft^2 and the storage coefficient ranging from 0.1 to 0.16. The specific capacity of the wells varies from 25 to 140 gpm/ft. Given the limited size of the four aquifers, it is apparent that management must be conducted carefully, both quantitatively and qualitatively.

D. Water Quality

As stated above and shown in Table II-2, the groundwater quality increases in total dissolved solids (TDS) as one moves downstream. Because of extensive irrigation, the aquifers have deteriorated over the years, with the greatest increase in TDS occurring in Mission and Bonsall Subbasins. It is seen from Figure II-2 that each subbasin is separated from the others by a narrow gorge (constriction) in the

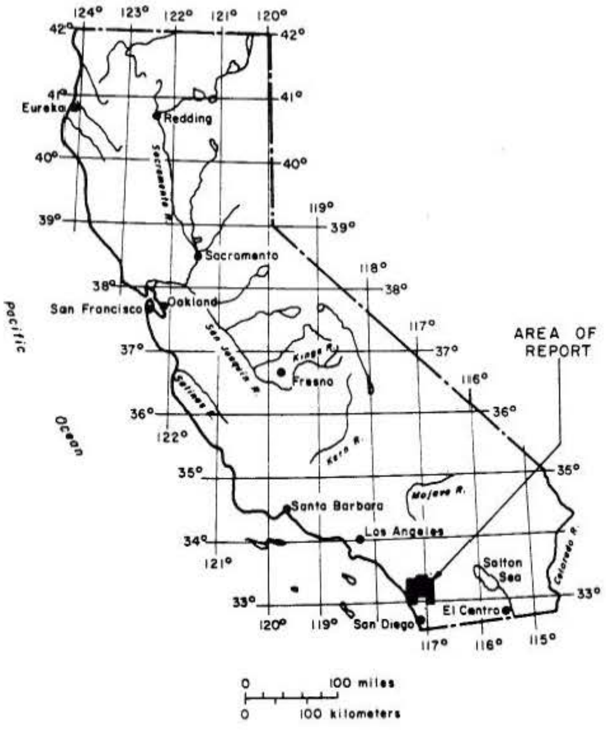


Figure II-1. Index Map to the Study Area

valley floor. This causes a *build-up* of groundwater and salt accumulation at these points.

As an example of aquifer degradation, the trends of two wells with the most complete water quality records are shown in Figures II-6 and II-7. Another well (No. 20-P-3) showed a more dramatic degradation, but this was caused in part by its proximity to the Bonsall waste water disposal site and therefore gives a slightly exaggerated picture of the aquifer degradation. This particular source of groundwater contamination is scheduled to be corrected in the future by further treatment and transport to the ocean by a land outfall.

Notice that the chemographs (i.e., graphs showing water quality vs. time) show a dispersion around the long term mean. Measurement of the TDS or electroconductivity (EC) of water is subject to large fluctuations over a short period of time and area; also, the possibility for sample contamination is ever present. Since the purpose of the studies reported herein was to study long term management effects, a mean historic value line was established for the main wells by regression correlation, to which the model to be subsequently discussed was calibrated.

The USGS report [13] and the CWQMS [21] gave two greatly differing figures for the salt mass balance in the Mission and Bonsall Subbasins for 1970. The USGS report estimated that 6,860 tons of salt per year were accumulating in the two subbasins, while the CWQMS estimated 49,490 tons annually. Field work conducted by the senior author revealed that all of the imported irrigation water (some 40,000 AF/year) is applied to the surrounding hillsides, which are under extensive cultivation with citrus crops. Consequently,

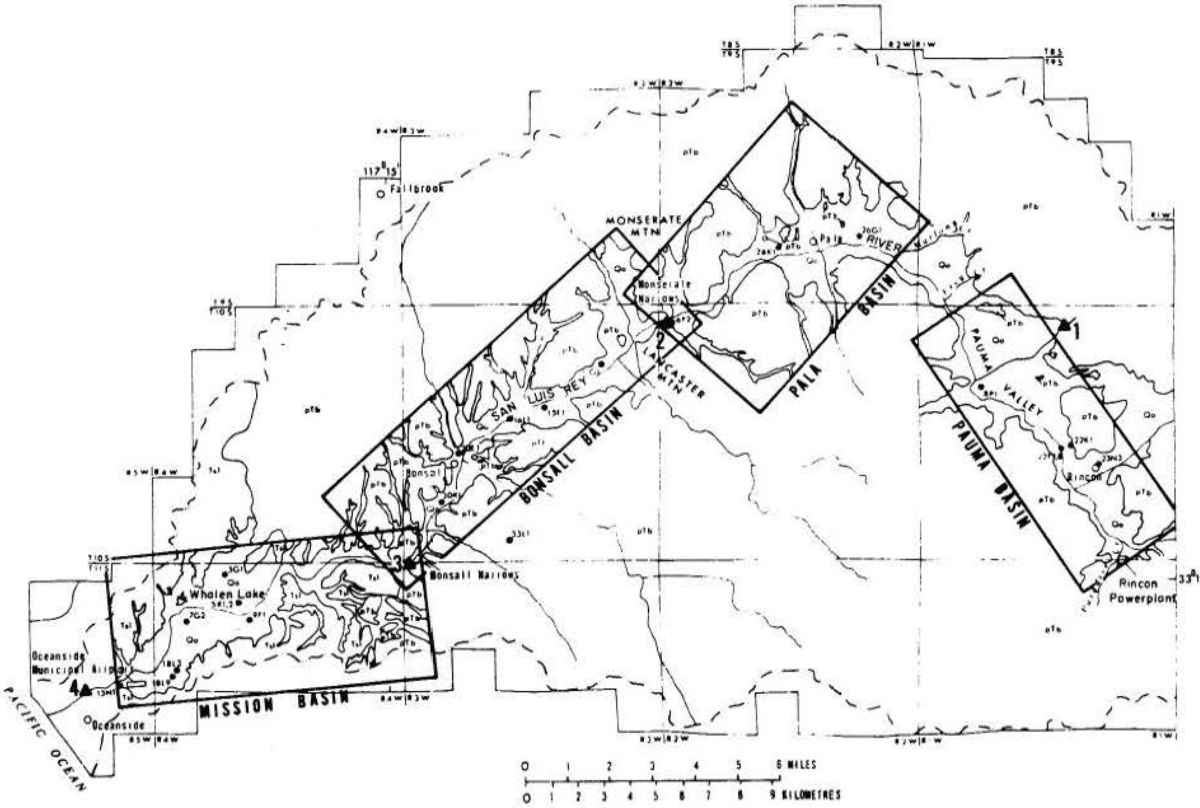


Figure II-2. Delineation of Subbasins within the Lower San Luis Rey River Basin [13] the differing estimates of salt inflow are partly due to the USGS considering only the alluvial aquifer and the CWQMS including the hillside irrigation.

One of the important questions is how much of the imported irrigation water which is applied to the hillsides will eventually reach the alluvial aquifer and when? The irrigation efficiency of the citrus grove irrigation systems is high, especially where the newer trickle or drip irrigation systems are used. Nevertheless, even these systems require the eventual leaching out of accumulated salts occasionally, and the effect this will have on the alluvial aquifer is unknown. Field investigations did reveal that some of the historically seasonal creeks were now flowing perennially. It appeared that this flow could have resulted from the mountain irrigation.

TABLE II-1

LAND USE IN THE LOWER SAN LUIS REY BASIN

<u>SUBUNIT 3A</u> (354,542 acres)

- includes 90% of the dwelling units of the San Luis Rey River Basin
- has 88% of the truck crops in the Basin
- has 56% of the citrus crops in the Basin
- includes 63% of the total irrigated pasture in the Basin

<u>SUBUNIT 3B</u> (98,900 acres)

- 30% is indian reservation
- 15% is forest reserve
- 16% is agriculture

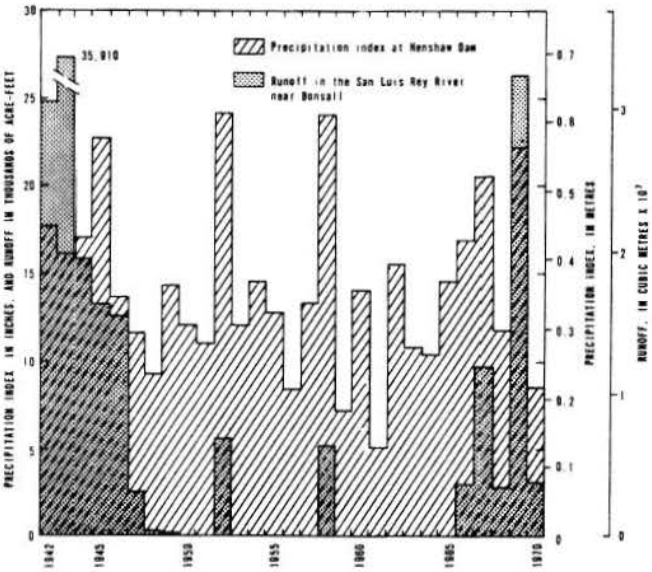


Figure II-3 Precipitation Index at Henshaw Dam and Runoff in the San Luis Rey River near Bonsall Narrows [13].

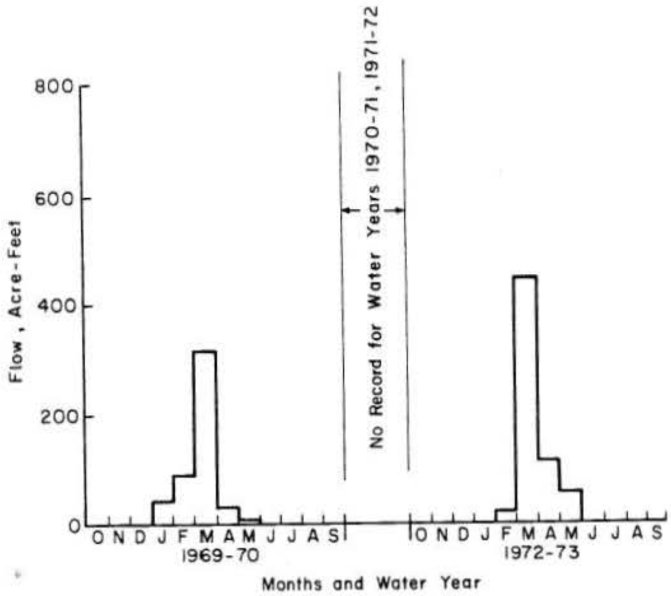


Figure II-4 USGS Gaging Station 11040000, San Luis Rey River at Monserate Narrows.

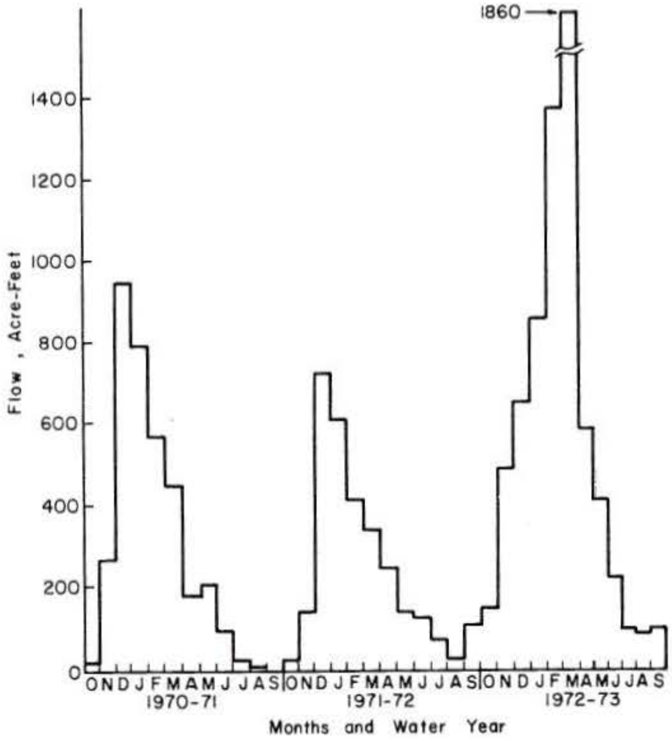


Figure II-5 USGS Gaging Station 11041000, San Luis Rey River at Bonsall Narrows.

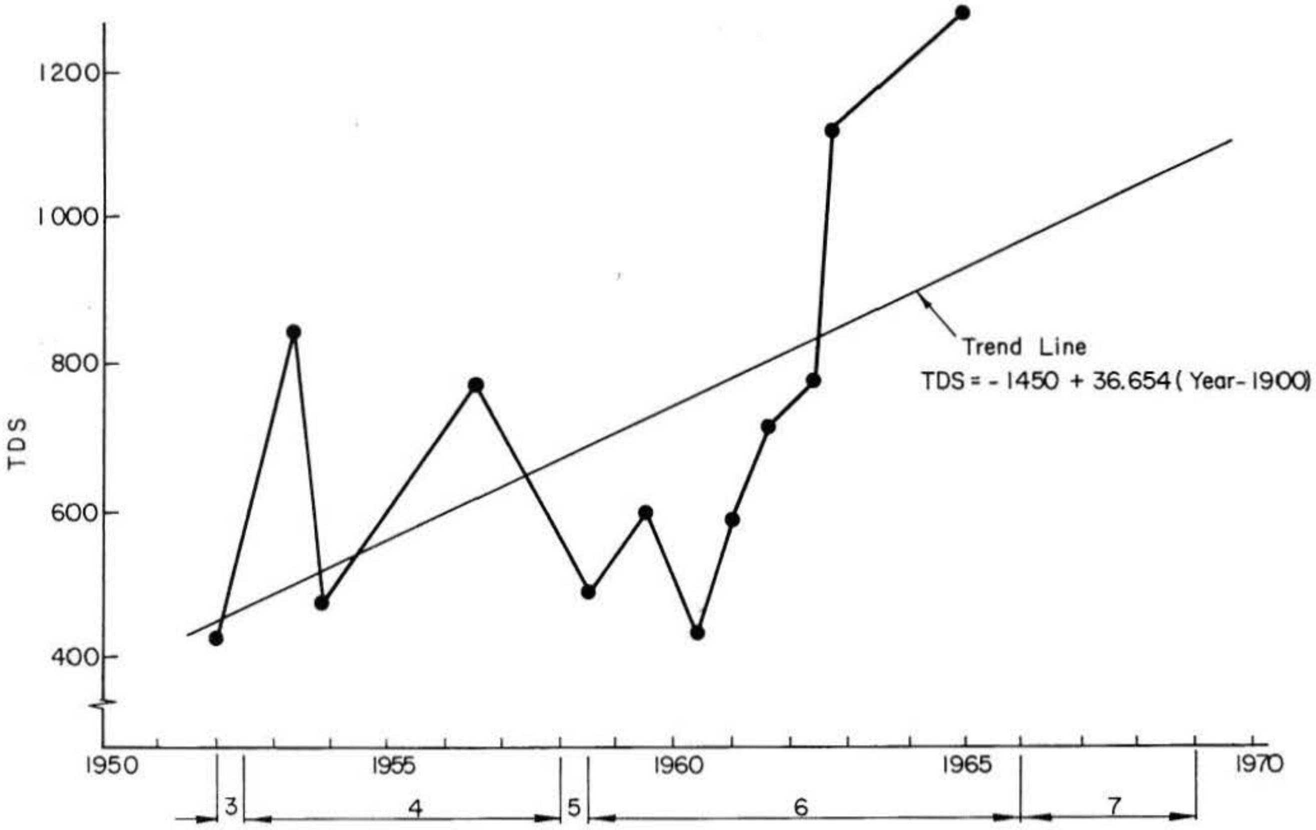


Figure II-6. Chemograph for Well 1-P-1, Bonsall (Node 4,43)

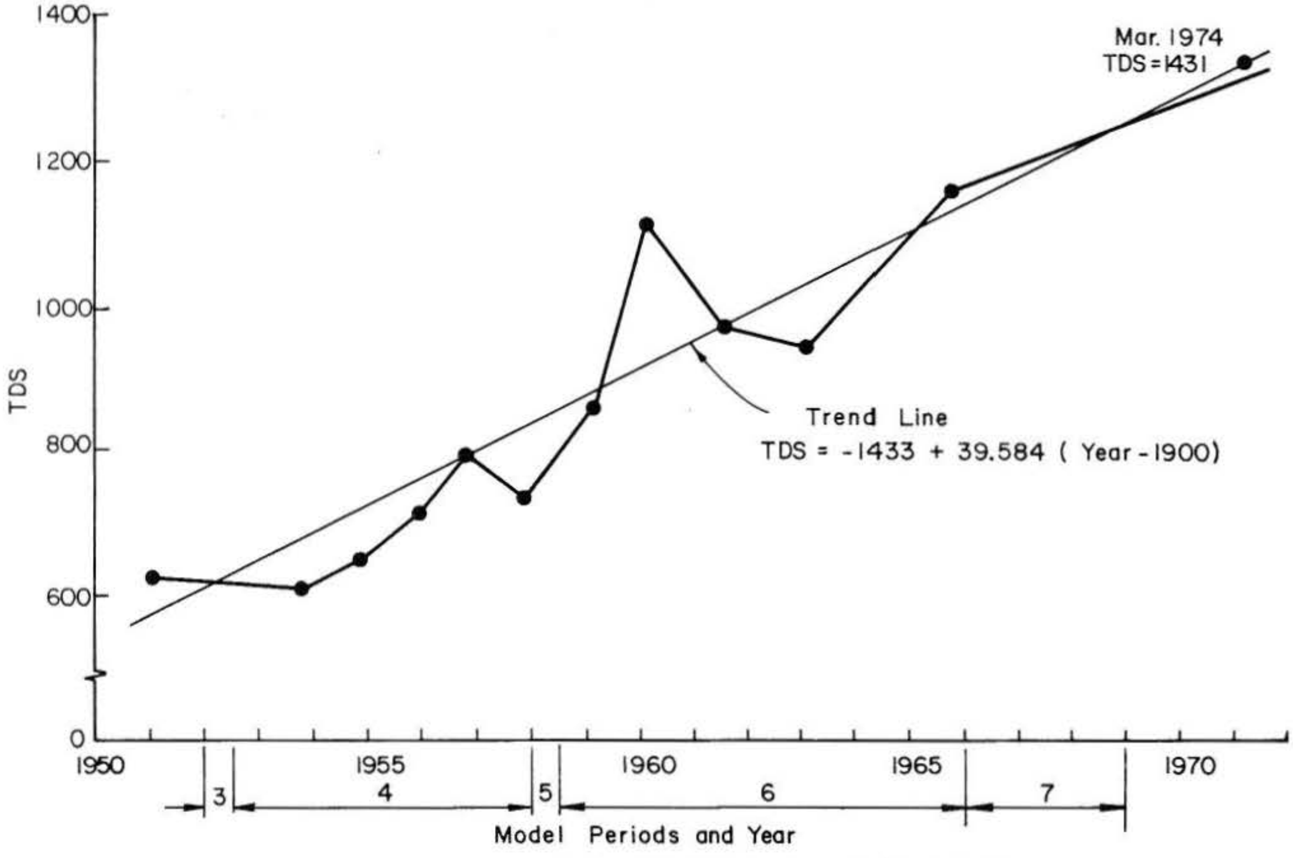


Figure II-7. Chemograph for Well 12-F-1, Bonsall (Node 2,40)

E. Existing Institutional Structures Relating to Water

The San Luis Rey River is located in California Region 9 for water planning purposes, which is the San Diego Region. Within the San Luis Rey area, there are numerous water districts and municipal supply agencies. Most of these buy Colorado River Water, which has a rather high salinity level, wholesale from the Metropolitan Water District of California. It is expected that in the future they will purchase good quality California State Project Water for mixing purposes. Table II-3 shows the composition of the Metropolitan Water District of Southern California.

The various agencies within the Santa Margarita--San Luis Rey planning area are listed in Table II-4. These agencies have shown a remarkably cooperative attitude among themselves. Together, they have formed the Santa Margarita--San Luis Rey Watershed Planning Agency (WPA). Absent from this list are the various Indian tribes which have reservations in the river basin. There had been some discussion of including them in the WPA; however, the Indians are presently involved in litigation concerning rights to Lake Henshaw Water. The effects of this litigation remain to be seen.

The WPA is a confederation of the agencies within the two river basins and has operated on a remarkably low overhead. Often, the lack of cooperation between small agencies prevents any type of regional planning, let alone action. However, it appears that the usual political and sociological constraints, which have prevented regional planning in other areas, may not apply here. The ability of the WPA to act as a central agency to implement river basin management schemes, such as the ASTRAN Method, will probably be tested in the near future.

TABLE II-2

GROUNDWATER CHARACTERISTICS OF THE LOWER SAN LUIS REY RIVER BASIN [13]

SUBBASIN	AREA (acres)	NUMBER OF WELLS	WATER QUALITY (TDS in mg/1)	SPECIFIC YIELD (AF)	SAFE YIELD (AF)
Mission	6000	80	1000-5000	90,000	10,300
Bonsall	5600	45	500-4000	40,000	2,800
Pala	5500	33	300-1500	53,000	4,700
Pauma	9500	75	300-1000	140,000	15,900

TABLE II-4

MEMBER AGENCIES OF THE SANTA MARGARITA--SAN LUIS REY WATERSHED PLANNING AGENCY [21]

Bonsall Heights California Water District

City of Carlsbad

DeLuz Heights Municipal Water District

Eastern Municipal Water District

Fallbrook Public Utility District

Fallbrook Sanitary District

Mootamai Municipal Water District

City of Oceanside

Pauma Municipal Water District

Pauma Valley Community Services District

Rainbow Municipal Water District

Rancho, California Water District

Riverside County Flood Control and Water Conservation District

San Diego County

San Luis Rey Municipal Water District

San Luis Rey Water Conservation District

Santa Rosa Ranches Water District

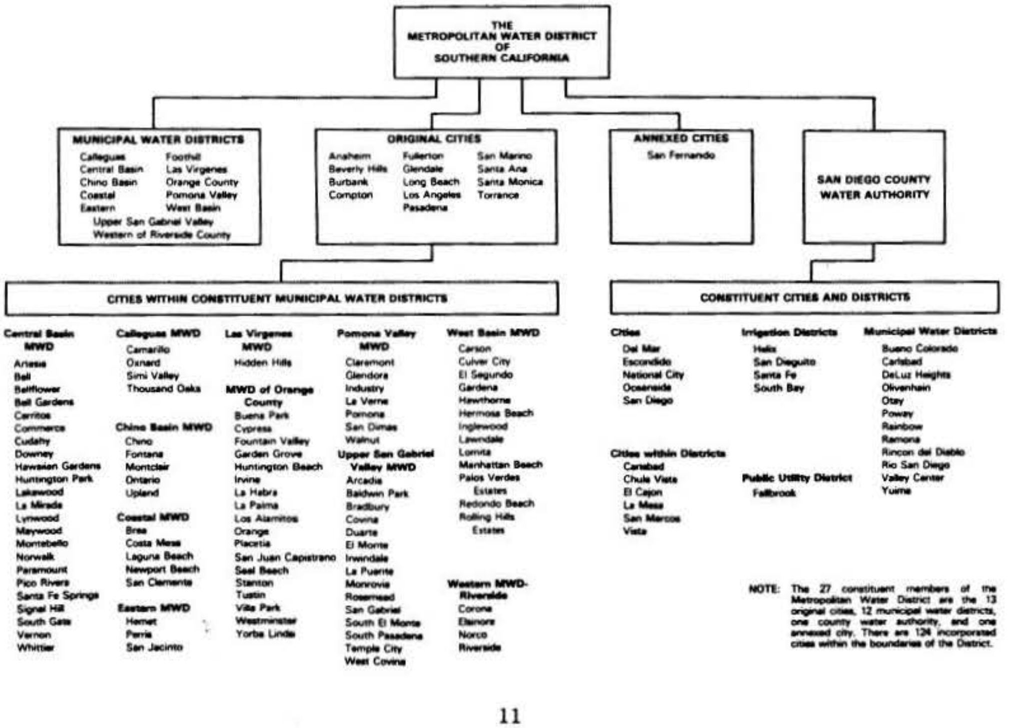
Valley Center Municipal Water District

Vista Irrigation District

Western Municipal Water District

Yuima Municipal Water District

TABLE II-3. COMPOSITION OF THE METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA [14]



NOTE: The 27 constituent members of the Metropolitan Water District are the 13 original cities, 12 municipal water districts, one county water authority, and one annexed city. There are 124 incorporated cities within the boundaries of the District.

Chapter III
STREAM-AQUIFER SIMULATION MODEL

A. Overview of Groundwater Modeling

Mathematical modeling, as an alternative to physical and other types of models, is increasing in popularity throughout the engineering disciplines. This trend has been precipitated by the availability of fast and accurate digital computers which can handle large quantities of data, and to a lesser extent, by analog computers. Considering only the particular area of stream-aquifer systems, one may divide the computer models into three types; according to the way in which the fundamental equations of flow through porous media are solved: (1) analog models, (2) finite difference models, and (3) finite element models. The method of characteristics is another solution procedure which is used primarily for water quality models. It is beyond the scope of this report to detail the development of these techniques. If they are unfamiliar to the reader, references are noted that give further detail.

Analog models are constructed on analog computers which are able to perform the continuous mathematical operations in the model that simulate groundwater movement. This is accomplished through electrical circuitry composed of variable resistors, inductors, and capacitors. The major disadvantage of analog models is their inflexibility, since a new network of these electrical elements must be constructed for each aquifer modeled.

Both finite difference and finite element models utilize the digital computer. They approximate the continuous solutions of partial differential equations (PDE's) with discrete solutions. This is necessary because of the difficulty of analytically obtaining continuous solutions to general flow equations. The digital computer can generate discrete solutions by numerical differencing procedures which closely approximate the continuous solutions. Finite element techniques, which have recently received increased attention, use variational calculus to derive the difference equations which numerically solve the PDE's. In comparing the finite element method with the finite difference method, one text states:

> "For simple regular mesh networks, the difference equations derived by the two methods are identical. However, for certain problems, the finite element method has several advantages. Boundary conditions are handled naturally by the method in contrast to the finite-difference method, where special formulas have to be developed for the boundaries in many instances. The size of the *elements* can be varied readily. Small elements may be used where variations are less severe. Also the presence of inhomogeneities and anisotropy is taken into account quite easily" [20].

Though many investigators claim that finite element models are superior, they are not as readily available or well documented as finite difference models. For this reason, the latter approach was used here. The finite difference method solves a PDE by constructing difference equations which approximate the PDE. The discretization in space is accomplished by designing a grid system and then expanding the PDE about values at the centers (or *nodes*) of each of the rectangles via the Taylor Series. Appropriately adding or subtracting these resulting equations from each other yields the finite difference formulas for the first and second order derivatives. A discretization in time is also carried out and the resulting difference equations are then solved by some kind of iterative procedure (see Carnahan, et.al. [1]). The most popular iterative procedure for groundwater modeling is the so-called alternating direction implicit procedure (ADIP), as discussed in Reddell and Sunada [19].

B. Water Quantity Model

The finite difference water quantity model used in this research is the Pinder-Bredehoeft Model [18]. This model was chosen for two reasons: (1) it is one of the most popular, proven models, and (2) it has recently been connected with a water quality model. The Pinder-Bredehoeft Model solves the two-dimensional flow equation, sometimes called the Boussinesq Equation (in tensor notation):

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + W(x_i,t) \qquad \text{(III-1)}$$

in which:

x_i = the spatial cartesian coordinates (i=1,2) (L)

T_{ij} = the second order transmissivity tensor (L^2/T)

S = the storage coefficient (dimensionless)

h = the piezometric surface above some datum(L)

W = the volume flux per unit area (L/T)

The boundary conditions are:

$$\left.\begin{aligned}\frac{\partial h(x_1',x_2',t)}{\partial x_i} &= 0 \quad , \quad i=1,2\\ h(x_1'',x_2'',t) &= \text{given constant}\end{aligned}\right\} \qquad \text{(III-2)}$$

in which:

(x_1',x_2',t) = spatial impermeable boundary points

(x_1'',x_2'',t) = spatial points bordering a body of surface water

and the initial conditions are:

$$h(x_1,x_2,0) = \text{given constant} \qquad \text{(III-3}$$

Letting $x_1 = x$ and $x_2 = y$, this equation can be expressed as

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad \text{(III-4)}$$

If the coordinate axes, x and y, are aligned with the principle transmissivity components T_{xx} and T_{yy}, then the T_{xy} and T_{yx} components become zero and the two corresponding terms cancel out. Equation III-4 simplifies to:

$$T_{xx}\frac{\partial^2 h}{\partial x^2} + \frac{\partial T_{xx}}{\partial x}\frac{\partial h}{\partial x} + \frac{\partial T_{yy}}{\partial y}\frac{\partial h}{\partial y} + T_{yy}\frac{\partial^2 h}{\partial y^2} = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad \text{(III-5)}$$

Difference equations can be written for derivatives in the x-direction, y-direction, and with respect to time, at the discrete points i, j, k. For example, the difference formulas for the derivative terms in the x-direction are [17]:

$$\frac{\partial h}{\partial x} \approx \frac{h_{i-1,j,k} - h_{i+1,j,k}}{2\Delta x} \qquad \text{(III-6)}$$

$$\frac{\partial^2 h}{\partial x^2} \approx \frac{h_{i-1,j,k} - 2\,h_{i,j,k} + h_{i+1,j,k}}{(\Delta x)^2} \qquad \text{(III-7)}$$

where Figure III-1 shows the spatial discretitation of the node system with the corresponding *cells*. Because the cell is considered to have uniform characteristics, the properties of the node automatically become that of the cell. In addition, the version of the Model used here assumes a constant transmissivity over time during a discrete model period, which only approximates the unconfined condition; however, the studies by Konikow and Bredehoeft [9] showed good results with this assumption.

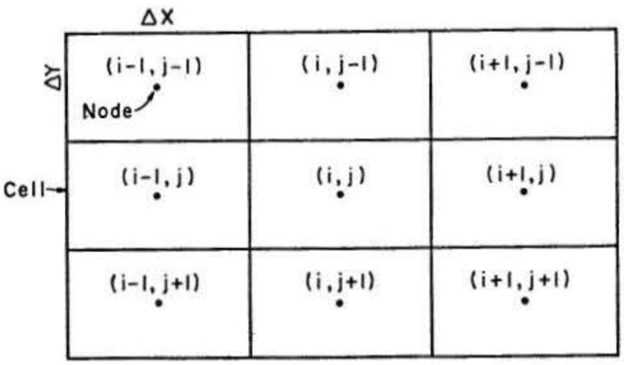


Figure III-1. Node and Cell System for Developing the Finite Difference Expressions

C. Water Quality Model

The water quality model used in this study is the one developed by Konikow and Bredehoeft [9]. When attached to the water quantity Pinder-Bredehoeft model, it is referred to here as the Bredehoeft-Konikow, or B-K Model. Before the salt transport equation in the B-K model can be solved, the solution to the previously described flow equation is needed. Equation III-5, gives the groundwater flow velocities associated with each cell; and from this, the convective and dispersive dynamics of salt movement can be calculated.

The basic salt *transport equation* solved by the model is:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(v_i C) - M(x_i,t) \qquad \text{(III-8)}$$

in which:

C = TDS concentration of the water (M/L^3)

t = time (T)

x_i = spatial cartesian coordinates (i=1,2) (L)

D_{ij} = second order dispersivity tensor (L^2/T)

v_i = seepage velocity in the x_i direction (L/T)

M = mass flux of the source or sink (M/L^3T)

In the B-K Model, this PDE is solved by a technique called the *method of characteristics*. The name arises from the use of characteristic curves which are substituted for the second order terms on the right hand side of equation III-8. Two excellent discussions of this approach are contained in Reddell and Sunada [19] and Gardner et.al. [4].

The concentration dynamics are approximated in the B-K Model by generating particles in each cell that have position and concentration, such as in Figure III-2(a). The model accuracy is proportional to the number of particles in each cell. The movement of these particles is governed by the characteristic curves, which yield their positions and concentrations. At the beginning of any discrete time step, each particle is given the same concentration as the cell it occupies. Each particle is then moved a certain distance in a direction computed from the seepage velocity multiplied by the increment of the time step. An example arrangement is shown in Figure III-2(b). After consideration of dispersion effects, the new concentration of each cell is calculated by averaging the concentration of the particles terminating in that cell.

The B-K Model can predict the piezometric surface and water quality for each node, plus provide mass balance information and other corollary data. Though it is still being refined, the model has been used by the United States Geological Survey (USGS) for a major study on the Arkansas River [9]. The Model was compared to detailed historical data and gave excellent results. A detailed documentation of the B-K Model may be obtained from the authors.

D. USGS Models

Prior to this research project, the USGS had calibrated the Pinder-Bredehoeft water quantity model for the historical period of 1947 through 1972 for all four subbasins in the Lower San Luis Rey River Basin. They had also operated the Model for a five-year period into the future (to 1977). The USGS report detailing the procedure and giving the results of the study also includes some salt mass balance calculations for each subbasin in the Lower San Luis Rey River Basin [13].

The Pinder-Bredehoeft Model, originally applied by the USGS to the study area, contained a variable cell dimension capability, which was used to construct the cell geometry for Bonsall Basin as shown in Figure III-3. Most of the cells were dimensioned 500 ft. x 1000 ft. or 1000 ft. x 1000 ft. This quantity model was calibrated by comparing it against available well hydrographs. The results of this comparison are shown in Figure III-4.

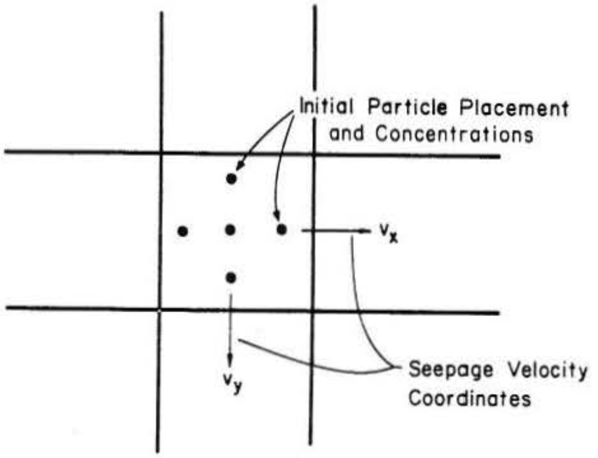


Figure III-2(a). Initial Particle Configuration in a Cell.

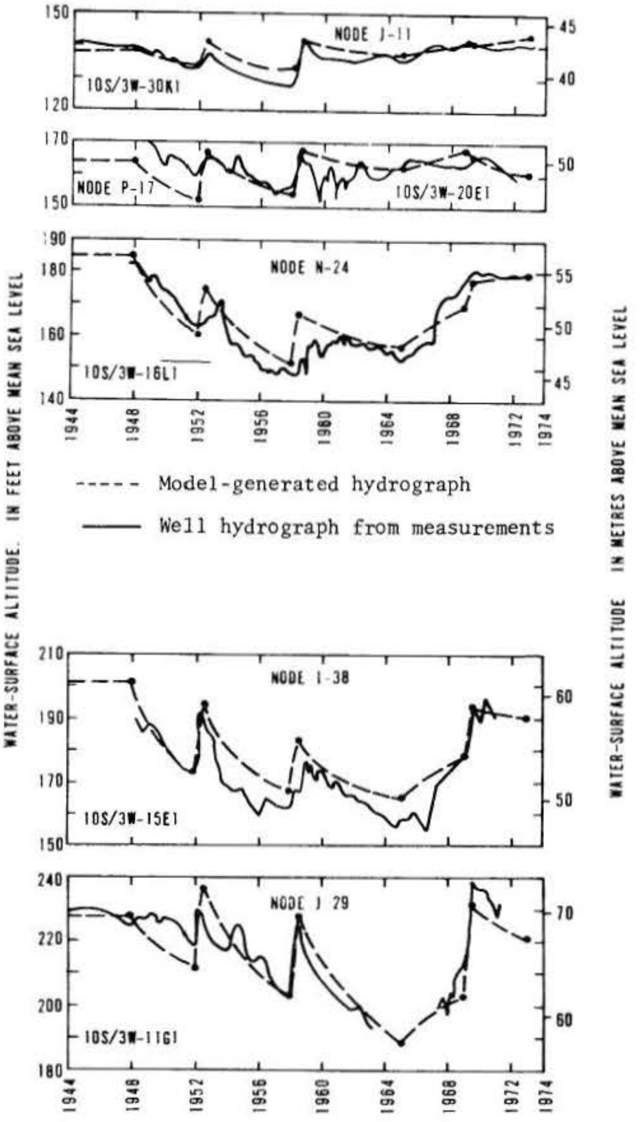


Figure III-4. Hydrographs of Wells in Bonsall Subbasin [13].

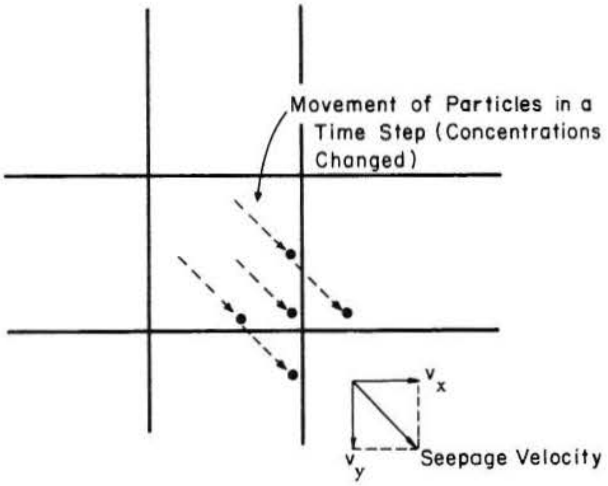


Figure III-2(b). Particle Configuration after a Time Step.

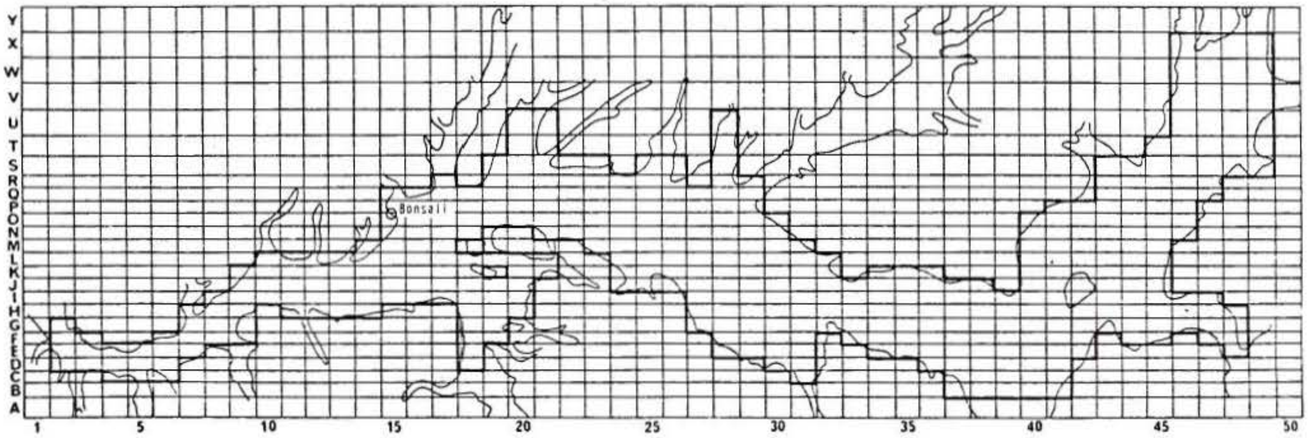


Figure III-3. Cell Geometry for the Pinder-Bredehoeft Model, Bonsall Subbasin [13].

The B-K Model also uses a version of the Pinder-Bredehoeft model for the quantity section. It does not, however, have a variable cell dimension capability. The cell dimensions of the B-K Model were therefore made a uniform 500 ft. x 1000 ft., which greatly increased computer time, but enabled the water quality section of the B-K Model to be used directly.

A large amount of rapid access core memory was needed for the B-K Model, using this finer uniform grid size, on the Colorado State University (CSU) digital computer. To correct this, a sophisticated technique of using *overlays* was adapted to fit the large Model onto the CSU system. Nevertheless, each computer run took so much time, that it was impossible to use the B-K Model as it stood, for management studies, without exceeding the research budget. Consequently, only one model period was run with the combined B-K Model. The water quality results were checked against the historic water quality data to see if the Model was reproducing the correct changes in water quality with the desired accuracy. When this was accomplished, the B-K Model was simplified into what is called the Adapted Model.

E. Adapted Model

The Adapted Model was developed by first, increasing the cell dimensions. Figure III-5 shows this coaser grid system. Because there are many arrays in the Model with dimensions corresponding to the size of the grid system, this simplified grid system considerably reduced the required core storage and computer time.

Second, some internal modifications were carried out which consisted of eliminating some arrays by a *doubling up* procedure. That is, in some instances, one array could be adapted to do the work of two. For example, instead of having three arrays, one for transmissivity, one for hydraulic conductivity, and one for aquifer saturated thickness, the hydraulic conductivity array was eliminated and calculated from the remaining two arrays when needed. The Adapted Model ran with significant savings in computer costs; moreover, the available data seemed to justify the use of a coarser grid system.

F. Model Calibration

Before the water quality section of the Adapted Model was studied, the Adapted Model was checked against the original Pinder-Bredehoeft Model to ensure that the larger cell dimensions and smaller arrays did not affect the quantity results.

The Adapted Model agreed very well with the more detailed USGS quantity model. The water table elevations agreed within ±1 foot for 95% of the nodes. The remaining nodes, usually in boundary cells, differed by no more than four feet. Slight adjustment of boundary nodes was necessary, in order to remain consistent with previous USGS work, since the boundary conditions were approximated by pumping and recharge wells. A comparison of Figure III-6 and Figure III-3 reveals that in addition to changing the cell dimensions, the Adapted Model slightly decreased the modeled area of the Subbasin.

Calibrating the water quality model consisted of two procedures: one comparing the historical water quality with the modeled water quality, and the other comparing the modeled salt mass balance with a mass balance computed directly from the data. The water quality comparison was the major aspect of calibration and is described below. The historic period during which water quality data were taken ranges from 1952 to present. (Some recent water samples are being collected at the authors' request). There were only three wells that had continuous records over this period of time; however, there were other wells that had intermittent data which were also used. The wells with continuous records had not been measured consistently, i.e., every six months or so, but had lapses of several years in some cases. Nevertheless, they provided an indication of the water quality trends in the basin.

As shown in Figures III-6 and III-7, there is considerable variation of water quality around the mean historic value line, and as mentioned above, this dispersion could not be modeled nor should it be modeled; consequently, the mean lines were used for the calibration procedure. Figures III-6, and III-7, and III-8 show the results of the calibration. The Model also followed the spot checks from the infrequent records of the other wells reasonably well.

The amount of salts transferred in and out of the aquifer and the change in TDS is sensitive to the quality of drainage water reaching the aquifer from irrigation. To arrive at this, the assumed 70% irrigation efficiency of the USGS report [13] was considered reasonable.

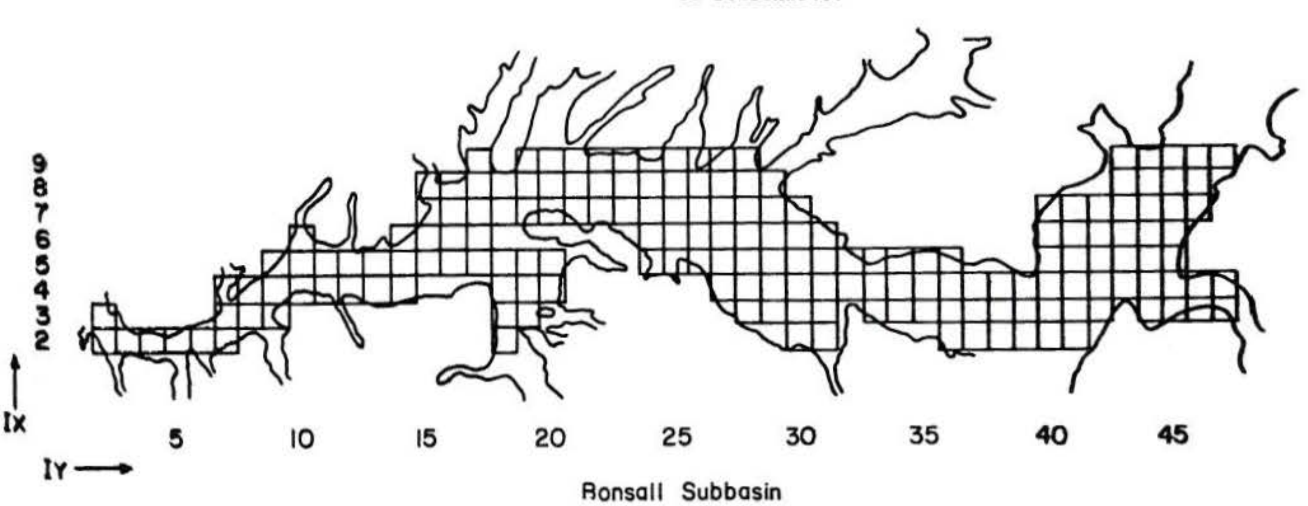


Figure III-5. Coarser Cell Array for the Adapted Model

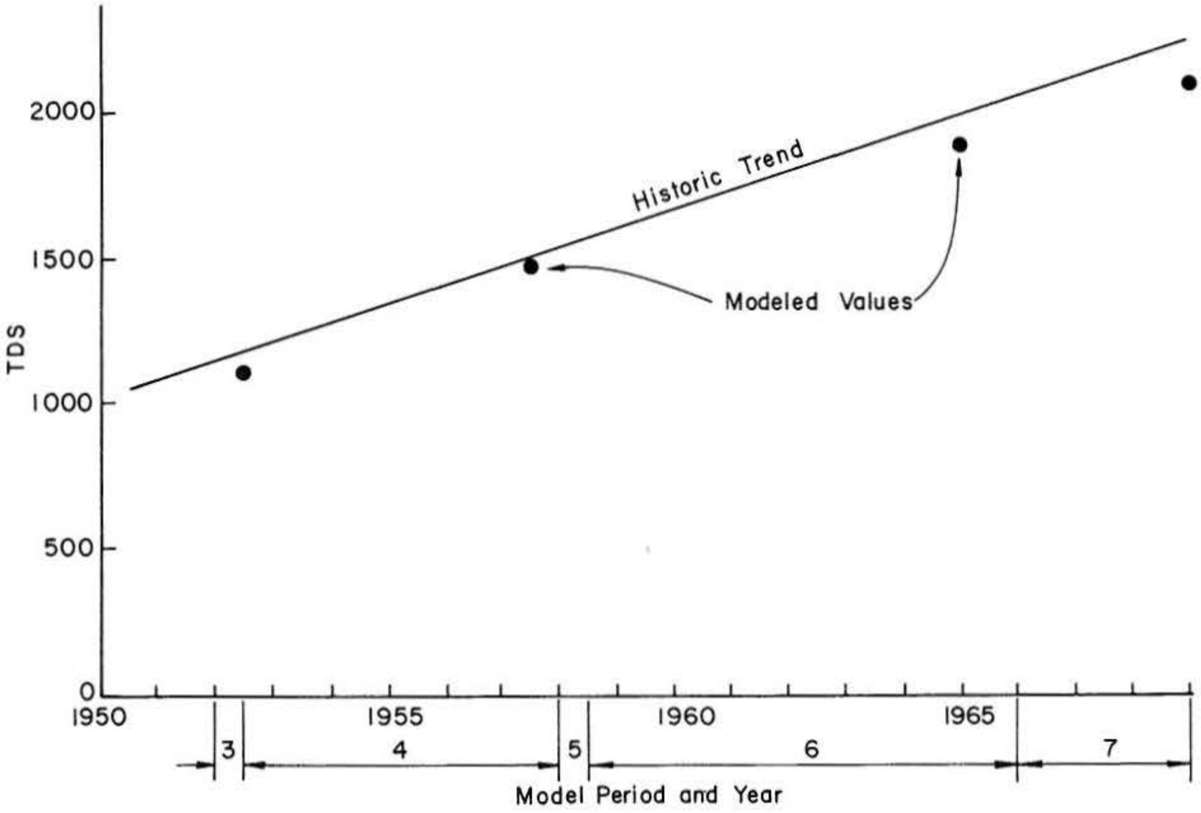


Figure III-6. Historic vs. Modeled TDS for Well 20-P-3 (Node 6,15)

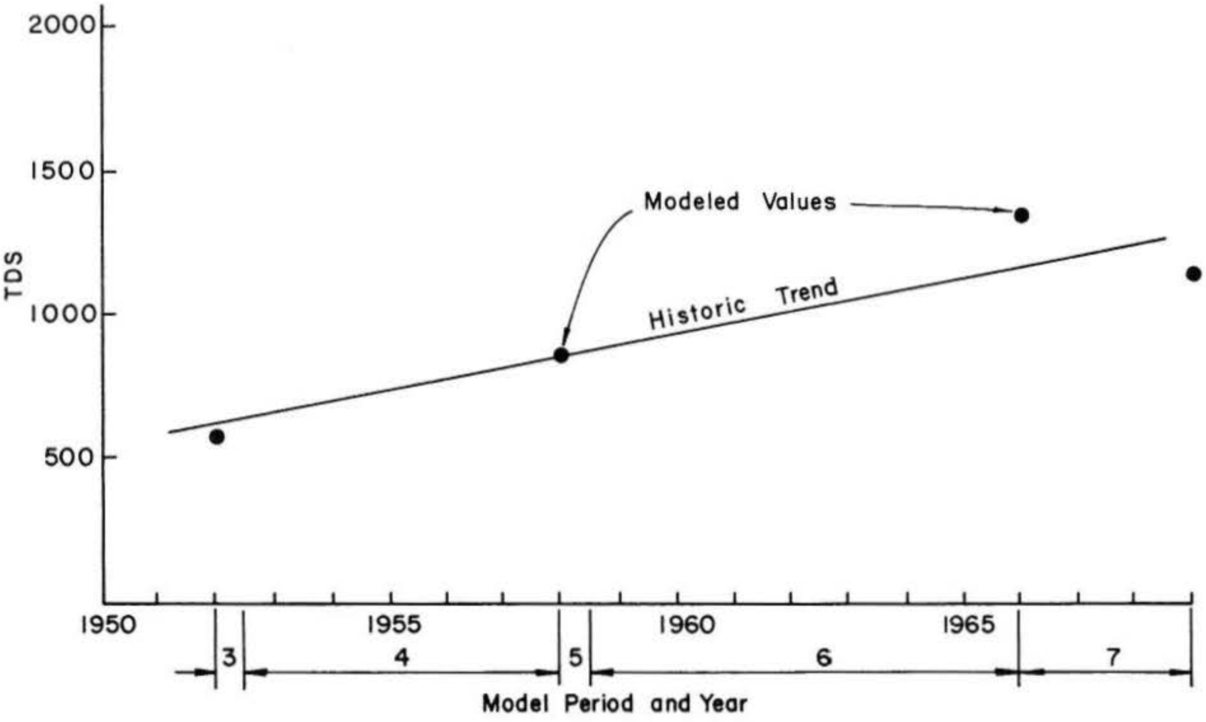


Figure III-7. Historic vs. Modeled TDS for Well 12-F-1 (Node 2,40)

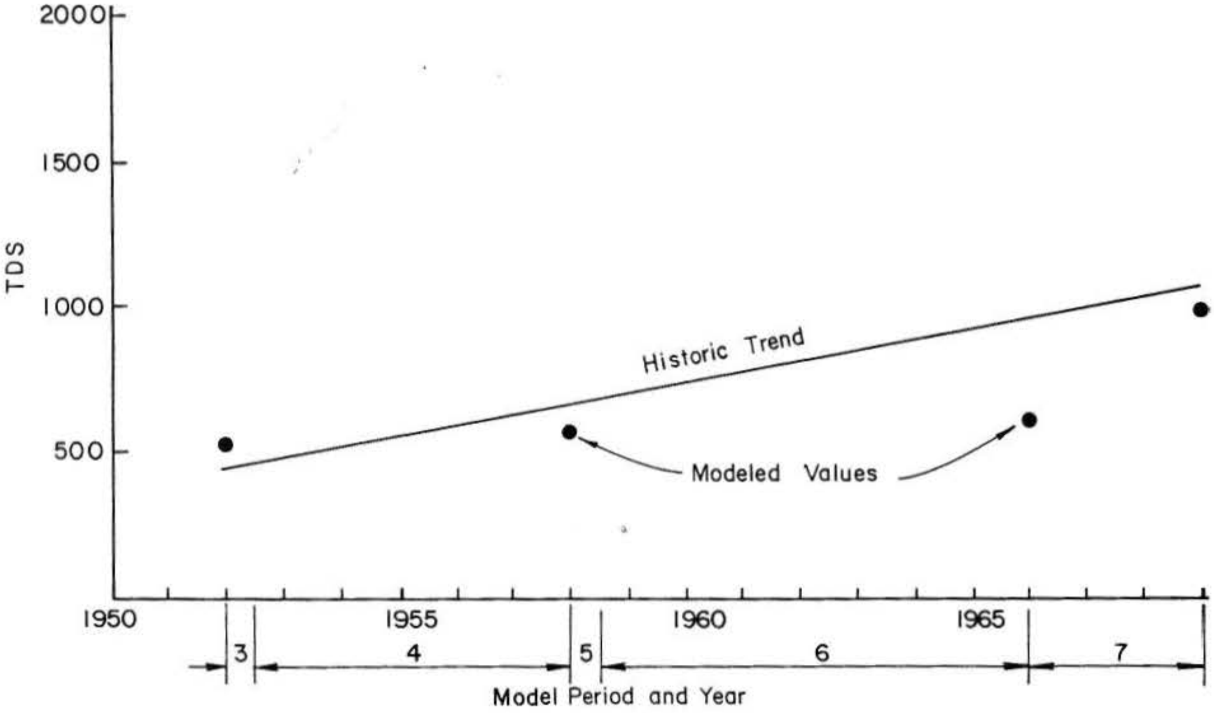


Figure III-8. Historic vs. Modeled TDS for Well 1-P-1 (Node 5,43)

If the water quality output of the Model fitted the long term trend line within ± 20%, the Model was considered calibrated. Konikow used ± 10% for his detailed one-year study of the Arkansas River [9], but then that was assumed to be the maximum accuracy that could be obtained, considering the wide variance of TDS actually measured in the field. For the long term historical study period used for the San Luis Rey River Basin, the ± 20% figure seemed adequate. As shown in Figures III-6, III-7, and III-8, the modeled results were usually within ten percent of the historic trend lines.

The selected values of the parameters D_{ij} in equation III-8, which produced the output shown in Figures III-6 to III-8, were based on suggestions in some unpublished USGS notes on the model [17]. Isotropy was assumed for the porous media, so that all that was required were estimates of longitudinal dispersivity ε_L (i.e., in the direction of the velocity vector) and transverse dispersivity ε_T (i.e., lateral to the velocity vector). The longitudinal and transverse dispersion coefficients are then computed as:

$$D_L = \varepsilon_L V$$

$$D_T = \varepsilon_T V$$

where V is the magnitude of the velocity vector. From these values of D_L and D_T, the D_{ij} in equation III-8 are easily computed, as shown in Reddell and Sunada [19]. The suggested value of ε_L was 100 ft., with $\varepsilon_T/\varepsilon_L$ given as 0.3. These values gave what appeared to be reasonable results, so that no adjustments were made.

It is important to realize that such a long term model only shows trends and with the relatively limited data available, it would be of little value, if not actually misleading, to attempt a finer calibration or give more detail. As any modeler knows, a model can be made to fit any data by *adjusting* the parameters. The subjective judgment as to when the adjustment becomes excessive is important to the reliability of the model. For the Adapted Model, it was felt that the limited data suggested a larger cell geometry and more general interpretation of the model results.

Chapter IV
MANAGEMENT ALGORITHM

A. Introduction

The management algorithm is developed in four steps;

1. Define the management problem in general terms,
2. Quantitatively formulate the management proplem by defining the objective function and constraints,
3. Apply an optimizing method to solve the quantified problem, and
4. Interface the optimizing model with the simulation model.

In general terms, the problem is to control aquifer degradation in Bonsall Subbasin in the most economical way, within the hydrologic, physical, environmental, and non-quantifiable constraints. The ultimate goal is management of the entire river basin, but this is not pursued here. The questions to be answered are: from which sources should water be obtained and to which areas should the water be applied? Ideally, this should be accomplished in such a way that the aquifer will remain stable over the long run, considering both quantity and quality. However, even if this ideal proves to be unobtainable, arresting the degradation of the aquifer for some years or decades would be extremely beneficial.

As will be explained subsequently, the total management algorithm does not necessarily find *the* least-cost solution, but rather generates a *family* of least-cost solutions. Each least-cost solution produces a certain salt mass balance in the basin; consequently, decision makers can choose a desired least-cost solution based on both costs and subjective considerations as to the benefits of controlling degradation. For example, allowing water quality to sightly degrade may be preferable to keeping it constant, because of financial constraints. In other instances, improving the groundwater quality may be more desirable.

Since the basic idea behind the ASTRAN method is to appropriately transport groundwater from one place to another, then this suggests that the optimizing model might conform to a linear transportation problem format. There are, of course, a number of efficient codes available for solving such problems, such as the Ford-Fulkerson primal-dual algorithm. The optimizing model is, in reality, a *screening model* which rejects uneconomical feasible solutions and supplies alternative least-cost management strategies to the simulation model, which then tests them as to their ability to control salt degradation.

As illustrated in Figure IV-1, a dialogue between the optimizing model and the simulation model can be established which centers around a certain overall management decision variable that will be explained later.

The optimizing model is basically a static one in that optimization is performed over the model time periods in a sequential manner. There appears to be no need to optimize over all model periods at once.

The basin quantity and quality conditions produced at the end of a specified period of time, due to application of the management technique, serve as the initial conditions for the subsequent period. The model periods may be historical, or they may be projections into the future. The historical model periods defined by the USGS were catagorized as wet, medium, or dry. From Figures III-6 to III-8, it can be seen that some of the model periods were several years in length.

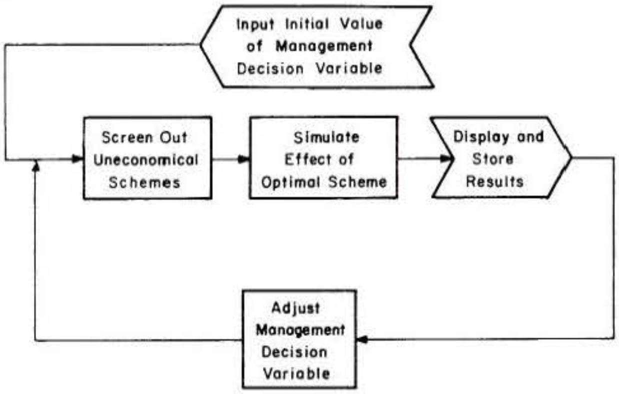


Figure IV-1. Simplified Flow Diagram of the Management Algorithm

B. Screening Model

The classical transportation problem as applied to this management problem is formulated as follows:

$$\min_{q_{ij}} \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} q_{ij}$$

$$i=1,\ldots,n$$
$$j=1,\ldots,m$$

subject to:

$$\left.\begin{array}{l} \sum_{j=1}^{m} q_{ij} \leq s_i,\ i=1,\ldots,n \\ \\ \sum_{i=1}^{n} q_{ij} \geq d_j,\ j=1,\ldots,m \\ \\ q_{ij} \geq 0\ ,\ i=1,\ldots,n\ ;\ j=1,\ldots,m \end{array}\right\} \qquad \text{(IV-1)}$$

in which:

c_{ij} = the cost of transporting water from source section i to demand section j ($/AF)

q_{ij} = the amount of water transferred from i to j (AF/yr)

s_i = the amount of water available at source section i (AF/yr)

d_j = the amount of water needed at demand section j (AF/yr)

Before solving the transportation problem for Bonsall Subbasin, the source and demand sections must be identified. For demonstration purposes, the Subbasin was divided into four sections, which define source and demand locations in the basin corresponding to the above transportation problem formulation. Though this decision was rather arbitrary, the basis for it was (1) to make sure that the total irrigated area in each section was about the same, and (2) to have an adequate number of irrigation wells in each section. The maximum number of sections that it would be possible to define would occur if each section corresponded to one grid of the discretized finite difference approximation. The minimum number of sections would be two. If too many sections are defined, the management algorithm may become unduly complex. If too few are defined, the management algorithm may not yield information of sufficient detail upon which to base actual management decisions.

Figure IV-2 shows the actual sections used for the management algorithm in this study. Referring to the transportation problem, s_i, $i=1,\ldots,4$, represent the maximum quantities of pumped groundwater available from each section j; the d_j, $j=1,\ldots,4$, are the irrigation demands for each section j. The maximum amount of imported State Project water (a mixture of Colorado River water and water from Northern California) that is available is designed as s_5, and s_6 represents the maximum amount of groundwater available from an upstream basin. Maximum exported water available as supply to downstream basins or to be placed into an outfall is identified as d_5. Export is needed to maintain the proper water quantity and quality balance.

The transportation problem must now be augmented by a problem constraint on the average concentration (over a model period) of water applied to any section. This is the key factor in controlling degradation, since if it is assumed that upstream groundwater is of better quality, then restriction on average concentration will encourage transport of upstream groundwater to downstream lands. The ASTRAN Method is therefore indirectly effected. The *screening model* is then defined as the transportation problem augmented by the water quality constraint. The basic transportation code must therefore be abandoned and the standard or revised simplex code used instead for solving the screening or optimizing model.

The water quality constraint can be easily understood by decision makers, since it is based on the well known leaching formula [5]:

$$D_w = \frac{EC_{dw}}{EC_{dw} - EC_w} \times ET \qquad \text{(IV-2)}$$

D_w = the depth of the supplied irrigation water for leaching (cm)

ET = the evapotranspiration or consumptive use (cm)

EC_{dw} = the electroconductivity of the drainage water percolating past the root zone (micromhos/cm^2)

EC_w = the electroconductivity of the applied irrigation water (micromhos/cm^2)

A regression correlation analysis was conducted for the San Luis Rey River Basin which yielded the following relationship:

$$TDS = -2 + 0.683\ EC \qquad \text{(IV-3)}$$

in which:

TDS = the total dissolved solids (mg/1)

EC = the electroconductivity (micromhos/cm^2)

Figure IV-3 shows a plot of points used in the analysis. The coefficient of correlation was 0.985.

The leaching formula must now be rearranged in order to establish a linkage between the screening model and the simulation model. The dependent variable should be drainage water quality and the independent variables should include all of the possible sources of water and their qualities. Also, quality is now expressed in terms of TDS. The water quality constraint is

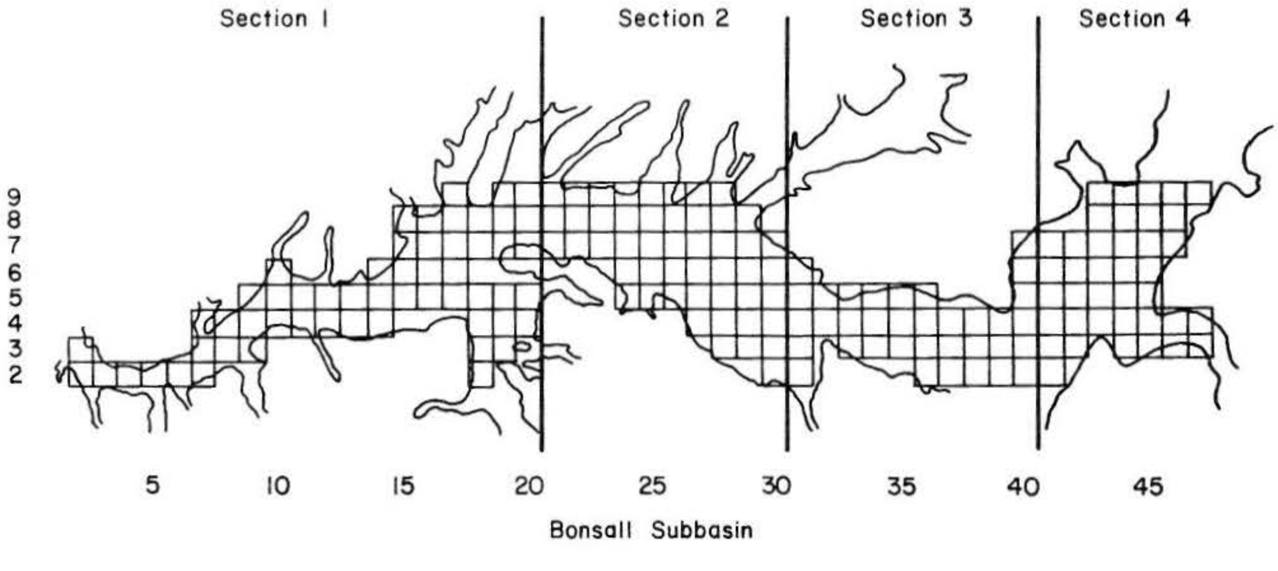


Figure IV-2. The Division of Bonsall Subbasin into Source and Demand Sections.

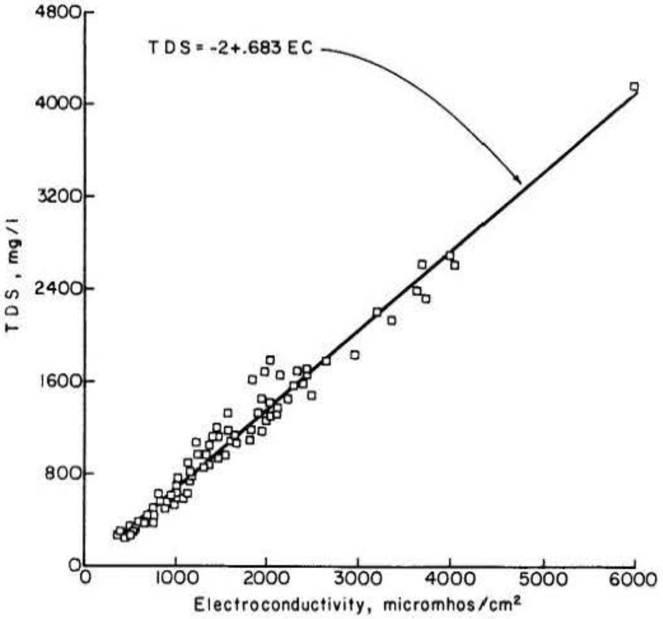


Figure IV-3. Plot of TDS vs. EC

$$C_{dj} = \frac{\sum_{i=1}^{6} q_{ij}C_i}{(\sum_{i=1}^{6} q_{ij}) - ET_j} \leq C_{mj} \qquad \text{(IV-4)}$$

in which:

C_{dj} = average TDS concentration of the drainage water at section j over a model period (mg/l)

C_{mj} = upper bound on average TDS concentrations of the drainage water at section j (mg/l)

C_i = average TDS concentration of irrigation water from source section i (mg/l)

q_{ij} = amount of water transferred from source section i to demand section j (AF/yr)

ET_j = evapotranspiration at section j (AF/yr)

Realistically speaking, the C_i will vary over the model period, and are a function of the q_{ij}. Since the primary function of the screening model, however, is to provide rough management guidelines that are subsequently checked by the simulation model, a representative invariant value of C_i is used. Rearranging equation IV-4 to fit the standard linear programming constraint format:

$$C_{mj}\sum_{i=1}^{6} q_{ij} - \sum_{i=1}^{6} q_{ij}C_i \geq C_{mj}ET_j \text{ , } j=1,\ldots,4 \qquad \text{(IV-5)}$$

Figure IV-4 shows the location of the various waters and their corresponding qualities.

The basic management decision variable is C_{mj}. Various combinations of values for C_{mj} could be selected and the screening model solved for each set of values. With a solution in hand, the computed optimal water distribution quantities, q^*_{ij}, are now available as *screened* data that can be inserted into the simulation model, which will then predict the effect on salt balance in the basin. Note that equation IV-5 is a linking constraint between the screening model and the simulation model in that by varying C_{mj}, the resulting optimal q_{ij} will be influenced, which will in turn influence the salt balance predicted by the simulation model.

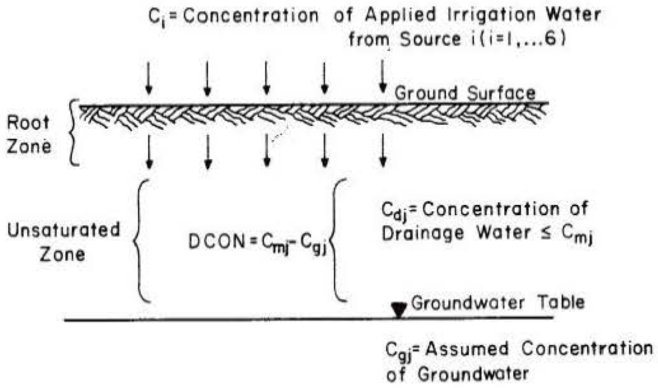


Figure IV-4. Water Quality Schematic of Demand Node j

In order to simplify the process of changing C_{mj}, a variable DCON is defined which is independent of j;

$$DCON = C_{mj} - C_{gj} \qquad \text{(IV-6)}$$

in which C_{gj} is the average quality of the groundwater at demand location j , over a model period.

Consequently, DCON may be thought of as the maximum allowed difference in concentration between the drainage water and the groundwater. The variable DCON is the device used to perturb the screening model, which in turn, generates the inputs to the simulation model. Figure IV-1 illustrates this process in a simplified manner, where the *management decision variable* referred to is DCON and the *effect of optimal scheme* is the predicted distribution of concentration over the basin, at the end of the time period, as generated by the simulation model.

Several additional constraints are added in order to maintain certain historic or projected water balances in each section and over the entire subbasin, with the only variation occurring in intrabasin water transfers, as generated via the ASTRAN technique. The first of these is a constraint to ensure that a proper quantity balance is maintained in the basin during a particular model period. Assuming that net subsurface inflow and outflow is approximately zero, then total imported water, plus total natural recharge minus total exported water and consumptive use, must equal some prescribed level ΔW:

$$\sum_{j=1}^{4} q_{5j} + \sum_{j=1}^{4} q_{6j} - \sum_{i=1}^{4} q_{i5} = \sum_{i=1}^{4} ET_i - \sum_{i=1}^{4} NR_i + \Delta W \qquad \text{(IV-7)}$$

where NR_i is the natural recharge in section i.

In addition, any desired historical or projected water balances can be specified at the sectional level:

$$\sum_{j=1}^{5} q_{kj} - \sum_{i=1}^{6} q_{ik} = ET_k - NR_k + \Delta W_k \ , \ k=1,\dots,4 \qquad \text{(IV-8)}$$

Finally, only enough water should be pumped and applied to the same section as actually demanded, in order to prevent the screening model from pumping large amounts of this *cheap* water for leaching and perhaps encouraging inefficient irrigation. This can be stated as:

$$q_{ii} \leq d_i \ , \quad i=1,\dots,4 \qquad \text{(IV-9)}$$

Interestingly enough, this constraint appeared to have very little influence on the solutions.

Notice that there is the possibility of allowing the supply and demand constraints to be expressed in terms of various combinations of inequalities and equalities:

$$\begin{aligned} \sum_j q_{ij} \ &\begin{Bmatrix} \leq \\ = \end{Bmatrix} \ s_i \\ \sum_i q_{ij} \ &\begin{Bmatrix} \geq \\ = \end{Bmatrix} \ d_j \end{aligned} \qquad \text{(IV-10)}$$

However,

$$\begin{aligned} \sum_j q_{ij} &\leq s_i \\ \sum_i q_{ij} &\geq d_j \end{aligned} \qquad \text{(IV-11)}$$

gives the most flexibility. These combinations have important management implications. For example, allowing the demand to be exceeded permits artificial recharge, if it is needed to maintain the proper salt balance.

In summary, the screening or optimizing model can be written as:

$$\min_{\substack{q_{ij}, \\ i=1,\dots,6; \\ j=1,\dots,5}} \ \sum_{i=1}^{6} \sum_{j=1}^{5} c_{ij} q_{ij}$$

subject to:

$$\sum_{j=1}^{5} q_{ij} \leq s_i \ , \ i=1,\dots,6$$

$$\sum_{i=1}^{6} q_{ij} \geq d_j \ , \ j=1,\dots,5$$

$$C_{mj} \sum_{i=1}^{6} q_{ij} - \sum_{i=1}^{6} (q_{ij} C_i) \geq C_{mj} ET_j \ , \ j=1,\dots,4$$

$$\sum_{j=1}^{4} q_{5j} + \sum_{j=1}^{4} q_{6j} - \sum_{i=1}^{4} q_{i5} = \sum_{i=1}^{4} ET_i - \sum_{i=1}^{4} NR_i + \Delta W$$

$$\sum_{j=1}^{5} q_{kj} - \sum_{i=1}^{6} q_{ik} = ET_k - NR_k + \Delta W_k, \ k=1,\dots,4$$

$$q_{ii} \leq d_i \ , \ i=1,\dots,4$$

$$q_{ij} \geq 0 \ , \ i=1,\dots,6 \ ; \ j=1,\dots,5$$

C. Total Management Algorithm

The screening model (or optimizing model) can now be linked with the simulation model (discussed in Chapter III) to form the total management algorithm. Future research will undoubtedly connect them formally into one model; as yet, however, efficient codes are not available for this so that the linkage is accomplished iteratively and sequentially. The primary means of linkage is the decision variable DCON.

A general flow chart of the management algorithm is given in Figure IV-5. The basic steps in the algorithm can be listed as follows:

1. Choose an initial historical or projected model period for which all required initial conditions of water quantity and quality are given.

2. Start with initial guesses for C_{gi} and DCON (which gives C_i and C_{mi}) for the screening model. These may be based on historical data or trial runs with the simulation model.

3. Run the screening model and obtain optimal water distribution q_{ij} for all i,j.

4. Operate the simulation model using the q^*_{ij} and given initial water quantity and quality conditions, and other relevant data. If the total quantity applied to any section exceeds the demand, the remainder must be allocated over the potential recharge grids of the section in such a way that unattractive extremes in water level will not occur. For this study, excess water was allocated in such a way that water levels stayed between ten feet above bedrock and five feet below the ground surface, for each node.

5. For the given value of DCON, the simulation model predicts water levels and TDS levels, over each grid in the basin, for the end of the model period. For each section, average concentrations over the model period can then be computed. These values become new estimates of C_{gi}, and we return to Step 3. This procedure continues until there is reasonable agreement between successive sets of C_{gi}.

6. At the end of the iterative process of Step 5, the final quantity and quality predictions computed by the simulation model then serve as initial conditions for the next model period, and we return to Step 2. This process continues for all model periods. Notice that the parameters c_{ij}, s_i, and d_j may change with each model period.

7. Having sequentially considered the desired number of historical or projected model periods, the overall basin degradation can be noted. If the rate of

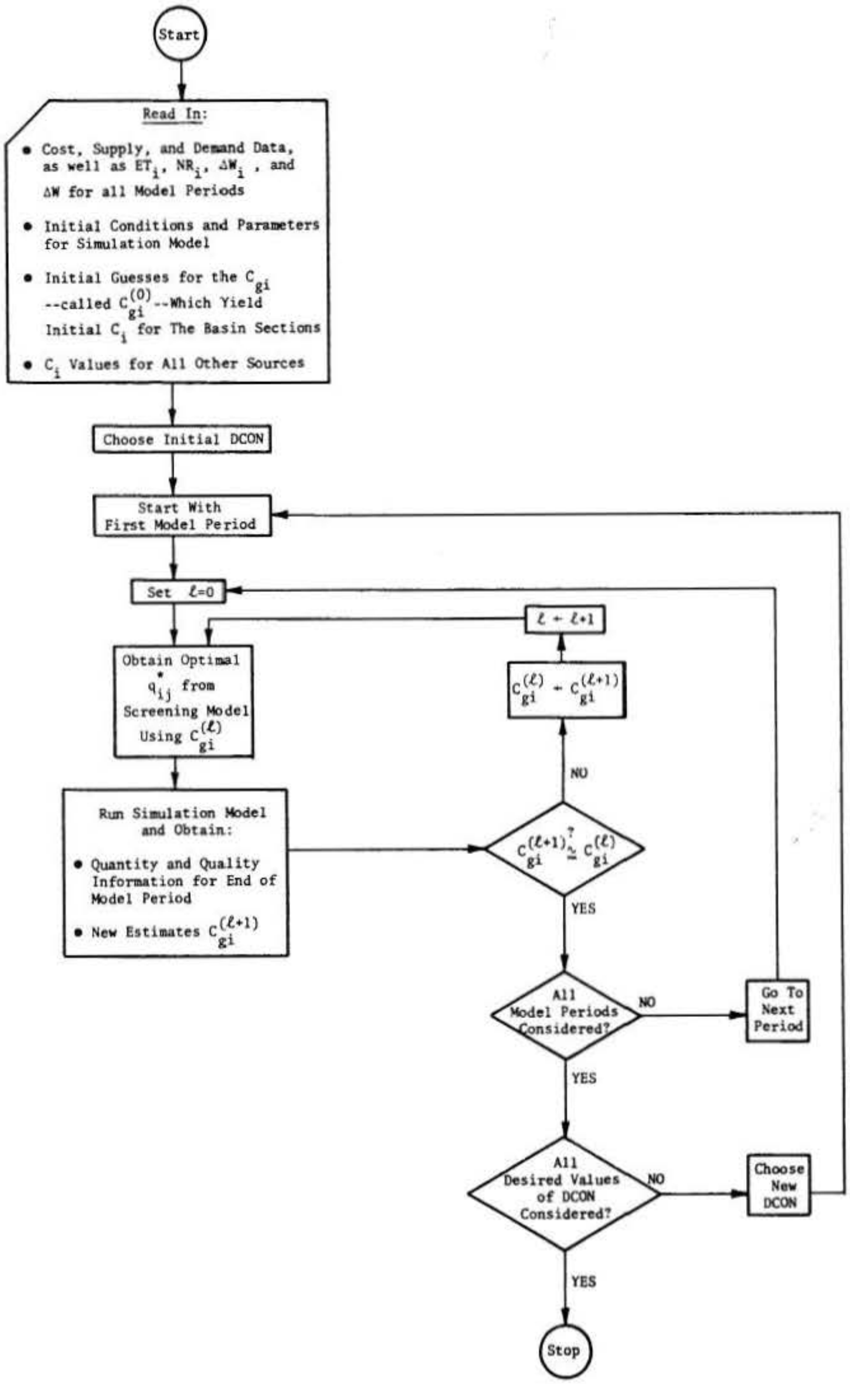


Figure IV-5. Flow Chart for the Management Algorithm

degradation is too high, then DCON should be reduced, which will more greatly restrict the average concentration of the applied water. When the above process is repeated for this lower value of DCON, the total cost will increase. A range of DCON values can be selected so as to estimate the costs associated with various degrees of degradation control.

Chapter V displays the results of the total management algorithm so as to highlight the sensitivity of the algorithm to DCON and the cost to the Subbasin for an average change in salt concentration ΔC over the basin. Normally, a water manager would have two objectives: (1) stabilize quantity mass balance ($\Delta W = 0$) and (2) stabilize the long term salt mass balance ($\Delta S = 0$). The goal is to stabilize the quantity objective, and use the aquifer efficiently as a storage reservoir during dry periods, when $\Delta W \leq 0$, and during wet periods when $\Delta W \geq 0$, so that the long term $\Delta W = 0$. Table IV-1 shows how the salt concentration balance ΔC can vary with ΔW and the total salt balance ΔS. With the management algorithm thus constructed, the next chapter presents the results of applying it to Bonsall Subbasin.

TABLE IV-1

POSSIBLE SALT CONCENTRATION CHANGES RESULTING FROM COMBINATIONS OF HYDROLOGIC AND SALT BALANCE

HYDROLOGIC BALANCE (ΔW)	SALT BALANCE (ΔS)	CONCENTRATION CHANGE (ΔC)
Positive	Positive	Increase or Decrease
Positive	Neutral	Decrease
Positive	Negative	Decrease
Neutral	Positive	Increase
Neutral	Neutral	None
Neutral	Negative	Decrease
Negative	Positive	Increase
Negative	Neutral	Increase
Negative	Negative	Increase or Decrease

Chapter V
COMPUTATIONAL RESULTS

A. Model Inputs

In order to evaluate the feasibility of the ASTRAN method, and gain experience with the management algorithm, a ten-year historical period consisting of a dry period (model period 6), an average period (model period 7), and a wet period (model period 8), was selected. Model period 6 was 7-1/2 years long, starting from July 1958; model period 7 was 3 years long, starting from January 1966; and model period 8 was 6 months long, starting from January 1969. Two reasons prompted the decision to use this particular historical period: (1) prior to 1958, Bonsall Subbasin groundwater had not degraded beyond the point of usability for irrigation, and (2) this period of time contains the most accurate and extensive records of water quantity and quality.

In 1958, groundwater quality in Bonsall Subbasin was in roughly the same position as the present quality in the upstream Pauma and Pala Subbasins. In order to make the results obtained for the Bonsall Subbasin more directly applicable to Pauma and Pala, some assumptions were applied to the water quality input. For example, the imported Colorado River water has ranged from a TDS of 700 to 800 mg/l, but as State Project water is added, this quality is projected to improve well below a TDS of 500 mg/l. Consequently, the imported water was conservatively assigned a TDS of 500 mg/l.

The screening model requires specification of average groundwater concentration levels C_{gi} (which yield the C_i). For this study, these values were computed by averaging, over each Section, concentration levels that were given for the *beginning* of the model period. For model period 6, they were the actual historical levels. For the remaining model periods, they were the levels at the end of the previous model period as computed by the simulation model. The iterative process described in the previous chapter, for finding the proper *average* concentrations over each model period, did not seem to be necessary since concentrations did not vary appreciably under the ASTRAN method. Figure V-1 shows the average C_{gi} values used for the beginning of model period 6, in relation to the actual TDS profile.

One of the important constraints is the maximum amount of pumped water that can be supplied from each section. In the absence of artificial recharge, the maximum sectional supply (s_i) would be the safe yield, or the amount of water naturally flowing through the aquifer. If sufficient artificial recharge were available, however, the maximum sectional supply would be limited by the aquifer characteristics (i.e., how fast the aquifer can transmit water from artificial recharge areas to a pumping well).

There are several ways one might estimate the maximum amount of water that can be transmitted through an aquifer. For this study, it has been approximated by Darcy's law. A representative hydraulic conductivity over each section was estimated, as well as the maximum realistic hydraulic gradient over each section. By using an average depth of saturated thickness and the length of each section, maximal flow rates could be estimated. The smallest of these, 3200 AF/yr, was assigned as the s_i value for all sections i. Several smaller yields (i.e., s_i = 2800 AF/yr) were used in the screening model in order to see what effect this would have on the solutions. When the maximal sectional supply s_i was decreased to 2800 AF/yr, the solution to the screening model was similar to the solution that used 3200 AF/yr, though the resulting TDS levels computed by the simulation model tended to be higher.

Table V-1 lists the quantity and quality data for the various sources, in addition to demand data. The amount of available upstream groundwater is a debatable figure. The most conservative procedure would be to set this amount to zero, and rely totally on imported water. Cost comparisons of the two approaches will be given later. Evapotranspiration ET_i was estimated by assuming an irrigation efficiency of 0.70.

In applying the screening model results, q^*_{ij}, to the simulation model, a one-acre artificial recharge area was assumed to have a capacity of recharging 1200 AF/yr into the aquifer. This included one day a week for cleaning operations, and an average of four feet per day of infiltration. Since the largest irrigation well in the Bonsall Subbasin has a capacity of 964 AF/yr, this was considered to be the maximum probable capacity of any well.

The quantity balance for the entire basin was set at

$$\Delta W = -\sum_{i=1}^{4} ET_i + \sum_{i=1}^{4} NR_i \ .$$

Thus, the right-hand side of equation IV-7 is zero. This ensured that the historical hydrologic balance in the basin would be maintained, since it implied that total water imported into the basin, as specified by the ASTRAN method, must equal the total exported water.

Likewise, historical values of ΔW_k were used in order to preserve historical sectional water balance. It should be noted that in actually running the screening model, q_{k5}, q_{5k}, and q_{6k} were not included in equation IV-8. Since they turned out to have positive values when computed by the management algorithm, the sectional balances under the ASTRAN method did not exactly correspond to the historical sectional balances. Future calculations should include them.

The objective function cost coefficients, c_{ij}, in the screening model were conservatively estimated as follows. First, all obviously nonoptimal transfers of water, such as transporting poor downstream groundwater upstream, were assigned an arbitrary penalty cost of $1000/AF. Next, the costs of transporting groundwater in unlined canals were calculated as shown in Tables V-2 and V-3. The use of unlined canals is reasonable since the goal is to encourage downstream recharge. It is assumed that the relatively even topography of the basin will allow gravity flow and any required pumping can be handled by the existing system. Each c_{ij} value ($i=1,\ldots,4$; and $i \geq j$) was then calculated by adding groundwater cost to transportation cost. For example, applying one acre-foot of groundwater to the same section from which it was pumped would cost $30.62, according to Table V-2. If the water were to be transported one section downstream, the unit cost would be $30.62 + $1.50, or $32.12. The cost of artificial recharge was considered negligible

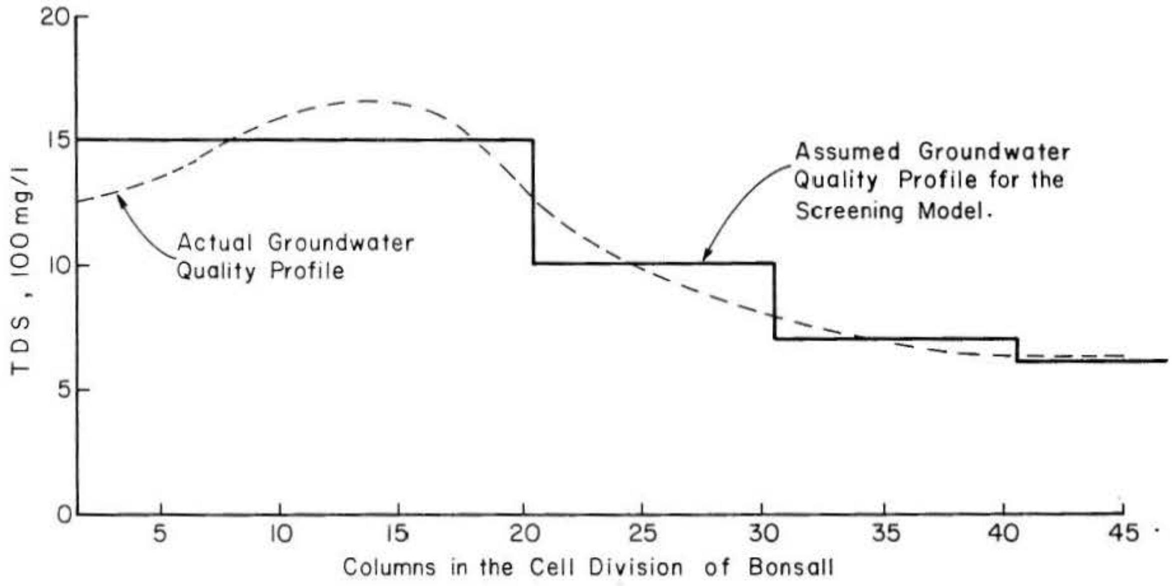


Figure V-1. Water Quality Profile for Bonsall Subbasin.

since the cost of purchasing land for artificial recharge purposes is normally balanced by the value of excavated sand and gravel.

The costs itemized in Table V-2 assume a 30-year life and a discount rate of 8%. Well drilling costs are assumed to be $52/ft and the average depth of a well, 200 feet. The assumed power cost is $0.06/KWH, with a pumping head of 150 feet and overall well efficiency of 0.72. These pumping costs are extremely conservative in that they ignore any current pumping capacity in the subbasin.

The price of State Project water was determined during a field trip, after interviewing several officials of the existing water districts in the San Luis Rey area. For Bonsall Subbasin, State Project water does not retail for less than $52/AF, so this was the cost assigned to c_{5j}. State Project water in the Pauma Subbasin retails at $75/AF and is projected to increase. Consequently, the cost of $52/AF is conservative and if the cost increases in relation to the groundwater cost, the ASTRAN method should prove to be more beneficial.

All of the c_{ij} data are summarized in Table V-4. Notice that the cost of exporting water from each section is the same for all sections, and corresponds to c_{ii}, $i=1,\ldots,4$. This is because it is assumed that export can be accomplished by simply pumping water into the river channel.

In discounting the capital investments, the annual cost is not sensitive to the life of the structure after 30 years; however, it is sensitive to the discount rate. This is a debatable number; however, 8% was used as a rough approximation. Another important point is that the costs, while hopefully realistic, are not all inclusive, but primarily meant to provide a means of comparing the sensitivity of total cost to various levels of degradation control, using the ASTRAN method.

B. Results of the Management Algorithm

In order to display the results of the management algorithm, based on the ASTRAN method, a series of figures have been prepared in order to (1) compare the aquifer degradation allowed by the ASTRAN method with the actual historical degradation, (2) to illustrate the screening model solutions, and (3) to illustrate the trade-offs in choosing which DCON value to use as the basis for a management strategy.

First, Figures V-2 and V-3 show the historical degradation of Bonsall Subbasin in contrast with the degradation that would have occurred under the ASTRAN method. Figure V-2 gives the computed change in TDS for a cluster of downstream nodes which are proximate to a well having accurate and extensive water quality data. Figure V-3 shows the average change in TDS for all of section 4 (farthest upstream) in the Bonsall Subbasin. In as much as the water quality data and boundary conditions are only roughly known, this latter comparison is more conservative and not as dramatic as the former; moreover, since the quality of the water in section 4 was good, less improvement was possible. The improvement is more noticeable downstream because the degradation builds up more rapidly due to the geologic constriction between the subbasins. That is, salts *pile up* at the downstream end of the subbasin. Consequently, Figure V-2 shows a more dramatic improvement than Figure V-3.

To further display the results of the management algorithm, Figures V-4 through V-12 show the screening model solutions for various values of DCON. Exported water is designated as EXW, upstream groundwater as USGW, and State Project water as SPW. All the quantities shown are in units of acre-feet per year. The arrows represent water imported, exported, or transported from section to section. For example, in Figure V-4, $q_{31} = 1659$ is the quantity transported from section 3 to section 1.

TABLE V-1

WATER QUANTITY AND QUALITY DATA

	Model Periods								
	6			7			8		
	c_i (mg/e)	s_i (AF/yr)	d_i (AF/yr)	c_i (mg/e)	s_i (AF/yr)	d_i (AF/yr)	c_i (mg/e)	s_i (AF/yr)	d_i (AF/yr)
Section 1	1500	3200	1228	*	3200	1117	*	3200	752
Section 2	1000	3200	832	*	3200	750	*	3200	845
Section 3	700	3200	667	*	3200	1083	*	3200	595
Section 4	600	3200	729	*	3200	817	*	3200	1069
State Project Water (5)	500	20000	NA	500	20000	NA	500	20000	NA
Upstream Groundwater (6)	500	3500	NA	600	3500	NA	650	3500	NA

* determined by simulation model
NA not applicable

TABLE V-2

COST CALCULATIONS FOR IRRIGATION GROUNDWATER

Item	Annual Amount	$/Acre Foot
Fixed Costs:		
Capital Recovery for Well	$ 923	$ 5.56
Insurance and Taxes	190	1.14
Total Fixed Costs	$1113	$ 6.70
Variable Costs:		
Operation and Maintenance	$1040	$ 6.27
Electrical Energy	1930	11.63
Revenue Tax for MWD	1000	6.02
Total Variable Costs	$3970	$23.92
TOTAL COSTS	$5083	$30.62

TABLE V-3

COST CALCULATIONS FOR ASSUMED CANAL DESIGN

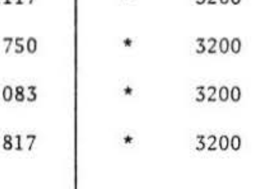
Item	Annual Cost/mile	Cost AF/mile
Fixed Costs:		
Capital Recovery for Lined Canal	$2176	
Annual Maintenance Costs	800	
TOTAL COSTS	$2976	$1.50 (Lined) $0.75 (Unlined)

Note the following assumptions:

1. Concrete lining is 2 inches thick, which yields 5.33 cu. yds. of concrete for 100 lineal feet.
2. The cost of concrete in place is $87/cu. yd., which includes all excavation and engineering work. This yield an initial cost of $4.64/ lineal foot.

TABLE V-3 (Continued)

3. Assuming that the average annual flow of the canal is 2000 AF, the cost per AF is $1.50/ mile.
4. The average distance between consecutive supply and demand sources is 2 miles, which is the average distance between section mid-points.
5. The assumed canal design is as follows:



The equation for flow in a trapezoidal channel (assumed design) is

$$Q = \frac{1.486(z + 1/x)^{5/3} D^{8/3} S^{1/2}}{1/x + 2(z^2 + 1)^{1/2} n}$$

in which:

$b = 2$ ft.
$D = 1.73$ ft.
$e = 1$ ft.
$z = e/D = 0.578$
$x = D/b = 0.865$
$S = 0.005$ (slope of channel)
$n = 0.013$ (roughness factor for concrete)

which gives: $Q = 38$ cfs (27,500 gpm; 33,500 AF/yr)

6. Since the cost in Item 2 above, which aggregates excavation and concrete costs together, was the only one initially available to the authors, a figure that is one-half of the cost computed in Item 3, namely $0.75/mi/AF, was arbitrarily selected for unlined canals.

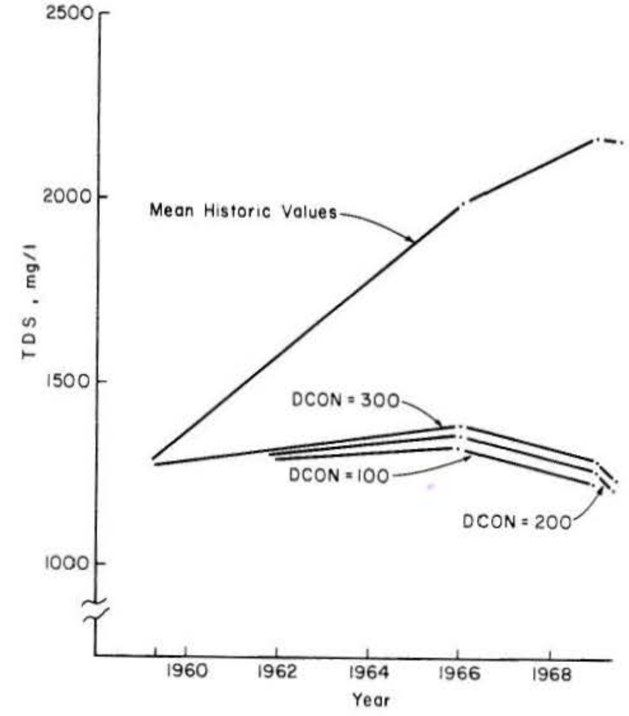


Figure V-2. Comparison for a Cluster of Nodes in Section 1. (Downstream)

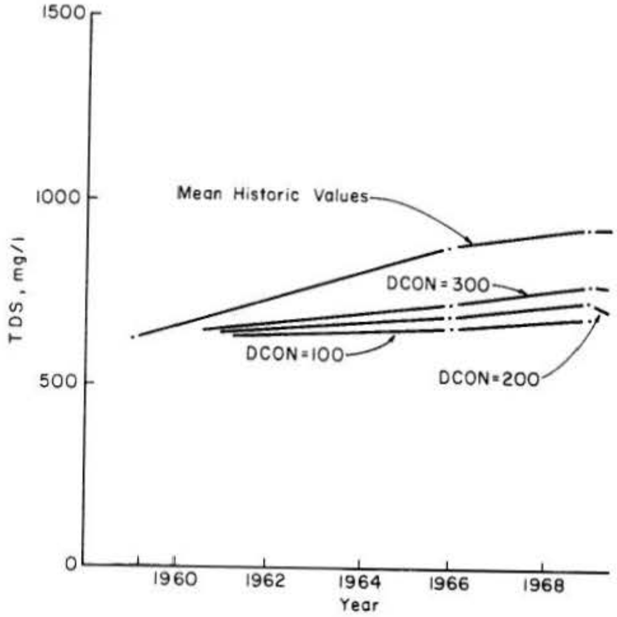


Figure V-3. TDS Comparison for the Average of all Nodes in Section 4. (Upstream)

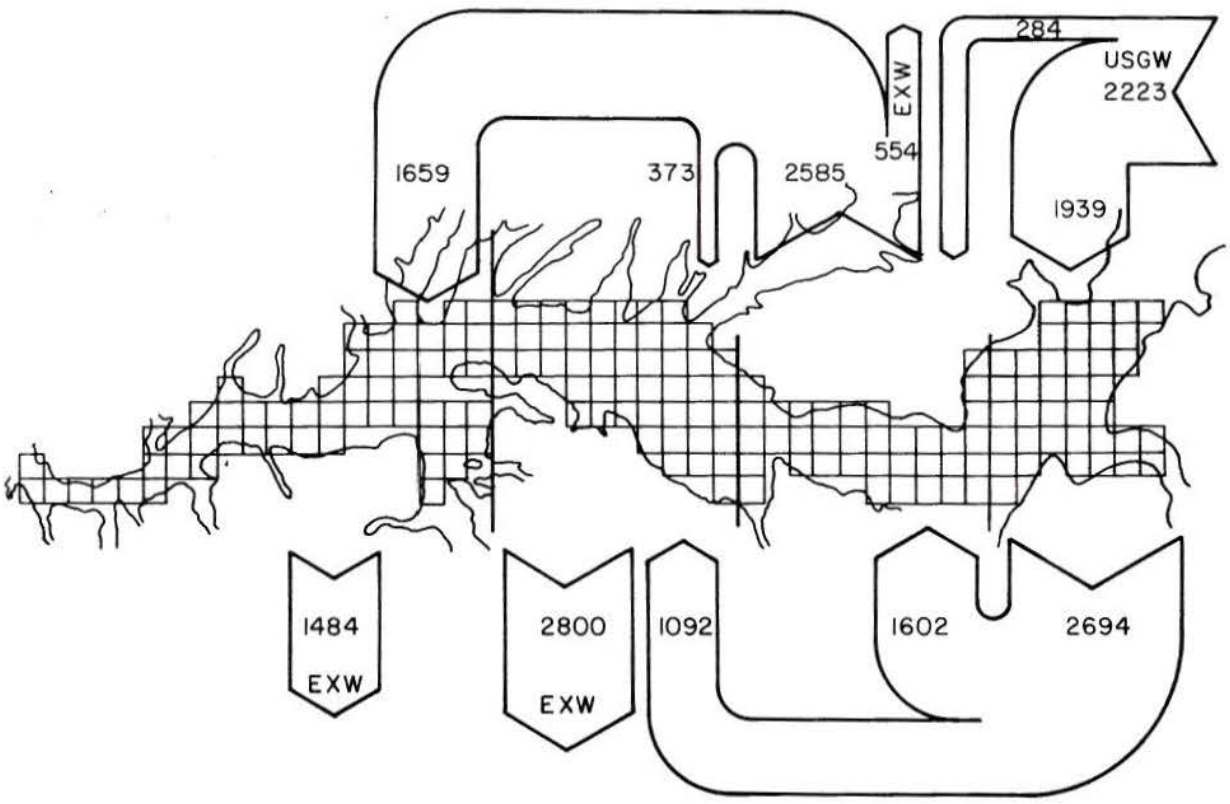


Figure V-4. Optimal Water Distribution, Period 6, DCON = 100

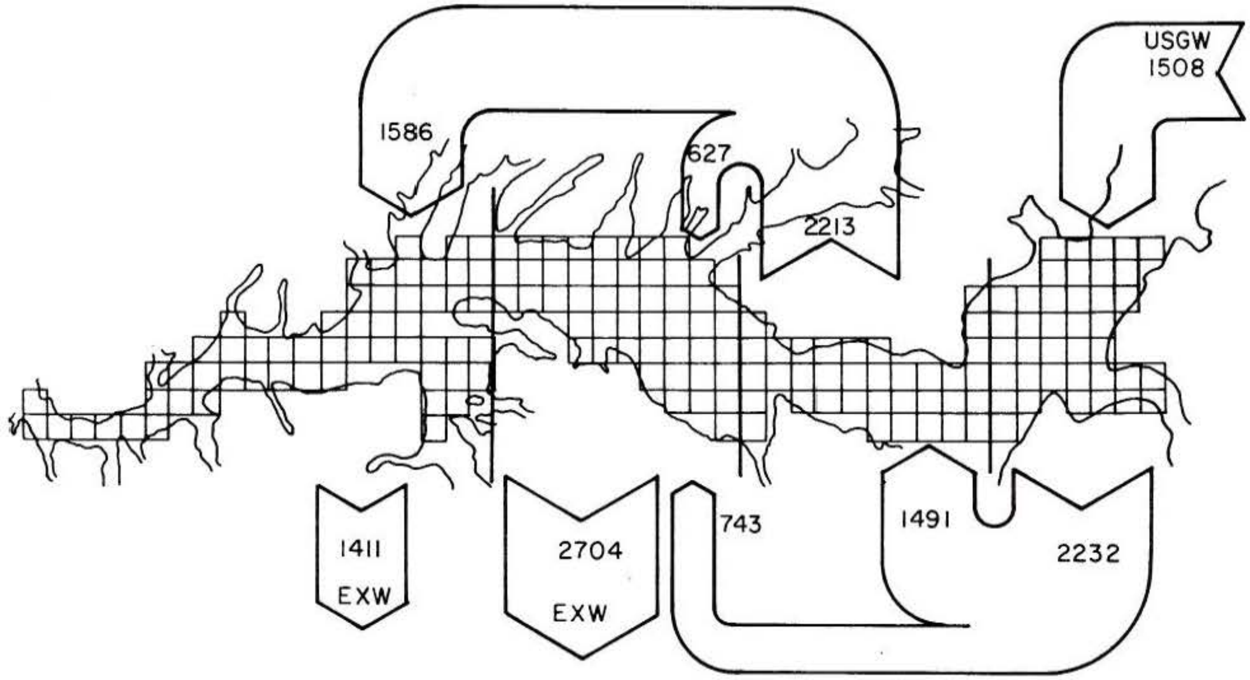


Figure V-5. Optimal Water Distribution, Period 6, DCON = 200

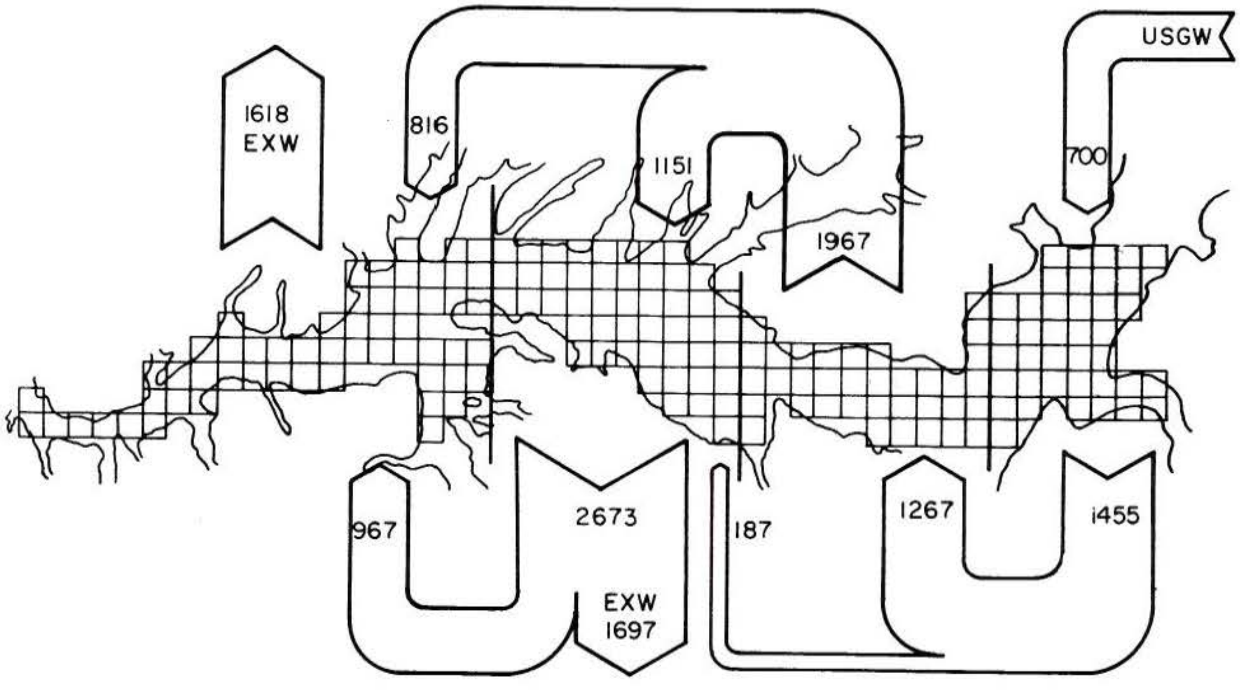


Figure V-6. Optimal Water Distribution, Period 6, DCON = 300

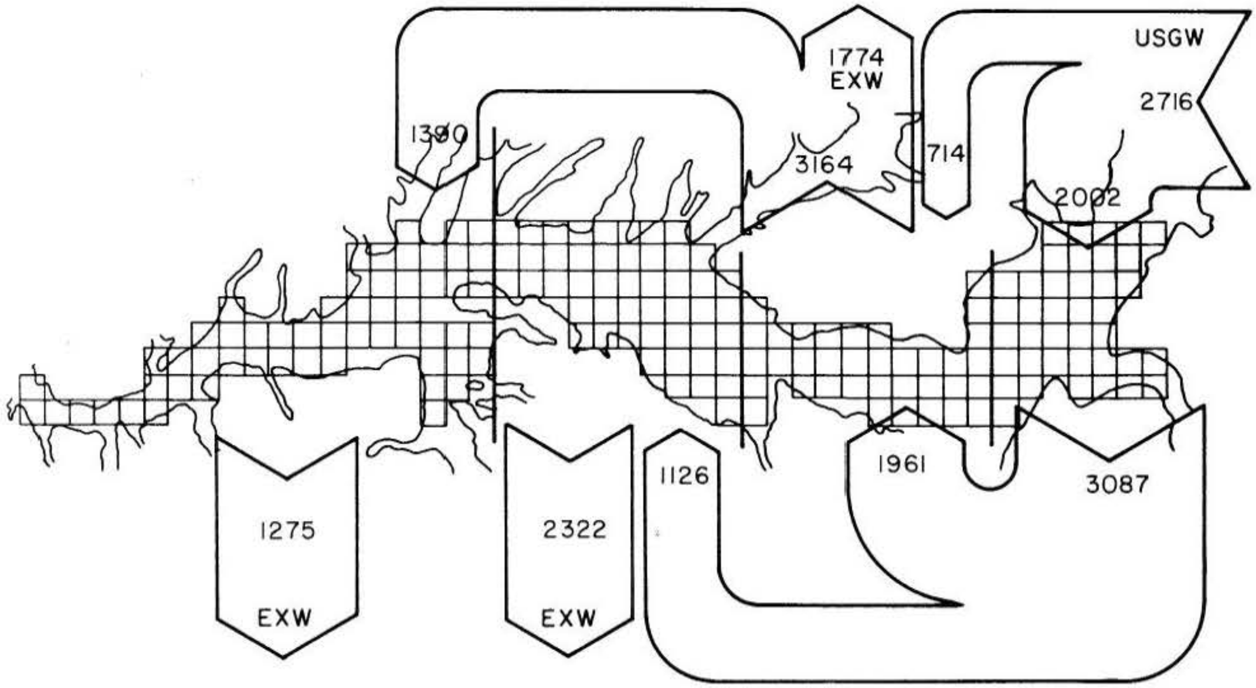


Figure V-7. Optimal Water Distribution, Period 7, DCON = 100

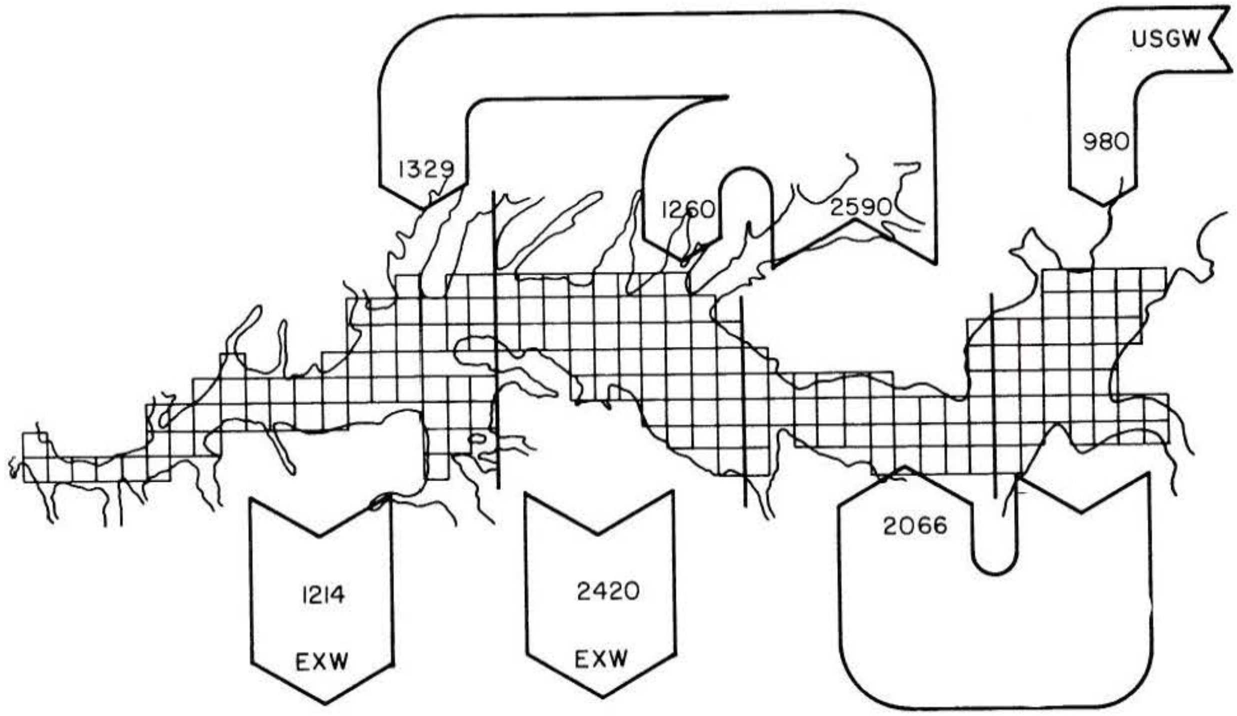


Figure V-8. Optimal Water Distribution, Period 7, DCON = 200

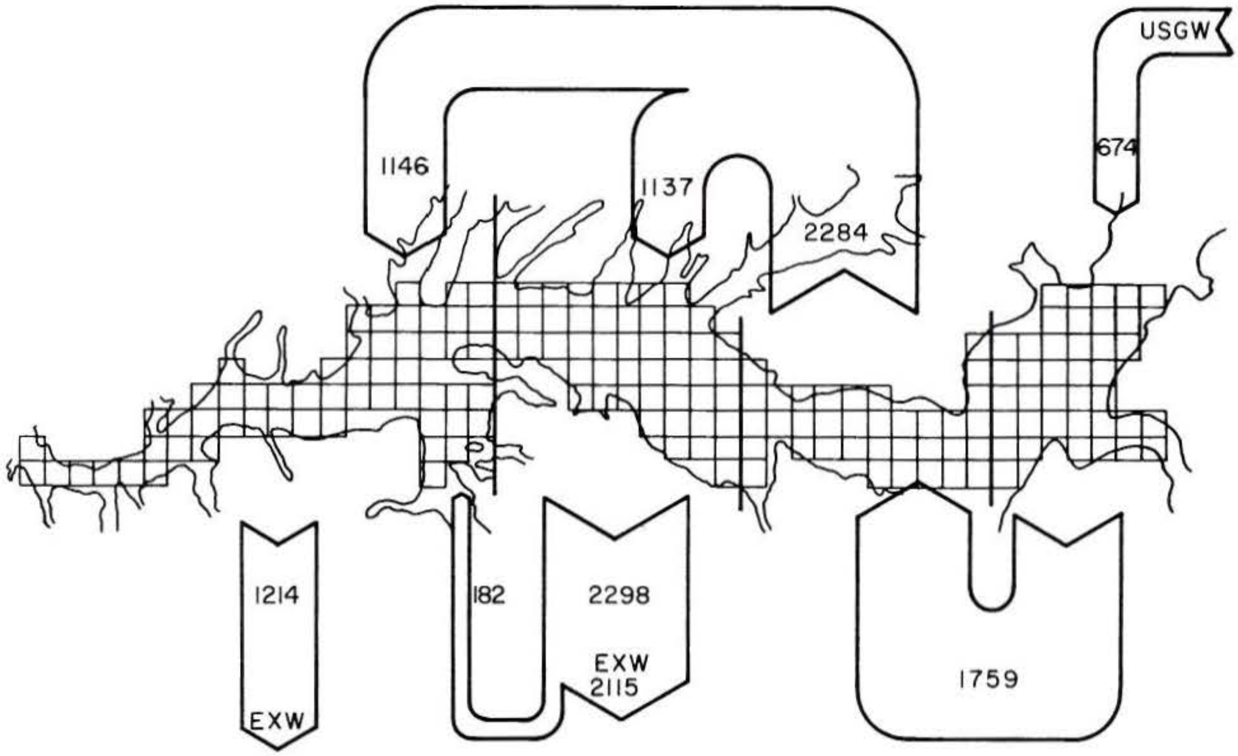


Figure V-9. Optimal Water Distribution, Period 7, DCON = 300

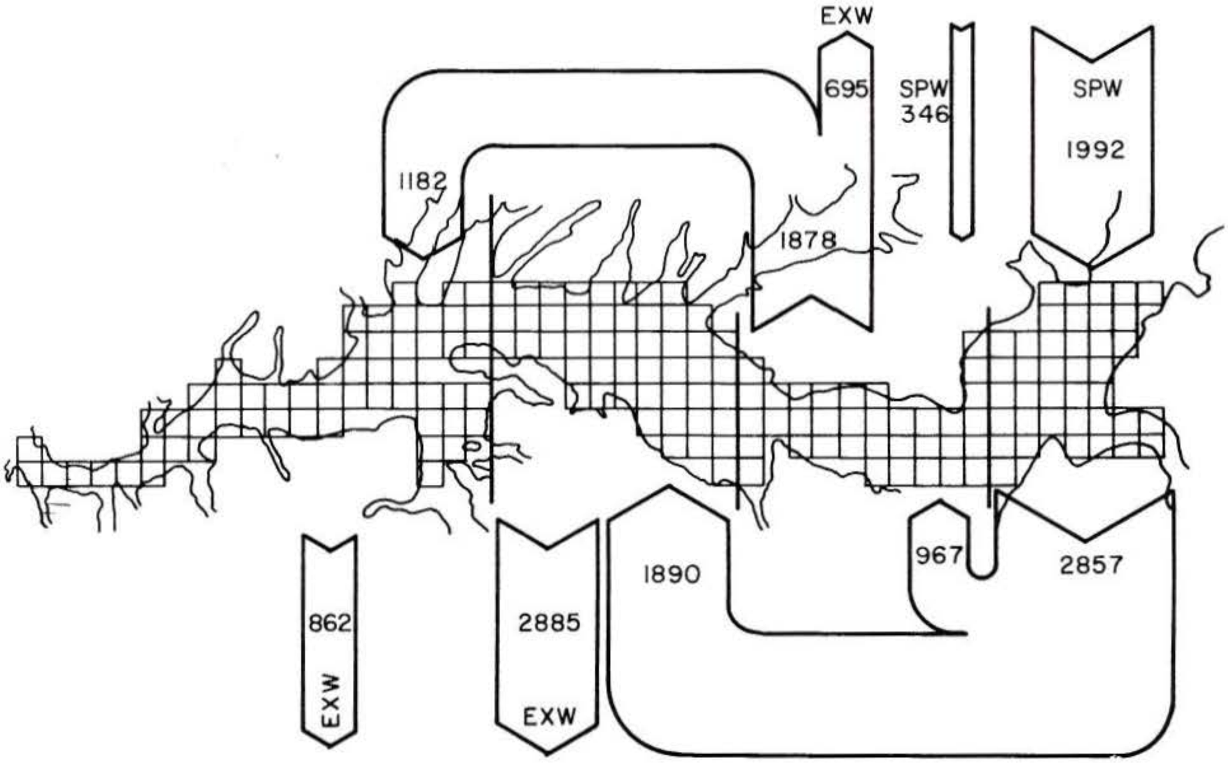


Figure V-10. Optimal Water Distribution, Period 8, DCON = 100

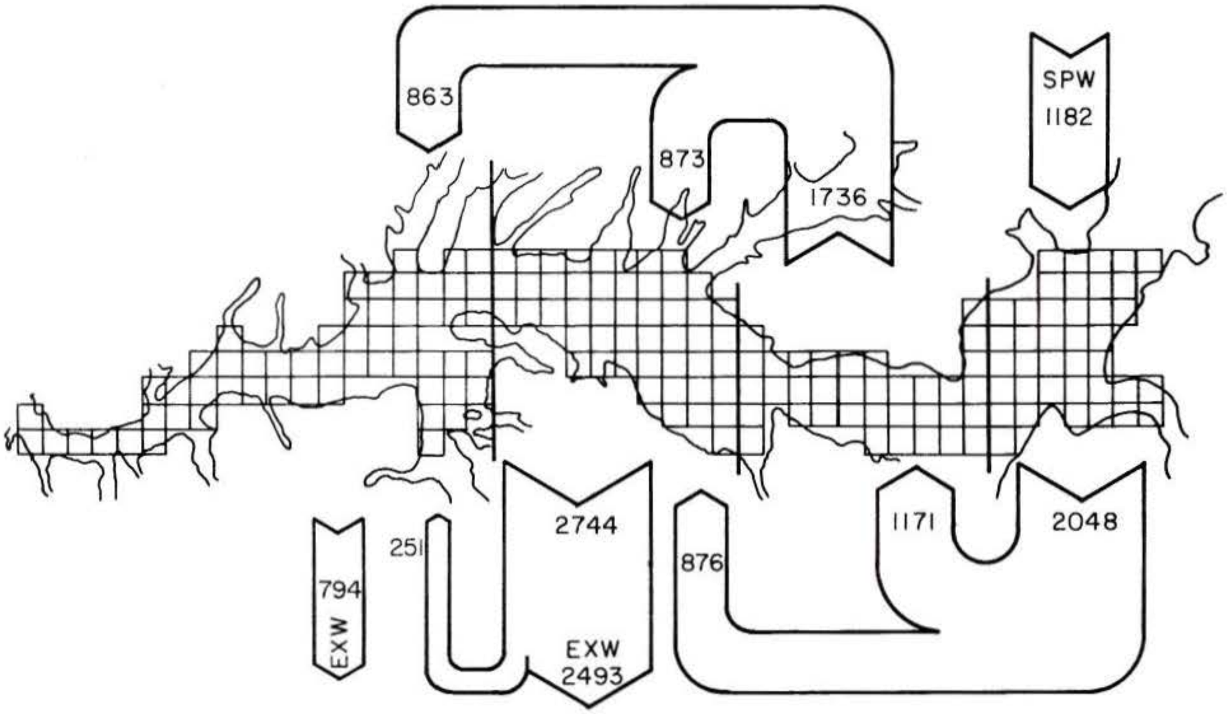


Figure V-11. Optimal Water Distribution, Period 8, DCON = 200

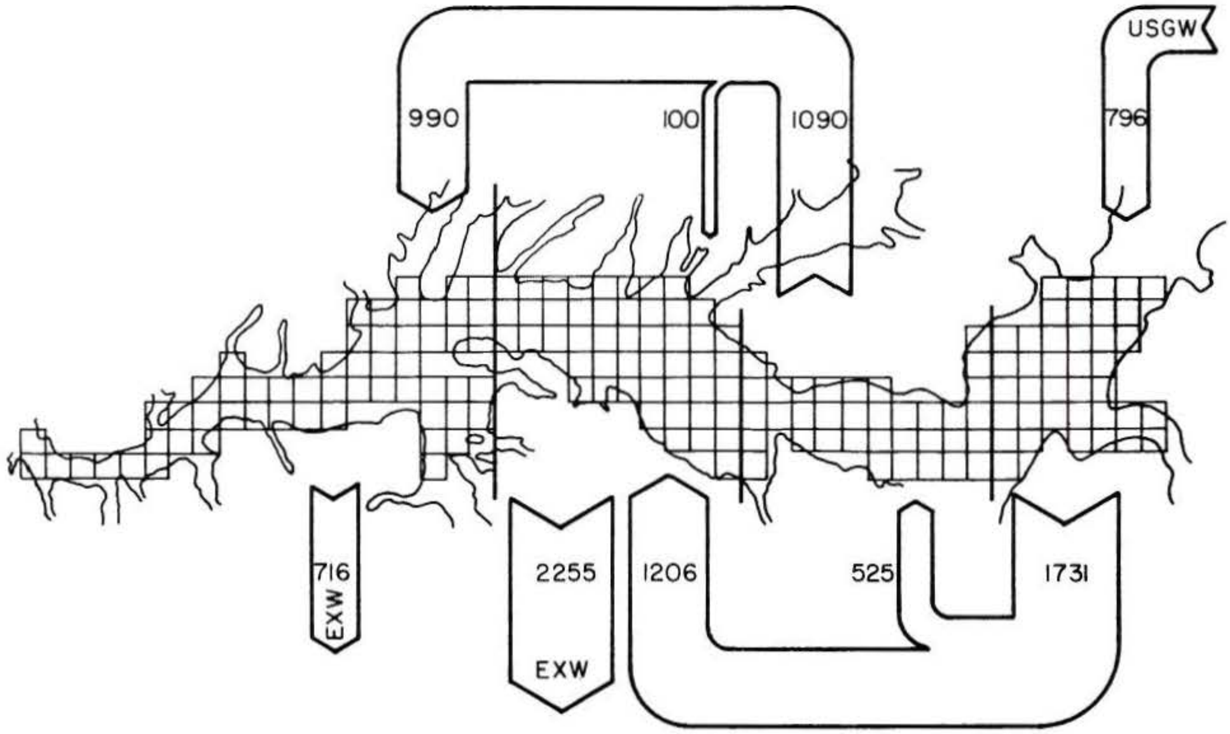


Figure V-12. Optimal Water Distribution, Period 8, DCON = 300

TABLE V-4

TRANSPORTATION COST DATA ($/AF/yr)

SUPPLY SECTIONS (i)	DEMAND SECTIONS (j) 1	2	3	4	5^+
1	30.6	1000	1000	1000	30.6
2	32.1	30.6	1000	1000	30.6
3	33.6	32.1	30.6	1000	30.6
4	35.1	33.6	32.1	30.6	30.6
5^*	52	52	52	52	1000
6^{**}	36.6	35.1	33.6	32.1	1000

* State Project Water (SPW)

** Upstream Groundwater (USGW)

\+ Exported Water (EXW)

Note that often a section is called upon simply to export water out of the subbasin, which actually implies that salts are being exported, in order to maintain a proper quality balance. The portion of this water that could possibly be productively used in the next downstream subbasin will be known when all of the subbasins are combined into one management model. The remaining water would be placed in an outfall and exported out of the entire basin. The more water that can be used, the more economical the total strategy becomes. There was some amount of imported water applied to hillside irrigation areas outside the boundaries of the basin during the historical period. But, since irrigation efficiencies are high in these areas, this amount was assumed negligible.

It is obvious that application of the ASTRAN method requires the pumping, transport, and application of more water than is needed for irrigation demand. These quantities tend to be higher for the drier periods. The export quantities were found to be well within the expected available capacity in the river channel. The quantity of natural groundwater flow to Mission Subbasin downstream was relatively unchanged by the ASTRAN method though quality was significantly improved.

Figure V-13 displays the results of a sensitivity analysis on total cost and salt balance (ΔS), as a function of DCON, for model period 6. The plots for the other periods are similar. They imply that the decision maker must pay a greater amount for aquifer improvement if DCON is decreased from 200 to 100, than a decrease from 300 to 200. Whether or not this cost is justified depends upon the benefits received.

To further clarify the sensitivity of cost to aquifer degradation, Figure V-14 shows the plot of average cost vs. average concentration balance ΔC over all three model periods. The same investment parameters of 8% and 30 year project life have been assumed. These costs would vary if the DCON decision variable were not held constant over the entire subbasin. It should be noted that these costs were estimated under the more conservative assumption that all upstream groundwater (USGW) must be replaced by the more expensive State Project water (SPW).

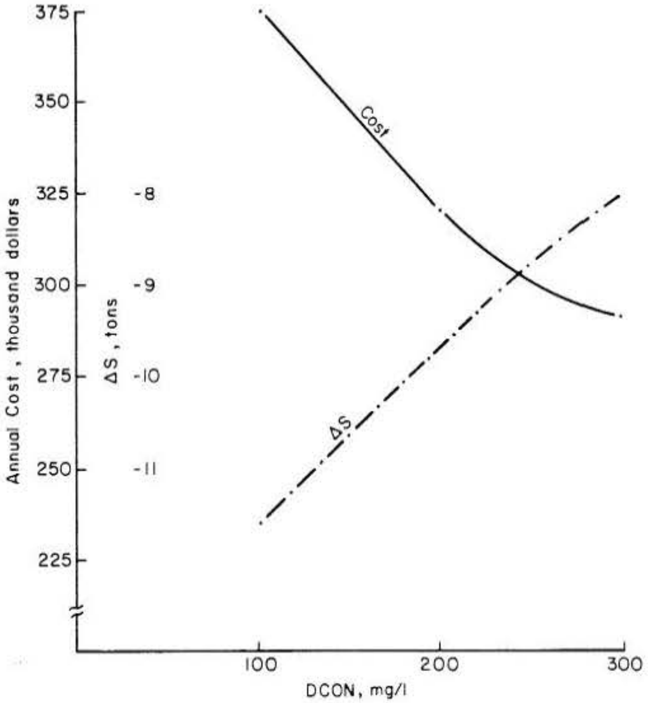


Figure V-13. Sensitivity Analysis for Period 6 over the Bonsall Subbasin (Upstream Groundwater Assumed Available)

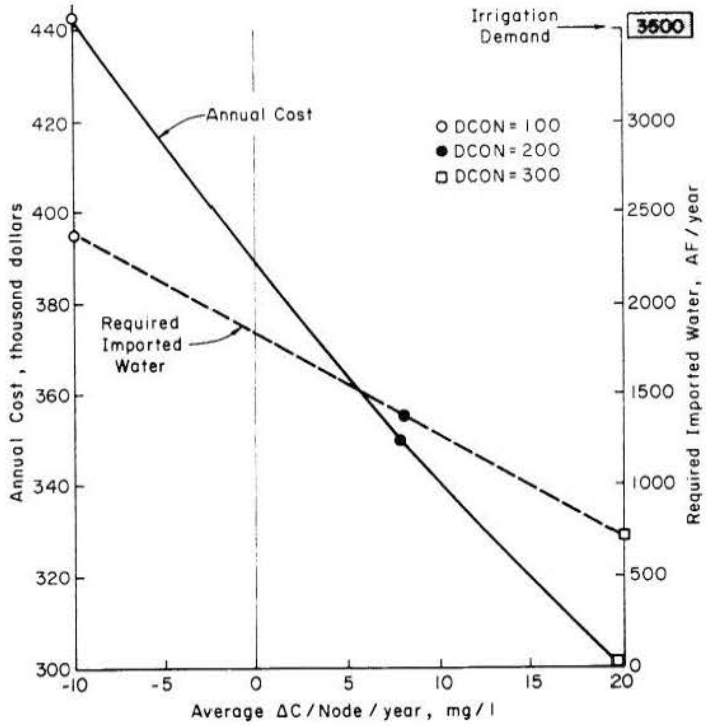


Figure V-14. Average Cost and Required Imported Water vs. Average ΔC for Periods 6 through 8 in Bonsall (Assuming No Upstream Groundwater Available)

Figure V-14 also gives the average annual amounts of imported water required by the ASTRAN method, over all three model periods, for various levels of degradation control. These amounts can be compared with the average annual irrigation water demand over the three periods, which was around 3500 AF/yr. It is also assumed here that no upstream groundwater is available, and that the amounts shown as USGW in Figures V-4 to V-12 must be replaced with State Project water.

C. Discussion of Results

One advantage in utilizing an aquifer as a storage reservoir is that flow in porous media is slow enough so that control decisions do not need to be effected on a short term basis. It would probably be adequate to operate the stream-aquifer system on a one year lag time, with the hydrologic input from the previous year dictating the strategy of the present year. Also, a series of observation wells to monitor water levels and groundwater quality could furnish data to aid the decision maker in modifying the management strategy. It would be helpful, if not necessary, to monitor the electroconductivity (EC) of the applied water to ensure that the quality of the mixture applied was close to that quality called for by the management algorithm. The manager should not blindly follow the distribution scheme submitted by the screening model, but temper it with engineering judgment. Hopefully, the screening model can be improved to where it will accurately predict system operating cost.

Though in the past, the concept of safe yield has been criticized, the term will be used here to denote the conditions necessary for nondegradation in water quality and a long-term steady state in groundwater storage. Therefore, the goal of managing the total river basin, as well as the various subbasins, is to stay within the safe yield of the stream-aquifer system or to have maintained only small long-term changes in stored water and concentration level. Again, the ideal situation is that over the long-run $\Delta W = 0$ and $\Delta C = 0$.

These goals may, of course, be relaxed to fit fiscal and economic constraints; however, examination of the previously displayed results yields the following conclusions:

1. As the goal of $\Delta C = 0$ is approached, the marginal cost increases.
2. As ΔC decreases, the amount of water forced through the aquifer by the ASTRAN method increases. That is, the transport rate of salts downstream must increase.
3. The balances ΔW and ΔC should be allowed to vary (within bounds) as long as the long-term values in a total management program approach zero. Table V-5 shows how this might occur. For example, the stored water (ΔW) during a dry period decreases. This, combined with other factors, causes the concentration balance (ΔC) to increase.

TABLE V-5

REACTION OF HYDROLOGIC AND SALT BALANCE TO PRECIPITATION

Precipitation	Water ΔW	Concentration ΔC
Dry	<0	>0
Average	≈0	≈0
Wet	>0	<0

4. As DCON is increased (which is the same as relaxing the quality constraint or increasing (ΔC), the distance water is transported downstream is decreased. This can be observed by comparing Figures V-4 through V-6 or any three figures for the same pumping period.

It can be seen from Figure V-14 that the cost of achieving a concentration balance of $\Delta C = 0$ is around \$390,000. As a means of comparison, the Joint Administration Committee of the Santa Margarita - San Luis Rey Watershed Planning Agency has estimated the cost of extensive agricultural sewering or tiling in Pauma and Pala Subbasins to be about \$ 44,600,000 [21]. In examining the 50-year land use projections for the San Luis Rey River Basin, the average projected agricultural land use in Pauma and Pala combined is about the same as that projected for Bonsall Subbasin. This gives an annual cost of \$ 3,900,000, using the same project life and discount rate used for cost estimates in the screening model. Notice also from Figure V-14 that the amount of required imported water is roughly one-half of the demand at $\Delta C = 0$, and tends to vary linearly with ΔC.

The results of these modeling studies on Bonsall Subbasin suggest the following general attributes of the ASTRAN method:

1. It appears to be a truly cost-effective, low capital investment approach to salt degradation control (requiring about 10% of the cost of tiling for this case study).
2. It encourages the conjunctive use of both surface water and groundwater for satisfying irrigation demand (requiring 50% imported water and 50% groundwater for this case study at $\Delta C = 0$).
3. Unlike capital intensive alternatives such as desalinization and tiling, it is a flexible degradation control approach that allows decision makers to alter future management policies in response to future needs.

Chapter VI
IMPLEMENTATION

A. Legal Constraints

There are three important non-quantifiable constraints that must be considered: (1) legal, (2) sociological, and (3) political. All three of these must be considered in applying the ASTRAN method to the actual real-world situation in the San Luis Rey River Basin, or any other basin. It is difficult to generalize in these areas, so that the primary emphasis will be on the situation exiting in the San Luis Rey area. Hopefully, some general insights can be drawn from this emphasis that could be helpful when considering the application of the ASTRAN method to other areas.

Though legal constraints are usually non-quantifiable, they are more binding, perhaps, than those that are quantifiable. One of the problems with legal constraints, as well as the other constraints discussed in this chapter, is the inability to predict consequences of actions accurately. For many alternatives, the legal consequences must be decided in the courts, so not even the best water lawyer can gainsay the results. Nevertheless, the probable results of present and future litigations need to be evaluated and future plans modified accordingly.

California probably has the most complex water law system in the United States. It operates under a combination of the Riparian Doctrine and the Doctrine of Prior Appropriation. Basically, the Riparian Doctrine, which originated in humid England, says that any land owner whose land borders a body of water (or overlies an aquifer) has a right to share of that water. The Doctrine of Prior Appropriation says, *first in time, first in right*. That is, the first person to put water to beneficial use has a right to that water. Later appropriators, even though they have land next to a source of water, can only use whatever water is left over, if any. Generally speaking, in California, the Doctrine of Prior Appropriation applies to Federal lands and the Riparian Doctrine to non-Federal lands; however, there are exceptions. The San Luis Rey River Basin consists of both Federally administered lands (the Indian reservations) and private lands. It is possible that the various interests in the total river basin could reach an out-of-court settlement or agreement on the management of the river basin, but this remains to be seen.

The legal problems inherent in total river basin management, such as those that would be encountered in the San Luis Rey River Basin, result from attempts to establish overall control of water distribution. This is not as complex for surface water as it is for groundwater. Some have recommended a taxing system and others a pricing system. Cummings and McFarland [2] have investigated the economics of taxing and Weschler [24] has investigated the actual use of taxing in California. It was concluded from the latter study that few, if any, water districts were using a taxing system to optimally distribute water. It may be that a combination of pricing and taxing is the answer.

An example of taxing groundwater pumping can be found in the Orange County Water District [16]. All of the well pumps are metered and taxes assessed each year to pay for the extensive artificial recharge program. The District heavily subsidizes agricultural water by assessing the municipal and industrial (M and I) water a much heavier tax. If the Santa Margarita-San Luis Rey Watershed Planning Agency (WPA) can gain the legal status of a water district covering the entire basin, then there is an excellent chance that it could institute these management concepts. The control of pumping is important in order to prevent individual farmers from pumping and applying water on their own land, if that will accelerate the degradation problem. If such a practice were widespread, the ASTRAN method would be rendered ineffective.

A pricing system for water could possibly be established by the WPA such that the price includes the cost of managing the entire system. Such a cost was included in arriving at groundwater costs in the screening model objective function. This would include recharge costs, extra pumping costs, and increased distribution system costs. In spite of these costs, however, managed conjunctive use of surface water and groundwater would still probably be more economical than massive importation of State Project water only. The central river basin authority, which is assumed here to be the WPA, could use the taxing system as a negative control and the pricing system as incentive, if such is needed, after the political system is established.

There are some additional legal items. For example, how can the WPA prevent a farmer from drilling a well and violating the overall optimal plan? Unless well drilling in the river basin can be controlled, it may be necessary to use alternate legal means. The Public Health Department in California has used its powers to control well pumping. In as much as California does not have an individual comparable to the State Engineer found in most Western states, some alternative method of limiting individual action must be sought.

Presently there are several court cases in the San Luis Rey area. The City of Escondido and the Vista Irrigation District are seeking a settlement with the local Indian tribes and their representatives concerning future rights to surface water that has in the past been leased by these cities from the Indians. It will be years before the courts can settle some of the complex questions, but this should not hinder the progress of planning if these court cases are taken into consideration and the possible outcomes allowed for in the planning.

B. Political Constraints

As has been implied in the previous section, there must be a political organization that can tax and sell water. Normally, this is difficult to bring about. Historically, such attempts have been fraught with failure. However, since the WPA has already been formed and there seems to exist a spirit of cooperation in the area, the possibility of vesting the WPA, or some similar organization, with the necessary political authority is encouraging. Such a success might provide an example for other basins, and in impetus to follow suit.

Basically, what is needed is a water district with authority that spans the entire river basin. A federa-

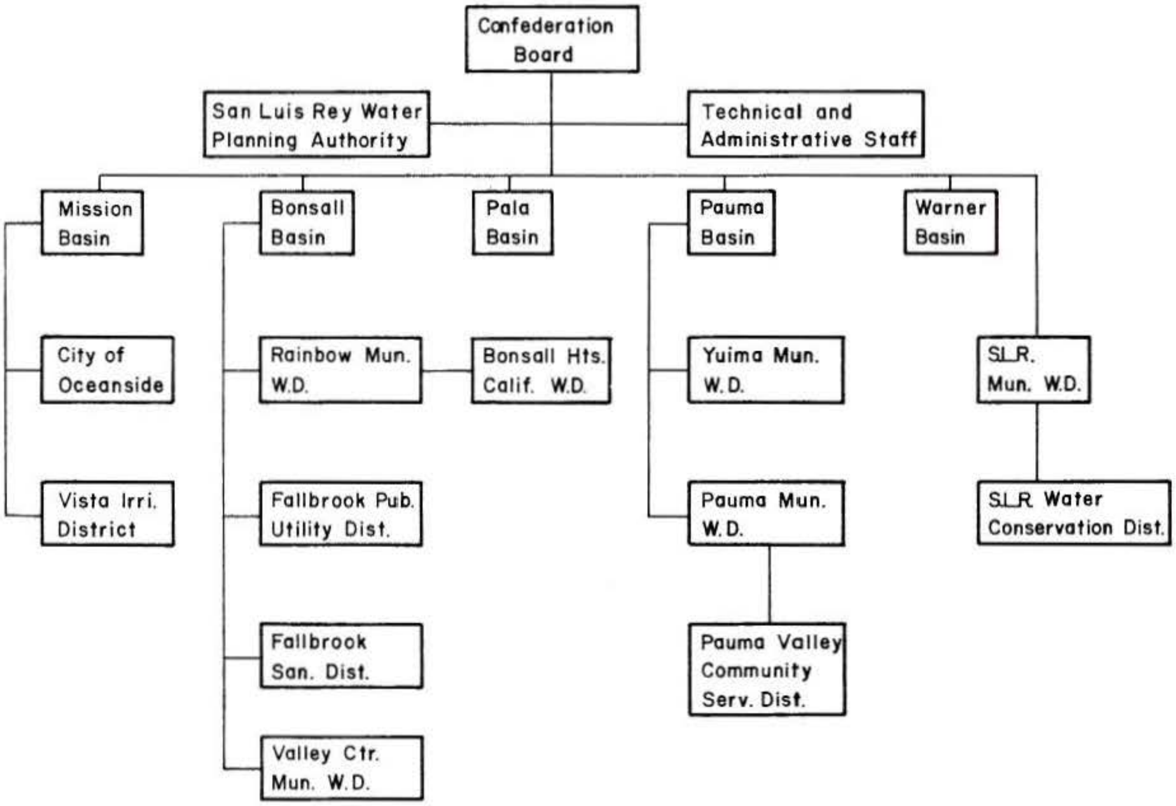


Figure VI-1. Suggested Political Organization for Managing Water in the San Luis Rey River Basin.

tion of the existing districts, as listed in Table II-2, might be most feasible. Several instances have been recorded where existing districts balked at being replaced by a large district, but agreed to send representatives to a central council that would exercise the same authority as the proposed large district.

Figure VI-1 shows a simple block diagram of a possible quasi-political organization to administer the overall basin water distribution. This would be a confederation of the existing districts, and would have three important responsibilities: (1) to coordinate the purchasing of all water, (2) to allocate optimal quantities and qualities of water, and (3) to set water prices and regulate taxes.

The purchasing of water would consist of buying the correct amount of State Project water and mixing it with various quantities and qualities of groundwater. For example, when all of the subbasins are joined in an overall management model, good quality imported water would probably be sent to upper Pauma Subbasin, in order to maintain a proper water quality gradient over the whole area. That is, since upper Pauma Subbasin has the best quality groundwater, so the best quality imported water might be needed to maintain a proper salt balance. This, of course, is only speculation, and is given for illustration purposes only.

Allocating the water would require a degree of technical administration. The proper quantities and qualities would have to be delivered to each section of each subbasin. The total distribution system should be built for maximum future flexibility. In other words, it should allow for future expansion and change in land use. Perhaps each district would receive the water from the WPA and sell it to the user; however, this would be in accordance with the overall optimal policy established by the WPA.

The pricing system and taxing system should raise enough revenue to support the long-term needs of the whole river basin. Possibly, the pricing system would solve the financial constraints while the taxing would be used as more of a penalty payment.

C. Sociological Constraints

Sociological constraints are the most difficult to assess. They are closely tied to the political constraints but also connected to legal, fiscal, and economic constraints. In the past decade, planners and managers have learned that public involvement is necessary in any public or quasi-public project. Pursuing the direction of establishing a large district to control the total river basin requires much skill and knowledge. Fortunately, people with such qualities appear to be available in the WPA. There are local land owners that have been in the area for many years. Several have the trust and respect of all the existing agencies and are examples of the happy circumstance when such catalysts exist.

The sociological issues may be clarified when an actual well owned by an independent farmer needs to be integrated into an overall system. The farmer knows what his well will produce and how it operates. To trade this for an unproven scheme is asking a lot of even the most enlightened farmer.

Several factors indicate that the sociological constraints may not be as difficult as might be expected. The existing structure of the WPA is a significant step toward marshalling the public behind the total river basin management concept. Also, Federal and State money that has been made available to the WPA should encourage the various smaller districts in their cooperative effort.

When considering the political constraints, the concept of a central organization as a federation of the smaller organizations has significant sociological implications. It is difficult for existing quasi-political institutions to surrender their authority to a larger entity. This has been decried by some, but has a rational psychological basis. Though there may be an element of not wanting to lose authority on the part of existing leaders, there is the aspect of shifting the decision making body further away from the grass roots, and people naturally resist this.

Often, changing from a small institution, where the constituents feel close to the governing body, to a large institution, where the people feel that their control has been taken away, can (and in some cases should) be resisted. For this reason, to have a workable transition from the many local bodies to a central authority, there must be a feeling of cooperation between existing institutions rather than a feeling of reorganization and change. Thus far, the latter seems to have been the most prevalent case.

The responsibility of engineers is to present water managers with technically feasible, cost effective alternatives, and display these alternatives in such a way that the decision makers and the public will be able to clearly see the issues and alternatives. Here, it is important *not* to attempt to manipulate public opinion to choose what engineers and managers perceive to be the *correct* solution, but rather to honestly aid them in making the decision. Actually, the engineer should be relieved at being removed from the responsibility of making final decisions. It is the duly elected public official, who is hopefully sensitive to the desires and needs of his constituency, that should bear this burden.

Chapter VII
SUMMARY AND CONCLUSIONS

A. Summary

A salinity management strategy called the Accelerated Salt TRANsport (ASTRAN) method has been developed for controlling groundwater degradation from irrigation drainage. The method encourages the transport of salts downstream in an accelerated manner by appropriately selected pumping, surface transport, and recharge schemes.

Successful application of the ASTRAN method to a stream-aquifer system appears to require the following conditions:

1. A combined average downstream transport rate of salts moving by pumped water, surface transport downstream, application, and drainage back to the saturated zone, which is considerably greater than the natural salt transport in the aquifer by convection and dispersion.

2. Relatively low required capital investment in additional pumping capacity, surface transport works, and artificial recharge facilities.

3. A source of at least some good quality imported water, local surface water, or groundwater to meet a portion of the demand.

4. A means of transporting salts out of the basin without simply transferring salt problems downstream.

A management algorithm has been constructed for applying the ASTRAN method in the most cost-effective manner. The degree of salt balance control is decided upon by a river basin management authority, based on information provided by the management algorithm. Feasible guidelines are given which enable operation of the stream-aquifer system within various political, sociological, and legal constraints.

The management algorithm consists of a screening or optimizing model which generates least-cost water distribution schemes, which are subsequently evaluated by an extensive quantity-quality simulation model as to their effect on the basic salt balance and nodal concentrations. The two models are linked by a water quality decision variable which allows the decision maker to choose various degrees of degradation control and evaluate the objective and subjective costs and benefits. Where there are sufficient data, a family of least-cost solutions can be evaluated and the desired one selected as the river basin operating policy.

Results from extensive modeling studies carried out on Bonsall Subbasin in the San Luis Rey River Basin, San Diego County, California, indicate that the ASTRAN method is:

1. A cost-effective approach to degradation control.

2. Encourages conjunctive uses of both surface water and groundwater; and

3. Is flexible enough to respond to future management needs.

B. Utility of Modeling for Management

The assumption of this research was that modeling is useful for managing and planning water resources systems. That is, of course, not a new finding, as others have given the same opinion [8]. To balance this conclusion, though, it is important to note that in simulation models the principle of GIGO (garbage in-garbage out) is practicularly applicable and the modeler has a moral and professional responsibility to verify his input or basic data.

Even though there are pitfalls in modeling, such as the mystique attached to a computer printout and the awe of the *black-box*, management algorithms (such as the one presented in this research) are necessary; moreover, intuitive solutions must be increasingly viewed with caution. To borrow a term from Forrester [3], the solutions of many complex systems are *counter-intuitive*. That is, not only may the seeming obvious solution not be best, but may produce the opposite of the results desired.

An example of the counter-intuitive nature of solutions was presented by Konikow and Bredehoeft [10]. It seemed obvious to many that the irrigation distribution canals should be lined to decrease the seepage loss of irrigation water in the Arkansas River system. An extensive computer simulation of the system, however, showed that such seepage losses aided in maintaining proper groundwater quality and to stop them would be detrimental to the aquifer as a whole.

As implied above, the use of simulation models in management studies has been mostly limited to operating the simulation model for several different management situations and comparing the results. There have been several suggestions that simulation models concerned with water quantity be simplified and linked to management algorithms; however, as yet the water quality aspect has not entered into this *total management* picture. This research has taken the next natural step and formalized the simulation model responses into a total management algorithm.

C. Natural Extensions of this Research

This research has pointed out the need for additional work in two important directions: (1) the development of efficient simulation models that contain both water quantity and quality aspects, and (2) combined simulation-management algorithms. There are many other areas in which the state-of-the-art needs to be extended, but these two seem to be the most pressing. More specifically:

1. There is a need for construction of efficient simulation models. The present finite difference stream-aquifer models are much too time consuming to be directly used in management studies. There have been investigations into more sophisticated simulation modeling techniques that use computer time more efficiently. One of the more promising areas appears to be the use of finite element models, which have the potential for greatly improving the modeling of stream-aquifer systems.

2. Labadie [11] has suggested using simplified models that are, however, more dependent on historical data for their calibration. An example of such models would be those which use discrete kernel functions for predicting water levels [15]. That is, in the absence of adequate historical well level data, simulation models can often be roughly calibrated by assigning reasonable values for aquifer characteristics. The simulation model can then generate synthetic well level data to augment inadequate historical data, which can then be used as a basis for calibrating these more computationally efficient models. This is because the latter models may not contain parameters that are physically interpretable, and are simply used to fit model output to available data. Having calibrated the efficient model, it can then replace the more computationally time-consuming simulation model in order to carry out comprehensive management studies.

3. Another need is to facilitate the use of simulation models by practitioners without their having to become proficient in modeling and experts on the inner workings of the model. At present, it is impractical for managers to use existing models without special training, due to their high complexity. However, as user instructions are simplified and clarified, they will become a more useful tool in the whole discipline of water resources.

4. In this research, a simulation model has been combined with an optimizing screening model in order to produce a management algorithm. This combined algorithm, however, is not a *hands-off* program in that the two models are linked and iterated via a human operator. The next natural step is to include these two processes in the computer code so the total algorithm can operate unaided. At present this can be done only by greatly increasing the computer cost; however, with efficient simulation models, the formal connecting of the two models may be accomplished economically.

5. There is a need for in-depth economic analysis concerning the use of management algorithms. Most managers and planners know that spending money for planning is economical, but this has not been demonstrated quantitatively. It would be helpful to managers, modelers, and planners if it could be shown that a good plan is more economical than a poor one. In this study, the results seem beneficial and appear to justify the cost perhaps more dramatically than some other river basin because the degradation of the San Luis Rey aquifer had been pronounced irreversible and any financially feasible solution would be welcome. However, there are cases when little formal planning is effected and the solution or alternative chosen is not the best possible. The extra cost of good planning should save money in the long run.

6. The problem of controlling stream-aquifer degradation can be easily formulated (though not so easily solved) as a multi-objective optimization problem by including environmental impact, aquifer degradation, agricultural production, etc., explicitly in the objective function. This is in contrast to the approach taken here of including aquifer degradation in the constraints and solving for a range of possible limits. In this way, no explicit decision is made on an appropriate degradation level. The general problem of analyzing trade-offs between diverse and noncommensurate objectives is a current subject of intense investigation, such as the work of Haimes and Hall [6]. Future studies should be directed at applying some of these newly developed techniques to the aquifer degradation problem.

7. For this particular study, perhaps the most uncertain source of groundwater degradation is the imported water that has been, and is being, used for hillside irrigation. How much and when will this water reach the alluvial aquifer? This is an important long-range question that needs some careful research to provide an answer.

8. Finally, as has been stated, the ASTRAN method is not set forth as a single-handed cure for degradation in stream-aquifer systems. It is only part of the solution and meant to be used in conjunction with other management schemes. There is a need to evaluate all of the various ways the water quantity and quality can be managed in a river basin or subbasin to see which combinations of these means produce the *best* solutions. Again, economics enter into the picture along with the environmental effects; however, sensitivity analyses in these areas are needed.

Returning to the importance of groundwater quality as defended in Chapter I; problems, such as aquifer degradation that may take decades to correct, must be properly anticipated. The obvious reason is that the time may not be available for a belated decision, that would correct the problem, to have a beneficial effect. This is especially important when one considers that some of the most critical salt buildup problems occur in the developing nations, which in turn have the most critical food and water shortages. The intellectual resources of the water planning and management institutions need to direct a considerable amount of energy to solve these problems, both by devising means of prevention, and strategies for correction.

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