Title

Optimal Management of Groundwater Basins of Degraded Water Quality for Conjuctive Use

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OPTIMAL MANAGEMENT OF GROUNDWATER BASINS OF DEGRADED WATER QUALITY FOR CONJUCTIVE USE

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ABSTRACT

In Southern California and elsewhere in heavily populated arid areas, existing potable water delivery and supply systems are increasingly being overtaxed in meeting current and projected water demands, both on an annual and peak demand basis. In a number of cases, such as portions of Riverside County, Southern Orange County, and San Diego County, numerous small groundwater basins, often with degraded water quality, could be integrated into the local water delivery systems providing new water supply and storage elements to the systems. Several water agencies in Southern California are already trying to accomplish this, however, the complex dynamic nature of the problem make it difficult to assess costs and benefits and to select the optimal alternative.

The purpose of this research is to analyze management alternatives and to develop methods for evaluating costs and benefits in order to optimize the use of these groundwater basins for conjunctive use. The San Juan Basin, located in Southern Orange County, was used as a basis for this research. A mathematical model of the basin was used to evaluate the basin as a storage element for sustained yield, drought emergency reserves, and summer peaking supply. Simulations were also conducted in order to determine the effect of pumping on groundwater TDS. Based on the simulation results, functions for TDS versus yield were developed. These functions were incorporated into an optimization algorithm developed to minimize the cost of water production for specified yield amounts. The results of this procedure for various yield amounts were compared in order to choose a management scheme which provides as much additional potable water as possible for seasonal use while keeping the cost of production comparable with the prices of imported water. Results indicate that groundwater production is economical when compared to importing water.

LIST OF TABLES

Chapter 1

Introduction

1.1 Purpose

The State of California is struggling to stretch water supply in order to meet current and future demands. Many agree that the combination of population growth, environmental restraints and the fact that no major projects have been added to the state's water system in 20 years will create continued water shortages, even in years of average precipitation. Southern California is the most susceptible to drought and is hit the hardest by insufficient potable water supplies due to its arid climate and highly populated urban areas. Although growth has slowed recently, officials still predict the state's population will reach 63 million by 2040, up from nearly 31 million recorded in 1992. Arizona is also in the process of trying to reclaim half of the 1.2 million acre-feet of Colorado River water now used by the Metropolitan Water District of Southern California (McClurg,1993a).

In many areas of Southern California, small groundwater basins, often of degraded water quality, exist which could be incorporated into the local water delivery systems in order to provide new water supply and storage elements. There are several water supply managers. This research is unique in that there have been few attempts to use formal optimization techniques in groundwater basin management and even fewer attempts, if any, to include groundwater quality in these optimization algorithms.

Specific objectives are to apply these procedures to the San Juan basin in order to maximize the withdrawals of marginal to low quality in situ waters, to use the basin for storage of imported MWD water, and to withdraw stored water during times of drought and emergency. The variables which must be considered in such a management plan include the flow capacity of a desalting plant, which is required because of poor quality groundwaters, the quality of the supply stream to the plant, and the size and location of extraction wells and artificial recharge facilities.

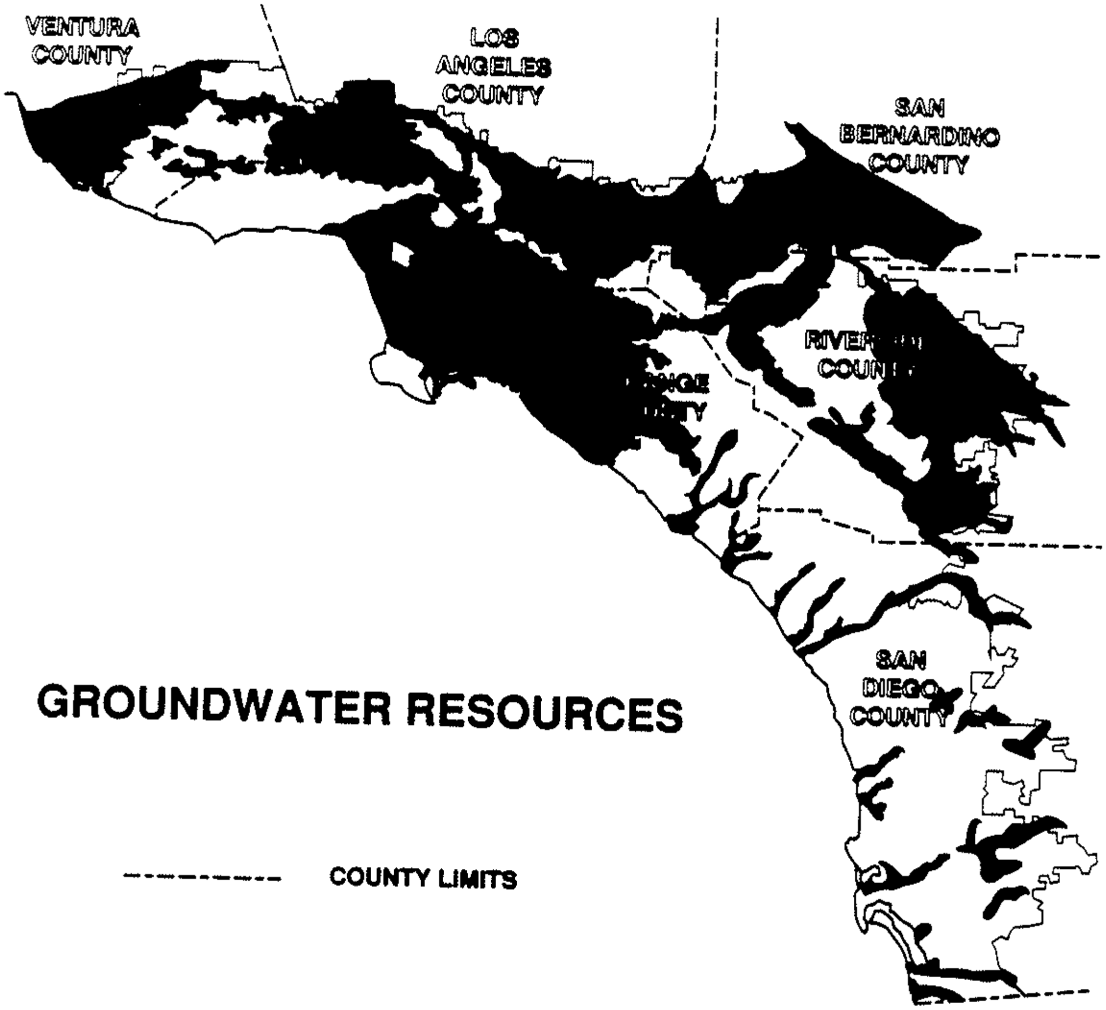

VENTURA COUNTY
LOS ANGELES COUNTY
SAN BERNARDINO COUNTY
RIVERSIDE COUNTY
ORANGE COUNTY
SAN DIEGO COUNTY
GROUNDWATER RESOURCES
COUNTY LIMITS

Figure 1

the basin and at the edges where wells would no longer reach water regardless of how dearly these users value it. There is also high risk of overdraft which can result in land subsidence in some cases and degradation of water quality in many cases.

"The natural drought, the population increase and demand for more water and endangered species restrictions are all making water managers realize they have to be much more efficient and focus on better water management - including groundwater management," said Carl Hauge, Chief Hydrogeologist for the Department of Water Resources (McClurg, 1993).

Widespread degradation of water quality in California's aquifers threatens existing groundwater production and is a primary deterrent to expanded conjunctive use. In many basins, expensive treatment is needed in order to make effective use of their storage capabilities. According to studies conducted by the Metropolitan Water District, each of the 15 major groundwater basins in their service area contain some sort of contamination (Figure 2). Large amounts of this groundwater are not utilized due to high levels of TDS. These "brackish" groundwater supplies could provide considerable amounts of potable water if treated. Brackish groundwater is defined as groundwater supplies which exceed primary maximum contaminant levels of inorganic solids or groundwater containing significant levels of TDS (>1,000 ppm), but considerably less TDS than that found in sea water (35,000 ppm).

The Metropolitan Water District is conducting a study to determine the amount of brackish groundwater in Southern California and the cost of reclaiming it. Preliminary results have found that on the order of 150,000 acre-feet of additional annual well production could be achieved through the treatment of brackish groundwater (MWD Discussion Paper, 1990). These brackish groundwater resources have not been tapped because the cost of desalination has traditionally been very high.

As regulations become more stringent, groundwater resources will further be s trained. Historically, groundwater with unacceptable amounts of TDS was blended with imported water or well water of good quality. As concentrations of TDS increases, blending becomes insufficient. Blending groundwater is also likely to come under stricter regulations in the future by the California Department of Health Services' guidelines.

Without blending, groundwater producers have three options. First, they can drill new wells in order to avoid the poor quality groundwater. Second, they can abandon the production of groundwater altogether and replace it with imported water. Lastly, they can treat the groundwater using a desalination process. The first two options have been chosen by many pumpers because they are more easily accomplished and less expensive. However, these options leave salts which spread to other portions of the basin and do not utilize the storage resource. Only recently has serious consideration been given to pump-and-treat solutions, but the high cost of treatment continues to be an impediment.

1.4 Elements of Groundwater Management

Effective basin management encompasses much more than hydrology and engineering. It involves legal rights, powers and responsibilities, as well as complicated issues of economic financing and organization (Krieger and Banks, 1962). Even the ideal hydrological management plan may not be implemented due to competing interests or lack of organization. Before an agency can concern themselves with how to use a basin and its water supplies most efficiently, there must be a working governance system. Along with hydraulic management of basins, an overview of the political issues of management will be discussed and how they can affect policy and decisions.

1.4.1 Hydrologic Aspects of Groundwater Management

Many different management possibilities are available for groundwater basins but it is difficult to assess costs and benefits and to select the "best" management alternative. Water managers would like to know the long term costs and benefits to base decisions upon. Management strategies can range from doing nothing, which will result in the least expense but will provide no new water or storage, to pumping as much as possible, which can damage the basin and result in extremely high costs making it more economical to purchase water from other resources. The challenge is to determine a strategy somewhere

The sizes and locations of pumping wells must be determined if they have not already been dictated. Both depend on the storage capacity and thickness of the aquifer. Farmers, water districts, local cities and other entities have long established pumping rights which cannot be taken away and will effect any proposed plan. The cost of construction and maintenance as well as the desired yield will also be key factors in making these decisions. Transmission pipelines represents a considerable expense which can be reduced by locating wells closer to treatment facilities when possible.

The timing and amount of groundwater withdrawal depends on the desired use of the aquifer as a seasonal storage element, a sustained supply or a drought reserve supply. Regardless of the aquifer's use, the amount and timing of withdrawal will effect the TDS of the water into the treatment plant. Factors such as sea water intrusion and outflow to the ocean can also be controlled by pumping. The amount pumped is constrained by the amount of water in storage and the flow capacity of the desalting facility.

The amount and timing of artificial recharge will effect the amount of possible seepage to stream channels and outflow to the ocean from coastal basins such as the San Juan Basin. If too much water is recharged at one time, some will be "lost" due to rising water. Recharge near the ocean will reduce sea water intrusion, but some of the recharged water will be lost to the ocean.

human welfare costs. In each of the eight cases policies were implemented simply to prevent the basin from being destroyed by overdraft rather than develop the most efficient management of the resource.

With the exception of Orange County, each of these basins have established adjudications which restrict pumping to safe yield levels in order to prevent overdraft. This is a lengthy and expensive legal process where pumping rights are established by a court and then monitored by a court-appointed watermaster. Adjudications only control the demand side of basin use. The water supply into the aquifer is not controlled. Some adjudications do allow production beyond the safe yield provided that the basin is replenished with imported water. In some basins in Southern California adjudications have driven out smaller users who could not afford court costs. These users would have been able to still enjoy their 1 to 2 acre-feet per year at lower costs than imported water had it not been for the adjudication procedure.

Pump taxes have been implemented in the Orange County Water District area in order to help pay for recharge. Rather than having limited pumping through adjudications, a supply of water to the basin prevents overdraft. However, the absence of assigned pumping rights in Orange County means that pumpers cannot receive anything in exchange for giving up their right, even though their stopping benefits other pumpers. There is also a risk of resource depletion during years of drought when the basin may not be recharged.

frequently articulate their "mission" as the steps are taken to carry it out. Of course there will always be disagreement about the best course of action to take. An agency must also constantly review how successful their efforts have been and determine what impeded their progress and where they erred.

It must be known in what ways the basin is connected to other water supplies. One basin's pumping activity can effect surrounding basins' water levels as well as surface waters. Water districts may have to work together in order to solve conflicts and ensure that everyone can gain effective use of their own resource. For example, in the Los Angeles coastal plain the West Basin is adjacent to the Central Basin. The Central Basin is the West's main source of freshwater supply. The West Basin tried to replenish their water supply by not pumping, yet at the same time the Central Basin continued to pump and lower water levels. As a result, water stopped flowing from the Central Basin into the West Basin and the West was not being replenished. In this case, as in many others, cooperation between two or more water basins is needed.

The interconnection between surface and groundwater has also been the cause of controversy. It has been estimated by hydrologists with the U.S. Geological Survey that up to 30 percent of the water in surface streams and lakes comes from groundwater. Large increases in pumping can decrease surface water flow as more surface water percolates out of the rivers to replace the groundwater (McClurg, 1993b).

1.5 The San Juan Basin Case

The recently adopted mission of the San Juan Basin Authority is:

> "to develop and maintain a reliable, good quality and economical local water supply for the residents in the San Juan Basin by maximizing use of local ground and surface water, the San Juan Creek and its tributaries, with due consideration for the preservation and enhancement of the environment, including, but not limited to, the natural resources, fish and wildlife, infrastructure improvements, and the cultural heritage of the area."

The need for developing local water supplies to the maximum extent in the San Juan Basin area is highlighted by a report released by the California Department of Water Resources (Bulletin 106-93). In their five-year update of the California Water Plan, it is predicted that California's water demand will increase 3.8 million acre-feet by the year 2020, up to 10.5 million acre-feet. This is assuming 1.0 million acre-feet of urban water conservation. Shortages of 0.4 million acre-feet in the South Coast region are expected for average years and 1.0 million acre-feet for drought years, even with the planned Domenigoni Reservoir. If the Sacramento - San Joaquin Delta problems are not solved, shortages could be larger. In drought years, statewide water shortages could exceed 7 million acre-feet by the year 2020.

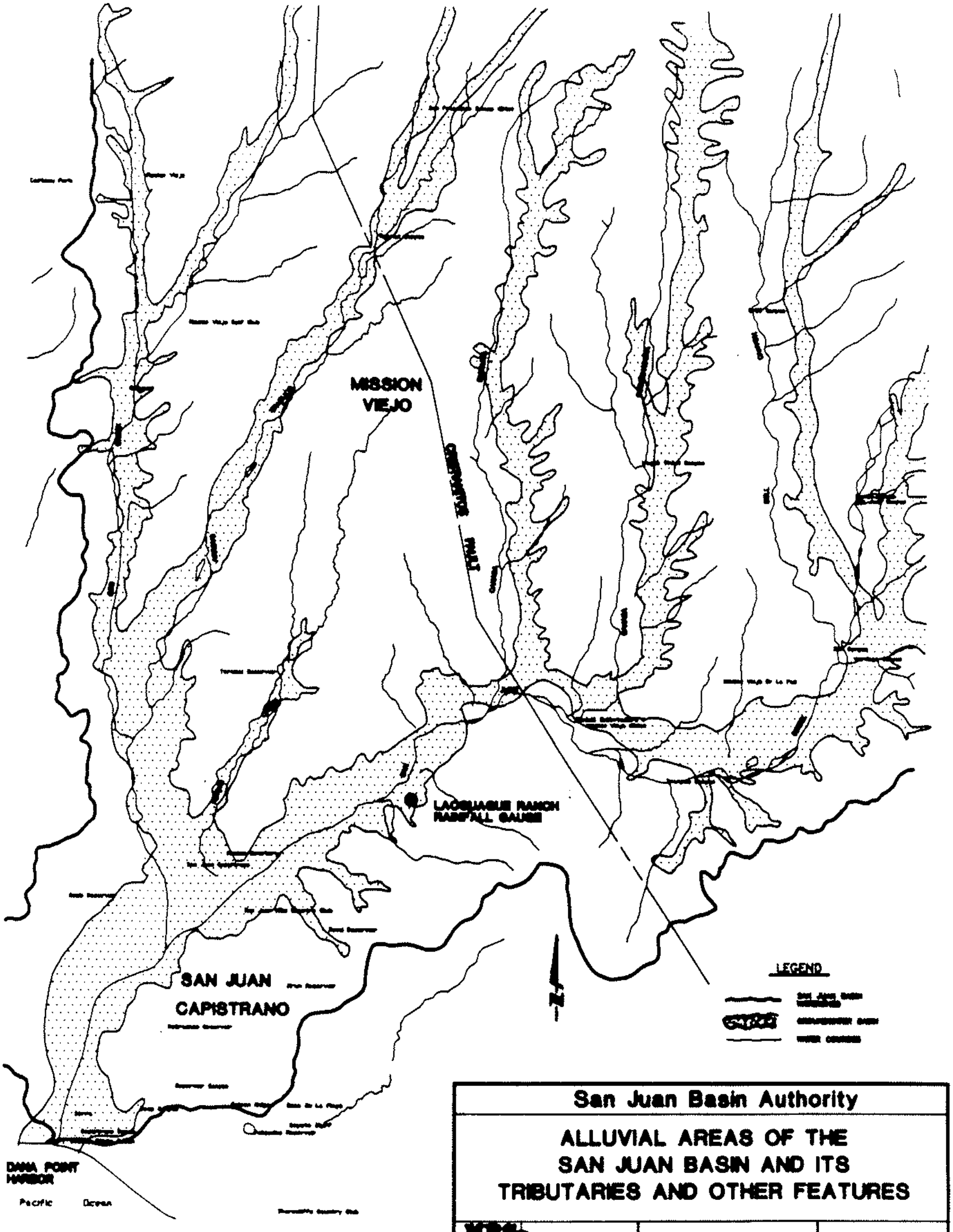
Chapter 2

Hydrogeology of the San Juan Basin

2.1 Description of the Basin

This research relies on previously published reports for information on the geology and hydrologic factors of the San Juan Basin. A 1994 report prepared by NBS/Lowry Engineers and Planners, "San Juan Basin Groundwater Management and Facility Plan", was the primary source of such information.

The San Juan Basin is a small unconfined coastal groundwater basin in Southern Orange County (Figure 3). Groundwater exists in the alluvial fill of the San Juan Canyon area and its tributaries, which include Trabuco and Oso Canyons (Figure 4). The alluvial valley fill is generally shallow with depths ranging from 200 feet at the coast to essentially zero at the ends of the small alluvial fingers of the tributaries. The alluvial fill is also narrow with typical widths of less than one-half mile in the main canyons. The widest

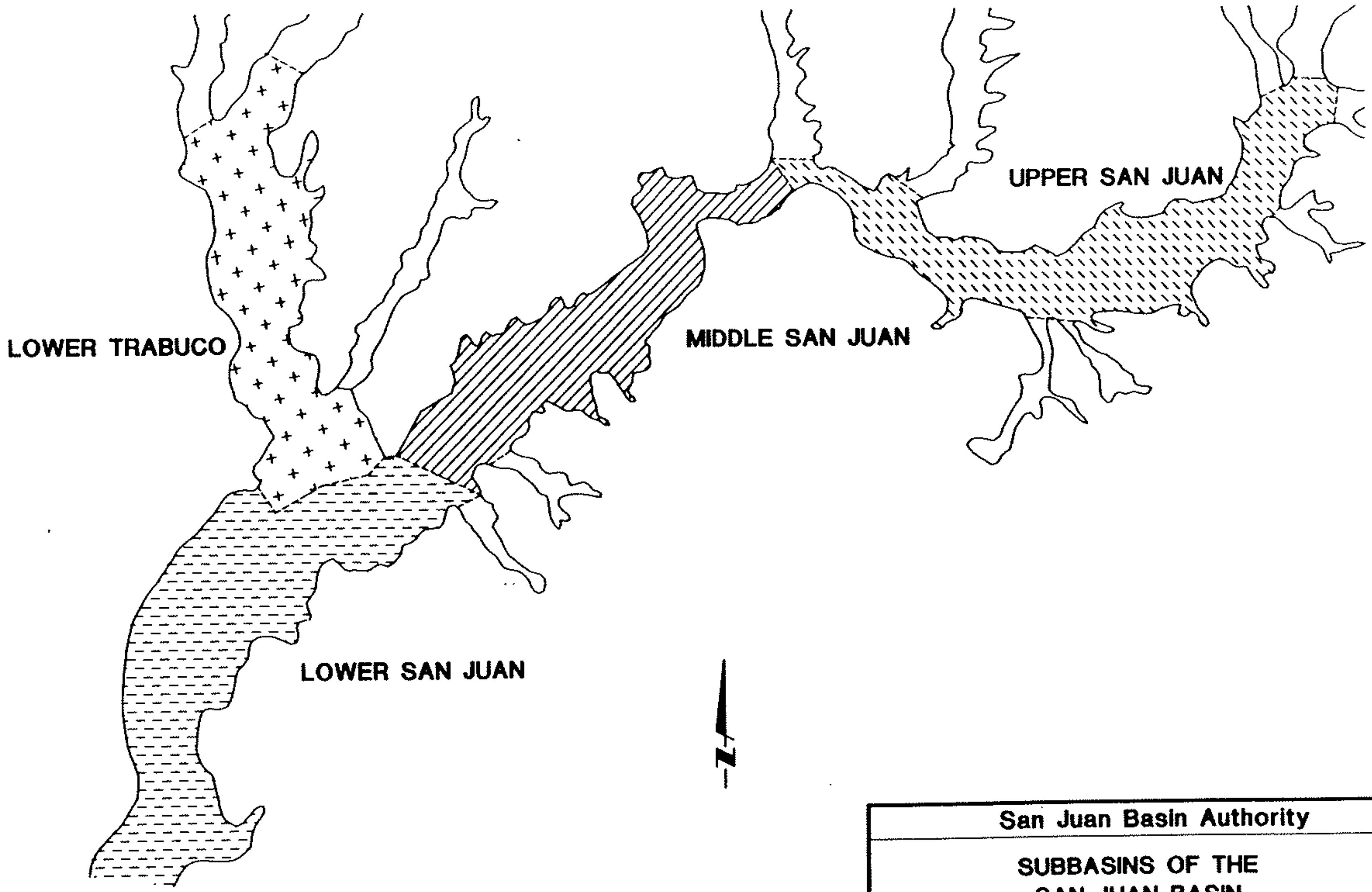


San Juan Basin Authority

ALLUVIAL AREAS OF THE
SAN JUAN BASIN AND ITS
TRIBUTARIES AND OTHER FEATURES

NBS LOWRY

FIGURE 4



San Juan Basin Authority

SUBBASINS OF THE
SAN JUAN BASIN

NBS LOWRY

FIGURE 5

2.2 Inputs and Outputs to the Basin

Groundwater typically flows downslope from the canyons toward the Pacific Ocean. The groundwater in the main subbasins originates from subsurface inflow from tributary alluvial fingers, streambed and rainfall percolation, and some applied water percolation from landscape and agricultural irrigation. Outflow from the basin occurs through subsurface outflow to the ocean, phreatophyte extraction, and well extraction's. High groundwater levels in some reaches of the San Juan Creek cause the watertable to intersect with the creek bottoms, causing seepage into the creek. This "rising water" subsequently percolates back into the basin or flows out to the ocean as streamflow.

A schematic of these input and output components for the saturated zone of the basin are depicted in Figure 6. Also included in the figure is a component for artificial recharge. Though artificial recharge has not occurred in the past, it is one of the major elements of an effective conjunctive use plan.

Estimates for the San Juan Basin inputs and outputs for a study period of 1979-90 are tabulated in Table 2. As can be seen from the table, the primary source of recharge to the basin is subsurface inflow from the small alluvial tributary fingers. Discharge occurs mainly through pumpage in the main basin. It will also be noticed form Table 2 that the basin was in overdraft by an average of 2000 acre-feet per year. The percolation of

Table 2
ESTIMATED INPUTS AND OUTPUTS FOR THE SATURATED ZONE OF THE SAN JUAN BASIN, 1979-90
(ACRE-FEET)

Year	Percolation of Precipitation	Percolation of Applied Water	Streambed Percolation	Subsurface Inflow	Total Inflow	Pumpage	Phreatophyte Extraction	Rising Water	Subsurface Outflow	Total Outflow	Net
1979.	1295.	934.	811.	1038.	4078.	5644.	417.	2239.	393.	8693.	-4615.
1980.	1816.	934.	3407.	1941.	8098.	5644.	417.	1106.	977.	8144.	-46.
1981.	459.	934.	318.	2118.	3829.	5644.	417.	488.	827.	7376.	-3547.
1982.	942.	934.	632.	2300.	4808.	5644.	417.	300.	812.	7173.	-2365.
1983.	1715.	934.	2579.	2350.	7578.	5644.	417.	507.	934.	7502.	76.
1984.	729.	934.	490.	2401.	4554.	5644.	417.	209.	832.	7102.	-2548.
1985.	833.	934.	568.	2451.	4786.	5644.	417.	101.	801.	6963.	-2177.
1986.	1047.	934.	729.	2467.	5177.	5644.	417.	63.	801.	6925.	-1748.
1987.	645.	934.	399.	2468.	4446.	5644.	417.	16.	727.	6804.	-2358.
1988.	597.	934.	361.	2452.	4344.	5644.	417.	0.	625.	6686.	-2342.
1989.	983.	934.	634.	2469.	5020.	5605.	417.	0.	590.	6612.	-1592.
1990.	1000.	934.	634.	2494.	5062.	5404.	417.	0.	557.	6378.	-1316.
Mean Annual	1005.	934.	964.	2246.	5148.	5621.	417.	419.	740.	7197.	-2048.

Table 3

GROUNDWATER QUALITY OF THE SAN JUAN BASIN

(mg/l)

Subbasin	TDS	SO	Iron	Mn
Lower San Juan	1500 - 2000	500 - 750	> 2.0	0.5, - 1.5
Lower Trabuco	1000 - 1500	250 - 500	0 - 0.3	0 - 0.05
Middle San Juan	500 - 1000	250 - 500	0.3 - 2.0	0.5 - 1.5
Upper San Juan	0 - 500	0 - 250	0 - 0.3	0 - 0.05

2.4 Mathematical Model

A previously developed two-dimensional model of the San Juan Basin was used in this research to evaluate the hydrologic response and water quality resulting from various management schemes. The model is based upon Darcy's Law and the two-dimensional continuity equation for an unconfined aquifer. It is assumed that groundwater flows in a horizontal plane relative to the earth's surface. The equation is as follows, where x and y are the horizontal coordinates, t is time, h is the saturated thickness, H is the elevation of the water table, Q_A is a source/sink term such as pumping, K_x and K_y are hydraulic conductivity in the x and y directions respectively, and S_y is the specific yield:

$$\frac{\partial}{\partial x}\left(K_x h\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y h\frac{\partial H}{\partial y}\right) = S_y\frac{\partial H}{\partial t} + Q_A$$

In this case the basin is assumed to be isotropic; K_x and K_y are equal. The above equation also assumes that basin materials are nondeformable and locally homogeneous. Inputs, represented by Q_A, are assumed to travel through the unsaturated zone in a short period of time.

In order to solve the above equation, initial conditions and boundary conditions are required. The initial conditions are known or assumed water table elevations over the

Due to the complicated nature of the basin and its boundary conditions, the basin flow equation can not be solved analytically. Consequently, a numerical model was developed by using the finite element method. The basin was discretized into triangular elements as shown in Figure 8. The state variable of the model is water surface elevation, which is assumed to be a linear plane in each element. The flow equation was then reduced to a system of linear ordinary equations that can be solved using a computer. The resulting equation is as follows:

$$S]H + [P]\dot{H} = F$$

where [S] is a known symmetric matrix representing the hydraulic conductivity and geometry of the basin, [P] is a known symmetric matrix representing the specific yield of the basin, $\underline{F}$ is a vector representing sources, sinks and boundary conditions, $\underline{H}$ is a unknown vector of water surface elevations, and $\dot{\underline{H}}$ is the temporal vector of unknown water surface elevations. The Crank-Nicolson method is used to solve the temporal vector of the finite element equation.

As seen in Figure 8, the basin was divided into 163 triangular elements with 122 nodes on the vertices of the elements. The boundaries were approximated by straight lines. Fixed head boundary conditions at the coast are located at nodes 119 through 122.

Subsurface inflow boundary conditions are located at nodes 1, 2, 3, 27, 34, 36, 71, 75, 80, 84, 85, and 87. All other boundary nodes represent no-flow boundary conditions.

Eight zones, as seen in Figure 8, were used to specify basin hydraulic parameters. Hydraulic conductivity, specific yield, and porosity may be specified for each zone. These parameters are shown in Table 4 for each zone. The nonlinear nature of the subsurface inflow boundary conditions make it necessary to use a second numerical model to determine these inflows. This model is based upon a lumped parameter cascaded cell approach. The structure of this model and the hydrologic components included are depicted in Figure 9. Each region is divided into several reaches. Based upon a water budget concept, inflow to a subsequent reach is equated with the computed outflow from the adjacent upstream reach.

To estimate water quality in the basin a model was developed using integrated finite differences. Since the sediments in the basin are shallow relative to the basins aerial dimensions, it is assumed that the concentration is uniform over the vertical profile. The water quality model was incorporated into the flow model and uses the same finite element grid. The water quality model was used in this research to estimate differences in groundwater quality resulting from alternative management strategies.

Since desalination would be implemented regardless of the management scheme chosen, there is no need to maximize groundwater quality. However, the cost of

Table 4

HYDRAULIC PARAMETERS USED FOR THE CALIBRATED SAN JUAN BASIN MODEL

Parameter Zone	Hydraulic Conductivity (ft/day)	Specific Yield	Porosity
1	125	0.18	0.3
2	100	0.18	0.3
3	125	0.13	0.3
4	100	0.13	0.3
5	60	0.12	0.3
6	70	0.13	0.3
7	48	0.10	0.3
8	36	0.10	0.3

Chapter 3

Optimization

Arriving at a "Best" Groundwater Management Scheme

3.1 Optimization Process

3.1.1 Basic Concepts

Optimization, in general, is any process used to arrive at a "best" solution to a problem given a set of circumstances which limit the options. Decisions such as choosing which college to attend and choosing which house to buy are made every day by comparing alternatives, without using any formal procedures or techniques. With increasing numbers of variables and constraints, it can become much more difficult to determine the optimal solution to a problem. In such cases, a quantitative approach to decision making may be desired. Such procedures are used in economics, engineering, variables are the controllable set of parameters which identify the alternatives. Often, a problem will include restrictions which define the acceptable values that the decision variables may assume. These restrictions, which are called constraints, limit the range of acceptable alternatives. The second component required in all optimization problems is a quantitative measure of the desired goal. This measure is a function of the decision variables and is called the objective function. The objective function represents some quantity which is to be optimized. The solution to an optimization problem is the set of values for the decision variables which result in the desired maximum or minimum value of the objective function.

A general optimization problem may be expressed as follows:

$$\begin{array}{lll} \text{minimize} & f(\mathbf{x}) & \mathbf{x} \quad \Re^{n} \\ \text{subject to} & g_i(\mathbf{x}) = 0 & i = 1,\ldots,l \\ & h_i(\mathbf{x}) \leq 0 & i = 1,\ldots,m \end{array}$$

where $\mathbf{x}$ denotes the values of the n decision variables, $x_1, x_2, \ldots, x_n$ in the set of real numbers, $g_i(\mathbf{x})$ and $h_i(\mathbf{x})$ are constraints conditions, and $f(\mathbf{x})$ is the objective function (Ratschek and Rokne, 1988). By simply replacing $f(\mathbf{x})$ with $-f(\mathbf{x})$ the problem becomes one of maximizing $f(\mathbf{x})$. Any point $\mathbf{x}$ in $\Re^{n}$ that satisfies $g(\mathbf{x})$ and $h(\mathbf{x})$ is called a feasible point.

mathematical nature of the objective function, problems are classified as linear, non-linear, or quadratic. Further, non-linear problems are classified as smooth, non-smooth or sparse. Similar to the objective function, constraints are also classified by function type. If the constraints are not functions, but merely restrict the decision variables by providing upper and lower bounds, the problem is said to be simply bounded. Finally, problems may be classified into two categories based on the decision variables. If one or more decision variable is restricted to a set of discrete values, the problem is classified as discrete or combinatorial. If such restrictions do not exists the problem is said to be continuous. Further classifications can also be useful in solving optimization problems. Classifying a problem will help distinguish amongst types of optimization problems and help to determine the best method of solution (Gill *et al.*, 1981; Rao, 1979).

Common methods of solution include techniques such as linear, non-linear and quadratic programming. These methods are used to solve problems with objective functions and constraints that classify the problem in the same category as the technique is named. There are also many solution methods for discrete optimization problems. Integer and mixed integer programming can be used for those problems where one or more of the decision variables are forced to take on only integer values (Gill *et. al.*, 1981).

3.2 Combined Simulation-Optimization Models for Groundwater Management

Simulation models are often combined with optimization models in order to evaluate various groundwater management alternatives. These combined simulation-optimization models take into account the particular behavior of a given groundwater system and determine an optimal operating policy given certain objectives and constraints. Typically, the combined modeling technique incorporates the simulation model as constrains in the optimization model. Two different techniques may be used to accomplish this. They are the 'embedding method' and the 'response matrix approach' (Gorelick, 1983).

The embedding method directly incorporates numerical approximations of the groundwater equations as constraints in the optimization problem. As a result, decision variables in the management model include the dependent variables in the simulation model, such as hydraulic heads or concentration at each node, as well as the controllable variables of interest. A major drawback to this approach is that numerical difficulties are likely to arise for large scale problems, especially if commercial linear programming solution routines are used.

In the response matrix approach, and external groundwater simulation model is used to develop unit response functions which describe the influence of a pulse stimulus,

3.3 Evaluation of Management Choices for San Juan Basin

3.3.1 Use of the Basin: Identifying the Problem

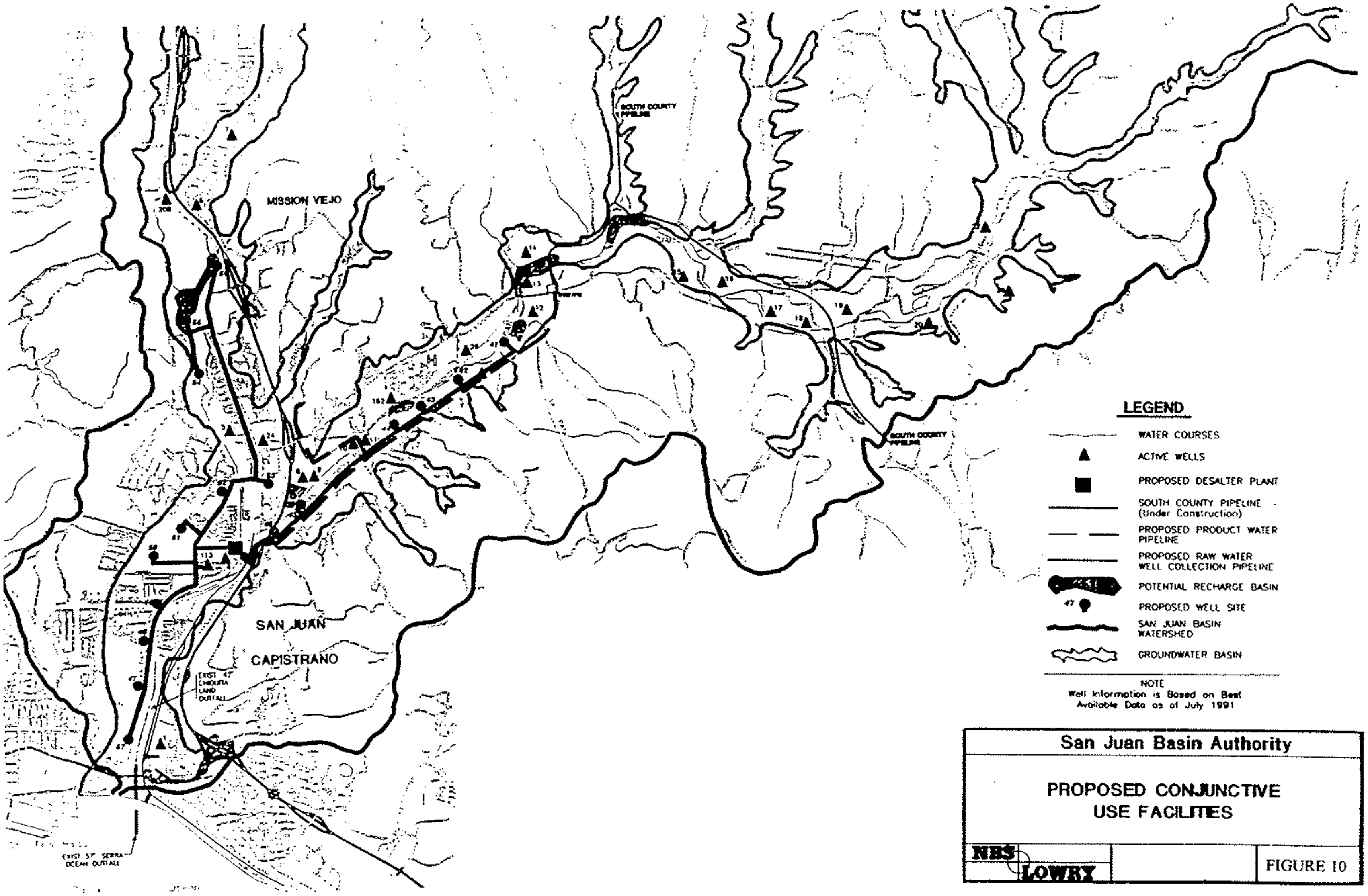
There are many questions that must be answered before determining an "optimal" management plan for an entire groundwater basin. First, it must be decided what purpose the basin will serve, if any. In other words, identify the problem. This is a question that cannot be answered quantitatively. It is a political decision usually determined by the water agency in charge of the basin. The answer is often vague and in the form of a mission statement. The mission of the San Juan Basin Authority, as stated previously, is "to develop and maintain a reliable, good quality and economical local water supply for the residents in the San Juan Basin by maximizing use of local ground and surface water..." . In accordance with this mission, the plan proposed in this research is to incorporate the San Juan Basin into the local water delivery system as part of a conjunctive use plan which would provide both seasonal and emergency drought supply.

As mentioned previously, groundwater basins are most useful when used as storage elements to store water during periods of abundance for use during periods of shortage. This will also allow the agency to take advantage of storage incentive programs

Most state and federal financial assistance programs are loan programs that provide low-interest funds for the construction of treatment plants and transmission pipelines. The potential funds available through these programs vary greatly from year to year. The Water Conservation Bond Law of 1988, administered by the California Department of Water Resources, is a possible source of funding which can provide a low-interest loan for up to $5 million for the project. The United States Bureau of Reclamation's funds the construction of desalting plants, wells, and pipeline facilities through its Small Projects Program. This program provides grants which fund 25 percent to 50 percent of the capital cost of a project. A conjunctive use project for the San Juan Basin should qualify for both forms of financial assistance.

3.3.2 Optimization Choices: Determining Alternatives

The next question is, what is to be optimized and what method is to be used? One can optimize the cost of building and operating the project, the locations of pumping wells and recharge facilities, the location of the treatment plant, and the amounts and timing of recharge and extraction. Formal optimization techniques for locating pumping wells, recharge facilities, and a desalinization plant are difficult to develop due to the fact that such decisions are very site specific. As a result, procedures for choosing optimal locations for these facilities are largely qualitative. Locations will depend on many external factors such as land ownership and land use on the surface of the basin.



San Juan Basin Authority

PROPOSED CONJUNCTIVE USE FACILITIES

FIGURE 10

Since desalination will be implemented regardless of the management scheme chosen, there is no need to maximize groundwater quality. However, increased levels of pumping will increase seawater intrusion causing greater levels of TDS in the supply stream to the treatment plant. Since the cost of desalination directly depends on feedwater quality, functions relating TDS and well extraction were developed to incorporate into the optimization scheme. The mathematical simulation model of the San Juan Basin was used to accomplish this by using a method similar to that of the unit response function method. Simulations were run for various pumping levels at potential well locations. The increases in TDS caused by unit increases in pumping rates were plotted in order to derive a set of equations for the basin which approximate water quality as a function of yield. Results are presented in Section 3.4.1.

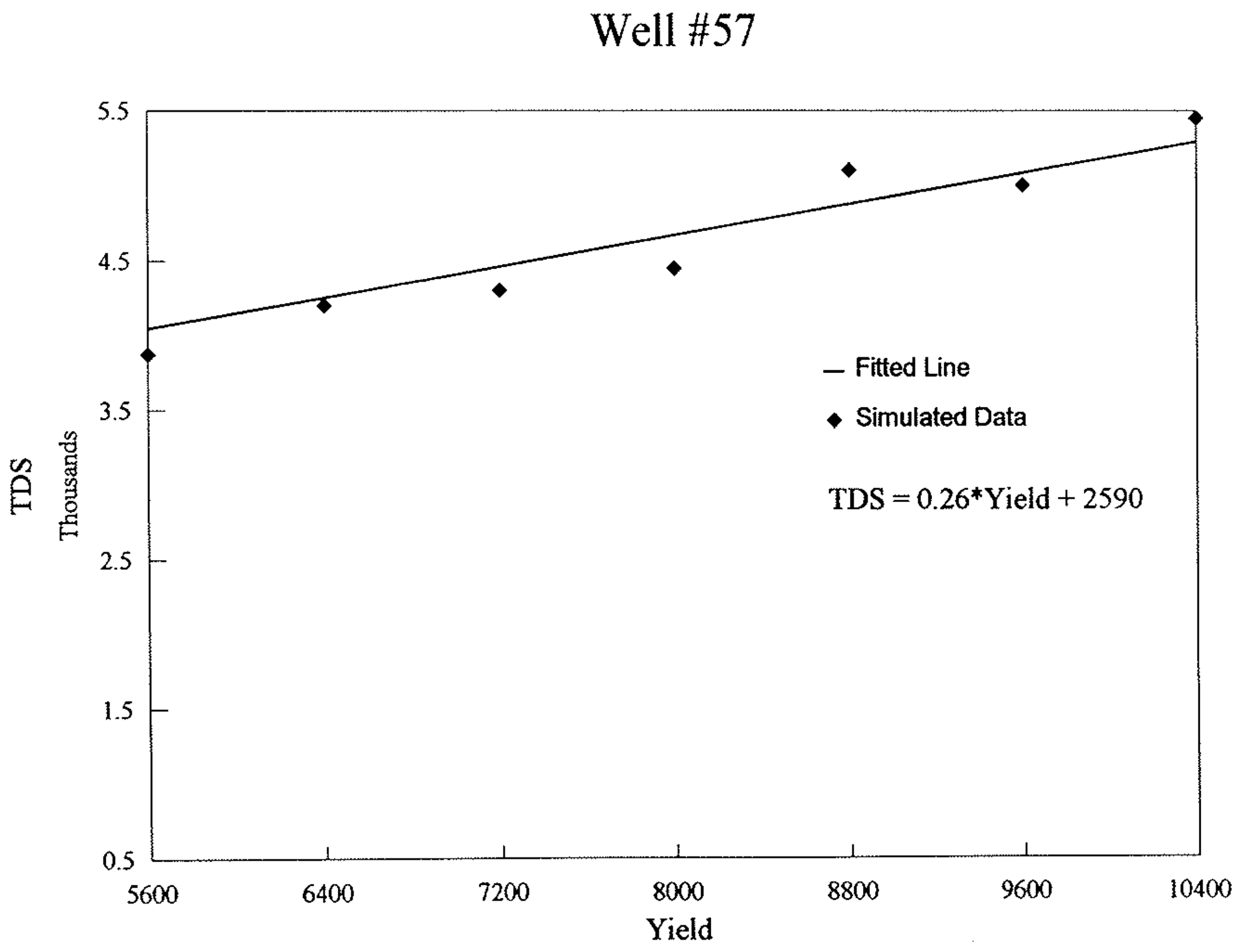
20,020 acre-feet. Some of this water will be lost to subsurface outflow unless water table gradients at the coastline are controlled. Pumping in the lower basin may be used to control gradients in order to prevent outflow to the ocean. Pumping in the lower basin may also be used to induce seawater intrusion and increase sustained yield. However, this will also increase TDS in the lower basin.

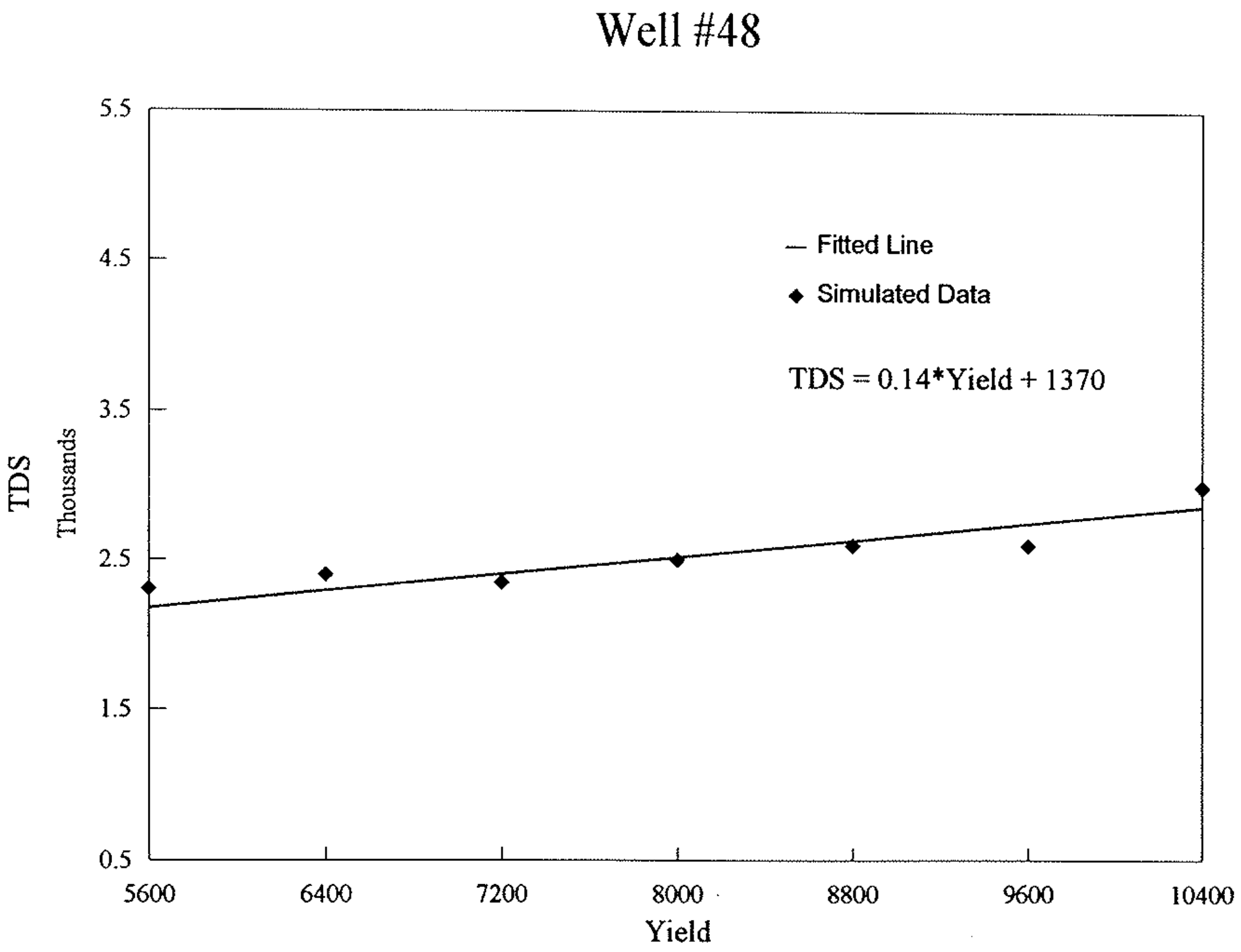
Under historical conditions, it was found that a sustained yield of natural in situ groundwater of about 5,200 acre-feet per year is available provided no subsurface outflow to the ocean or rising water occur. Pumping beyond this amount will cause an overdraft of the basin. Strategically however, to overdraft the basin slightly can be beneficial in making additional storage available for recharge during wet years and helping to minimize rising water. Preliminary studies were also used in order to determine maximum pumping amounts from any one well, which is limited by the depth of sediments in the basin. It was found that the three wells nearest the coast, wells 57, 47 and 48, can pump about 3200 acre-feet per year each for at least three years while the remaining three wells can pump about 1600 acre-feet per year for a three year period.

The recharge basins chosen for this research are indicated on Figure 10 as potential recharge basins numbers 5 and 6 located in the Lower Trabuco Basin. When compared to recharge from the other potential facilities, recharge in the Lower Trabuco Basin resulted in the least amount of rising water and lower levels of TDS. Since large amounts of pumping schemes. This is expected since the amount of inflow from the ocean will depend on the gradient caused by all the pumping within the lower basin rather than on the amount pumped from an individual well.

The average TDS for pumping schemes resulting in the same total yield was then determined at each well. Using this procedure, TDS was plotted against total yield for each of the six wells. This was done for both sustained yield without recharge and for seasonal pumping with recharge. From each plot, a best fit linear function was determined for each well in order to estimate groundwater TDS as a function of yield. For sustained yield, these plots and functions are shown in Figure 11. For seasonal pumping with recharge they are shown in Figure 12.

As expected, these figures illustrate that wells closer to the coast have higher levels of TDS. In the case of sustained yield without recharge, it can also be seen from the functions that wells nearer to the ocean have steeper slopes, i.e., TDS increases more quickly with increasing yield. When seasonal pumping with recharge occurs, water quality actually improves slightly at some wells as yield increases. This is because fresher water is used to replace the poorer quality groundwater which has been extracted. However, too much water recharged at one time will cause water to be lost as rising water.


Well #57
TDS
Thousands
5.5
4.5
3.5
2.5
1.5
0.5
5600
6400
7200
8000
8800
9600
10400
Yield
— Fitted Line
◆ Simulated Data
TDS = 0.26*Yield + 2590


Well #48
— Fitted Line
◆ Simulated Data
TDS = 0.14*Yield + 1370
TDS
Thousands
5.5
4.5
3.5
2.5
1.5
0.5
5600
6400
7200
8000
8800
9600
10400
Yield

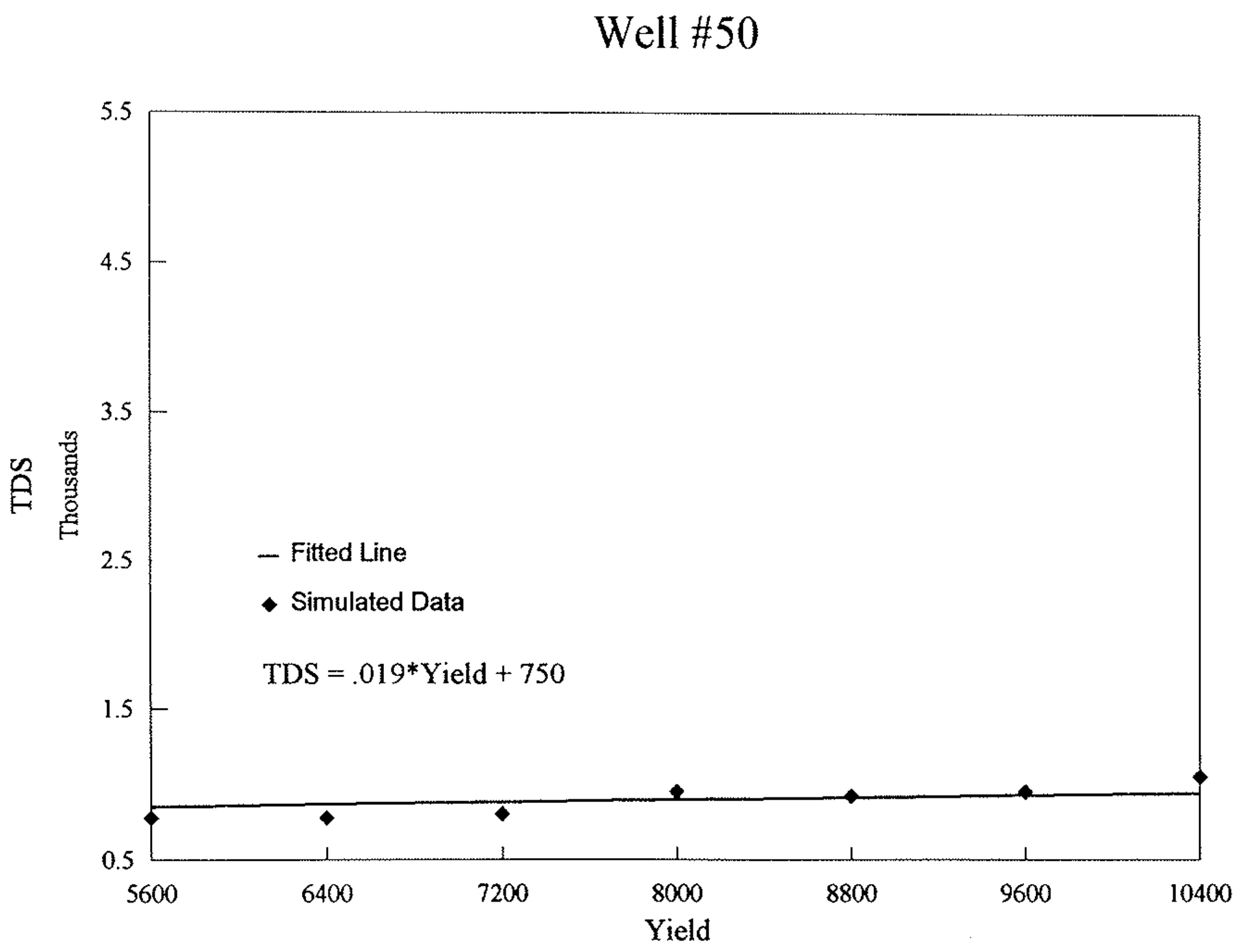
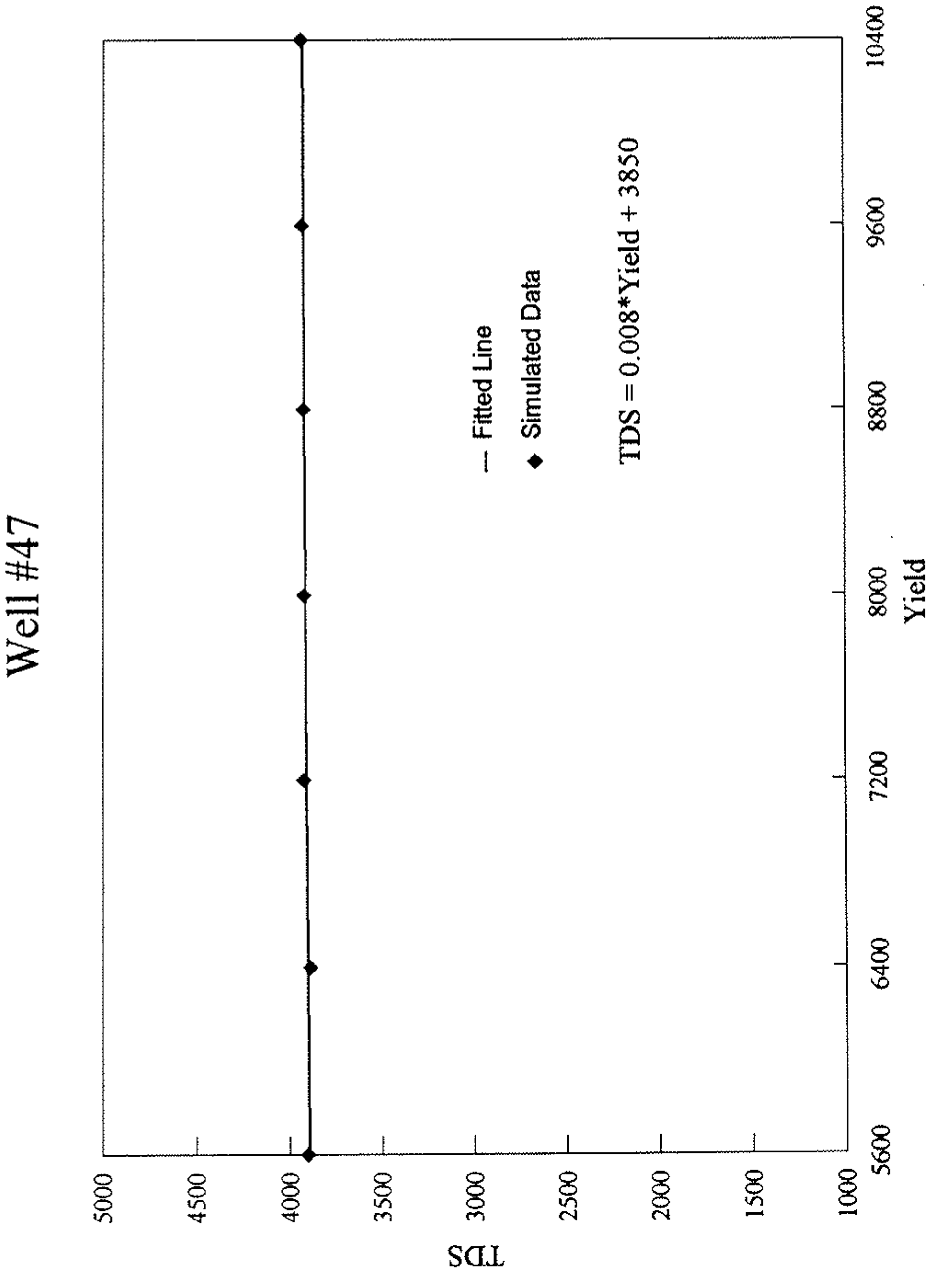
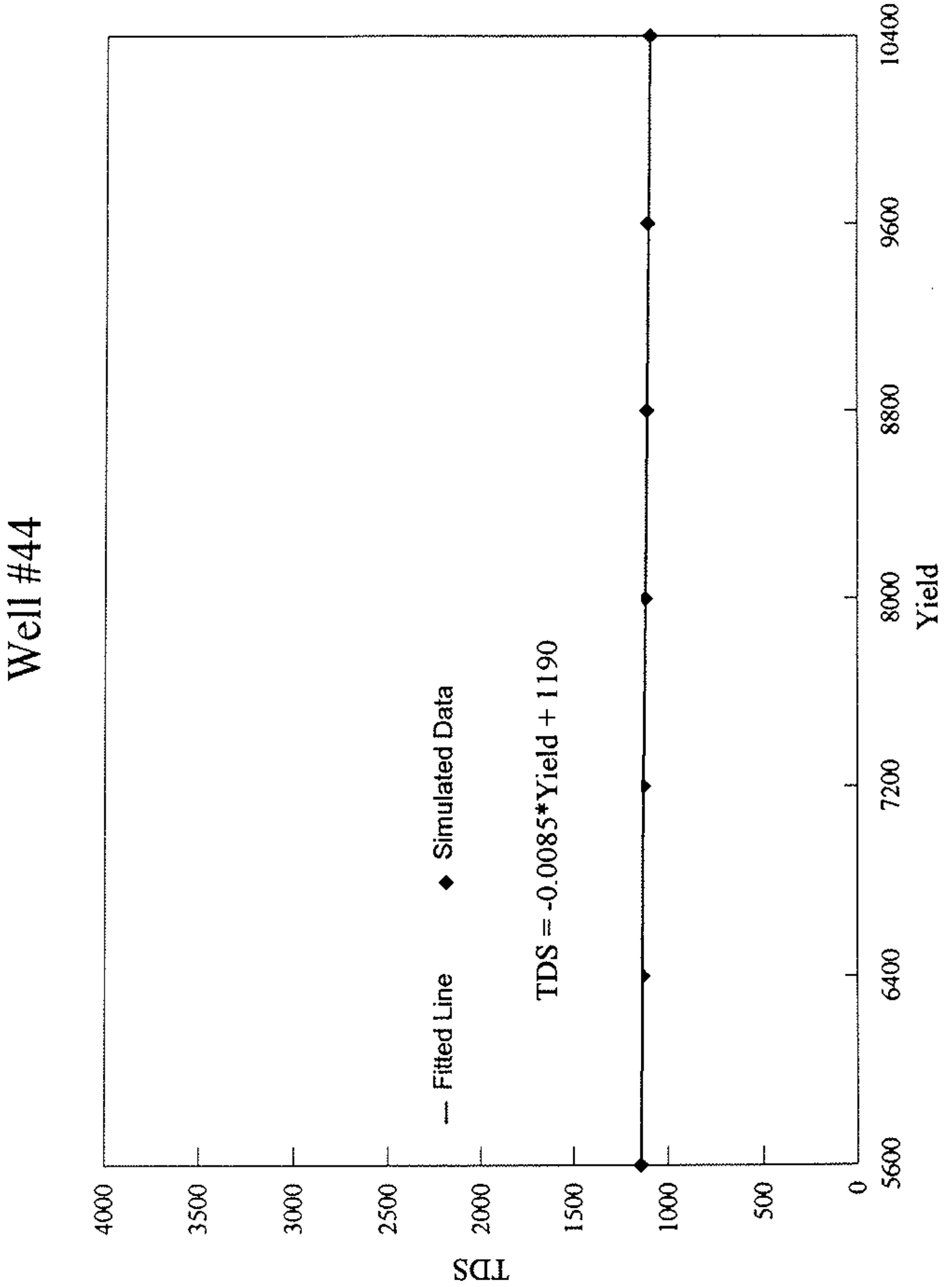
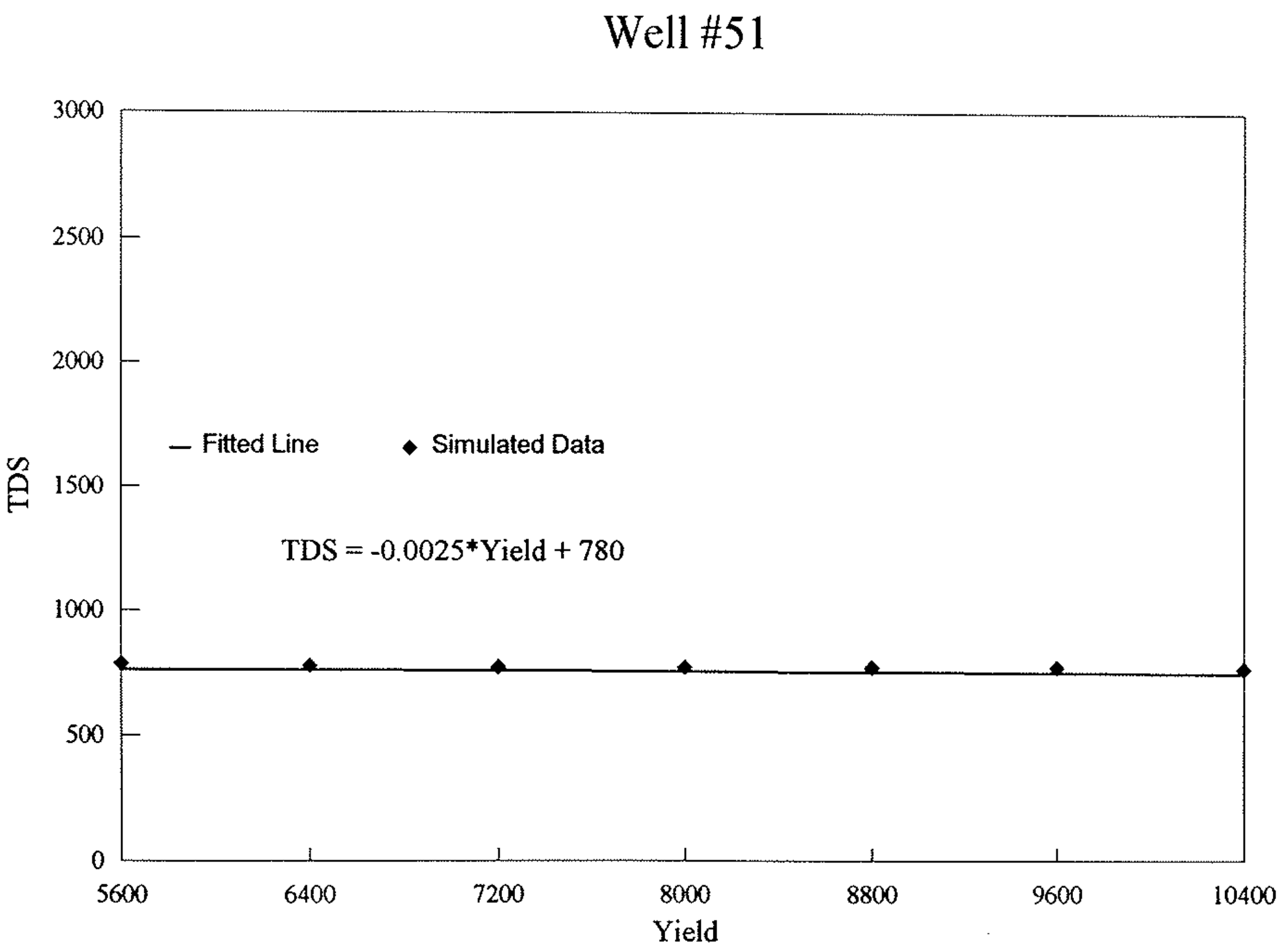

Well #50
TDS
Thousands
5.5
4.5
3.5
2.5
1.5
0.5
5600
6400
7200
8000
8800
9600
10400
Yield
— Fitted Line
◆ Simulated Data
TDS = .019*Yield + 750

FIGURE 12

FUNCTIONS FOR TDS VERSUS YIELD
SEASONAL PUMPING WITH RECHARGE


Well #47
TDS
5000
4500
4000
3500
3000
2500
2000
1500
1000
5600
6400
7200
8000
8800
9600
10400
Yield
— Fitted Line
◆ Simulated Data
TDS = 0.008*Yield + 3850


Well #44
— Fitted Line
◆ Simulated Data
TDS = -0.0085*Yield + 1190
TDS
4000
3500
3000
2500
2000
1500
1000
500
0
Yield
5600
6400
7200
8000
8800
9600
10400


Well #51
TDS
3000
2500
2000
1500
1000
500
0
— Fitted Line
◆ Simulated Data
TDS = -0.0025*Yield + 780
5600
6400
7200
8000
8800
9600
10400
Yield

water in order to increase sustained yield without removing large amounts of water from storage.

The following objective function and constraint conditions were used to determine the least cost pumping and treatment scheme for various amounts of demand:

MIN $\sum_{i=1}^{m} c_i x_i + \sum_{i=1}^{m} f_i y_i$ for *m* potential well locations

such that $\sum_{i=1}^{m} x_i = d$

$x_i \leq s_i y_i$

$x_i \geq 0$ for all *i*

$y_i = 0, 1$ $i = 1, 2, \ldots, m$

where c_i = cost per acre-foot per year to pump and treat water from well *i*

x_i = the number of acre-feet per year pumped at well *i*

f_i = the fixed capital cost per acre-foot per year associated with well *i*

y_i = 1 if well *i* is built, 0 if it is not

d = specified demand

s_i = supply capacity for well *i*

Table 5

CAPITAL COSTS FOR GROUNDWATER PRODUCTION

DESCRIPTION	COST (1993 dollars)
Well Capital Cost	$250,000 ea.
Product Line, 24 in.	$120/LF installed
Brine Line, 12 in.	$60/LF installed
Raw Water Lines	$5/LF/inch diameter installed
Desalter Plant	$1.3 per gal/day
Desalter Site	$800,000
Desalter Pumping Stations	$158/are-foot product water
Recharge, 40 acres	$1,000,000

separately for each specified demand and are also added to the optimized cost produced by the above formulation. These costs include desalter plant capital costs, desalter pumping station capital costs, recharge capital and variable costs, well variable costs, and pump station fixed and variable costs.

The remaining costs, which are functions of well location and TDS, were used in the objective function. They are the well capital costs, raw water line capital costs, desalter variable costs, and well fixed annual costs. All costs are totaled before comparing them with MWD water prices.

The only costs, c_i, included in the objective function are the desalter variable costs. As seen in Table 6, the desalter variable cost is a function of feedwater TDS. The TDS of the water extracted at each well is determined form the functions developed in Section 3.4.1 for TDS verses total yield or demand. With cost as a known function of TDS and TDS as a known function of demand, equations which relate cost and demand were easily developed and included in the optimization formulation. The remaining costs included in the objective function are the fixed costs, f_i, related to construction of a well.

Results of the optimization procedure are tabulated in Table 7. Projected costs for both pumping with and without recharge and projected costs for MWD non-interruptible service are shown. As stated previously, in the pumping with recharge scenario, pumping occurs during the summer months with recharge of any amount pumped in excess of 5,200 acre-feet per year occurring in the winter months. The pumping without recharge scenario consists of sustained pumping for three consecutive years with recharge occurring over several years following the pumping.

The results shown in Table 7 do not include savings which may be obtained through MWD incentive programs. MWD's Groundwater Recovery Program will fund the amount spent in excess of MWD's non-interruptible water rate, not to exceed $250 per acre-foot. This savings alone, as shown in Table 8, brings production costs for every pumping scheme to a maximum of the MWD water rates. Any other incentive programs applied to the project would result in a savings over MWD prices. Groundwater TDS at each of the six wells are shown in Tables 9 and 10 for pumping with and without recharge respectively.

3.5 Choosing an Alternative

Based on the optimization results, it would be in the best interest of the San Juan Basin Authority to develop all suggested facilities which include the six extraction wells, two recharge facilities, and one 8 mgd desalting facility. To avoid lost water due to rising water, the recommended pumping scheme would be to pump 7,200 acre-feet per year above the historical pumpage of 5,644 acre-feet per year for summer peaking supply while

Table 9

TDS at each Well for Various Pumping Amounts *

Seasonal Pumping with Recharge

ll 57		Well 47		Well 48	
Yield (ac-ft)	TDS (mg/l)	Yield (ac-ft)	TDS (mg/l)	Yield (ac-ft)	TDS (mg/l)
5,600	3,952	5,600	3,895	5,600	2,075
6,400	3,960	6,400	3,901	6,400	2,071
7,200	3,967	7,200	3,908	7,200	2,068
8,000	3,974	8,000	3,914	8,000	2,064
8,800	3,982	8,800	3,920	8,800	2,060
9,600	3,989	9,600	3,927	9,600	2,057
10,400	3,997	10,400	3,933	10,400	2,053

ll 44		Well 50		Well 51	
Yield (ac-ft)	TDS (mg/l)	Yield (ac-ft)	TDS (mg/l)	Yield (ac-ft)	TDS (mg/l)
5,600	1,142	5,600	785	5,600	765
6,400	1,136	6,400	783	6,400	763
7,200	1,129	7,200	781	7,200	761
8,000	1,122	8,000	779	8,000	759
8,800	1,115	8,800	777	8,800	757
9,600	1,108	9,600	775	9,600	755
10,400	1,102	10,400	773	10,400	753

* See Figure 10 for well locations.

recharging 2000 acre-feet per year during the winter months. For drought supply, the maximum yield of 10,400 acre-feet per year is recommended with recharge occurring over the 4 years following the drought.

Lumped basin inputs and outputs for this pumping scheme are presented in Table 11 as pumping Scheme 1. A 24-year period was used based upon historical natural inputs and outputs similar to the 12 year period used for the calibration simulations. However, surface and subsurface inputs were increased in order to reflect increases in landscape irrigation runoff from imported water in the tributary areas. Seasonal pumping was simulated over the 24 year period along with two three year drought periods.

As can be seen, the basin was slightly overdraft and there was significant amounts of seawater inflow to the basin. During years of normal pumping, only small amounts of rising water occur.

In order to maximize extraction's over the 24 year period, pumping may be increased during normal years. Table 12 presents the lumped basin inputs and outputs resulting from seasonal extraction's of approximately 9,800 acre-feet per year with winter recharge of 4,800 acre-feet per year. This pumping scheme also includes the same two three year drought periods as pumping Scheme 1. As can be seen in Table 12 both seawater inflow and rising water increase significantly for pumping Scheme 2. The net overdraft on the basin decreased slightly from the previous scenario.

Table 12
HYDROLOGIC BALANCE FOR SAN JUAN BASIN
PUMPING SCHEME 2
(ACRE-FEET)

Year	Percolation of Precipitation	Artificial Recharge	Percolation of Applied Water	Streambed Percolation	Subsurface Inflow	Total Inflow	Pumpage	Phreatophyte Extraction	Rising Water	Subsurface Outflow	Total Outflow	Net
1	1295.	4800.	934.	2299.	2447.	11775.	15644.	417.	4131.	-2863.	17329.	-5554.
2	1816.	4800.	934.	4618.	2815.	14983.	15644.	417.	2474.	-3505.	15030.	-47.
3	459.	4800.	934.	1993.	2932.	11118.	15440.	417.	1816.	-3681.	13992.	-2874.
4	942.	4800.	934.	2346.	3008.	12030.	15440.	417.	1539.	-3751.	13645.	-1615.
5	1715.	4800.	934.	4048.	3018.	14515.	15480.	417.	1817.	-3683.	14031.	484.
6	729.	4800.	934.	2309.	3031.	11803.	16344.	417.	1397.	-3469.	14689.	-2886.
7	833.	4800.	934.	2439.	3071.	12077.	16140.	417.	902.	-3454.	14005.	-1928.
8	1047.	4800.	934.	2607.	3065.	12453.	16065.	417.	834.	-3458.	13858.	-1405.
9	645.	7500.	934.	2337.	3073.	14489.	15440.	417.	1998.	-3661.	14194.	295.
10	597.	7500.	934.	2385.	3065.	14481.	15440.	417.	2515.	-3802.	14570.	-89.
11	983.	7500.	934.	2743.	3070.	15230.	15440.	417.	2653.	-3760.	14750.	480.
12	1000.	7500.	934.	2834.	3059.	15327.	15480.	417.	2757.	-3728.	14926.	401.
13	1295.	4800.	934.	3047.	3056.	13132.	15440.	417.	1604.	-3719.	13742.	-610.
14	1816.	4800.	934.	5243.	3028.	15821.	15644.	417.	2011.	-3612.	14460.	1361.
15	459.	4800.	934.	2582.	3038.	11813.	15440.	417.	1768.	-3698.	13927.	-2114.
16	942.	4800.	934.	2904.	3090.	12670.	15440.	417.	1597.	-3746.	13708.	-1038.
17	1715.	4800.	934.	4540.	3073.	15062.	15644.	417.	1889.	-3669.	14281.	781.
18	729.	4800.	934.	2845.	3067.	12375.	16344.	417.	1502.	-3504.	14759.	-2384.
19	933.	4800.	934.	2981.	3093.	12741.	16140.	417.	1019.	-3449.	14127.	-1386.
20	1047.	4800.	934.	3124.	3082.	12987.	16140.	417.	980.	-3436.	14101.	-1114.
21	645.	7500.	934.	2759.	3087.	14925.	15440.	417.	2217.	-3648.	14426.	499.
22	597.	7500.	934.	2783.	3078.	14892.	15440.	417.	2690.	-3782.	14765.	127.
23	983.	7500.	934.	3112.	3081.	15610.	15480.	417.	2807.	-3747.	14957.	653.
24	1000.	7500.	934.	3175.	3068.	15677.	15448.	417.	2890.	-3727.	15028.	649.
Mean Annual	1009.	5700.	934.	3002.	3021.	13666.	15668.	417.	1992.	-3606.	14471.	-805.

Table 13
HYDROLOGIC BALANCE FOR SAN JUAN BASIN
PUMPING SCHEME 3
(ACRE-FEET)

Year	Percolation of Precipitation	Artificial Recharge	Percolation of Applied Water	Streambed Percolation	Subsurface Inflow	Total Inflow	Pumpage	Phreatophyte Extraction	Rising Water	Subsurface Outflow	Total Outflow	Net
1	1295.		934.	2233.	1966.	6428.	10644.	417.	2454.	-1407.	12108.	-5680.
2	1816.		934.	4473.	2454.	9677.	10644.	417.	793.	-1477.	10377.	-700.
3	459.		934.	1779.	2623.	5795.	10644.	417.	488.	-1701.	9848.	-4053.
4	942.		934.	2089.	2730.	6695.	10644.	417.	380.	-1910.	9531.	-2836.
5	1715.		934.	3750.	2769.	9168.	10644.	417.	450.	-1879.	9632.	-464.
6	729.		934.	1954.	2797.	6414.	15644.	417.	350.	-3062.	13349.	-6935.
7	833.		934.	2039.	2840.	6646.	14710.	417.	399.	-3642.	11884.	-5238.
8	1047.		934.	2202.	2839.	7022.	13829.	417.	280.	-3705.	10821.	-3799.
9	645.	7500.	934.	1899.	2857.	13835.	10371.	417.	262.	-2910.	8140.	5695.
10	597.	7500.	934.	1888.	2848.	13767.	10644.	417.	531.	-2247.	9345.	4422.
11	983.	7500.	934.	2236.	2836.	14489.	10644.	417.	1946.	-1660.	11347.	3142.
12	1000.	7500.	934.	2350.	2796.	14580.	10644.	417.	2469.	-1442.	12088.	2492.
13	1295.		934.	2606.	2781.	7616.	10644.	417.	254.	-1525.	9790.	-2174.
14	1816.		934.	4785.	2776.	10311.	10644.	417.	325.	-1508.	9878.	433.
15	459.		934.	2055.	2799.	6247.	10644.	417.	263.	-1759.	9565.	-3318.
16	942.		934.	2324.	2857.	7057.	10644.	417.	228.	-1981.	9308.	-2251.
17	1715.		934.	3961.	2856.	9466.	10644.	417.	293.	-1953.	9401.	65.
18	729.		934.	2138.	2856.	6657.	15644.	417.	251.	-3108.	13204.	-6547.
19	933.		934.	2202.	2879.	6948.	14591.	417.	216.	-3647.	11577.	-4629.
20	1047.		934.	2348.	2869.	7198.	13680.	417.	212.	-3705.	10604.	-3406.
21	645.	7500.	934.	2030.	2881.	13990.	10368.	417.	196.	-2913.	8068.	5922.
22	597.	7500.	934.	1997.	2869.	13897.	10644.	417.	458.	-2256.	9263.	4634.
23	983.	7500.	934.	2319.	2855.	14591.	10644.	417.	1896.	-1659.	11298.	3293.
24	1000.	7500.	934.	2421.	2813.	14668.	10644.	417.	2447.	-1431.	12077.	2591.
Mean Annual	1009.	2500.	934.	2503.	2769.	9715.	11631.	417.	743.	-2270.	10521.	-806.

Pumping Scheme 1 is recommended with extraction's of about 7,200 acre-feet per year above historical pumping during summer months and recharge of 2,000 acre-feet per year during winter months. During drought years a maximum of about 10,000 acre-feet per year may be extracted. Pumping and recharge amounts should be adjusted from year to year based on monitoring of basin conditions.

Such a management plan prevents lost water to subsurface outflow while increasing yield through seawater inflow. Though this results in increased TDS of feedwater to the desalter facility, treatment of the water remains economical.

Jones, L., R. Willis, and W. W.-G. Yeh, 1987, "Optimal Control of Nonlinear Groundwater Hydraulics Using Differential Dynamic Programming", *Water Resources Research*, 23(11), 2097-2106.

Krieger, James H., and Harvey O. Banks, 1962, "Groundwater Basin Management", *California Law Review No. 50*, 56-77.

Makinde-Odusola, B. A., and M. A. Marino, 1989, "Optimal Control of Groundwater by Feedback Method of Control", *Water Resources Research*, 25(6), 1341-1352.

McClurg, Sue, 1993a, "Innovations in California Water", *Western Water*, July/August.

McClurg, Sue, 1993b, "Groundwater Management", *Western Water*, November/December.

Ratschek, H. and J. Rokne, 1988, *New Computer Methods for Global Optimization*, Ellis Harwood Limited, Chichester, 299p.

Wagner, B. J. and S. M. Gorelick, 1987, "Optimal Groundwater Quality Management Under Parameter Uncertainty", *Water Resources Research*, 23(7), 1162-1174.

Wagner, B. J. and S. M. Gorelick, 1989, "Reliable Aquifer Remediation in the Presence of Spatially Variably Hydraulic Conductivity: From Data to Design", *Water Resources Research*, 25(10), 2211-2225.

Wanakule, N., L. W. Mays, and L. S. Lasdon, 1986, "Optimal Management of Large-Scale aquifers; Methodology and Applications", *Water Resources Research*, 22(4), 447-465.

Warren, J. E., and H. S. Price, 1969, "Flow in Heterogeneous Porous Media", *Soc. Pet. Eng. J., 1*, 153-169.

Willis, R., and W. W-G. Yeh, 1987, *Groundwater Systems Planning and Management*, Prentice-Hall, Englewood Cliffs, N.J..

Yazdanian, A., and R. C. Peralta, 1986, "Sustained-yield groundwater planning by goal programming", *Ground Water*, 24(2), 157-165.