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AN ENGINEERING ECONOMIC ANALYSIS OF A PROGRAM FOR ARTIFICIAL GROUNDWATER RECHARGE[1]

Eric G. Reichard and John D. Bredehoeft[2]

ABSTRACT: This study describes and demonstrates two alternate methods for evaluating the relative costs and benefits of artificial groundwater recharge using percolation ponds. The first analysis considers the benefits to be the reduction of pumping lifts and land subsidence; the second considers benefits as the alternative costs of a comparable surface delivery system. Example computations are carried out for an existing artificial recharge program in Santa Clara Valley in California. A computer groundwater model is used to estimate both the average long term and the drought period effects of artificial recharge in the study area. For the example problem, the benefits of reduced average annual pumping lifts and reduced incremental subsidence are greater than the total costs of continuing the existing artificial recharge program. Benefits for reduced subsidence are strongly dependent on initial aquifer conditions. The second analysis compares the costs of continuing the artificial recharge program with the costs of a surface system which would achieve the same hydraulic effects. Results indicate that the costs of artificial recharge are considerably smaller than the alternative costs of an equivalent surface system. In evaluating a particular program, consideration should also be given to uncertainties in future supplies and demands for water as well as to the probability of extreme events such as droughts.
(KEY TERMS: artificial recharge; cost-benefit analysis; Santa Clara Valley.)

INTRODUCTION

Artificial recharge is the process of augmenting the amount of water that would replenish the groundwater system under natural conditions. It is commonly carried out with either injection wells or infiltration ponds. Todd (1980) provides a description of the various possible recharge methods. Artificial recharge schemes are in existence in many parts of the United States (Signor, *et al.*, 1970). Recharge programs are particularly numerous in the State of California. For a given area, the economic worth of an artificial recharge scheme will be a function of the relative costs and benefits of the program.

The application of cost-benefit analysis to water resources has been discussed by many researchers (e.g., Eckstein, 1958; Hirshliefer, *et al.*, 1960; James and Lee, 1971; Hanke and Walker, 1974). Cost-benefit analyses are routinely carried out for potential water resource developments.

Artificial recharge is a major part of many programs for conjunctive use of ground and surface water. There is a considerable body of literature dealing with conjunctive use and its potential benefits. Maknoon and Burges (1978) provided an extensive bibliography of relevant work. The specific costs and benefits of artificial recharge have been discussed by Bear (1979), Todd (1965, 1980), and Widmer (1966). Possible benefits of artificial recharge include:

1) Reduction of pumping lifts
2) Reduction of land subsidence
3) Prevention of seawater intrusion
4) Using aquifer for storage
5) Using aquifer for treatment
6) Using aquifer for conveyance

These benefits fall into two general categories. In the first category are benefits 1, 2, and 3, which are the direct result of a reduction in the net rate of groundwater withdrawal. Note that benefits 2 and 3 (reduction of subsidence and prevention of seawater intrusion) are actually indirect benefits, since they are achieved via a reduction in pumping lifts. In the second category are benefits 4, 5, and 6, which are associated with utilizing the groundwater system rather than surface facilities for storage, treatment, and conveyance.

Reducing the net rate of groundwater withdrawal can be achieved by artificially recharging water, or by reducing the rate of pumping. Assuming a constant total water demand, the principal way to reduce actual groundwater pumpage is by delivery of surface water.

Recharge facilities may provide additional benefits such as recreational use. In the Santa Clara Valley, for example, a number of the recharge ponds are a part of park/recreation complexes. In this study, however, only those benefits directly related to the actual process of artificial recharge are dealt with.

The management objectives associated with the two categories of benefits described above are quite different. In one case the goals are to reduce pumping lifts, land subsidence, and

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[2]Respectively, Hydrologist and Regional Hydrologist, U.S. Geological Survey, Water Resources Division, 345 Middlefield Road, MS 466, Menlo Park, California 94025.

seawater intrusion. In the other case the goal is to replace a surface delivery system. Since artificial recharge is being compared with two distinct alternatives, two separate analyses are called for.

The first analysis evaluates the benefits of a recharge program in terms of reduced pumping lifts and reduced land subsidence (seawater intrusion effects in the study area are assumed to be negligible). These benefits are attributable to the net decrease in groundwater withdrawal. When the water is recharged it tends to raise water levels and, hence, reduce pumping lifts and land subsidence. However, as pointed out by Todd (1965), this water could also be stored, treated, and conveyed to users on land. This additional surface water would supplant pumping and, therefore, have a hydraulic effect similar to artificial recharge. The areal distribution of water levels would, of course, be somewhat different. The second analysis involves considering the relative merits of artificially recharging the water as opposed to storing, treating, and conveying it on land.

Principal costs of artificial recharge (using infiltration ponds) for both analyses include:

1) Water costs
2) Land costs
3) Construction costs of ponds and works
4) Operation and maintenance costs of ponds
5) Construction costs of conveyance structures and pumping facilities to transport water to recharge sites (if needed)
6) Energy costs of transmitting water to recharge sites (if needed

In the second analysis, energy costs of pumping recharged water back out of the aquifer and the costs of wells must also be considered.

With sufficient data, it is possible to quantify these costs and benefits for an existing or proposed recharge program in a given area. However, there have been few exercises of this type done in the past. Two recent studies have looked at the economics of artificial recharge in agricultural areas. Supalla and Comer (1982) estimated the benefits of artificial recharge using a "reconnaissance level" analysis which assumed a simplified hydrologic system. Karlinger and Hansen (1983) compared the cost of supplying irrigation water with artificial recharge to the irrigation costs of a surface delivery system. A digital groundwater model was used to estimate pumping costs.

In the discussion that follows, the two alternate economic analyses discussed above are demonstrated. The methodologies are applied to an existing artificial recharge program in the Santa Clara Valley. The program in the Santa Clara Valley is one of the most extensive in the country and, therefore, was considered an appropriate field situation in which to test a number of ideas. The hydraulics of the groundwater system are explicitly incorporated into the analyses by use of a digital groundwater model. Hydrologic results of the groundwater model, along with economic data, form the basis for evaluating the artificial recharge program.

Artificial recharge is carried out with either imported water, reclaimed water, or water which would have otherwise flowed out of the basin. In addition, an artificial recharge program is likely to be carried out only by a basin-wide authority. Santa Clara Valley is fortunate in having (at least for now) an abundant supply of imported water available for potential recharge and having a single entity – the Santa Clara Valley Water District (SCVWD) – that is responsible for all wholesale water supply in the basin. The SCVWD does all the recharging and collects pumping taxes from groundwater users.

In the analyses described below, it is assumed that there is a given water demand to be met. The problem studied involves choosing the appropriate method for supplying that demand. It is also assumed that there is water available to recharge. The cost of obtaining that water is not considered. The question dealt with is whether the water should be artificially recharged, not whether it should have been obtained in the first place.

The numbers used to compute the various costs and benefits are considered to be realistic, but uncertainties in the system preclude accepting them as more than estimates. For the analyses described below, the present value of a given stream of costs or benefits is calculated as follows:

$$PV = K + \sum_{t=1}^{n} V(t) / (1+r)^t \tag{1}$$

where:

PV	=	present value of costs or benefits
K	=	initial costs
V(t)	=	costs or benefits in year t
r	=	annual discount rate
n	=	number of years in planning period

In all computations, costs are expressed in constant 1982 dollars. The discount rate, r, reflects the real time value of money. It does not incorporate inflation. If all relevant nominal costs are expected to rise at the same rate, then the exclusion of inflation from the analysis is justified.

SANTA CLARA VALLEY

Hydrologic Development

The area investigated is shown in Figure 1. It consists of the northern part of the Santa Clara Valley in California.

The first reservoirs and percolation facilities in the Santa Clara Valley were constructed in the 1930's. The current recharge program consists of 13 sets of ponds which have a total surface area of more than 300 acres. The four major recharge areas are along Penitencia, Coyote, Guadalupe, and Los Gatos Creeks (see Figure 1).

The importation of imported water has been equally as important as the construction of reservoirs, canals, and recharge facilities. Since 1952, municipalities in the Santa Clara Valley have purchased water imported by the City of San Francisco

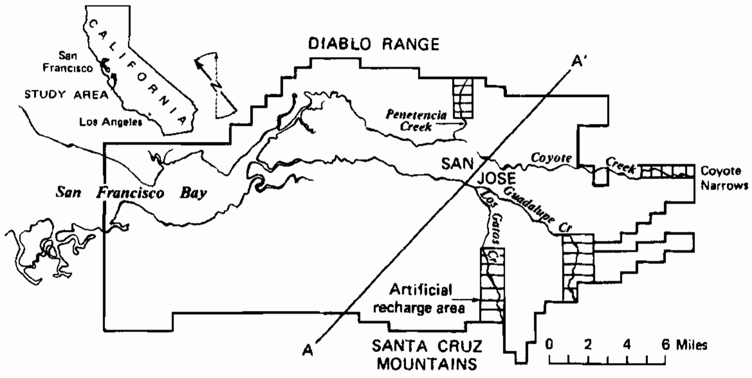

Figure 1. Map of Study Area with Location of Artificial Recharge Areas.

from the Sierras. The volume of annual artificial recharge increased significantly in 1965 when water from the South Bay Aqueduct of the California Water Project became available. Currently, an average of 140,000 acre-feet of water is imported annually.

Associated with the extensive pumping of groundwater in the Santa Clara Valley has been land subsidence due to compaction of fine-grained materials in the basin. This subsidence has been discussed in great depth by Poland (Poland and Green, 1962; Poland and Davis, 1969). Figure 2 shows estimated subsidence in the northern Santa Clara Valley for the period from 1934 to 1967. Water levels recovered significantly in the late 1960's and early 1970's. Poland (1978) attributed this recovery to a combination of increased availability of imported water, favorable climatic conditions, decreased pumpage, and increased recharge. Associated with the rise in water levels was a halt to additional subsidence. Land that had already subsided, however, did not recover.

Hydrogeology

Of greatest hydraulic significance in the Valley are the quaternary alluvial deposits. Coarse sand and gravel are mainly found in abandoned stream channels near the outer margins of the basin. Materials become finer toward the Bay. Figure 3 shows a geologic cross-section across the valley. The discontinuity of the deposits is typical of the structure within the alluvium. This heterogeneous nature of the alluvium leads to a rather complicated groundwater flow sytem.

Groundwater conditions along the margins of the valley are essentially unconfined and it is there where most natural recharge occurs and where all the artificial recharge facilities are located (see Figure 1). Toward the center of the valley, as the amount of fine-grained deposits increases, groundwater conditions become confined. Most of the groundwater development has occurred near the center of the valley, where the alluvium is thickest.

GROUNDWATER MODEL

Leaky Aquifer Formulation

To model the system, numerous simplifications had to be made. The flow regime was treated as two layers: a confined aquifer and a water table aquifer separated by a confining unit. Only heads in the confined unit were active; heads in the upper unconfined unit were held at constant values which were set as a subdued replica of the land surface topography.

A leaky aquifer formulation was adopted in which flow between the two aquifers is a function of the relative hydraulic heads as well as the thickness and vertical conductivity of the confining layer. To account for the fact that there are numerous layers of clay rather than one large unit, the system was idealized as a confined aquifer containing a series of 10-foot-thick clay layers and overlain by an upper clay unit with a thickness equal to 10 percent of the total clay thickness. It was assumed in the model that communication between the unconfined and confined aquifers occurs only across the upper clay unit. Land subsidence was considered to be due to transient leakage from the series of 10-foot thick clay layers. Figure 4 is a schematic representation of how the hydrologic system was conceptualized.

Original input data for the groundwater model used in this study was based, to some extent, on previous unpublished work done by Perry Wood at the U.S.G.S. The actual code used was a slightly modified version of the alternating-direction-implicit finite difference model of Bredehoeft and Pinder (1970).

Transient Leakage Routine

The land subsidence described earlier represents compaction when water is released from storage in the fine-grained layers. A subroutine was included in the groundwater model to account for the transient leakage of water from the clay units. Bredehoeft and Pinder (1970) suggested a routine for modeling the transient leakage from a single clay layer in response to changes in head at one boundary. In the Santa Clara Valley,

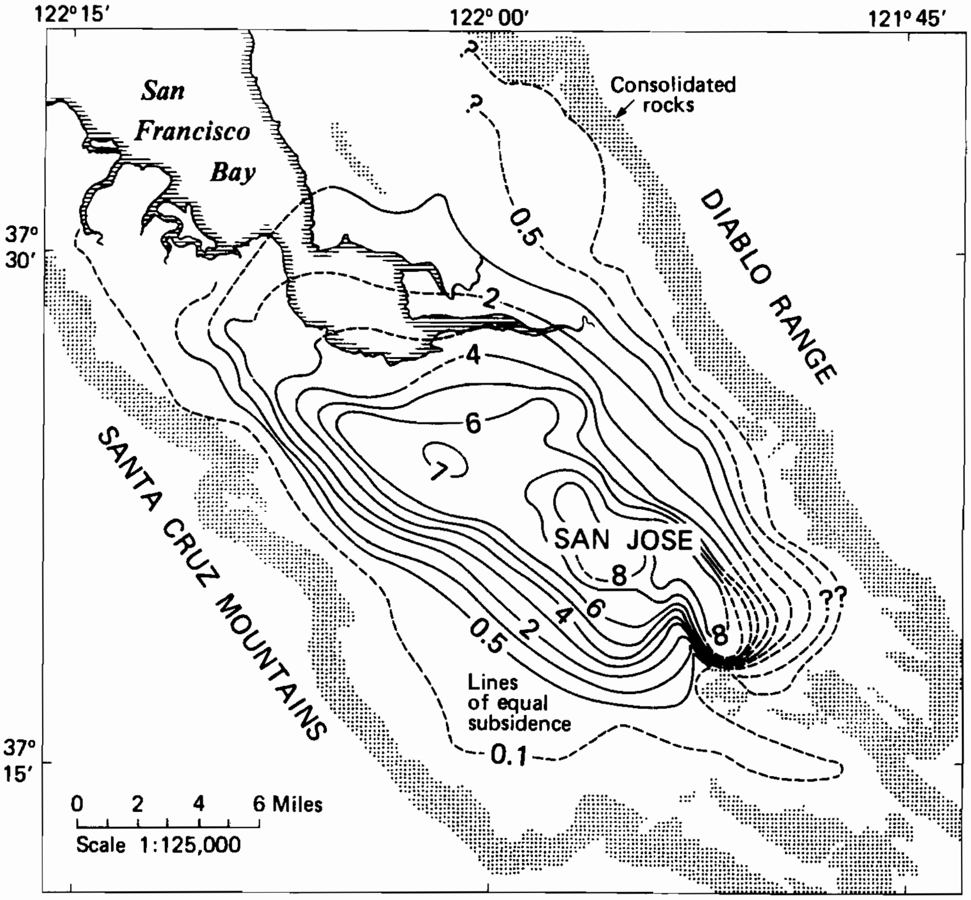

Figure 2. Estimated Land Subsidence in Northern Santa Clara Valley 1934-1967 (contours in feet) (based on Poland, 1978).

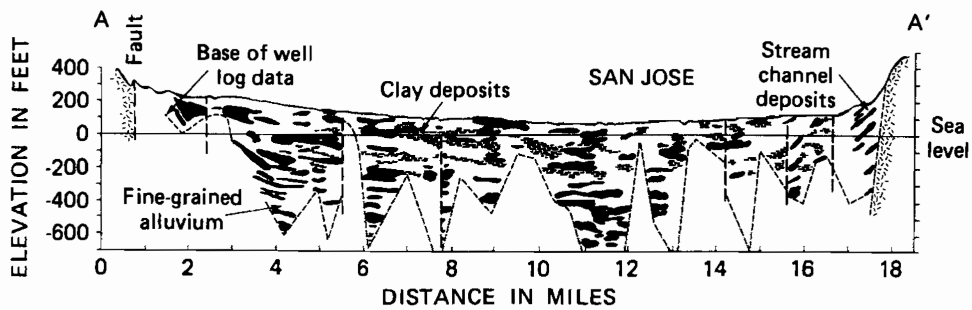

Figure 3. Typical Cross Section Through Santa Clara Valley (see Figure 1 for location of section) (from California Department of Water Resources, 1975, Figure 3).

where there are numerous lenses of clay (see Figure 4), it is more accurate to consider head changes at both the upper and lower boundaries of the clay layers. The total volume of water released from the clay is considered to equal the volume of subsidence. The water from the clays is incorporated into the groundwater flow equations as an additional source term.

Data Input and Model Calibration

Parameters required in the groundwater model are described in Table 1.

The model was first calibrated for a steady state case using 1915 water levels. Figure 5 shows model-calculated 1915 water levels. Actual 1915 potentiometric heads, based on the map of Clark (1924) are shown in Figure 6. Further calibration

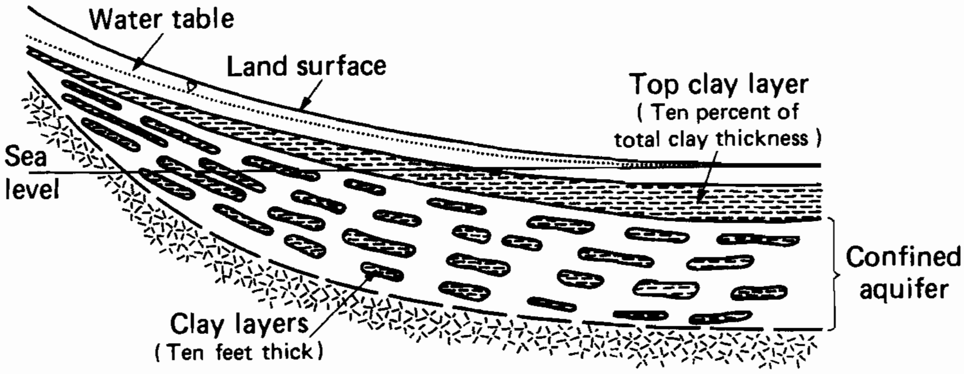

Figure 4. Schematic of Santa Clara Valley Groundwater System as Conceptualized for Digital Model.

was done for a transient case for the period from 1915 to 1934. The pumping values used were estimated based on municipal records, population figures, well inventories, and utility records.

TABLE 1. Input Parameters for Groundwater Model.

Transmissivity: Initial values based on specific capacity data.

Storativity: Set at 0.001.

Total Clay Thickness: Initial values based on estimates of depth to bedrock and percentage of clay from California Department of Water Resources (1967) and drillers logs.

Average Thickness of Clay Layers: Taken as 10 feet on the basis of bore hole data (Johnson, *et al.*, 1968).

Vertical Conductivity of Clay: Value of 3.5×10^{-9} feet/second determined by calibration.

Specific Storage of Clay: Value of 5.0×10^{-5}/foot determined by calibration.

Finally, the model was run for the period from 1963 to 1966. It was during this period that artificial recharge in northern Santa Clara Valley became significant. Annual volumes of pumping and recharge were obtained from the SCVWD. Artificial recharge ponds were incorporated into the model simply as recharge nodes in the active aquifer. When compared to measured water levels for 1966 (Santa Clara Valley Water District, 1967), the model-calculated levels reasonably matched the general features of the basin. However, a number of local features were poorly reproduced. This is most likely due to the fact that the model assumes a single continuous aquifer, whereas water is actually being drawn from a number of lithologic units which have an uncertain degree of hydraulic connection. Stresses in certain areas of the basin are, therefore, likely to have more pronounced effects than the model predicts.

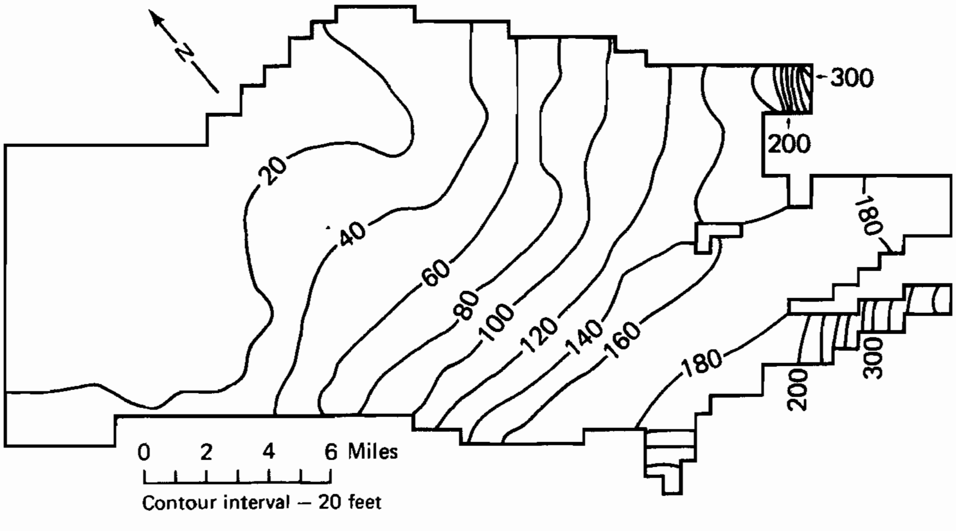

Figure 5. Model-Calculated Steady State (1915) Groundwater Levels (elevation above mean sea level).

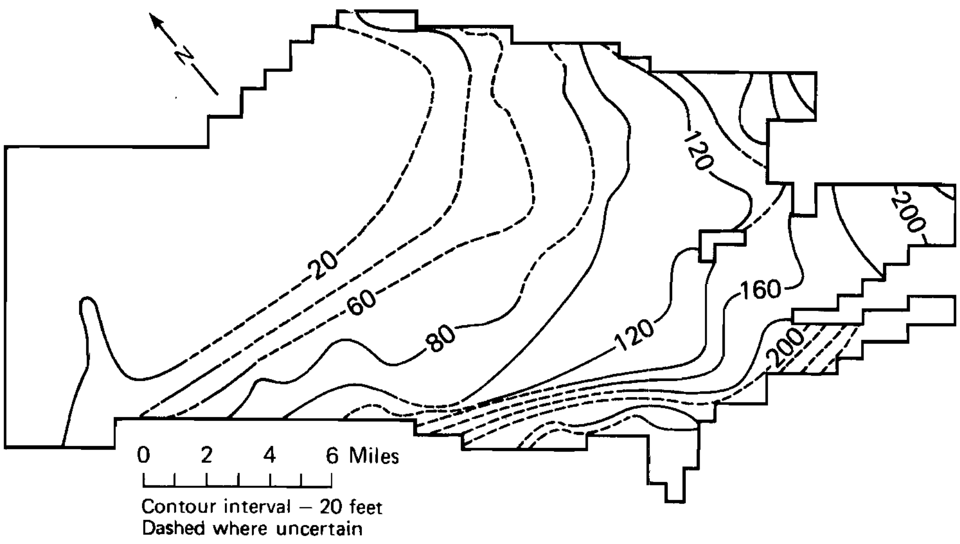

Figure 6. Measured 1915 Groundwater Levels (elevation above mean sea level) (from Clark, 1924).

HYDRAULIC EFFECTS OF ARTIFICIAL RECHARGE

The groundwater model was first run for a 40-year period, using model-calculated 1966 water levels as initial conditions. Most of the recharge facilities were in existence long before the mid-1960's, but recharge volumes only became significant at that time. An annual pumping rate of 150,000 acre feet and annual rate of artificial recharge of 100,000 acre feet were used. These represent average rates during the 1970's (Santa Clara Valley Water District, 1981). The areal distribution of pumping and recharge quantities was based on the distribution in 1966. Figure 7 is a plot of computed water levels at the end of 40 years. Because of the manner in which leakage between the unconfined and confined aquifers is treated, the model reached steady-state conditions in approximately two years. As described above, thickness of the confining layer between the two aquifers was assumed to be 10 percent of the total clay thickness. The model would have taken longer to reach steady state had a thicker confining layer been assumed.

The model was then rerun for the 40-year period with zero artificial recharge. Pumping levels were maintained at 150,000 acre feet per year. Figure 8 shows water levels for this second case at the end of 40 years. The model achieved steady state after approximately three years.

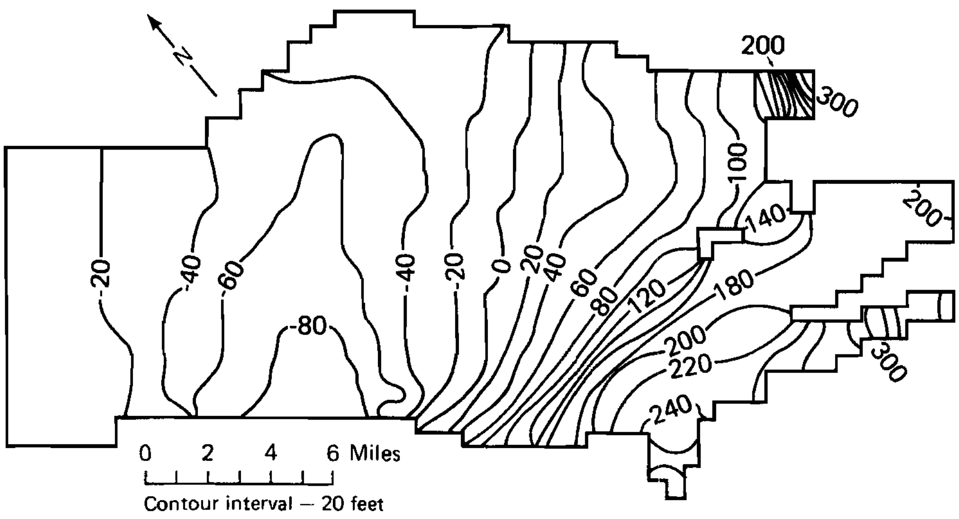

Figure 7. Model-Calculated Groundwater Levels at the End of 40 Years with Artificial Recharge (elevation above mean sea level).

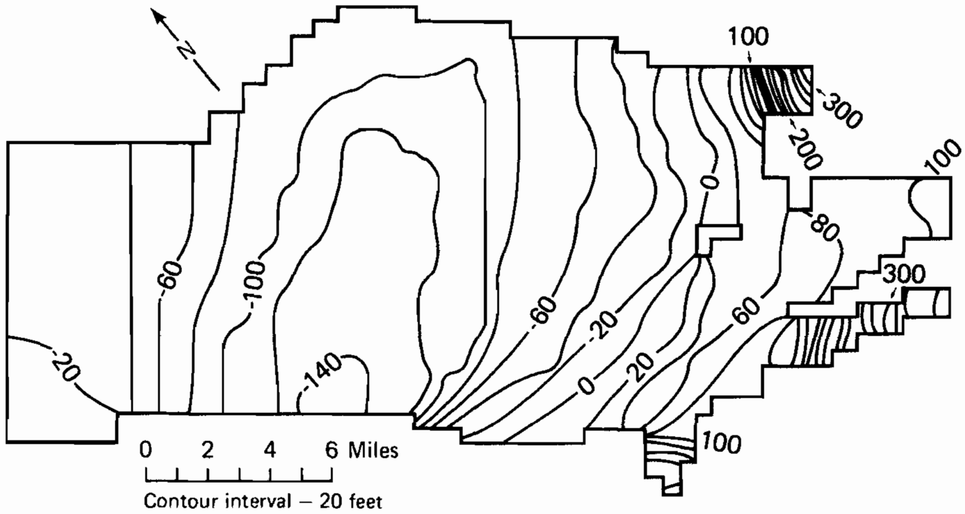

Figure 8. Model-Calculated Groundwater Levels at the End of 40 Years Without Artificial Recharge (elevation above mean sea level).

Comparison of Figures 7 and 8 indicates that the artificial recharge program in Santa Clara Valley has maintained hydraulic heads at a significantly higher level than they would have been otherwise. Resulting land subsidence was also computed for both runs. There was no additional subsidence with artificial recharge. Total additional subsidence for the entire period without artificial recharge averaged 1 foot in the center of the valley.

The model results suggest that the system could achieve steady state with no artificial recharge, without drastically drawing down water levels. As the model is formulated, all 150,000 acre feet of annual pumping is drawn from leakage from the constant water table. The key question is whether there is actually enough water available from streamflow, direct rainfall, and return flow from lawn and agricultural irrigation to provide this quantity of water. A water balance for the basin indicates that such a long-term annual rate of recharge is not unreasonable. The fact that water levels remained nearly constant in the early 1960's, when there was much less artificial recharge and average annual pumpage of more than 180,000 acre feet, also indicates that considerable natural recharge can be induced in the Valley. However, an institution responsible for providing water supply for a region is also concerned with possible future increases in groundwater demand and the occurrence of such extreme events as droughts.

In the Santa Clara Valley, 150,000 acre feet per year is probably close to the limit of natural plus man-induced recharge in the basin. Since there is uncertainty as to how much more could be supported, artificial recharge provides a useful buffer against future increases in pumping. Such increases in pumping could occur as a result of a regional increase in water demand or from a decrease in the supply of imported water. In addition, the SCVWD is responsible for attempting to meet water demands every year, including periods of drought. The added storage provided by artificial groundwater recharge allows the basin to withstand a longer drought than it would otherwise be able to do. In the economic analyses described below, only the benefits of average reductions in pumping lifts and subsidence are quantified. In actually determining the utility of an artificial recharge program, however, consideration should also be given to these sorts of potential hydraulic risks.

An estimate of the hydraulic effects that could result from a drought was obtained from the groundwater model. To simulate periods of water scarcity, leakage from the water table was allowed only along the margins of the basin. Two additional runs were carried out for both the "with artificial recharge" and "without artificial recharge" cases. Results show that water levels without artificial recharge would fall to as much as 350 feet below sea level, whereas with artificial recharge, no water levels were below –200 feet.

ECONOMIC ANALYSIS

The following two analyses are based on the results of the groundwater simulations described above. As in those simulations, 1966 groundwater levels are taken as initial conditions.

Analysis 1: Artificial Recharge vs. No Project

Economic Value of Reduced Pumping Lifts and Reduced Subsidence. This first analysis considers benefits associated with a reduction in the net rate of pumping. In the Santa Clara Valley, these benefits relate to reduced pumping lifts and reduced land subsidence. The benefits of reduced pumping lifts are calculated in terms of savings in energy costs. A 100 percent efficient pump would require 1.02 kwh to lift

1 acre-foot of water 1 foot. A recent U.S.G.S. survey of 2000 wells in the San Joaquin Valley in California (Diamond and Williamson, 1983) indicated an average pumping efficiency of 54 percent. It seems reasonable to assume that the average efficiency in the Santa Clara Valley is close to this value. A pump with a 54 percent efficiency requires 1.89 kwh of energy per acre-foot per foot of lift. Multiplying this by an energy cost of \$0.06/kwh (based on regional electric rate schedules) yields a unit pumping cost of \$0.113/acre-foot/foot. Equation (2) was used to compute annual benefits of reduced pumping lifts:

$$B_t = e \Sigma_i P_{it} L_{it} \tag{2}$$

where:

- B_t = benefits from reduced pumping lift in year t (dollars)
- e = unit energy cost of pumping (\$0.113/acre foot/foot)
- P_{it} = pumping in node i in year t (acre-feet)
- L_{it} = reduction in pumping lift in node i in year t (feet)

The resulting benefits are \$1,679,000/year. If it would be necessary to deepen existing wells without artificial recharge, then this foregone cost should be included as an additional benefit related to the reduction in pumping lifts.

The total costs of all subsidence that has occurred in the Santa Clara Valley have been discussed by Poland (1978), Fowler (1981), and Aron (1969). Estimates range from 15 million dollars to 131 million dollars. For this study it seemed reasonable to use a total cost somewhere near the middle of these estimates and, therefore, a value of 70 million dollars was chosen. This total cost represents the costs of repairing damaged well casings, sewers, and bridges, of building and raising levees, and of constructing drainage pumpage stations. As shown in Figure 2, total subsidence in the center of the valley has been an average of 8 feet. Dividing the total subsidence costs of 70 million dollars by 8 feet yields an average unit cost of subsidence of 8.75 million dollars per foot. Since the artificial recharge program has reduced subsidence in the center of the basin by an estimated average of 1 foot, total undiscounted economic benefits are taken as 8.75 million dollars. Since nearly all the incremental subsidence occurs in the first year of the period, the benefits of subsidence reduction are discounted one year to yield totals of 8.2 million dollars with a 7 percent discount rate and 8.0 million dollars with a 10 percent discount rate.

The implicit assumption here is that the costs of subsidence are linear. Actual subsidence damage will depend on geographic location and the type of structure. For a particular structure, incremental damage after the first several feet of subsidence is likely to be small. As subsidence occurs over time, however, different structures are affected. Therefore, the total costs of subsidence damage to all affected structures may be close to linear.

Santa Clara Valley is an area which has already experienced considerable subsidence. As shown above, the incremental subsidence prevented by artificial recharge since the late 1960's is not large. It is interesting to consider how much more subsidence could have been prevented if there had been an extensive artificial recharge program from the beginning of water development in the Santa Clara Valley. To look at this question, the groundwater model was rerun for a 50-year period using the computed 1915 water levels as initial conditions. Pumping was again set at 150,000 acre-feet per year, and the model was run both with and without recharge. Results indicate as much as 3 feet of subsidence could have been prevented in the center of the Valley had artificial recharge been carried out, at its present scale, from 1915 on. This estimate is significantly larger than the incremental subsidence that is computed when only the effects of artificial recharge since 1966 are considered. It suggests that the magnitude of the benefits from an artificial recharge program may depend greatly on the initial state of the aquifer.

Benefits of reduced subsidence and pumping lifts are shown in Table 2. Using a discount rate of 7 percent, the 40-year discounted sum of economic benefits of artificial recharge relating to its reduction of pumping lifts and of subsidence is 31 million dollars. When a 10 percent rate is used, the total benefits are 24 million dollars.

TABLE 2. Summary of Economic Analysis 1 Using Two Alternate Discount Rates.

	r=7 Percent	r=10 Percent
DISCOUNTED COSTS OF ARTIFICIAL RECHARGE (million 1982 dollars)		
Land (\$32,000/acre x 324 acres)	10.4	10.4
Operation (\$480,000/year)	6.4	4.6
TOTAL	17.0	15.0
DISCOUNTED BENEFITS OF SUBSIDENCE AND PUMPING LIFT REDUCTION (million 1982 dollars)		
Subsidence Reduction	8.2	8.0
Reduced Average Pumping Lift (\$1,679,000/year)	22.4	16.4
TOTAL	31.0	24.0

Costs of Artificial Recharge in Analysis 1. Since nearly all of the capital facilities for artificial recharge in the Santa Clara Valley have been in place for many years, the costs considered will be those of continuing the existing program. Where these differ from the costs of starting a new program, the differences will be noted.

The SCVWD estimates current costs of construction (predominantly excavation and hauling away material) at \$168,000/acre (Santa Clara Valley Water District, 1980). Land costs in northern Santa Clara Valley are among the highest in the country. Current land value is about \$200,000/acre. SCVWD recharge facilities take up 324 acres of land. No additional construction costs are required to maintain the existing program. The land cost of continuing artificial recharge equals the difference between the present value of the potential income stream which could be earned from the land without recharge facilities and the costs of removing these facilities. The value of the income stream that the land could generate over 40 years is considered to be reasonably reflected in the current market price of land. Two points regarding this assumption should be made. The first is that, although land costs are actually a measure the land's value over perpetuity, the difference between a 40-year and an infinite stream of returns is very small for any significant discount rate. The second point is that the portion of current land prices that can be attributed to the capitalized benefits due to the presence of an existing recharge program is considered negligible.

The cost of dismantling the current recharge facilities is assumed to be equal to the cost of constructing them. The land costs of continuing the artificial recharge program are, therefore, \$32,000/acre (\$200,000/acre-\$168,000/acre), or a total of \$10,368,000 (\$32,000/acre x 324 acres). If one were to start a new program, the total capital costs of artificial recharge would be the market land value plus construction costs minus the present value of the cost of removing the facilities at the end of 40 years.

Annual operating costs (including the periodic cleaning of the ponds) are \$4.80/acre foot (Santa Clara Valley Water District, 1980) yielding a total annual operating cost of \$480,000/year (\$4.80/acre-foot x 100,000 acre-feet/year). The actual cost of purchasing imported water is not considered here. As stated in the introduction, it is assumed that the decision has already been made to purchase the water. Also not considered here are any costs associated with transporting the water to the recharge sites.

Costs of artificial recharge as perceived in this first analysis are tabulated in Table 2. As can be seen, land is the major cost of artificial recharge in the Santa Clara Valley; the use of percolation ponds is a land-intensive operation. The amount of land required to recharge a given quantity of water in a particular area is, of course, a function of the permeability of the underlying soil and sediments. Maximum recharge rates at Santa Clara Valley percolation facilities range from 0.5 to 6.0 feet per day (California Department of Water Resources, 1975). In general, the more permeable the recharge sites, the less land required and the lower the cost of artificial recharge.

Using a discount rate of 7 percent, the total discounted costs of continuing artificial recharge are 17 million dollars. Total costs are 15 million dollars when a 10 percent discount rate is used.

Results of Economic Analysis 1. In this first example analysis, the discounted benefits of continuing the artificial recharge program are from 1.5 to almost 2 times the discounted costs. Given current market land values, however, the capital costs of starting a new recharge program would outweigh the benefits.

Analysis 2: Artificial Recharge vs. Surface Storage and Distribution

The second analysis seeks to determine whether artificial recharge or surface storage and distribution is the most economical way of handling additional supplies of water. It is assumed that either the benefits of reduced average pumping lifts and subsidence exceed the costs of artificial recharge in Analysis 1, or that an evaluation of potential hydraulic risks has led to the conclusion that some sort of program is necessary. In either case, the problem is to choose the program which can achieve the desired hydrologic effects at the lowest cost.

Costs of Artificial Recharge for Analysis 2. As in the first analysis, relevant costs are those associated with continuing the existing program. All the cost components described earlier are included in this second analysis. When comparing artificial recharge with an alternative program, however, the cost of pumping the recharged water back out of the ground must also be considered. Total costs of artificial recharge, as perceived in this second analysis, are shown in Table 3.

TABLE 3. Summary of Economic Analysis 2 Using Two Alternate Discount Rates.

	r=7 Percent	r=10 Percent
DISCOUNTED COSTS OF ARTIFICIAL RECHARGE (million 1982 dollars)		
Land (\$32,000/acre x 324 acres)	10.4	10.4
Operation (\$480,000/year)	6.4	4.6
Pumping (\$1,695,000/year)	22.6	16.5
Well Maintenance (\$67,500/year)	9.5	7.2
Well Replacement	1.2	0.7
TOTAL	50.0	39.0
DISCOUNTED ALTERNATIVE COSTS (million 1982 dollars)		
Treatment		
a) Capital Cost	90.0	90.0
b) Fixed O&M (\$2,034,000/year)	27.5	20.2
c) Variable O&M \$1,440,000/year)	19.2	14.1
Storage (\$15,000,000/year)	200.0	146.6
Conveyance		
a) Capital Cost	14.7	14.7
b) O&M (\$88,000/year)	1.2	0.9
TOTAL	352.0	286.0

Assuming an average pumping lift of 150 feet, annual costs to users of pumping the recharged water back out of the ground are $1,695,000 ($0.113/acre-foot/foot x 150 feet x 100,000 acre-feet/year). To pump the 100,000 acre-feet/year of water is considered to require forty-five 2000 gpm capacity wells pumping an average of 70 percent of the time. Annual maintenance costs are set at $1,500/well for a total of $67,500/year. Assuming a capital cost per well of $100,000 and an average well life of 20 years, the discounted cost of replacing wells halfway through the study period will range from 0.7 to 1.5 million dollars, depending on the discount rate. If one were considering the costs of starting a new artificial recharge program, the costs of initial well installation would also have to be included.

Costs of Alternative Program. The alternative to artificially recharging the 100,000 acre-feet of water is to store it in surface reservoirs, treat it in treatment plants, and convey it to users via pipelines and/or canals. These costs are tabulated in Table 3.

Artificial recharge allows water to be stored in the aquifer rather than on land. While it is true that some of the artificially recharged water in the Santa Clara Valley passes through existing storage facilities, additional storage capacity would be required if there was no artificial recharge. It is assumed here that a full 100,000 acre-feet of additional reservoir yield would be needed. By modifying the operation of existing facilities, however, it is possible that less than this amount of additional yield would be required.

The alternative costs of storage will be a function of how much storage capacity is required to provide an annual yield of 100,000 acre-feet. The amount of storage capacity needed to provide a given annual water yield is highly dependent on location of the facility, seasonal timing of imported water, and seasonal hydrologic conditions in the basin. Estimates of the cost of additional reservoir yield in the Santa Clara Valley range from $77/acre-foot/year to $430/acre-foot/year (Santa Clara Valley Water District, 1975). This figure incorporates both operating costs and amortized capital costs. A value of $150/acre-foot/year was assumed reasonable for this study. This yields an alternative storage cost of $15,000,000/year ($150/acre-foot/year x 100,000 acre-feet).

Most of the water artifically recharged is nonpotable. Adsorptive processes act to treat this water as it flows through the groundwater system. To provide 100,000 acre-feet per year of treatment capacity is considered to require construction of a 180 mgd treatment plant. Cost estimates for such a plant are based on both published reports (Santa Clara Valley Water District, 1980) and on subsequent unpublished cost updates by the SCVWD. Capital costs of a 180 mgd plant are taken as 90 million dollars ($500,000/mgd x 180 mgd). Fixed Operation and Maintenance (O&M) costs are $2,034,000/year ($11,300/mgd/year x 180 mgd). Variable O&M costs are $1,440,000/year ($14.40/acre-foot x 100,000 acre-feet/year).

Conveyance of 100,000 acre-feet per year from the four main recharge areas to the center of the valley through the aquifer system is considered equivalent to 16 miles of 3-foot diameter reinforced pressure pipeline. Capital costs for such a system would be $14,784,000 (84,840 feet x $175/foot). Annual O&M costs are six-tenths of one percent of capital costs or $88,700/year (Santa Clara Valley Water District, 1975).

Results of Economic Analysis 2. The calculation of the present value of the two 40-year cost streams is tabulated in Table 3. The computed costs of artificial recharge in Santa Clara Valley range from 39 to 50 million dollars, depending on the discount rate. The alternative costs range from 286 to 352 million dollars. As can be seen, continuation of artificial recharge can achieve the same hydraulic results as the alternative program of surface storage, treatment, and conveyance for a much smaller cost. If one were considering starting a new artificial recharge program, additional land costs, pond construction costs, and the costs of initial well construction would have to be considered. Computations show that this would add approximately 100 million dollars to the costs of artificial recharge, but total costs would still be considerably less than those for the alternative surface program.

CONCLUSIONS

The above analyses use the Santa Clara Valley as a test case for examining the economic returns to artificial recharge. A digital groundwater model is used first to determine both the long term and drought period hydraulic effects of the artificial recharge program starting with 1966 groundwater levels. Two distinct economic analyses are demonstrated. In the first analysis, the costs of artificial recharge are weighed against the benefits which result from a decrease in the net rate of groundwater withdrawal – reduction of average annual pumping lifts and reduction of land subsidence. If this first analysis indicates that these benefits exceed the costs of artificial recharge, or if the potential risks associated with potential changes in water demand and supply and with the occurrence of droughts make some sort of program necessary, than a second analysis is carried out. In this second analysis, benefits of artificial recharge represent the alternative costs of surface storage, treatment, and conveyance. In both analyses, best estimates of the various unit costs and benefits were used.

The results of the first example analysis indicate that the discounted benefits derived from reduced average pumping lifts and reduced land subsidence exceed the discounted costs of continuing the artificial recharge program. It was also found that the magnitude of such benefits as subsidence reduction may be very sensitive to the initial aquifer state.

The second example analysis compares the costs of artificial recharge with a surface alternative which would achieve the same hydraulic results. This second analysis indicates that the costs of the alternative program of surface storage, treatment, and conveyance would be considerably more than the costs of continuing an artificial recharge program.

The case study described here considered a specific existing program. However, the economic viability of an existing or proposed recharge plan in any area could be analyzed by the same sort of analyses. Whether or not artificial recharge is actually feasible in a particular basin will also be a function of two important noneconomic factors: 1) the availability of a source of water to recharge, and 2) the type of institutional management of the basin.

Several extensions of the work described here are possible. Since, in many cases, artificial recharge facilities will also serve other uses, it may be worthwhile to investigate situations in which the economic benefits of artificial recharge are considered as only one component of a multiple purpose water development. Also of interest is the problem of choosing the "best" recharge program for a particular area. To determine what that program is requires the application of management methods to find number, size, and location of ponds, as well as the annual volume of recharged water which achieves various management objectives at minimum cost.

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