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PARTIAL PROJECT COMPLETION REPORT

OWRT PROJECT NO. A-069-ARIZ

DEVELOP WATER MANAGEMENT METHODS FOR WATERSHEDS SUBJECT TO INTENSIVE DEVELOPMENT

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Investigator:

D. Davis - Hydrology and Water Resources

Graduate Student:

H. B. Robotham

The University of Arizona
Tucson, Arizona

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ABSTRACT

A water resources management study for the Sonoita Creek watershed was conducted in order to develop a usable water resources management plan for the area and to resolve possible conflict among the different water demands in the basin. These water demands are classified as municipal and domestic, recreation and agriculture.

Six potential water resources management alternatives are developed and compared using the standardized cost-effectiveness methodology. This approach enables thorough and efficient comparison of the alternatives with respect to both quantifiable and unquantifiable criteria. Each alternative considers developing either the ground water or the surface water resources of the watershed. Also, each alternative considers some method of treated sewage effluent disposal.

The algorithm ELECTRE I is used to select the most suitable plan for the watershed. This procedure is used because of its simplicity and its proven usefulness in analyzing multiobjective decision problems.

With the available information on the ground and surface water resources of the watershed, the choice of alternatives is reduced to one, namely, construction of a small reservoir at Redrock Canyon. Evaporation control measures are needed in order to reduce evaporation losses from the reservoir. The reservoir would serve as a supplemental source of water for the town of Patagonia and for the Sonoita Creek Sanctuary.

INTRODUCTION

This study investigates various water resources management alternatives for the Sonoita Creek watershed. The study was conducted because of the increasing concern over the adequacy of the watershed's water resources in meeting future water demands in the area.

The study area is the portion of the Sonoita Creek watershed which contributes surface runoff to Lake Patagonia. The watershed is about 240 square miles in area and is located in southeast Arizona (Figure 1).

The watershed is drained by Sonoita Creek and its tributaries. Surface flow in the creek is intermittent along much of the 19 mile reach; however, the flow becomes perennial towards the lower end of the creek.

The small towns of Sonoita and Patagonia are the main population centers in the watershed (Figure 1).

The water resources of the watershed have so far been adequate for meeting the different water demands in the area. These demands can be classified as municipal and domestic, agricultural, and recreational. Agricultural and recreational demands are expected to remain fairly constant over the next twenty years. However, municipal and domestic demands are expected to triple during the same period. This large increase in municipal and domestic water demand is expected to be due mainly to a large population influx resulting from the start of mining activities in the area. Much of the population is expected to settle in and around Patagonia. A large increase in municipal and domestic water demands in the watershed, especially in and around Patagonia, necessarily implies increased pumping from the current source of water, the Sonoita Creek aquifer, unless supplemental water supplies are developed. There is increasing concern, however, that the aquifer may be unable to support this added demand. The low productivity of Patagonia's water supply wells during periods of low aquifer recharge coupled with the generally poor water quality in other sections of the aquifer are the main reasons for this concern. The city wells are presently located in an area of very good water quality. The water quality meets the requirements for municipal and domestic use as prescribed by the Environmental Protection Agency (EPA, 1970). However, well yields in this area are low, only about 300 gallons per minute. Well yields in other sections of the aquifer can be much higher -- up to 1,200 gallons per minute in some instances. However, the ground water in these areas is unsuitable for domestic use because of its high total dissolved solids -- up to 1,100 parts per million.

The need for further development and proper management of the watershed's water resources is very evident. As part of the water resources management study the reuse and proper disposal of secondary treated sewage effluent from the Patagonia sewage treatment plan is considered. This component of

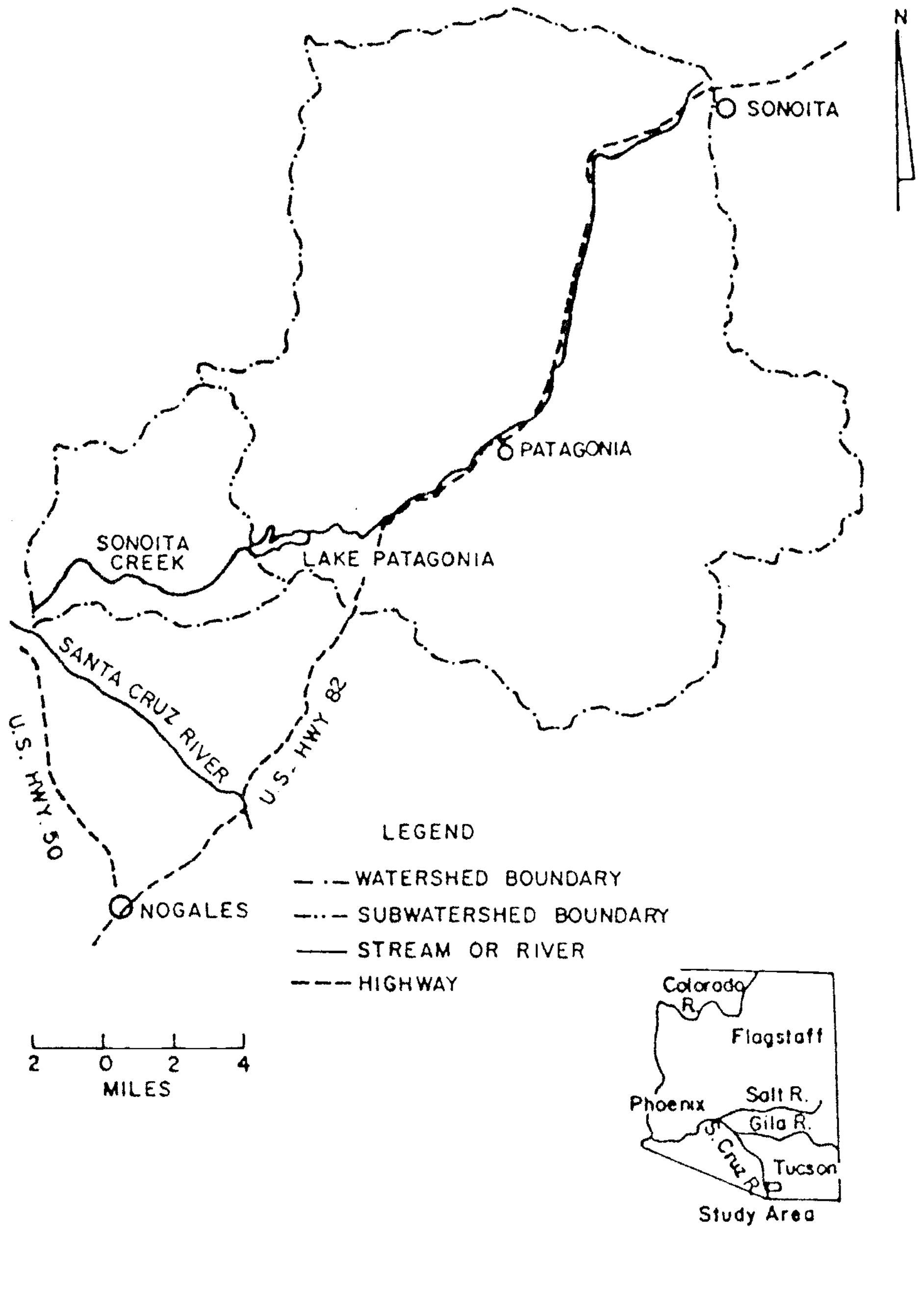


Figure 1. Location of Sonoita Creek watershed in Arizona.

the study is important because of its possible negative consequences on the environments of the Sonoita Creek sanctuary and Lake Patagonia. The Sonoita Creek sanctuary has long served as a refuge for rare and endangered species of birds and fish while Lake Patagonia is part of an important recreational complex in the area.

METHODOLOGY

The standardized cost-effectiveness methodology (CE) is selected to develop and compare alternative system solutions for the Sonoita Creek water resources management study. The methodology was developed by Kazanowski (1968) in order to dispel the criticisms that the lack of uniformity in many previous CE evaluations had caused. In recent years this approach has had widespread application in the areas of hydrology and water resources. Important applications of the methodology to water resources problems include: development of the Lower Mekong River Basin (Chaemsaithong, 1973), long-range planning in the Central Tisza River Basin in Hungary (David and Duckstein, 1976), and comparison of alternative water reuse systems in Tucson (Duckstein and Kisiel, 1977). The methodology is particularly suited to water resources problems because of the multiplicity of objectives and the sometimes unquantifiable nature of both cost and effectiveness.

The algorithm ELECTRE I is used, in conjunction with the standardized CE approach, to analyze the merits of the alternative systems. This procedure is used because of its simplicity and its proven usefulness in analyzing multiobjective problems.

The systems framework for this study was developed by Diaz-Pena (1978). For his thesis he expressed all the criteria in qualitative terms, then performed a subjective evaluation of the systems capabilities. By quantifying some of the criteria a more objective evaluation is used in this study.

THE SONOITA CREEK WATERSHED

The studies done by Schroder (1915); Feth (1947); Halpenny, Green and Dansinger (1964); Nasseridin (1967); and Ben-Asher, Randall and Resnick (1976) are the main sources of information concerning the hydrology and geology of the Sonoita Creek watershed. Much of this information is summarized in Robotham (1979).

Ground Water Resources

Most of the water demands in the Sonoita Creek basin are met by ground water. All municipal and domestic water demands in Patagonia are met by ground water pumped from the aquifer. Irrigation water demands at the

Box-T Ranch are completely met by ground water while these demands are satisfied by spring water at the Rail-X Ranch. Recreational demands are met by surface storage and surface flow but may be influenced by the ground water levels in the aquifer especially during periods of low aquifer recharge. With a substantial increase in municipal and domestic water demands projected for the future, the dependence on ground water to meet these demands will significantly increase unless other water supplies are developed.

The Aquifer

The Sonoita Creek watershed is underlain by alluvium ranging in age from Tertiary to Recent (Nasseridin, 1967). Older volcanic rocks surround the alluvial deposits on the east, south and west (Schrader, 1915). Nasseridin (1967) divides the alluvium into five units according to their age and lithology. According to him alluvial units No. 4 and No. 1 are the main water-bearing beds in the basin. Both units have fairly high permeability and are tapped by most irrigation and domestic wells.

The principal aquifer, alluvial unit No. 4, outcrops over much of the basin thus providing a large permeable area for recharge during the rainy season. Alluvial unit No. 4 outcrops mainly along Sonoita Creek and its tributaries and forms the alluvial fill of the inner valley. This unit is also a very important recharge area during the rainy season.

Ground water occurs under water table conditions in alluvial unit No. 1 and under semi-artesian conditions in alluvial unit No. 4.

The general movement of ground water in the basin is towards Sonoita Creek from the surrounding hills then southward along the channel fill of the creek (Figure 2).

The hydraulic properties of the aquifer were determined using the results of pumping tests conducted by Halpenny et al. (1964) for the Water Development Corporation in 1959. Transmissivity values range from 9,500 gallons per day per foot (gpd/foot) to 260,000 gpd/foot. Estimates of storage coefficient range from 0.30 for the unconfined aquifer to 6.09×10^{-5} for the deeper confined aquifers (Nasseridin, 1967). The large variation in the estimates can be partly explained by the existence of several faults and fracture zones in the area.

Ground Water Resources Potential

Municipal and domestic water demands in the Sonoita Creek watershed are expected to increase from about 180 acre-feet at present to a projected estimate of 580 acre-feet by the year 2,000 (Diaz-Pena, 1978). Other water demands in the basin, namely, agricultural and recreational are expected to remain fairly constant over the next twenty years. At present industrial water demands are insignificant. This is expected to remain as such

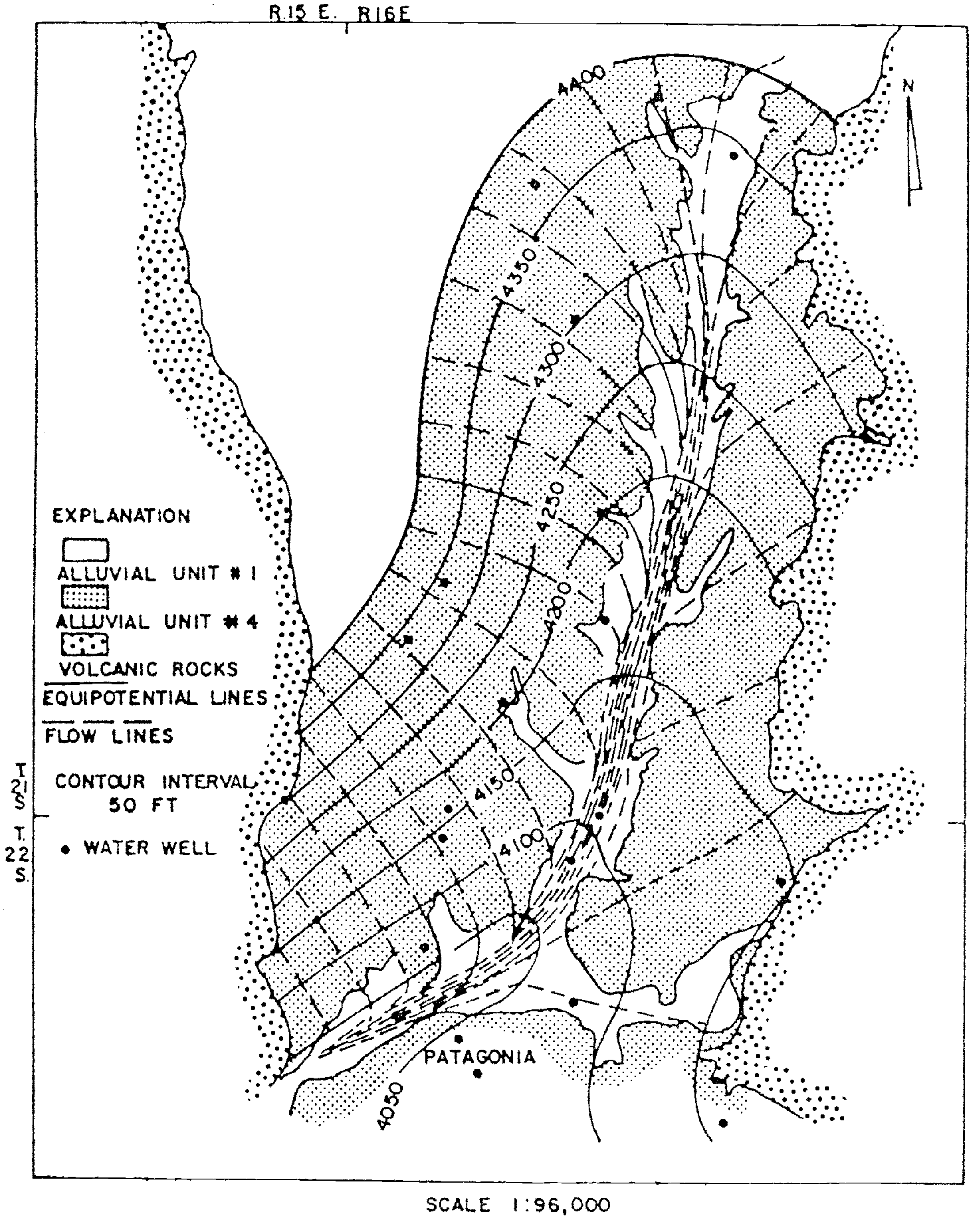


Figure 2. Generalized ground water flow net for the Sonoita Creek aquifer, based on 1966 water levels

since the mining companies are expected to obtain water for their operations from sources outside of the watershed.

At present the ground water reservoir is able to support the water demands that are dependent on ground water. A major concern is whether this resource can continue to support these demands as municipal and domestic demands continue to increase.

Estimates of mean annual aquifer recharge (15,900 acre-feet) and discharge (12,000 acre-feet) indicates that on the average, recharge does balance discharge. This would suggest that approximate steady-state conditions exist in the watershed when viewed on a yearly basis. One can expect, therefore, that on the average the ground water resources of the watershed can meet the projected water demands in the area for at least another twenty years.

A good measure of the aquifer's ability to meet sustained water demands is the practical sustained yield. This is the amount of water which can be removed annually without producing undesirable effects (Walton, 1970). For the Sonoita Creek aquifer these undesirable effects are poor water quality and substantial lowering of the water table to an extent where the perennial flow through the Sonoita Creek Sanctuary is adversely affected. The practical sustained yield is generally less than the mean annual recharge, otherwise, depletion of the ground water storage occurs. In attempting to determine the practical sustained yield it may be necessary to pump the aquifer at various rates and measure the drawdown at various locations. This is beyond the scope of this study. (Robotham (1979) used the results of pumping tests conducted by the Water Development Corporation in 1959 to estimate the drawdown at various distances from pumped municipal and irrigation water wells.)

Municipal water demand for the year 2000 was estimated to be 500 acre-feet (Diaz-Pena, 1978). With this demand, and an assumed maximum daily operation of city wells of 7 hours per day during peak demand periods (Ronald Campbell, Water and Sewer Director of Patagonia, 1979), the city wells will be required to produce at a combined rate of 1,064 gallons per minute (gpm). Four city wells each suitably located and producing 270 gpm can easily meet the 500 acre-feet demand for the year 2000. With the assumed pumping rate of 270 gpm for each well and using a conservative coefficient of transmissivity of 15,000 gpd/foot and coefficient of storage of 20 percent, the net drawdown at various distances from a pumped city well was estimated using the Theis Non-equilibrium well formula (Walton, 1970). Table 1 (taken from Robotham, 1979) summarizes the results for the pumping schedule of 7 hours of pumping and 17 hours of recovery each day.

These results indicate that city wells can be placed about 500 to 600 feet apart and operated simultaneously with negligible interference between wells. In addition pumping of these wells should not seriously affect

Table 1. Drawdown at various distances from a pumped city well after a daily cycle of 7 hours of pumping and 17 hours of recovery.

Distance from pumped well (feet)	Net drawdown (feet)
1	0.72
100	0.52
200	0.21
300	0.06

water levels in the southwest end of town and flow through the Sonoita Creek Sanctuary.

Agricultural water demand for the Box-T Ranch was estimated to be roughly 300 acre-feet per year (Diaz-Pena, 1978). Robotham (1979) used a conservative estimate of 600 acre-feet per year. During the irrigation period the crops are irrigated every two weeks. The wells are pumped for about 12 hours each day for six days. With this pumping schedule and the assumed demand of 600 acre-feet per year irrigation wells will be required to produce at a combined rate of 1,742 gpm. The ranch currently has three very productive wells which are capable of yielding 1,300 gpm, 1,000 gpm, and 338 gpm, respectively. For this study it is assumed that the two more productive wells are operated at 1,000 gpm and 800 gpm, respectively. Estimates of transmissivity in the vicinity of the irrigation wells range from 100,000 gpd/foot to 260,000 gpd/foot. Using a conservative estimate for transmissivity of 100,000 gpd/foot, a storage coefficient of 20 percent, and the assumed maximum pumping rate of 1,000 gpm, the net drawdown after one day of pumping an irrigation well was estimated using a modified form of the Theis well formula. Each daily cycle consists of 12 hours of pumping and 12 hours of recovery. Table 2 summarizes the results for various distances from the pumped well. After 14 days (that is, 6 days of pumping with the above schedule and 8 days of recovery) the drawdown at the pumped well is estimated to be 0.05 feet. At the end of a full year of pumping the cumulative effect is negligible. The pumping schedule discussed earlier is valid for the dry season and does not necessarily apply during the rainy season. In fact, the crops generally go unirrigated during periods of high rainfall. This means that the net drawdown estimates in Table 2 can be expected to be somewhat lower. The two high capacity irrigation wells are located roughly 700 feet apart and are well to the northeast of town. Although some interference between these wells can be

Table 2. Drawdown at various distances from a pumped irrigation well after a daily cycle consisting of 12 hours of pumping and 12 hours of recovery.

Distance from pumped well (feet)	Net drawdown (feet)
1	0.81
100	0.77
200	0.64
300	0.48

expected, their operation should have no effects on city wells, located at least a half mile to the west. Also, water table elevations in the southeast end of town and flow through the sanctuary should likewise not be affected.

Complete water quality analyses were done on sixteen water samples from wells in and around Patagonia (Halpenny et al., 1964). The results of the analysis indicate a range of total dissolved solids (tds) from 215 parts per million (ppm) to 1,113 ppm. Most of the dissolved solids consist of sulfate, bicarbonate and calcium derived mainly from the weathered material of the surrounding rocks. The sulfate content is quite high, up to 680 ppm, and may be related to the oxidation of pyrite contained in the rhyolitic volcanic rocks which outcrop on the east side of town. The hardness of the water is quite high, up to 800 ppm, and reflects the high bicarbonate content. In spite of the general poor quality of the ground water in some areas the city wells have been located in an area where the ground water quality is satisfactory for domestic and public use. Long-term qualities cannot be predicted with the available data. However, if future pumping is not too excessive, resulting in ground water mining, the present water quality should be maintained.

With the available information an accurate estimate of the practical sustained yield cannot be made at this time. It has been demonstrated, however, that total yearly discharge from the aquifer including pumping demands is somewhat lower than the recharge. It can, therefore, be reasonably assumed that the practical sustained yield is greater than the anticipated pumping demands.

Surface Water Resources

The development of the surface water resources of the watershed is severely constrained by the absence of perennial stream runoff and the high evaporation rates which characterize the area. Since the ground water resources of the area have so far been adequate for municipal and agricultural water demands no emphasis has been placed on developing a domestic surface water supply. Although it has been shown that the ground water resources of the basin are adequate for meeting future water demands (for at least another twenty years) alternative sources of water should be investigated and perhaps exploited if they prove to be in the best interests of the basin. The creation of Lake Patagonia and its development as an important recreational facility is one such instance where the exploitation of surface water resources has been beneficial to the area. A second recreational facility was planned for the Redrock Canyon area by the Arizona Game and Fish Department. However, this did not materialize because of strong opposition from environmental groups coupled with the excessive expected evaporation losses from the reservoir. At the present time Lake Patagonia and Redrock Canyon seem to be the most feasible sites for developing a surface water supply for the basin. The potential of these two sites, as future sources of water supply for the basin, was discussed by Diaz-Pena (1978) and later investigated by Robotham (1979).

The primary purpose of Lake Patagonia is recreation. The facility caters to activities such as boating, fishing, swimming and camping. To function adequately as a recreational facility, water levels in the lake should not be lower than five feet below spillway crest (3761 feet). Lower water levels would render the marina useless and the beaches unattractive. Maximum permitted water surface elevation is 3,779 feet. Above this level the marina and beaches would be flooded. To determine the adequacy of the lake as a recreational facility as well as a potential source of a water supply for Patagonia a detailed operation study was conducted (Robotham, 1979). This study is a simulation of the lake's operation over a period of time in accordance with an adopted set of rules (Linsley and Franzini, 1972). A planning horizon of 20 years was considered, however a longer period may become significant in the future. The rules associated with the operation of the lake consist of releases, withdrawals and the timing of these events. The study done by Robotham (1979) indicated that in extremely dry years water levels in the lake could fall as much as eight feet below spillway crest. This means that unless priorities on water demands are revised the lake could not function adequately both for recreation and water supply purposes. However, it is inconceivable that in such extreme situations water supply would not take precedence over recreation. Thus it was tentatively concluded that Lake Patagonia can serve both purposes adequately.

The Redrock Reservoir was originally conceived as a recreational facility. However, with the construction of the Lake Patagonia recreation complex and its subsequent purchase by the Arizona State Parks and Recreation Department, the need for a recreation facility in the area was fulfilled.

Furthermore, the original design was disqualified because of its size, cost, excessive evaporation losses and strong opposition from environmental groups. For the purposes of water supply a smaller, less costly reservoir was investigated. Diaz-Pena (1978) recommended an 850-acre-feet-capacity reservoir which would supplement Patagonia's water supply as well as providing low flow augmentation through the Sonoita Creek Sanctuary. Thus, its function would be similar to the water supply component of Lake Patagonia. Robotham (1979) investigated this design and concluded that the reservoir can serve as an adequate water-supply facility for at least twenty years if suitable evaporation-suppression techniques can be implemented.

Other Water Resources Improvement Measures

Direct methods of developing the water resources of the Sonoita Creek watershed have been discussed. These consist of further developing the ground water resources by proper placement of additional wells and developing the surface water resources by utilizing Lake Patagonia or by building a reservoir at Redrock Canyon. A more indirect method of improving the water resources situation in the watershed consists of reusing municipal and domestic wastewater.

Reuse of treated wastewaters is a water conservation measure which has been and is being practiced in many areas where surface and ground water supplies are dwindling. Although the water resources situation in the basin is not yet considered critical, efficiently reusing the area's wastewaters can be an effective measure in reducing the possibility of ground water overdraft as well as saving precious surface water. Also, the possibility of contamination of surface waters by domestic effluent makes reuse of these effluents even more attractive.

Sewage Treatment and Reuse

The existing sewage treatment facility in Patagonia is a package mechanical plant of the extended aeration type. The plant was designed for a maximum load of 80,000 gallons per day but can easily be upgraded to handle larger loads. The treatment system consisting of comminution, aeration, clarification and chlorination produces a good quality effluent; about 95 percent removal of BOD and suspended solids when operating at maximum capacity. The efficiency of the system is somewhat higher for smaller loads. Total dissolved solids (TDS) in the effluent are usually about 800 parts per million (ppm), which compares very well with that of the ground water in the area which can be as high as 1,113 ppm. Fecal coliform are usually totally removed.

The amount of effluent presently being produced in Patagonia is uncertain. From information obtained from Ronald Campbell (1979), Patagonia's Water and Sewer Services Director, it was learned that current plant output averages roughly 35,000 gpd. Maximum output was estimated at 50,000 gpd. The amount of effluent discharge was also estimated by adjusting the total water use by a factor of 70 percent (Linsley and Franzini, 1972). This method yielded an estimate of 112 acre-feet per year or about twice the maximum observed load. The discrepancy in estimates can perhaps be explained by the fact that not all residences in Patagonia are presently linked to the sewage treatment plant; many residences still use the traditional septic tanks. All residences are expected to be linked eventually with the treatment plant. With this in mind the estimate of 112 acre-feet per year is quite reasonable. This is expected to increase to about 350 acre-feet by the year 2000.

The use of treated sewage effluent for irrigation is an option which is being considered. Because of the good quality of the effluent it could be used directly or mixed with fresh water before application. The use of effluent in agriculture would save up to 112 acre-feet of ground water in the first year and as much as 350 acre-feet by the year 2000. The main problems which should be considered before implementing such a program are: contamination of the ground water by the nitrates which are inevitably contained in the effluent, salt accumulation in the soil, the effluent produced during periods when water demands for irrigation are low, and public acceptance. These problems are discussed in more detail in Robotham (1979).

APPLICATION OF THE COST-EFFECTIVENESS METHODOLOGY TO THE SONOITA CREEK WATER RESOURCES MANAGEMENT STUDY

The standardized cost-effectiveness (CE) methodology, as applied to the Sonoita Creek study, is discussed fully in Robotham (1979). The remainder of this report summarizes the study and presents the main conclusions and recommendations.

The approach consists of the following ten steps:

1. Define the objectives that the alternatives (systems) are to fulfill.

2. Identify requirements that are essential for the attainment of the objectives.

3. Establish system evaluation criteria (measures of effectiveness) that relate system capabilities to requirements.

4. Select fixed-cost or fixed-effectiveness approach.

5. Develop alternative systems (solutions) for accomplishing the objectives.

6. Determine capabilities of the systems in terms of the evaluation criteria.

7. Generate a systems-versus-criteria array.

8. Analyze merits of the systems.

9. Perform sensitivity analysis.

10. Document the rationale, assumptions, and analyses underlying the previous nine steps.

Objectives

The main objectives of the Sonoita Creek Basin water resources management study can be grouped under water demand, environment, disposal of treated sewage effluent and flexibility. A planning horizon of twenty years (1980 to 2000) is being considered.

Water Demand

The most economic means of fulfilling the water demands of the basin should be determined. These demands are:

1. Municipal and domestic.

2. Recreation, namely Lake Patagonia and the Sonoita Creek sanctuary.

3. Agriculture.

4. Rural activities.

Good quality water in sufficient quantities should be provided for these demands.

Environment

The water resources management plan that is implemented should have no negative effects on the environments of the sanctuary, Lake Patagonia and the National Forest areas.

Disposal of Treated Sewage Effluent

Treated sewage effluent from the Patagonia treatment plant should be efficiently reused. Other wastewaters produced in the basin should be adequately disposed of.

Flexibility

The plan should possess the necessary flexibility to undergo changes that become necessary as new elements are introduced or become more important in the future.

Systems Requirements

The systems requirements express the objectives quantitatively inasmuch as that is possible. All the requirements should be pertinent derivatives of the objectives. However, care should be taken in defining the number of such requirements as too few may result in invalid conclusions while too many may make it physically impossible to accomplish the desired objectives with any system (Kazanowski, 1968).

A planning horizon of 20 years was chosen because: (1) uncertainties involved in forecasting population growth and water use make a longer period unadvisable, and (2) structural changes which may be introduced would make a shorter period unrealistic.

Water Demand

Water demands are discussed under municipal and domestic, recreation, agriculture and rural use.

Municipal and Domestic. Municipal and domestic water demands in the basin are expected to increase significantly in the next twenty years. This increase is expected to be due primarily to the influx of population resulting from increased employment opportunities in mining-related activities and from the attractive scenic environment which typifies the area.

Considering the above factors Diaz-Pena (1978) projected total water use, in the communities of Patagonia and Sonoita, to the year 2000. Baseline data were obtained from the Mayor's Office in Patagonia and from the Arizona Department of Economic Planning and Development (ADEPD) report of 1971. A maximum per capita water use of 75,000 gallons per year was assumed, for the year 2000, after examining per capita water use in other small southwestern cities. Figure 3 gives total water use estimates for Patagonia for the years 1970, 1973, 1976 and projections to the year 2000. The high projection is assumed after consideration of data uncertainties and forecasting uncertainties.

Figure 4 gives the total water use forecasts for Sonoita for the period 1970 to 2000.

The plan should provide enough water to meet the high projection in Figure 3 and the median projection in Figure 4. Quality requirements for municipal and domestic water supply are those recommended by the EPA (1970).

Recreation. The recreational facilities that will be directly affected by a water resources management plan are the Nature Conservancy's Sonoita Creek sanctuary and Lake Patagonia.

Sonoita Creek Sanctuary: The sanctuary is a thickly vegetated tract of land which flanks Sonoita Creek. It extends from a few hundred feet

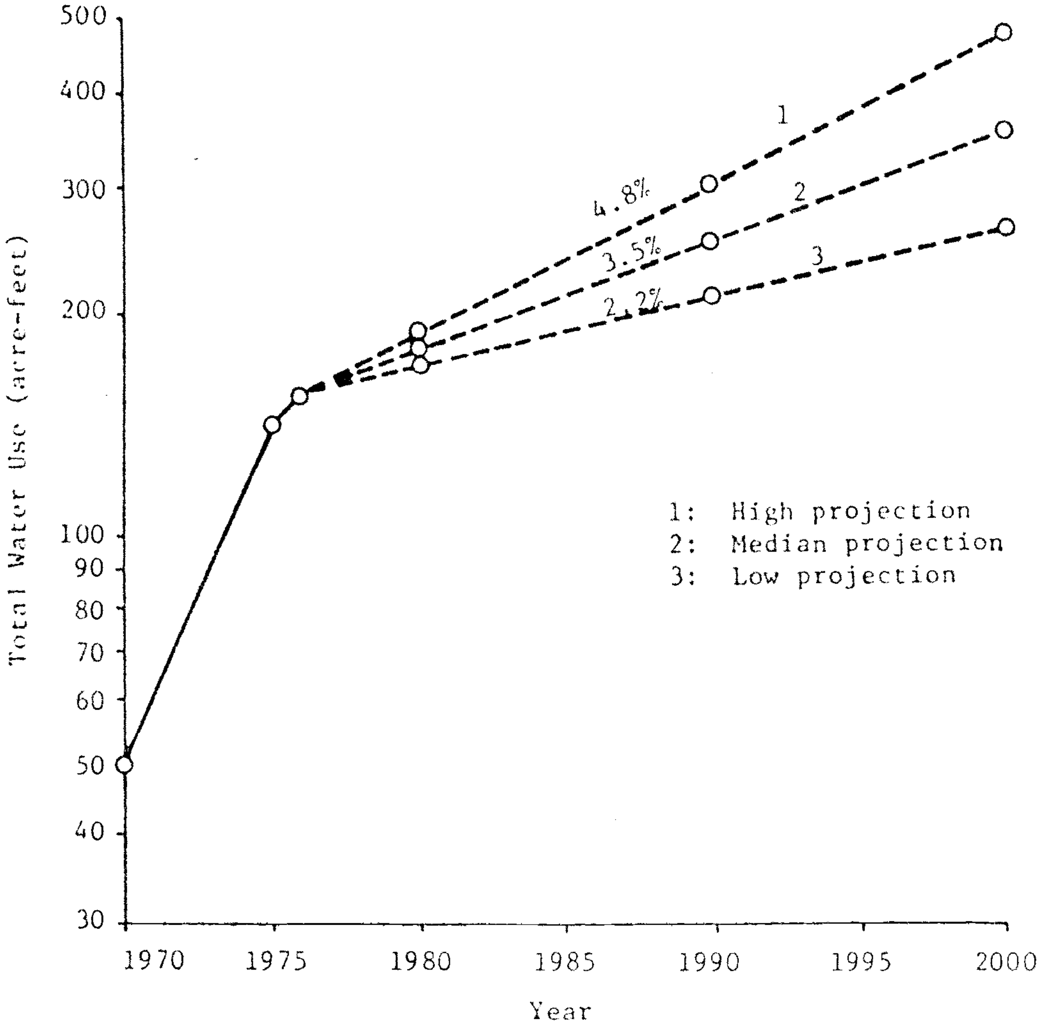


Figure 3. Total Water Use in Patagonia, Arizona, 1970-1976, and Forecast to the Year 2000. -- Based on population forecast, water use records from the Patagonia, Arizona, Town Clerk, and assumed rate of water use for the year 2000 equal to 0.23 acre-feet per year (75,000 gallons per person per year).

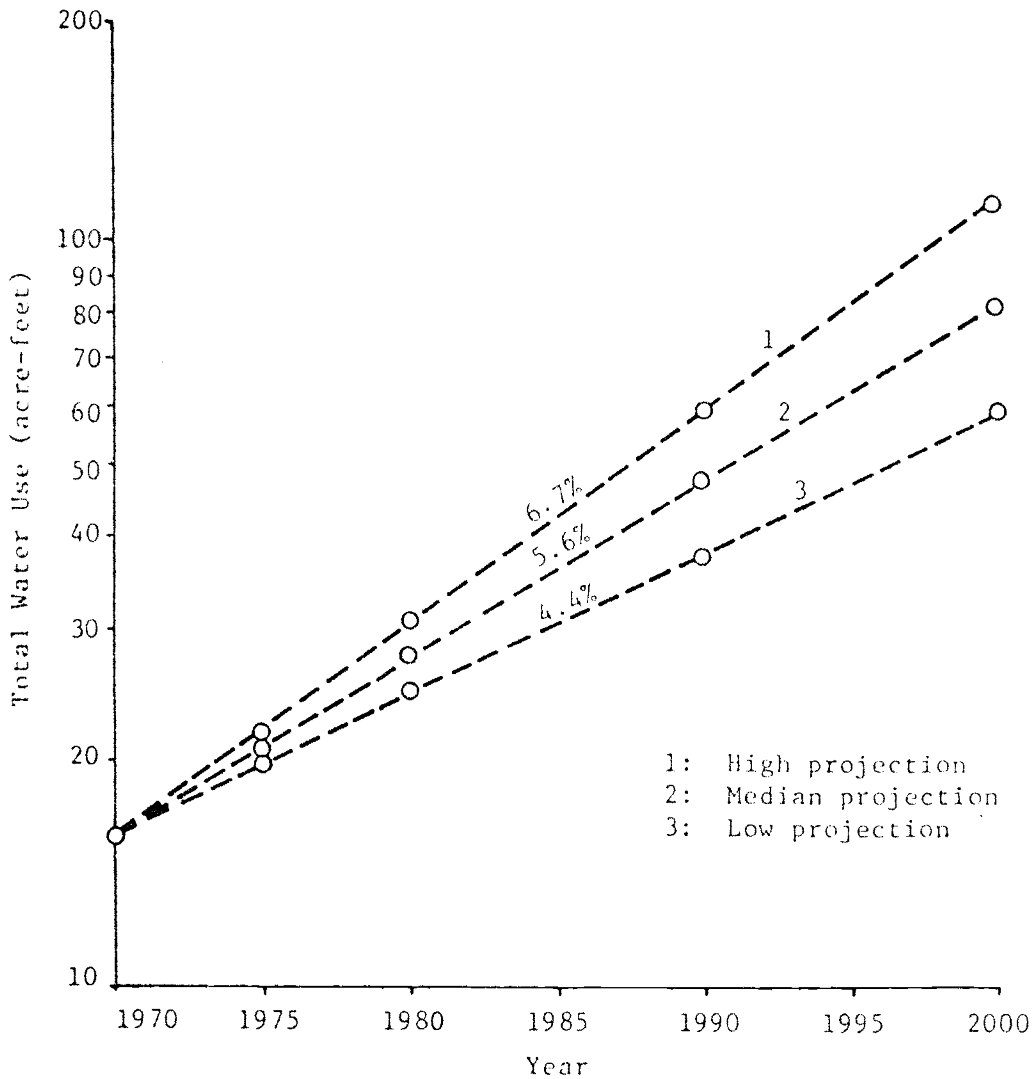


Figure 4. Total Water Use in Sonoita, Arizona. -- Projections for 1970-2000 are based on population projections and assumed rate of water use equal to 0.23 acre-foot per person per year by the year 2000.

downstream of Patagonia to about two miles upstream from Lake Patagonia. The sanctuary has served as a refuge for several species of rare and endangered fish and birds a list of which is given in the Office of Economic Planning and Development (OEPD) 1974 report. The Arizona Nature Conservancy District, in an effort to protect the wildlife in the sanctuary, is taking measures to maintain its unique environment. The continued perennial flow of good quality water through the tract is imperative in maintaining the environment and the wildlife it houses.

Through consultation with E. A. Stutt of the Department of Ecology and Evolutionary Biology, University of Arizona (1978), and Sol Resnick of the Water Resources Research Center (1978), a flow of 0.5 cfs was adopted as the minimum that was required to maintain the environmental status of the sanctuary (Diaz-Pena, 1978). This requirement is usually met by the natural flow in the creek throughout most of the year, even in dry years. However, in the future, the flow during the driest periods of the year may have to be maintained by artificial means.

The quality of water in the sanctuary is also of major concern. The Patagonia sewage treatment plant discharges treated sewage effluent into Sonoita Creek at the northern edge of the sanctuary. The quality of the effluent is very good, therefore its effect on the quality of water in the creek should be minimal. However, the high nitrate content of the effluent may encourage thick growth of weeds in the stream eventually clogging it and endangering the fishlife therein.

Although the return flow (both surface and subsurface) from the tailings ponds used by the mines could be a source of pollution, the quantity and quality of such flows are too uncertain to be considered in this study.

The water quality requirements for the creek are those prescribed by the EPA (1970) for fresh-water aquatic life.

Lake Patagonia: To maintain its function as a recreation facility water levels in Lake Patagonia should not fall under 5 feet below spillway crest. Otherwise the marina would become unusable and the beaches would be exposed and unattractive.

Many factors influence the water level in the lake. The most important ones are surface inflow, evaporation, precipitation and releases. In addition, the possibility of using the lake for water supply should be considered. An operation study was needed to determine the influence of these factors on water levels in the lake. This was done in the section on surface water resources of the basin.

Quality standards for the water in the lake are those recommended by the EPA (1970).

Agriculture. Agricultural activities in the basin are expected to remain reasonably constant over the next twenty years. The amount of water pumped by agriculture in 1975 was estimated to be about 600 acre-feet. This is expected to remain the same throughout the planning period.

Water quality standards are those stated by the EPA (1970) for agricultural purposes.

Rural Use. Total water used by rural residences and cattle ranches was estimated to be about 180 acre-feet in 1975. All of this water is obtained from private wells and perhaps a few springs. Rural water supply is assumed to be adequate and should not be affected by activities elsewhere in the area.

Environment

The environmental status of the Sonoita Creek sanctuary, Lake Patagonia and the National Forest areas should not be negatively affected. Water requirements for the sanctuary and lake have been discussed under water demand for recreation. In addition ground water levels in the vicinity of the sanctuary should not fall to levels where the vegetation will wilt or die because of lack of water. This requirement is significant especially if ground water pumping in Patagonia is excessive.

The environment of the National Forest may be affected by building a reservoir at Redrock Canyon. Within limits, this may be acceptable since the reservoir would be protecting other parts of the environment from the effects of excessive ground water depletion.

Disposal of Treated Sewage Effluent

Figure 5 gives the projected discharge of treated sewage effluent from the Patagonia plant. These projections are based on the water-use projections shown on Figure 3 with the assumption that volume of effluent equals 70 percent of total water use.

The management plan should provide means for the disposal of the high projection in Figure 5. Reuse of the effluent should be considered.

Flexibility

The plan should be flexible enough to cope with the many uncertainties which characterize the problem. These uncertainties include natural, strategic, technological and informational uncertainties.

Systems Evaluation Criteria

The systems evaluation criteria are measures of effectiveness (MOE) which determine the effectiveness of the proposed systems in meeting the

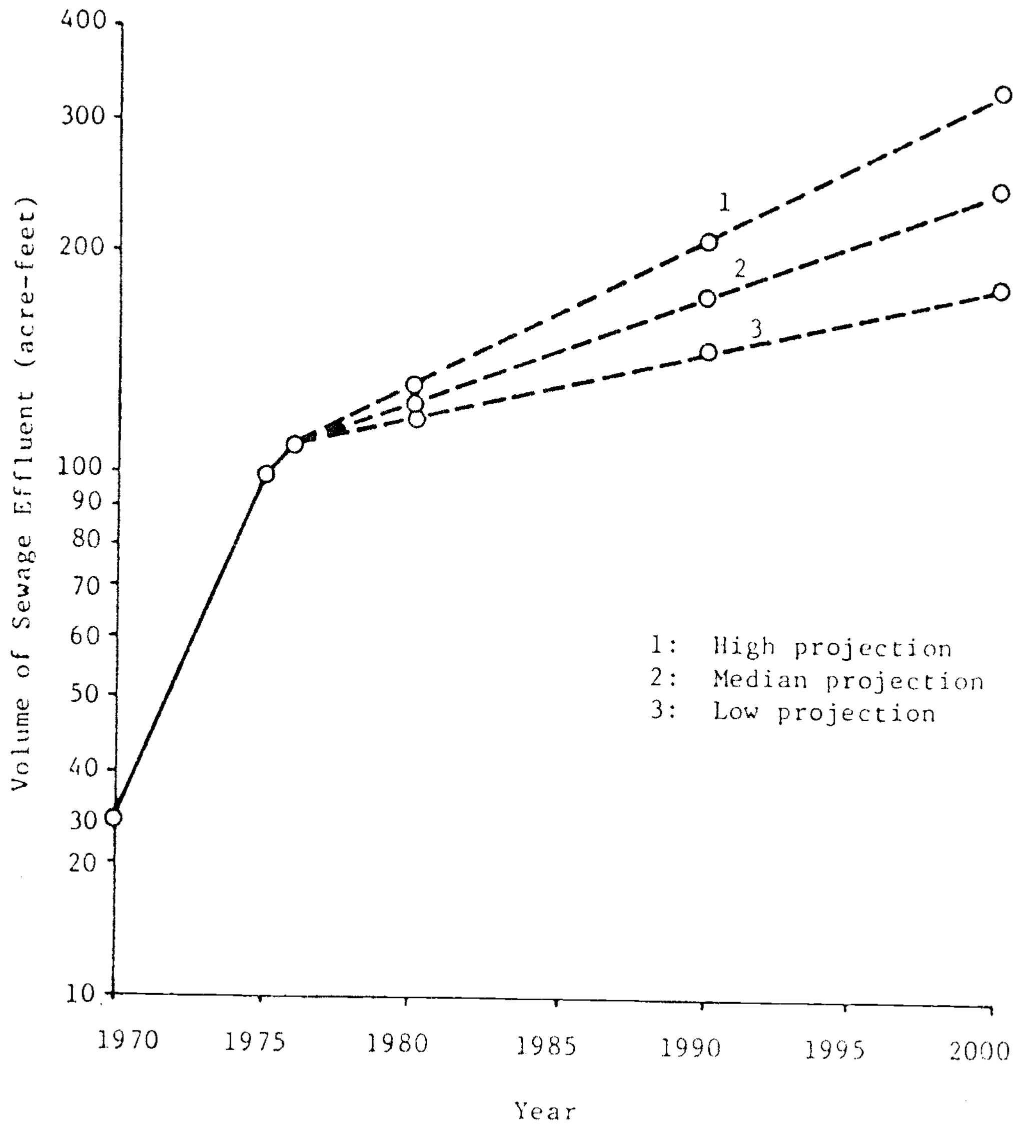


Figure 5. Sewage Water Effluent from Patagonia, Arizona. -- Projections to the year 2000 based on ADEPD (1971) report and estimated volume of domestic water use.

requirements. Selection of adequate criteria is generally based on professional judgment that is augmented by experience (Kazanowski, 1968)

Water Demand

Municipal and Domestic. The criteria for municipal and domestic water demand is an opportunity loss measured by the number of people that cannot live in the community for each acre-foot shortage of water. Tables 3 and 4 give the opportunity loss functions for the communities of Patagonia and Sonoita, respectively. These values represent the ratio between the projected population and the projected water use for the given year.

The criteria for water quality is given the qualitative rating of "very good", "good", "fair" or "poor."

Recreation. The criteria for water-quantity demand for Sonoita Creek is the probability that the minimum flow falls below the required flow of 0.5 cfs. It is practically impossible to obtain numerical estimates of these probabilities for each system because of the numerous uncertainties involved. Consequently, the qualitative ratings of "very likely", "likely", "unlikely" and "very unlikely" are adopted.

For Lake Patagonia, the criteria for water quantity demand should be an opportunity loss associated with the number of people that cannot or would not use the facility, as a function of water level depths below spillway crest. The present state of knowledge does not allow for determination of such a function because too many subjective elements are involved. However, the criteria can be expressed in qualitative terms as follows: acceptable for water levels in the lake that are not lower than 5 feet below spillway crest and unacceptable for lower levels.

The criteria for water quality demand for recreation are given the ratings of "very good", "good", "fair" or "poor."

Agriculture. The number of acres of agricultural lands that cannot be irrigated due to a shortage of water is the measure used for agricultural water demand. Using an estimate of 4 acre-feet of water per acre of irrigated land per year (for the Box-T Ranch), each acre-foot shortage of agricultural water leaves 0.25 acres unirrigated.

The criteria for agricultural water quality is "very good", "good", "fair" or "poor".

Environment

The environmental impact of each alternative on the sanctuary, lake and national forest is assessed using the following qualitative measures: "very beneficial", "beneficial", "unaffected", "detrimental" or "very detrimental".

Table 3. Opportunity loss for Patagonia

Year	Population per Acre-foot per Year
1980	5.00
1985	4.78
1990	4.50
1995	4.32
2000	4.26

Table 4. Opportunity loss for Sonoita

Year	Population per Acre-foot per Year
1980	8.68
1985	7.44
1990	6.15
1995	5.24
2000	4.35

Disposal of Treated Sewage Effluent

The effectiveness of the systems with respect to sewage effluent disposal is measured by the fraction of effluent not utilized.

Flexibility

The flexibility of the systems is measured by their ability to cope with uncertainties (sensitivity) and the ease with which they can be transformed in the future. Correspondingly, the two criteria are: "not sensitive", "sensitive", or "very sensitive"; and "not easy", "easy" and "very easy".

Selection of Fixed-Cost or Fixed-Effectiveness Approach

The choice between fixed-cost and fixed-effectiveness approaches is necessary in CE analyses and is, in general, not a trivial decision (Kazanowski, 1968). In the fixed-cost approach the alternatives are judged on the basis of the amount of effectiveness achieved for a given expenditure of resources. In the fixed-effectiveness approach the alternatives are evaluated on the basis of the amount of cost incurred or resources required to obtain a given level of effectiveness.

The nature of the objectives, which require certain minimum requirements to be met, necessitated the selection of a fixed-effectiveness approach.

Development of Alternative Systems

The importance of this step is stressed by Kazankowski who states that "the results of the evaluation can be no better than the conception of attractive candidate systems" (1968, p. 120). For this study the candidate systems are defined in sufficient detail to allow fairly reliable estimates of costs and effectiveness measures to be made.

Suitable alternatives were conceived by Diaz-Pena (1978) and Sol Resnick (1978). A brief description of each alternative is now given.

Alternative I

The first alternative considers the situation where the ground water resources in Patagonia are further developed to meet future municipal and domestic water needs in the city. The water needs of Sonoita and rural dwellings and ranches will continue to be supported by private wells and springs. Agricultural activity will continue to depend on pumped ground water at the Box-T Ranch and spring water at the Rail-X Ranch.

The existing sewage treatment plant in Patagonia would be expanded to accommodate the projected increase in sewage effluent. Discharge of effluent from the plant, into Sonoita Creek, will continue at the present site, at the northern edge of the sanctuary.

No provisions are made to supplement flow in the sanctuary.

Figure 6 illustrates the general movement of water in this system.

Alternative II

This alternative considers the piping of treated sewage effluent from the plant nine miles to a point downstream from Lake Patagonia where it is allowed to infiltrate into the alluvial deposits of the stream bed. The effluent would be driven by gravity. All other components of this alternative are the same as for Alternative I. Figure 7 shows the movement of water in this system.

Alternative III

The alternative features the building of a small reservoir at Redrock Canyon. This reservoir would serve primarily as a supplemental source of water for the town of Patagonia and for the Sonoita Creek Sanctuary when the base flow is critically low (below 0.5 cfs).

This alternative may require the construction of a water treatment facility to treat the water for municipal and domestic use. However, as discussed later, this alternative can be implemented in stages and the performance of the system evaluated at each stage. This could eliminate very expensive components of the alternative which werd originally thought to be necessary.

The other components of the alternative, namely effluent disposal and water demands for agriculture and rural activities, are the same as for Alternative II. Figure 8 shows the movement of water through this system.

Alternative IV

Treated sewage effluent from the Patagonia treatment plant would be piped 1.5 miles to the Box-T Ranch where it would be used for irrigation. This venture would save precious ground water which would normally be used for irrigation.

The water supply component of this system is the same as for Alternative I. It entails developing the ground water resources in Patagonia to meet future water demands in the town. No provisions are made to maintain the minimum base flow through the sanctuary. The general movement of water in this system is shown in Figure 9.

Alternative V

This alternative considers the possibility of using Lake Patagonia for water supply in a manner similar to the use of the Redrock reservoir. The sewage effluent disposal component of this system is the same as for

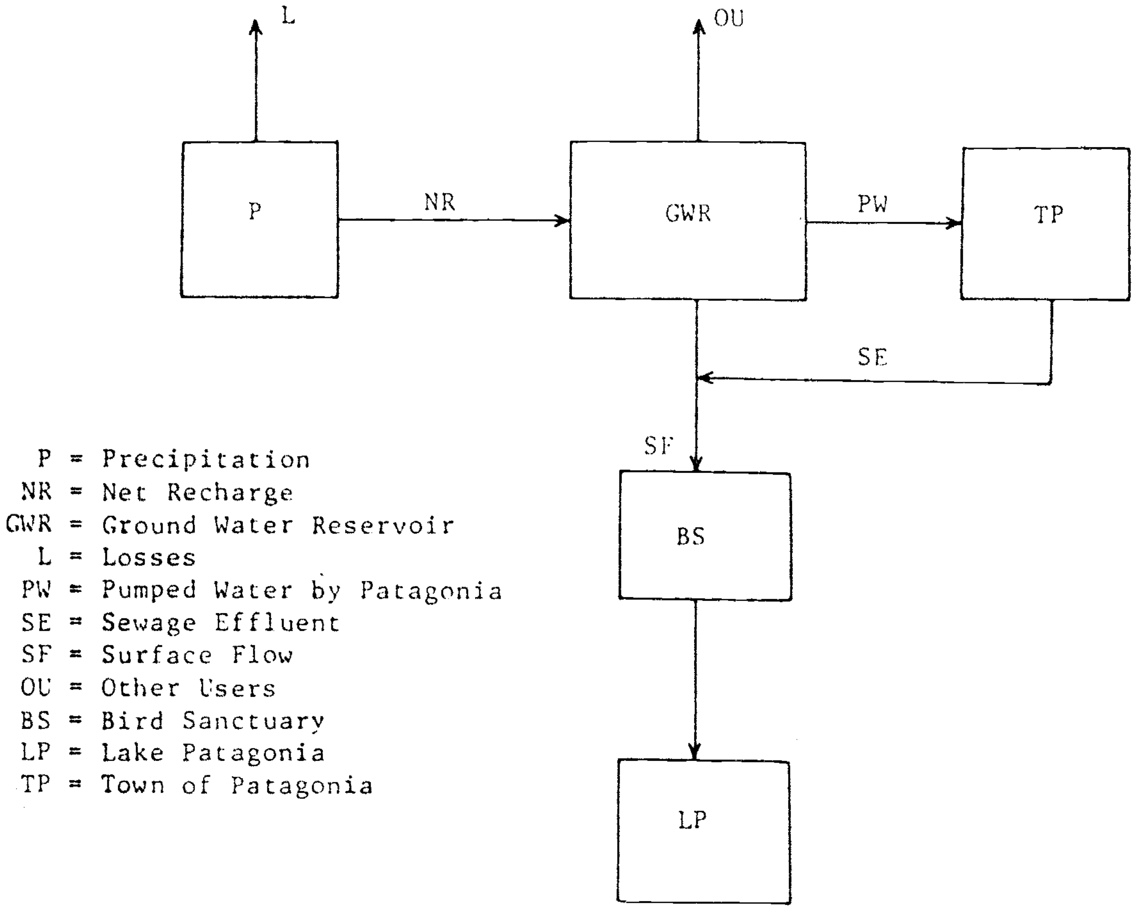


Figure 6. Alternative System I for the Sonoita Creek watershed.

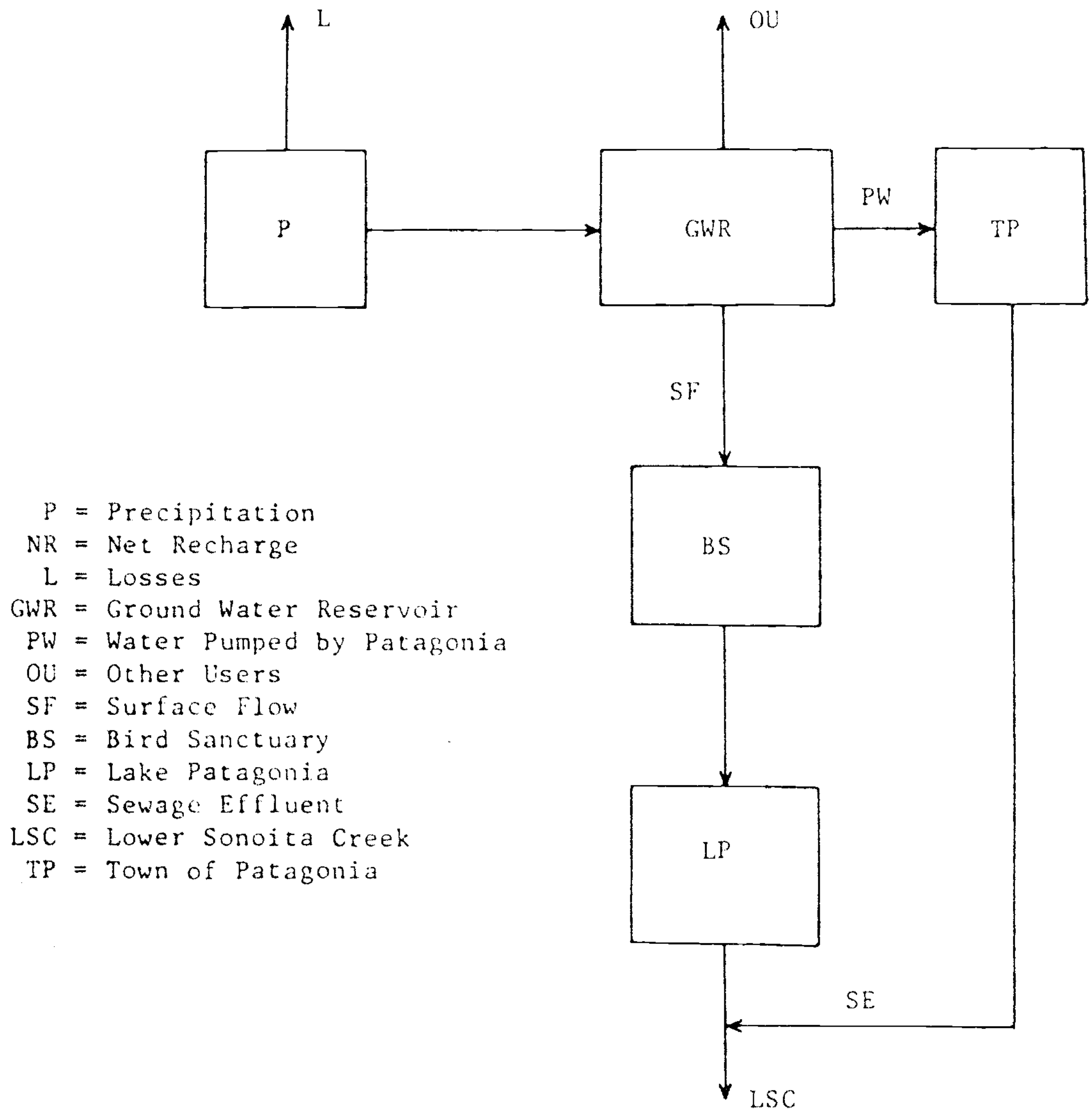


Figure 7. Alternative System II for the Sonoita Creek watershed.

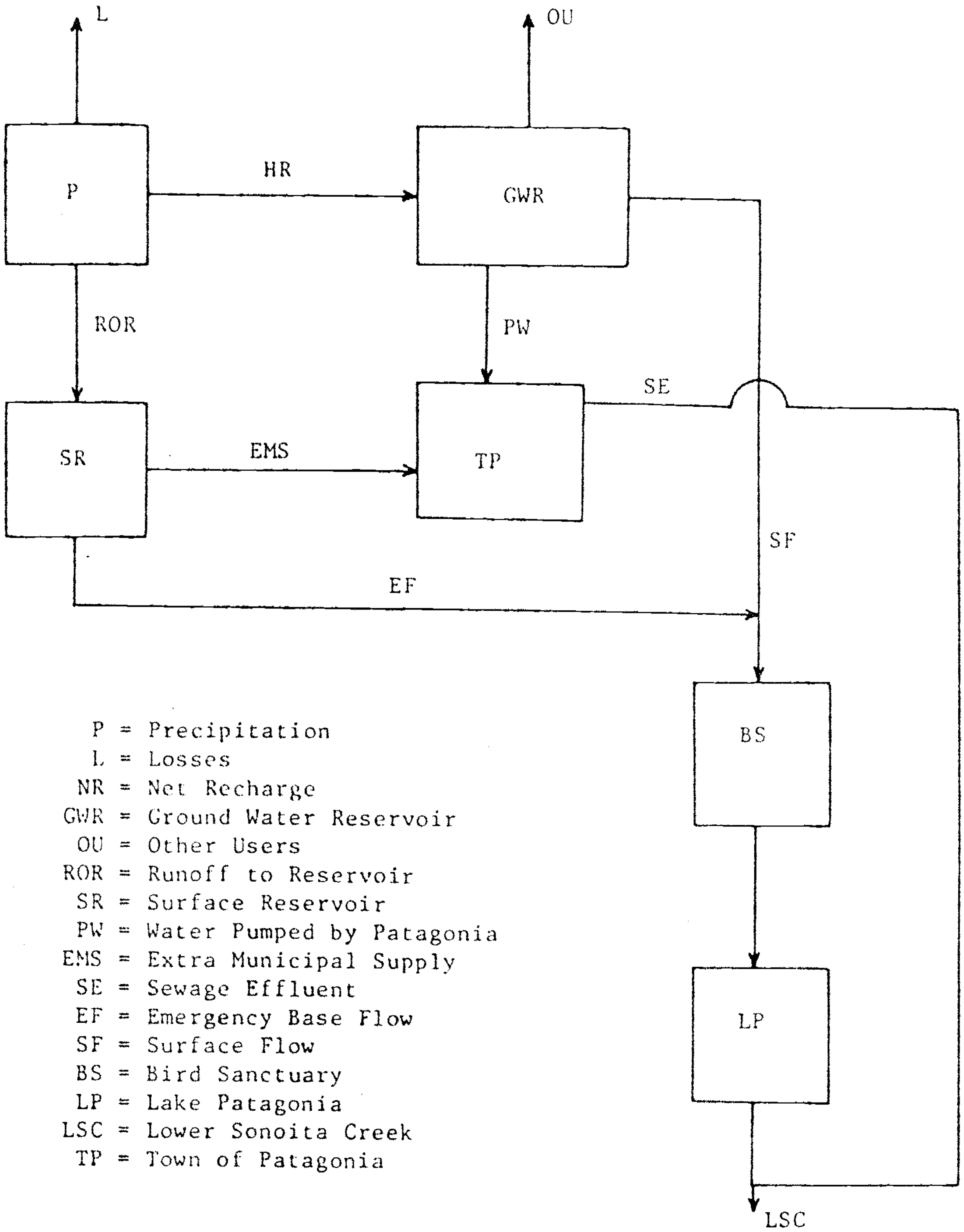
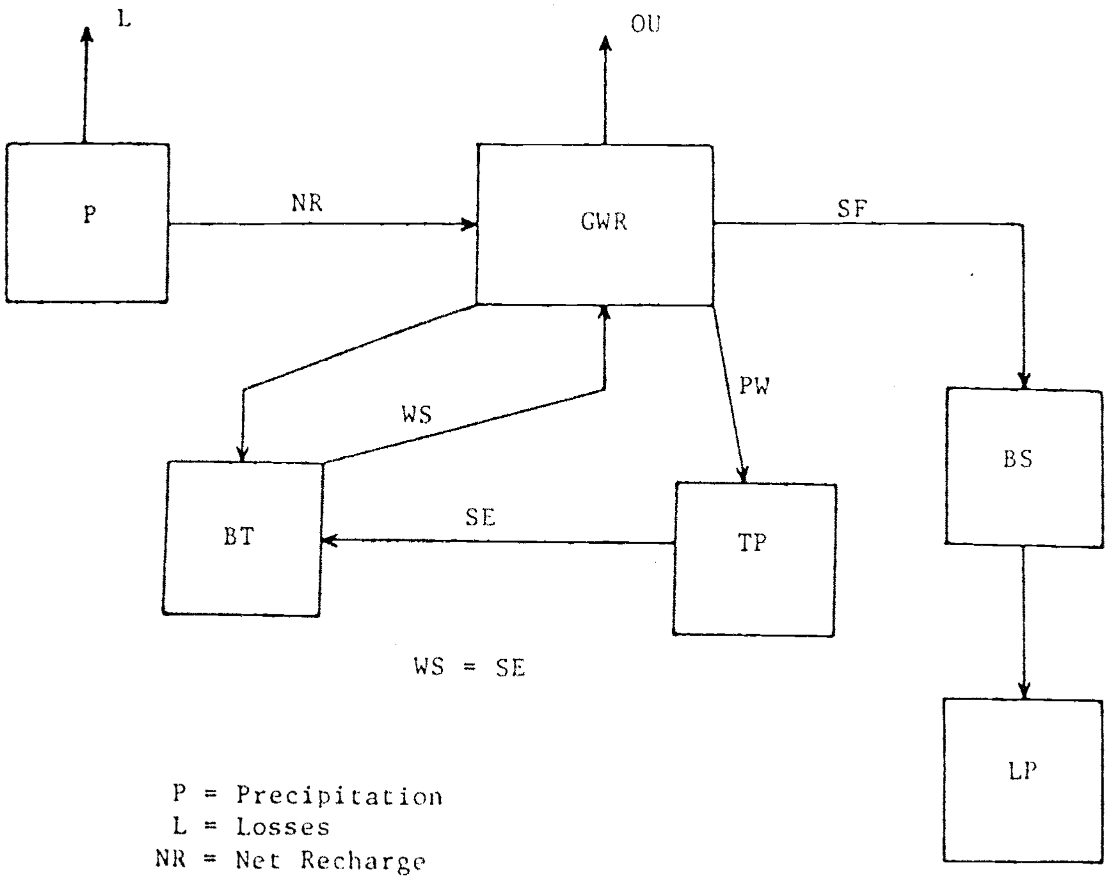


Figure 8. **Alternative System III for the Sonoita Creek watershed.**



P = Precipitation
L = Losses
NR = Net Recharge
GWR = Ground Water Reservoir
PW = Water Pumped by Patagonia
BT = Water Pumped by Box-T Ranch
OU = Other Users
SE = Sewage Effluent
WS = Water Saved from Agriculture
SF = Surface Flow
BS = Bird Sanctuary
LP = Lake Patagonia
TP = Town of Patagonia

Figure 9. Alternative System IV for the Sonoita Creek watershed.

Alternative II which involves piping the effluent, by gravity, beyond Lake Patagonia. Figure 10 illustrates the movement of water in this system.

Alternative VI

Treated sewage effluent from the Patagonia treatment plant would be piped about six miles to the Rail-X Ranch where it would be used for irrigation. An equal amount of water from Monkey Spring would be saved. The water supply component of this system is the same as in Alternatives I and II. This requires the development of the well system in Patagonia to meet future municipal and domestic water demands. Figure 11 illustrates the movement of water an this system.

Table 5 displays the main characteristics of each alternative in a manner which affords a quick comparison of the systems.

Capabilities of Alternative Systems

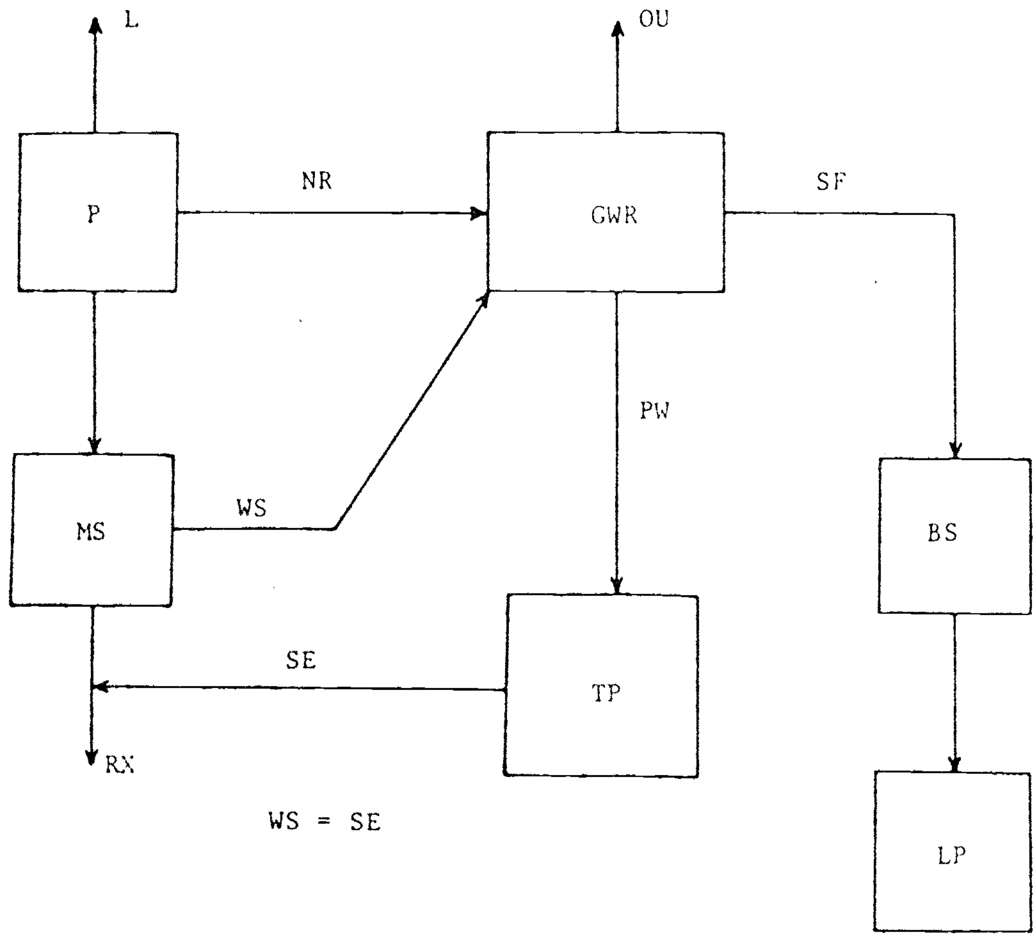
Once appropriate criteria have been identified and the candidate systems have been adequately defined, the next step is to express the abilities of these systems in terms of the criteria. In this study many of the criteria could not be quantified. In such cases qualitative measures were employed. The capabilities of each system, in terms of the developed criteria, is exhibited in the systems-versus-criteria array which is discussed next. Cost estimates for each alternative are given in Appendix A.

Systems-versus-Criteria Array

The systems-versus-criteria array is easily generated once the abilities of the candidate systems have been expressed in terms of the criteria. Let the criteria be identified as row entries and arranged in decreasing order of importance, while the systems are listed as column entries. This arrangement is particularly useful when many alternatives are being evaluated because less attractive candidates can be eliminated easily leaving the main contenders. The ultimate selection of the best system or systems is usually based on a judicious evaluation of the systems capabilities and requirements.

Generation of the systems-versus-criteria array, as suggested above, implies that the decision maker (DM) is able to rank the criteria by order of importance. The result of the evaluation depends on the importance assigned to each criterion. Therefore, it is of utmost importance that highly knowledgeable individuals be involved in the ranking process.

The ordering of the criteria for this study was done by Diaz-Pena (1978) in consultation with individuals who were considered to have considerable knowledge about the problem and the study area. Table 6 is a list of the evaluation criteria arranged by order of importance. Cost is listed first



P = Precipitation
L = Losses
GWR = Ground Water Reservoir
NR = Net Recharge
PW = Water Pumped by Patagonia
SE = Sewage Effluent
MS = Monkey Spring
RX = Water Used by Rail-X Ranch
WS = Water Saved from Agriculture
SF = Surface Flow
BS = Bird Sanctuary
LP = Lake Patagonia
OU = Other Users
TP = Town of Patagonia

Figure 11. Alternative System VI for the Sonoita Creek watershed.

Table 5. Main characteristics of each alternative

Alternative Systems	Patagonia Municipal Water Supply	Sewage Effluent	Agricultural Water Supply	Base Flow in Sonoita Creek Sanctuary	Lake Patagonia
I	From existing well and new wells in the future	Released at site upstream from Sonoita Creek Sanctuary	Unchanged, from wells and springs	No provisions made for maintaining minimum flow through Sonoita Creek Sanctuary	No use for water supply within the basin
II	Same as in Alternative I	Piped downstream of Lake Patagonia dam	Same as in Alternative I	Same as in Alternative I	Same as in Alternative I
III	From existing well and from Redrock Reservoir	Same as in Alternative I	Same as in Alternative I	Minimum flow assumed through sanctuary by water from Redrock Reservoir	Same as in Alternative I
IV	Same as in Alternative I	Pumped 1 mile up-stream for use in Box-T Ranch for irrigation	Box-T supple-mented with secondary treated sewage effluent	Same as in Alternative I	Same as in Alternative I
V	From existing well and from Lake Patagonia	Same as in Alternative I	Same as in Alternative I	Minimum flow assumed through sanctuary by water from Lake Patagonia	Used for supplemen-tary water supply to Patagonia and Sonoita Creek Sanctuary
VI	Same as in Alternative I	Pumped 6 miles up-stream for use in Rail-X Ranch for irrigation	Rail-X supple-mented with secondary treated sewage effluent	Same as in Alternative I	Same as in Alternative I

Table 6. List of criteria in order of importance

Requirement	Criteria	Rank
Cost	Magnitude	1
Water Quantity Demand		
i) Municipal	Number of people not able to live in community	2
ii) Recreational		
a) Sanctuary	Likelihood of shortage	3
b) Lake Patagonia	Acceptability	3
iii) Agricultural	Number of acres unirrigated	4
Water Quality Demand	Degree of quality	
i) Municipal		5
ii) Recreational		
a) Sanctuary		5
b) Lake Patagonia		5
iii) Agricultural		5
Environment	Effects	
i) Sanctuary		6
ii) Lake Patagonia		6
iii) National Forest		6
Treat Effluent Disposal	Fraction reused	6
Flexibility		
i) Sensitivity	Degree of sensitivity	7
ii) East of Transformation	Degree of trnasformability	7

because, in the fixed-effectiveness approach, cost becomes the most important criterion by which the systems are judged. Water quantity demand for municipal and domestic purposes is considered to be the most important non-monetary criterion. Flexibility, although listed last, is very important and should not be overlooked when judging the alternatives.

Kazanowski (1968) stressed the importance of having as few criteria as possible as long as this does not invalidate the results of the evaluation. With this in mind the criteria which measures flexibility (namely, sensitivity and ease of transformation) have been reduced to one; namely, degree of flexibility.

Table 7, the cost-effectiveness table, shows the capabilities of the systems with respect to each criteria. To improve clarity, the alternatives are arranged horizontally and the criteria vertically in decreasing order of importance.

Merits of Alternative Systems

Once the CE tableau has been generated dominated systems, those that are inferior in all respects to other systems, may be readily eliminated. A careful look at Table 7 shows that no system is totally dominated, therefore, no elimination can be made on this basis.

Systems can be eliminated on the basis that they do not achieve a certain minimum level of effectiveness for a given requirement. For instance, if a likely shortage of water for the sanctuary is considered unacceptable then all systems except III and V would be eliminated. These two systems would then be evaluated on the basis of the level of effectiveness achieved for each requirement and the cost incurred. If fair or bad water quality is considered unacceptatle for municipal and domestic purposes, system IV would be eliminated. Similarly, system I can be eliminated if fair water quality for the sanctuary is unacceptable. On the basis of many such evaluations system I was removed from further consideration since that system does not meet minimum acceptable levels of effectiveness for several important requirements. Also, system AV was disqualified because fair water quality, for municipal and domestic uses, was considered unacceptable.

If budgetary constraints were important then the more expensive alternatives may be eliminated. For example, if 1,000,000 dollars was the maximum that could be spent on any given system, alternative V would be disqualified.

The analysis that follows assumes that the remaining four systems (namely, alternatives II, III, V and VI) met all the requirements, in terms of cost and effectiveness, for them to be considered feasible. These systems have several levels of effectiveness, or ratings, in common. The criteria for which each system has the same level of effectiveness can be omitted and the systems evaluated on the basis of the remaining criteria. The modified CE tableau is given in Table 8.

Table 7. Cost-effectiveness tableau

Requirements	Criteria	Criterion #	Alternatives I	II	III	IV	V	VI
Cost	Magnitude	1	$157,000	$355,000	$927,000	$423,000	$1,612,000	$742,000
Water Quality								
i) Municipal	Number of people not able to live in community	2	0	0	0	0	0	0
ii) Recreational								
a) Sanctuary	Likelihood of shortage	3	Likely	Very likely	Very unlikely	Likely	Very unlikely	Likely
b) Lake Patagonia	Acceptability	4	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
iii) Agriculture	Number of acres not irrigated	5	0	0	0	0	0	0
Water Quality	Degree of quality							
i) Municipal		6	Good	Good	Very good	Fair	Very good	Good
ii) Recreational								
a) Sanctuary		7	Fair	Very good	Very good	Very good	Very good	Very good
b) Lake Patagonia		8	Very good	Very good	Very good	Very good	Very good	Very good
iii) Agricultural		9	Fair	Fair	Fair	Fair	Fair	Fair
Environment	Effects							
i) Sanctuary		10	Very detrimental	Beneficial	Very beneficial	Beneficial	Very beneficial	Beneficial
ii) Lake Patagonia		11	Unaffected	Unaffected	Unaffected	Unaffected	Detrimental	Unaffected
iii) National Forest		12	Unaffected	Unaffected	Detrimental	Unaffected	Unaffected	Unaffected
Treat Effluent Disposal	Fraction Reused	13	0	1	1	1	1	1
Flexibility	Degree of flexibility	14	Very good	Very good	Very good	Very good	Very good	Very good

Table 8. Modified cost-effectiveness tableau

Requirements	Criteria	Criterion Number	Alternatives II	Alternatives III	Alternatives V	Alternatives VI
Costs	Magnitude	1	$355,000	$927,000	$1,612,000	$742,000
Water Quantity						
Sanctuary recreation	Likelihood of shortage	2	Very likely	Very unlikely	Very unlikely	Likely
Water Quality						
Municipal	Degree of quality	3	Good	Very good	Very good	Good
Environment	Effects					
i) Sanctuary		4	Beneficial	Very beneficial	Very beneficial	Beneficial
ii) Lake Patagonia		5	Unaffected	Unaffected	Detrimental	Unaffected
iii) National Forest		6	Unaffected	Detrimental	Unaffected	Unaffected

The task of selecting the best system or systems is now undertaken. David and Duckstein (1976) presented a methodology that can be used for ranking alternatives or reducing the choice set to a small number of systems. This algorithm, known as Electre I, is selected because of its simplicity and the fact that its usefulness has been shown in many previous examples.

Electre I Algorithm

Let each system, i or j = 1,...,4 be characterized by a set of criteria, v = 1,...,6. The event that system j is preferred to system i for a given criterion is denoted $i<j$, and the case when i and j are equivalent is denoted i = j. In the Electre I algorithm the systems are compared using two indices called the concord index and the discord index.

Concord Index. The concord index, c(i,j), denotes the weighted relative frequency of viewpoints (criteria) where system j is preferred to system i. To define this index, let the criteria be divided into two classes: important criteria which are weighted "two" and secondary criteria with a weight of "one". Table 9 displays this classification. The concord index between systems i and j with a hypothesis $i<j$ is defined as:

$$c(i,j) = \frac{\text{sum of weights for criteria where } i<j}{\text{total sum of weights}}$$

For the case where i=j half the weight is used. Table 10 gives the concord indices for all the possible pairs of systems.

Discord Index. The discord index indicates the strength of the viewpoints in greatest disagreement with the hypothesis $i<j$. To define this index an interval scale common to all criteria should be defined which enables comparison of differences between alternatives. A certain number of points out of a maximum of 20 is assigned to each criterion. This leads to the intervals given in Table 9. These intervals can be interpreted as follows: environmental effects on the sanctuary are given a total interval of 15 which means that the difference between consecutive values of this criterion is 3 (there are five values for this criterion). The discord index, d(i,j), is then defined as the maximum normalized discord interval as follows:

$$d(i,j) = \frac{\text{maximum interval where } i>j}{\text{total range of scale}}$$

The discord indices between each possible pair of systems are given in Table 11.

Composite Graphs. With the concord and discord matrices having been determined the next step in the ELECTRE I methodology is to determine the dominant system or systems. This can be achieved with the use of composite graphs. These are graphs with each system occupying a node, and arrows indicating the preferred system. For example, II → III indicates that

Table 9. Evaluation criteria with their weights and scale interval for computing concord and discord indices

Number	Criteria	Weights (for Concord Index)	Maximum Scale Intervals (for Discord Index)
1	Costs	2	20
2	Likelihood of shortage of water for sanctuary	2	18
3	Degree of quality of municipal and domestic water	2	16
4	Environmental effects on sanctuary	2	15
5	Environmental effects on Lake Patagonia	1	15
6	Environmental effects on National Forests	1	15

Table 10. Concord Indices Matrix

System	II	III	V	VI
II	--	0.65	0.65	0.50
III	0.35	--	0.40	0.35
V	0.35	0.55	--	0.35
VI	0.50	0.56	0.56	--

Table 11. Discord Indices Matrix

System	II	III	V	VI
II	--	0.36	0.78	0.24
III	0.75	--	0.42	0.40
V	0.75	0.20	--	0.50
VI	0.25	0.20	0.53	--

system III is the preferred system. Composite graphs are defined by controlling the concord and discord indices simultaneously. More precisely, an arrow, $i \to j$, is in the composite graph only if the concord index, $c(i,j)$, is greater than or equal to a parameter p and the discord index, $d(i,j)$, is less than or equal to a parameter q.

Composite graphs, defined for various values of (p,q) are shown in Figure 12. The graphs clearly indicate that system III, the Redrock Reservoir alternative, is the dominant alternative under the assumptions of the algorithm. This is true for at least the range, $0.65 \geq p \geq 0.50$ and $0.25 \leq q \leq 0.50$, which shows that for this example the choice of systems resulting from ELECTRE I is fairly insensitive to the threshold values (p,q).

Sensitivity Analysis

In many instances the result of a cost-effectiveness analysis is very sensitive to the assumptions made. In some cases the conclusions reached may be significantly biased by these assumptions which are essential to the analysis. To be sure that the results are not dependent upon such biases, it is generally essential that sensitivity analyses be performed. This usually consists of careful reexamination of the previous steps and modifying assumptions, variables, estimates, etc. when they are based on subjective judgment and sketchy data.

In a study such as this, complete sensitivity analysis could be a research topic in itself. The task of covering the entire spectrum of assumptions will not be undertaken. Those assumptions which are characterized by several degrees of uncertainty and subjectivity will be examined in more detail. In general, these are the assumptions which have the most influence on the results of the analysis.

Objectives and Requirements

The main objective of the Sonoita Creek study is to develop a viable water management plan for the area. The plan should be able to meet the likely water demands of the basin, namely, municipal and domestic, recreation and agriculture.

It was considered unlikely that the mining companies would depend on water from within the basin to meet their demands. The main reason for this is the fact that the mining operations require large quantities of water. This, coupled with the fact that the water resources potential of the basin is quite small, forced the mining companies to look elsewhere for their water supply.

Municipal and domestic water use projections, although quite uncertain, are considered to be on the safe side. It was assumed that the city will be required to meet all municipal and domestic demands. This is not quite

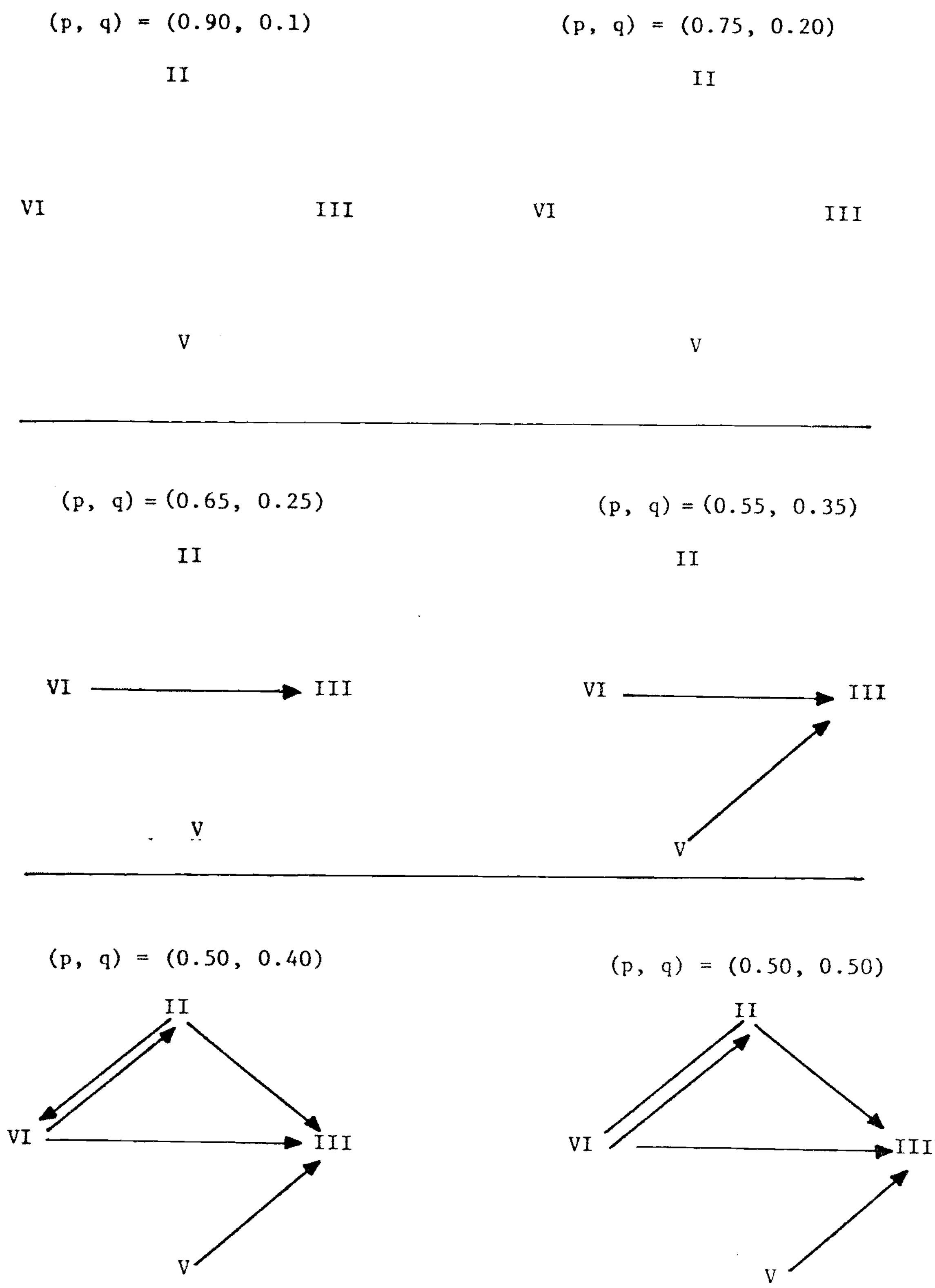


Figure 12. Composite graphs of ELECTRE I.

correct because many households still depend, and will continue to depend, on their own private wells to meet their water demands. This, coupled with the fact that unusually high (high for a small, unurbanized town) per capita water use rates were assumed supports the conjecture that municipal and domestic demands have been overestimated. It is, therefore, quite unlikely that these demands will be significantly higher than the projections. Even if demands are underestimated, the selected system, the Redrock alternative, is best equipped to handle this situation. If municipal and domestic demands are significantly lower than projected, this system would still be quite adequate; however, it is conceivable that a lower-cost system may have been preferred. A lower-cost system would most definitely depend largely on the ground water resources of the basin to meet municipal and domestic demands. As pointed out earlier, the placement of city wells is quite restricted because of the quality of the ground water in the area. The ground water best suited for municipal and domestic consumption is found where the well yields are just average. Therefore, a lower cost may not be quite adequate in terms of the quality of the water.

The water demands for recreation and agriculture are fixed and are expected to remain that way for some time in the future.

The projection of sewage effluent produced in Patagonia is just as uncertain as the projection for municipal and domestic water demand. However, the amount of effluent was not a major factor in the selection of the best system. Rather, the impact of the effluent on the environment and water supply was considered to be very important. Therefore, the production of significantly more or less effluent would not influence the choice of systems.

An important consideration which was not included as an objective in the cost-effectiveness analysis is the use of Lake Patagonia for flood-control purposes. This objective would be in conflict with the other objectives of water supply and recreation, and, perhaps, would significantly change the outcome of the analysis. It must be pointed out that significantly different alternatives would have been developed if flood control had been included as an alternative.

Systems Evaluation Criteria

The criteria measure the effectiveness of the systems in meeting the requirements and hence the objectives. It is, therefore, of uttermost importance that suitable and adequate criteria are developed. In a complex multiobjective problem, many important factors are unquantifiable. As a result, many of the measures of effectiveness have to be expressed in qualitative terms. This introduces significant subjectivity into the analysis, the consequences of which are difficult to predict. For instance, the use of more (or less) levels of appreciation for each criterion could affect the relative rating of a given system for that criterion. Even with the same number of appreciation levels for each criterion, a different analyst may rate each system differently. As long as the rating given to each system is consistent and reflects the decision maker's preferences, the results of evaluations by different analysts should also be consistent.

Costs. In the fixed-effectiveness approach, cost becomes the most important criterion by which the systems are judged. It is, therefore, important that fairly reliable estimates of cost be made. The cost estimates, in this thesis, are based mainly on information obtained from local dealers and contractors, and represent the best available estimates that can be made at the present time. In order to obtain very accurate cost estimates, the systems definition must be precise and detailed, a situation which is not generally recommended in cost-effectiveness analysis.

The choice of systems may be quite sensitive to cost. For instance, although systems III and V are about equally effective in meeting other requirements because of the big cost differential, system V was never preferred to the other three candidates for any values of p and q (see Figure 12). If system V was somewhat lower in cost, it is conceivable that both systems III and V would be nondominated.

Development of Alternatives

The alternatives for this study, were developed after careful consideration of the ground and surface water resources of the area. With possible minor modifications in components, these systems are considered to be the best alternatives which are capable of fulfilling the desired objectives of the study. Each alternative was defined in sufficient detail to allow fairly reliable estimates of cost and effectiveness to be made.

Slight modifications in two of the alternatives, namely systems III and V, were considered significant enough to, perhaps, alter the choice of systems. To check the validity of this assertion, two modifications were considered:

1. Using the water from Redrock Reservoir and Lake Patagonia for irrigation purposes instead of using it for municipal and domestic purposes.

2. Release water from Redrock Reservoir or pump water up from Lake Patagonia and allow it to infiltrate into the aquifer above Patagonia when the water levels in Patagonia and the flow through the sanctuary fell below certain limits.

Situation 1. The water from Redrock Reservoir and Lake Patagonia is used for irrigation on the Box-T Ranch and the better quality ground water is used for domestic purposes. This would save the cost of the water treatment plant, about 350,000 dollars, for alternatives III and V. In this situation, system III would still be preferred to system V because of its lower cost and less impact on recreation. Also, system III would be preferred to systems II and VI because of its better effectiveness in meeting the requirements and lower cost in the case of system VI.

It should be pointed out that because of the varying quality of the ground water (lower quality towards the northeast) additional city wells may have to be installed. This would slightly increase the cost of these alternatives, but the preferred choice should not be affected.

Situation 2. In this situation, water from Redrock Reservoir is released and allowed to recharge the aquifer in Patagonia. This would be done when water levels in Patagonia were considered too low or when the flow through the sanctuary was below the 0.5 cfs requirement. The water from Lake Patagonia would be used in a similar manner except that the water would have to be piped upstream from the town and allowed to infiltrate into the aquifer at that point.

The efficiency of water distribution and use in this situation may be very low. There is no guarantee that water released at Redrock will reach the desired destination when required, if at all.

The system involving Redrock Reservoir would decrease in cost substantially, about 534,400 dollars, to about 391,200 dollars. The Lake Patagonia alternative would decrease in cost only slightly, by about 350,000 dollars.

In this situation, system III, the Redrock Reservoir alternative, would still be preferred because it makes more water available for the different demands. It does this at a much lower cost than systems V and VI and more effectively than all systems.

In spite of the substantial reduction in efficiency, this modified version of system III is the most attractive alternative examined, mainly because of its lower overall cost.

Another minor modification of the alternatives is to release the treated effluent into Lake Patagonia instead of beyond the lake. This would reduce the cost of each alternative concerned by about 43,000 dollars. Recreation at the lake would benefit substantially if this is done. Firstly, the fish would benefit from the additional nitrogen which forms an important link in the food chain in surface waters. Secondly, water levels in the lake would be enhanced because of the additional water inflow. The effluent, because of its excellent quality, would have very little effect, if any, on the quality of the water in the lake.

Merits of Alternative Systems

Once the cost-effectiveness tableau is obtained, many methods can be used to rank the alternatives. The algorithm ELECTRE I was chosen because of its simplicity and its proven usefulness in many practical examples. Other methods, such as the expected value approach and ELECTRE II algorithm, were considered but were eliminated on the basis of their high complexity.

It was shown that the results of ELECTRE I are quite insensitive to the magnitude of the weights and interval scale assigned to each criterion and to the values of the parameters p and q. It may be of interest to determine the effects of changing the priorities, on the criteria, on the choice of systems. This can be achieved by reversing the weights for the concord indices. For instance, if environmental effects on the sanctuary, lake and National Forests were considered top priority in the basin, these criteria would be weighted "two" and the other criteria weighted "one." Table 12 gives the new weights for the concord indices. The discord indices do not change. Table 13 gives the new concord indices. Figure 13 shows the composite graphs for various values of (p,q). These graphs show that even with a change in priority to environmental influences, system III is still preferred. In fact, it can easily be deduced that system III would be preferred irrespective of the priorities on criteria.

Documentation of Analyses

This step of the cost-effectiveness analysis consists of documenting the rationale, assumptions, and analyses underlying the previous nine steps. Without such documentation, a clear understanding of the significance and limitations of the conclusions is unavailable. Kazanowski (1968) suggested that particular emphasis be placed on the documentation of the following:

1. Specific objectives to be fulfilled.

2. Essential requirements for attaining these objectives.

3. Systems capabilities and associated assumptions.

4. Systems cost and associated assumptions.

5. Systems evaluation and associated assumptions.

6. Conclusions, their limitations and sensitivity.

Very careful documentation of the rationale, assumptions and analyses of the cost-effectiveness methodology as applied to the Sonoita Creek water management study has been presented in this chapter. The main conclusions and recommendations are discussed later.

IMPLEMENTATION OF THE REDROCK RESERVOIR ALTERNATIVE

The analysis in the previous section showed convincingly that the Redrock Reservoir alternative is best suited to meet future water demands in the Sonoita Creek watershed. The sensitivity analysis which ensued showed

Table 12. New weights for concord indices

Number	Criteria	Weights
1	Costs	1
2	Likelihood of shortage of water for sanctuary	2
3	Degree of quality of municipal and domestic water	1
4	Environmental effects on sanctuary	2
5	Environmental effects on Lake Patagonia	2
6	Environmental effects on National Forests	2

Table 13. Concord indices matrix for sensitivity analysis

System	II	III	V	VI
II	-	0.60	0.60	0.55
III	0.50	-	0.45	0.30
V	0.30	0.60	-	0.30
VI	0.45	0.70	0.60	-

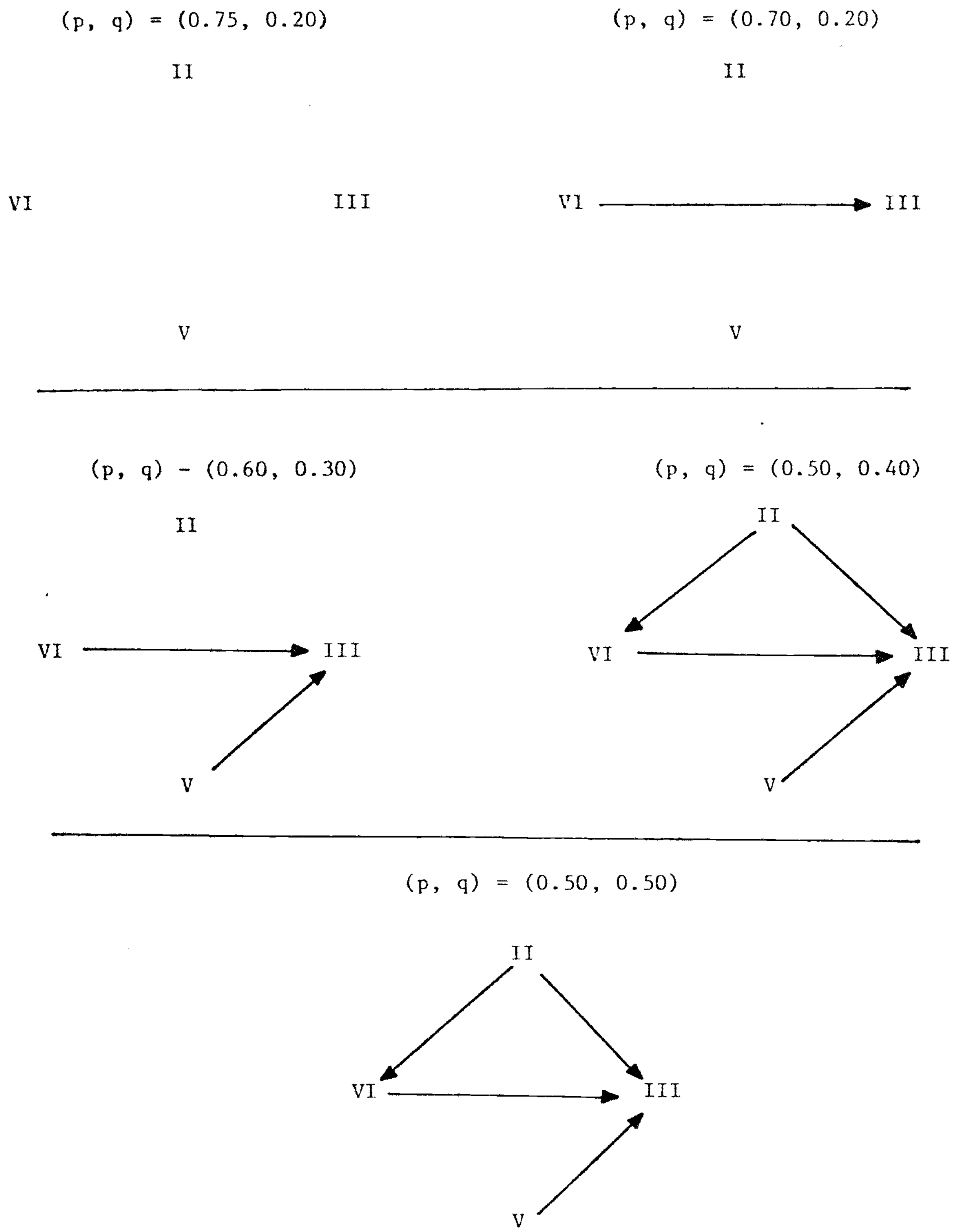


Figure 13. Composite graphs for sensitivity analysis.

that less efficient versions of this alternative are also preferred to the other alternatives under consideration.

The Redrock Reservoir alternative, as presented in the cost-effectiveness analysis, is very expensive; the estimated cost is roughly 900,000 dollars. It was shown that less costly versions of the alternative, although somewhat less effective in satisfying the objectives of the study, may be adequate in meeting future water demands in the watershed. With this in mind, possible stages in the implementation of this alternative are presented in this chapter. The effectiveness of the system in meeting water demands in the basin can be evaluated at each stage and the need for additional stages determined. This arrangement could save several thousand dollars in unnecessary expenditures.

The previously analyzed Redrock alternative requires constructing an 850-acre-feet-capacity reservoir at Redrock Canyon. Evaporation-control measures capable of reducing evaporation by at least 50 percent should be implemented. A piping system to convey the water by gravity to Patagonia and the Sonoita Creek Sanctuary would be needed. Also, a water treatment facility would be needed in Patagonia to treat the water before domestic consumption. Treated sewage effluent from the Patagonia sewage treatment plant would be piped to a point beyond Lake Patagonia and released into the stream. The total cost of this system is estimated to be about 926,000 dollars.

It is very evident that many structurally different systems can be conceived, all of which include a reservoir at Redrock Canyon. Although some of these systems are economically attractive, their effectiveness in meeting future water demands in the basin is questionable. The opposite may be true for the other systems. The Redrock Reservoir alternative, as developed for the cost-effectiveness analysis, assures high efficiency and effectiveness in satisfying the objectives of the study. It does this at a fairly reasonable "modern-day" cost. However, a small community such as Patagonia may not be able to afford such a system, especially if a large initial capital outlay is required. It is possible, however, to implement this plan in several stages. This would resolve the problem of large initial expenditure. Also, as was stated earlier, the performance of the system at each stage can be measured and the need for additional stages determined.

The following four stages for implementing the Redrock Reservoir alternative are suggested. The initial stage assumes that the reservoir has been constructed and is oeprational.

Stage I

Water is released from the reservoir and allowed to recharge the aquifer in Patagonia. This would occur when ground water levels in the Patagonia aquifer fall below a predetermined critical level. Also, water would be released when the flow through the Sonoita Creek Sanctuary falls below 0.5 cfs. An observation well may be needed to monitor water level fluctuations in the Patagonia aquifer. The critical water level may have to be determined after more detailed ground water studies are conducted in the area.

The effectiveness of this system was discussed in the section on sensitivity analysis. Although the system is quite attractive economically, its effectiveness in meeting the future water demands of the basin is questionable. This system encourages a possible waste of precious water--a resource which may become critical with increased water demands towards the end of the planning horizon.

Stage II

If the system in stage I proves to be insufficient for meeting the water demands in Patagonia and the sanctuary, an additional component may be added to improve its effectiveness. Instead of releasing the water through the gates of the dam, the water could be piped to the confluence of Redrock Canyon, Harshaw Creek and Sonoita Creek. At this point the water would be released and allowed to recharge the aquifer. Additional piping may be required to convey some of the water to the sanctuary.

This system costs about 150,000 dollars more than the system at stage I. The effectiveness of this system in providing additional water for Patagonia woudl be somewhat higher than at stage I. However, irrigation wells, located just north of the confluence, may withdraw some of this water. Also, there is no guarantee that this water will reach the city's wells which are located about 1.5 miles to the west.

Stage III

Stage III requires piping the water from the Redrock Reservoir to the Box-T Ranch where it would be used for irrigation. A pipeline to the sanctuary may also be necessary. An additional mile of piping to the Box-T Ranch may be required plus the possible need for pumps.

This arrangement would greatly relieve the pumping stress on the Patagonia aquifer. Of course, the water from the Redrock Reservoir cannot be expected to meet all the irrigation needs at the Box-T Ranch. Thus, some pumping of the aquifer for irrigation purposes may be necessary. With less pumping for irrigation, however, more water will be available for domestic and municipal uses.

Stages I through III necessarily require the addition of several city wells. As stated earlier, sites for such wells are severely constrained by the poor quality of the ground water in the area. Thus, although the water may be available, it may not be usable for domestic and municipal purposes.

Stage IV

Stage IV requires the addition of a water treatment facility in Patagonia. The water from the Redrock Reservoir would be piped into Patagonia where it undergoes treatment before use for domestic and municipal purposes.

As discussed earlier, this system essentially guarantees that all water demands in Patagonia and the sanctuary are met.

CONCLUSIONS AND RECOMMENDATIONS

The development of a viable water management plan, for the Sonoita Creek watershed, is necessary in order to resolve possible conflicts among potential water demands in the area. These demands consist of municipal and domestic, agricultural and recreational demands.

The problem was formulated within the framework of multi-objective decision analysis. The cost-effectiveness methodology was selected to develop and compare alternative system solutions for the study. This is an appropriate approach for this problem since it allows for the consideration of all the important factors, both quantitative and qualitative, involved in the decision-making process.

The algorithm ELECTRE I was used to rank the alternative system solutions. This approach was selected because of its simplicity and its proven usefulness in many previous examples.

Based on the results of the Sonoita Creek water management study, the following main conclusions and recommendations can be made.

1. The present state of knowledge concerning the ground water resources of the area, both quantity and quality, is still quite limited. Although the analysis of pumping tests data indicates that the aquifer can support additional water demands for years to come, the steady availability of water to sustain large demands is questionable. Before any concrete plans are made to further develop the ground water resources of the area, additional studies should be conducted for a better determination of aquifer properties, storage, dimensions, recharge and discharge area, etc. Water quality studies are also required in parallel with the quantity studies. The positioning of wells in the alluvium of the main channel or tributary channels may possibly depend on water quality in these locations.

2. Further development of the surface water resources of the basin, for water supply purposes, may be limited to Lake Patagonia and a potential site at Redrock Canyon. Lake Patagonia is quite capable of supplementing municipal and domestic water demands in Patagonia and flow

through the Sonoita Creek Sanctuary although in some instances recreation at the lake may be affected. A small reservoir at Redrock Canyon, performing similar functions, is also quite adequate as long as adequate evaporation control measures are implemented.

3. The most efficient and effective water management plan for Sonoita Creek watershed is to build a small reservoir with evaporation control at Redrock Canyon. With treatment, the water could be used directly for municipal and domestic purposes. Without the expense of a water treatment facility the water could be used for irrigation, at the Box-T Ranch, in lieu of better quality ground water. Another alternative is to release water from the reservoir and allow it to recharge the aquifers developed for domestic water supplies in the Patagonia area. This would be done when the ground water levels in these aquifers were too low or when the flow through the Patagonia-Sonoita Creek Sanctuary is below the minimum requirement. This system is less costly, but it may be an inefficient method for distribution and use of water.

   Although the present method of disposing treated sewage effluent from Patagonia by piping into the Sonoita Creek seems satisfactory, these plans may require piping the treated sewage effluent, from the Patagonia plant, beyond Lake Patagonia where it would infiltrate into the alluvial deposits of the stream bed. To save on cost, the effluent could be released directly into Lake Patagonia where it is expected to improve the recreational aspects of the lake. Further studies regarding disposition or use of the treated sewage effluent, considering both quantity and quality, are needed.

4. The choice of system, resulting from the use of ELECTRE I, is quite insensitive to the ranking of the criteria and the parameters of the algorithm.

APPENDIX A

ESTIMATING COSTS OF THE VARIOUS ALTERNATIVES

Table A.1. Itemized Cost of Alternative I

Item	Description	Estimated Cost ($100)
Drilling	For 10-inch-diameter well at $20.00/foot and 100 feet depth (includes equipment, labor), 5 wells	10.000
Development	Pump wells at 270 gpm for 8 hours at $0.05 per kilowatt-hour	.015
Pumps and Accessories	15-horsepower (hp) pumps and motors (5 pumps with motors)	20.300
	Other accessories, including starter, cable, etc.	7.500
Maintenance	Parts and labor for 20 years	5.000
Pumping Costs	$0.05 per kilowatt-hour	113.600
Total		156.415

Table A.2. Itemized Cost of Alternative II

Item	Description	Estimated Cost ($1000)
System I	Wells and pumping system	157.000
Pipes	9 miles of 6-inch-diameter clay at $3.00 per foot	142.560
Excavation	Excavation trench 9 miles by 2 feet by 3 feet. a) Equipment and operator, 75 feet per hour at $25/hour; b) Two laborers to smooth trench, 100 feet per hour at $6 each per hour	22.000
Surveying	Three-man crew working 10 days at $250 per day	2.500
Access Road	Equipment and labor, 1 mile per day at $100 per day	.900
Installation	Crew of six, laying 20-feet-length pipes at 15 minutes per pipe, at $7 per hour per laborer	25.000
Maintenance	Parts and labor for 20 years	5.000
Total		354.960

Table A.3. Itemized Cost of Alternative III

Item	Description	Estimated Cost ($1000)
Earth Dam and Spillway	Excavation and compaction of earth (7000 cubic yards at $6.00 per cubic yard)	42.000
Access Road	Four miles at 1 mile per day and $100 per day	.400
Water Intake Structure	Small tank	5.000
Pipes	Four miles of 6-inch-diameter steel pipe at $6.50 per foot plus 1 mile of 4-inch-diameter pipe at $4.00 per foot	158.400
Installation of Pipes	Equipment, labor, etc.	22.000
Water Treatment	Sedimentation, filtration, etc.	350.000
Effluent Disposal Component	Construct 9 miles of 6-inch pipeline	198.000
Pumps	Two pumps for city wells able to discharte at 270 gpm and lift 118 feet	5.800
Evaporation Control	25 acres of asphalt-chip-coated EPCR at 11 cents per square foot	120.000
Maintenance	Reservoir, treatment plant, pipes, etc.	25.000
Total		926.600

Table A.4. Itemized Cost of Alternative IV

Item	Description	Estimated Cost ($1000)
System I	Five additional wells	157.000
Pipes	1.5 miles of 6-inch-diameter clay pipe at $3.00 per foot	23.760
Installation	Equipment, labor, etc.	8.25
Pumps	Five-horsepower (hp) pump to lift effluent 49 feet at 217 gpm (2 pumps)	1.232
Operation	$0.05 per kilowatt-hour for 20 years	32.494
Storage Tank	2.5-million-gallon capacity (materials and labor)	200.000
Total		422.736

Table A.5. Itemized Cost of Alternative V

Item	Description	Estimated Cost ($1000)
Effluent Disposal Component	Construct 9 miles of 6-inch pipeline	198.000
Water Intake Structure	Small tank	5.000
Pipes	Ten miles of 10-inch-diameter steel pipe at $13 per foot	686.400
Pumps	Five main pumps and 5 emergency pumps, each capable of lifting 100 feet at 730 gpm	15.680
Boosting Stations	Four pump houses	20.000
Pumping Cost	$0.05 per kilowatt-hour, 7 hours per day for 20 years	327.000
Maintenance	Pumps, pumphouses, etc.	10.000
Installation	Excavation of trenches, laying of pipes, etc.	Shares these costs with effluent disposal component
Water Treatment Plant		350.000
Total		1612.080

Table A.6. Itemized Cost of Alternative VI

Item	Description	Estimated Cost ($1000)
System I	Five additional wells	157.000
Pipes	Six miles of 6-inch clay pipes at $3.00 per foot	95.040
Installation of Pipes	Equipment, labor, etc.	33.000
Pumps	Three 15-horsepower (hp) pumps capable of lifting 100 feet each at 217 gpm plus one 5-hp pump to lift effluent 49 feet at 217 gpm	10.000
Pumping Costs	$0.05 per kilowatt-hour at 217 gpm for 20 years	232.000
Boosting Stations	Three pumphouses	15.000
Storage Tank	2.5 mg (million gallon) capacity	200.000
Total		742.040

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