ECONOMIC ASSESSMENT OF THE CONSEQUENCES OF GROUND WATER USE

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ABSTRACT

The intensive use of ground water throughout the world is directly affecting social and economic development, particularly in those areas where it has been exploited indiscriminately without full knowledge of aquifer potential, causing collateral effects such as progressive lowering of water tables, increased pumping costs, cracking, land subsidence, infiltration of poor quality water, drying up of springs and shallow wells, saline intrusion, decreased river flow, and affecting fragile ecosystems such as deserts and swamps. Proper aquifer management should be considered in light of the many exploitation-related aspects such as physical, social, political, legal, constitutional, and administrative factors. Conjoining so many aspects requires methods of analysis that integrate them systematically such that within a planning process alternatives can be defined leading to the social and economic well-being of the regions dependent on ground water in combination with their other natural resources. Any attempt to solve problems deriving from intensive exploitation of ground water comes to economic considerations whose consequences must be analyzed carefully because of all their implications, both for the rational use of ground water resources and for continuing and/or evolving development of those areas where ground water is being exploited.

Within this context mathematical models are the most effective tool for determining the best way to use water resources; in conjunction with the economic aspects of water use, such models enable planners to define what actions, within an optimum investment criterion, will most effectively establish means of control for the proper use of water resources. In the case of the Hermosillo Coast in Mexico, an extensively irrigated area, the main source of supply is a large-capacity granular aquifer (saturated thicknesses varying from 60 to 200 m), with an average annual recharge of 350 Mm^3 that has been exceeded since 1949; exploitation reached a maximum in 1964 of 1137 Mm^3; by 1974 agriculture and all collateral economic activities had an uncertain future, the principal effects of overexploitation being sharply lowered water levels in the aquifer, saline intrusion with the consequent reduction of cultivated areas due to abandonment of wells producing salt water, and an inordinate increase in pumping costs. Alternatives were analyzed by a mathematical model that handled a linear program maximizing the annual net benefits obtained from agriculture as a function of the volume of water extracted from the aquifer, which, in conjunction with a simulation model of the aquifer's behavior, permitted determination of the effect on water levels. The results obtained within a 50-year planning horizon gave elements necessary for rational decision-making that have led to a gradual reduction of

extraction, changes in crop patterns, improvement of irrigation systems, and more recently, analysis of the possibilities of using waste water from the city of Hermosillo for irrigation and research leading to improvement and planting of halophytes in the coastal zone, ideal for their resistance to high salt concentrations.

1 INTRODUCTION

The role of ground water as a development factor is becoming more significant, as in many places the usable surface water supply is insufficient to meet the demand.

Ground water is being tapped into in many locations without full knowledge of how the aquifers behave or their potential supply capacity, often resulting in dramatic cases of ground water overexploitation.

2 ASPECTS CONNECTED WITH AQUIFER MANAGEMENT

2.1 Physical aspects

Ground water is made up of two main components: the renewable volume (seasonal recharging of the aquifer) and the nonrenewable volume (aquifer storage); in order to handle these deposits, their potential must be determined and also the existence or lack of alternative sources, so that combined use can be made of available water resources.

The current trend in aquifer management focuses on determining maximum and minimum water levels with the purpose of regulating the storage capacity, thus aiding development of economic activities that are unachievable otherwise. One must always bear in mind the probable effects on aquifer behavior so as to avoid economic collapse that might result from failure to reestablish the conditions prevailing when ground water exploitation began.

Ground water management, mainly in developing countries, answers not only to the particular environmental conditions (climate, hydrology, geology, etc.), but also to socio-economic pressure produced by development itself; this has meant that in some areas the amount of water extracted from the aquifers exceeds the amount that natural recharge can replace, leading to progressive drawdown of the piezometric levels and subsequent increased pumping costs, seawater intrusion into coastal aquifers, land subsidence, cracking, infiltration of saline or poor quality water, the drying up of springs and the rendering useless of galleries and shallow wells, ultimately bringing on severe economic consequences.

The true dimension of the economic problems generated by the use of ground water derives from uncontrolled overexploitation; therefore, in order for water management to be based on the fact that one is dealing with natural water storage and that temporary exploitation of reserves is possible, one must have a controlled overexploitation plan--this being the most suitable form of operation to obtain the greatest benefits for economic and social development, particularly in areas where water is scarce.

Exploitation of an aquifer may temporarily satisfy demands for water while more appropriate alternative sources are under development; likewise in the absence of the latter, this resource is used to produce a temporary economic and social benefit. In the first case periods of overexploitation can be interspersed with periods of recovery, and in the second case exploitation can be reduced to a suitable permanent level or it can proceed to complete exhaustion of the aquifer.

In Israel several periods of overexploitation have been used, followed by their respective recovery periods, man-aided recovery actions being effected; other examples are Ghazvin, Iran, where the alternative source is the Teleghan River, and the Azua Valley in Santo Domingo, where economic activities are ongoing and productive development continues.

Cases where ignorance of the consequences of overexploitation have caused irreparable damage to the aquifers are: Argolis in Greece and Larnaca in Cyprus. In Mexico dramatic situations are found in the Hermosillo and Guaymas Valleys, the Comarca Lagunera, and Santo Domingo, their economies--that were largely based on agriculture--having been seriously affected by a significant reduction in areas under cultivation because of encroaching salinity and increased pump lifts requiring greater energy consumption that makes pumping uncostworthy.

Various solutions have been attempted in answer to the devastating situations generated by overexploitation of aquifers: for example in Israel encroaching salinity has been halted by a battery of freshwater wells; in Maracaibo, Venezuela, redistribution of wells was suggested for the same purpose; in Dakar, Senegal, former levels were recovered thanks to the construction of a dam. Land subsidence from over exploitation affects the existing civil infrastructure (means of communication, buildings, water and sewage systems, dams, etc.); cessation of pumping in such cases in cities like Taipei, Venice and Mexico City was recommended with analysis of the economic consequences this would have, considering alternative sources as a solution.

A project involving overexploitation of an aquifer must be planned in such a way that it will give a maximum present value for the net benefits of the operations to be made over the project's lifetime. For this purpose planning models whose goal is near-optimum operation are used, taking into account the aquifers' physical limitations, the existence of limited imported water, and restrictions imposed by scant information, so common in our countries, among other factors. Overexploitation of ground water normally permits a favorable change in the net benefit on obtaining short-term benefits.

One must bear in mind that since most decisions in developing countries are eminently political, they have to be evaluated in economic terms, consumer participation oriented by a technical/adminstrative organization being desirable. Importation of water--this being understood to be the bringing of water from distant sources--up to now has been economically feasible when it is done for urban/industrial uses or related agricultural uses.

2.2 Legal, constitutional and administrative aspects

In those countries where legislation is based on property rights, certain obstacles hinder proper aquifer management; it is therefore necessary to provide some means of orientation and impose both legal and economic restrictions, for example, requiring those whose use of water results in increased costs for other users to be liable for the damage caused.

It is advisable to set up administrative procedures for the control and management of aquifers before problems become worse, while an abstract definition can still be arrived at and before overexploitation becomes evident. Control of ground water overdraft has been supported in some countries by legislation imposed on drilling companies and governmental supervision.

2.3 Social and political aspects

These aspects are particularly important in developing countries, where on many occasions the objectives of social welfare programs make it necessary to take measures that make little economic sense or are intended to relieve momentary socio-political pressure such as by creating jobs or increasing regional income.

Faced with the difficulty of solving this type of problem, it is felt that only a change in a society's socio-economic and political structure can, if not remedy the situation, at least weaken its conflictive emphasis.

Other social aspects are high population mobility in answer to economic pressures from internal conflict like the sale of land where the ground water is about to be exhausted or become saline and alternate sources are not available; or when other sources do not exist, due to contempt for the possibilities of ground water as a supplementary resource; if the available water is waste or brackish water, resistance to its use may be even greater. When the economic and social good so demands, a change in the use of water may be brought about, which becomes a means to control overexploitation, even though up to now there have been few cases of direct intervention requiring change through political or administrative action.

3 METHODOLOGY

3.1 Phases of study

In order to address the problem and with the purpose of proposing in a general way what methodology should be followed on considering the economic implications of ground water use, where there is only scant information to work with, particularly in the developing countries, it would be necessary to consider four phases of study:

PHASE I (Overview). Obtain an overview of ground water availability, problems and possibilities of using it, identifying those places that require in-depth studies. Availability, both in terms of quantity and quality of the water, is determined subregionally, seeking to provide ongoing extraction and overexploitation volumes in order to strike a balance in the regional planning process. These studies result in estimates and indication of possibilities and general conditions, backed up by available data, without their results being conclusive insofar as they might be weighed in making important decisions about investments for development. Missing or erroneous data may lead to mistaken results; special efforts must be made to revise and complement the data on which such studies are based.

PHASE II. Carry out geohydrologic studies to determine more accurately ground water availability and quality in terms of time and place, using mathematical analysis requiring direct, systematic sampling in order to establish the aquifers' conditions and behavior, as well as their location in the physical and socio-economic context where ground water is being exploited. Depending on the data available, simulation models of the aquifers can be prepared in order to predict water levels and quality under different plans for its use.

PHASE III. Integrate the physical aspects of Phase II with the economic and social aspects, thus making it possible to establish different ways of managing the aquifer under study. Economic consequences are determined on the basis of increased pumping and maintenance costs; infrastructure losses and reductions in agricultural production, both from exhaustion of the water supply and from salts deposited in the soil by use of poor quality water coming from induced migration, also produce social conflicts, mainly in those cases where the drinking water supply depends on ground water.

PHASE IV. Orient the studies to full utilization of a region's water resources, including surface and ground water, and when necessary, consider the recycling and reuse of the water within a multi-purpose planning process that covers social and economic aspects and goes beyond the simple concept of maximizing benefits in a benefit/cost analysis.

According to the proposed outline, the economic aspects are analyzed in Phases III and IV, and their connection will depend on the amount and quality of the available information; it could be said that the analysis process in both phases is the same, although the Phase IV process is much broader and allows for additional solutions and ground water management options.

3.2 Planning

Because of the different factors involved in analyzing economic aspects of ground water use and its correlation with surface water, it must be considered that this is a planning process where one must take into account society's objectives in order to achieve rational use of the available water resources, it being necessary that both planner and decision maker apply their judgement, intuition, experience, and knowledge of the region under study. The person in charge of planning will have to consider across-the-board possibilities in order to establish the options and their respective benefits and costs for a defined time frame within which the proposed objectives can be achieved. Selection of the proper option must include technical management feasibility coupled with a regional development process that reflects economic, population, social, and environmental conditions in combination with the water resource and engineering aspects that lead to the obtaining of net benefits.

The most effective water resource planning tools, in this computer age, are mathematical models. Planning is a dynamic process that can be characterized as a set of actions taking place over time that become modified in accordance with the information feedback produced. In all phases of this process questions are posed, and if they are properly answered, they lead to formulation of ever better plans. Obviously models of any type will not be the solution to all problems, and care must be taken to properly identify parameters, variables, and limitations.

Going back to the economic aspects, water management must be oriented such that its use will produce certain benefits, which are associated with the economic value assigned to them, depending on the desired end product. This implies that in the long run water, whether surface or ground water, must be considered as an input or raw material within a productive process whose transformation or utilization acquires more or less value according to the factors involved, principally those connected with availablity, whether quantitative (surplus or scarcity) or qualitative (pollution).

The planning process must be used in conjunction with an optimum investment criterion assisted by the following aspects:

(1) Guidelines for evaluating benefits and costs within the planning process that take into account negative and positive impact from achievement of desired objectives.
(2) Determination of interest rates to be applied to investments to be made in order to carry out the water management planning program, taking into consideration the expected benefits and the prevailing economic and social situation.
(3) Specification of budget limitations, both present and future, that hinder implementation of the proposed programs and plans.
(4) Determination of risks and uncertainties inherent to the proposed actions, seeking to reduce their impact on the desired results via sensitivity analysis of the main parameters bearing on the investment plans.
(5) Scheduling the implementation of each program or project considered in the planning such that its startup can be on the most suitable date and in logical order.

Determining the economic aspects of ground water use, pursuant to the above outline, requires collaboration of professionals from various fields: not only hydrologists and geohydrologists, but also economists, ecologists, sociologists, and lawyers so that the problems that are posed can be attacked in their true dimension, without omitting any sector of society in the proposed solutions.

4 CASE STUDY: THE HERMOSILLO COAST IN MEXICO

The procedure used to identify management options for the Hermosillo Coast aquifer in northwestern Mexico will serve to illustrate some of the above concepts (see Fig. 1).

4.1 Background

This study was undertaken as part of the National Water Plan for Mexico in 1974, with a planning horizon of 50 years, applying a Phase III (as mentioned above) breakdown to the study, considering that the socio-economic aspects depend on how the region's water resources are developed and that its primary economic activity is agriculture.

Said aquifer is geologically made up of sand and gravel with thicknesses varying from 60 to 200 meters and a thick underlying layer of clay that extends to the Gulf of California coast. The bedrock is volcanic rock and ground water occurs practically under unconfined aquifer conditions with transmissivity values of 0.03 m^2/sec to 0.10 m^2/sec. Low transmissivity sediment near the coast forms a geological barrier that has substantially

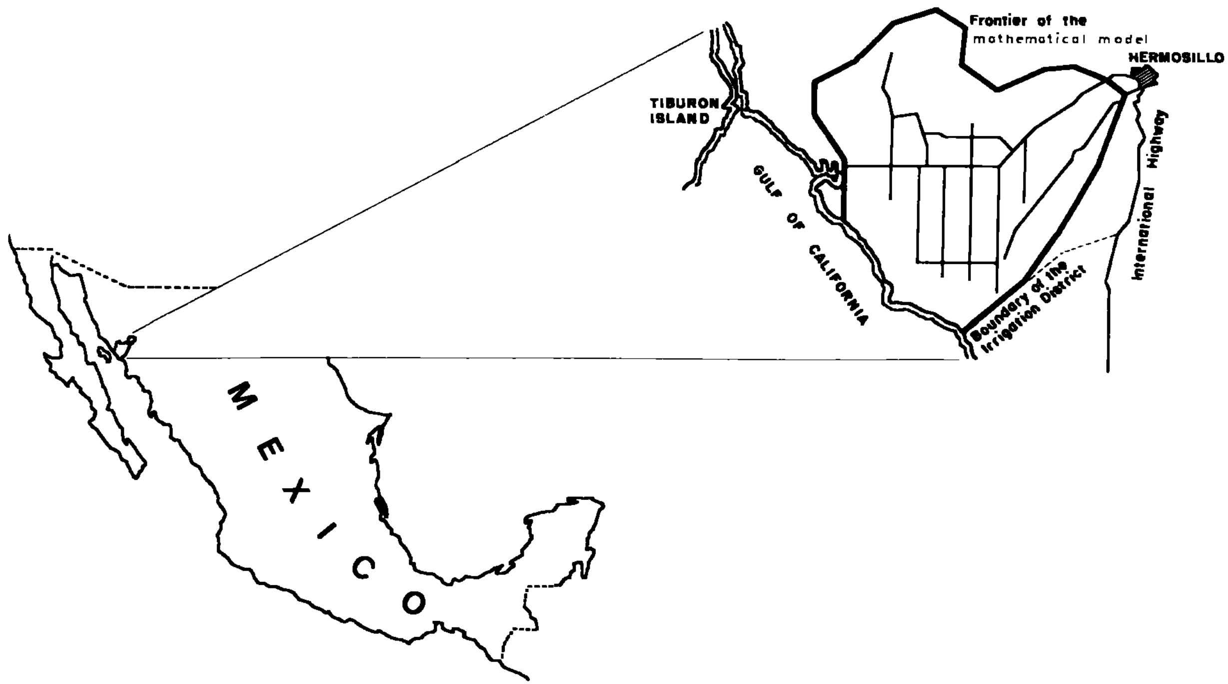

Fig. 1. Location of the Hermosillo Coast Aquifer.

slowed down saline intrusion. The storage coefficient has an average value of 0.15, median annual recharge is estimated at 350 Mm^3, and the volume stored is estimated to be 20,000 Mm^3.

In 1945 exploitation of ground water was around 18 Mm^3, gradually increasing to 860 Mm^3 in 1958, fluctuating afterwards to a maximum in 1964 of 1137 Mm^3 and a minimum of 760 Mm^3 in 1968. It is estimated that 20% of the volume extracted is returned to the aquifer through irrigation.

The Hermosillo Coast Irrigation District contains some 500 wells with an average extraction capacity of 80 l/s per well; the area susceptible to irrigation is 167,000 ha, the principal crops being cotton and wheat. Table 1 shows the main crops and areas planted during the 1972-1973 cycle, as well as economic data concerning production and water used, with the purpose of determining the net benefits obtained.

4.2 Description of the problem

Considering that this is a coastal aquifer, the effect of intensive exploitation translates into: (1) lower and lower water levels from exceeding the safe yield represented by the annual recharge and (2) increased salt content of the water extracted from the coastal zone due to inversion of the hydraulic gradient.

The zones most exposed to seawater intrusion are around the three former channels at the mouth of the Sonora River, where there is an average advance of 0.70 km/yr, while along the rest of the coastal front, it has been very slow thanks to the natural clay barrier.

4.3 Defining of alternatives

Taking into consideration that for some time drawdown has been almost three times estimated recharge, the primary risk is advance of the saline front, which would mean that large areas under cultivation would become useless, as would the existing irrigation infrastructure; the following alternatives were therefore suggested for study:

(1) Halt the seawater intrusion advance by applying engineering techniques such as formation of physical barriers (impermeable screens, batteries of wells for removal of salt water, etc.)

(2) Reduce extraction of ground water at the source.

(3) Import surface water coupled with reduced extraction.

Without considering technical possibilities, not even of importing water, the problem was reduced to stemming the seawater intrusion advance, taking into account the aquifer's large capacity, trying to avoid economic collapse and giving time to probe deeper into the salinization phenomenon, setting up a

CROP	AREA (ha)	GROSS VALUE (millions of US$)	GROSS VALUE PER HECTARE (US$)	FIXED COST PER HECTARE (US$)	NET VALUE PER HECTARE (US$)	WATER APPLICATION (m^3/ha)	NET VALUE OF CROPPING ACTIVITIES PER m^3 OF WATER (US$ X 10^{-3})
WHEAT	55,769	18.243	327	263	64	6,500	9.76
CHICKPEAS	19,031	10.139	533	364	169	6,000	28.16
SAFFLOWER	1,817	0.519	285	274	11	6,400	18.48
COTTON	28,247	30.732	1,088	927	361	9,500	38.00
SOYBEANS	1,658	0.796	480	222	258	7,000	36.88
SORGHUM	2,883	0.588	204	173	31	6,000	5.10
BEANS	309	0.164	533	173	360	5,500	65.36
SESAME SEEDS	2,186	0.939	430	291	139	6,000	23.04
CITRUS FRUIT	3,380	1.514	296	172	124	12,000	10.40
ALFALFA	652	0.542	792	160	632	12,000	52.64
GRAPES	1,606	2.544	1,082	536	546	7,700	70.82
WALNUTS	719	1.150	774	346	428	12,000	35.68
TOTAL	118,257	67.872					

Table 1. Crop pattern on the Hermosillo Coast during the 1972-1973 cycle

permanent monitoring system, and also defining actions that permit continued socio-economic development of the region within a framework of water resource conservation.

4.4 Tools used in the study

The mathematical model used for the analysis of alternatives is a sequential linear program in conjunction with a simulation model of aquifer behavior. Simulation enables the investigator to determine pumpage effects on ground water levels; its inclusion in the linear model gives a way of allowing for water resources and a measure of the objective function for each of the different options, operating at the beginning of each 5-year period on each section into which the study area was divided, selected because of their proximity to the coast and their similar transmissivity characteristics. In this way, in a 50-year planning horizon, the linear program will be run 50 times and the simulation model will give the changes in water levels annually.

The linear program for any year is expressed by an objective function that maximizes the net annual benefits obtained from agriculture, having as parameters: the value of production and the volumes of water used on each crop with the extraction costs for the pump heads corresponding to the exploitation policy being studied.

$$\text{Annual net benefit} = \text{Max} \sum_{i=0}^{n} \sum_{j=1}^{50} (V_{ij} - CL)X_{ij} \qquad (1)$$

Where V_{ij} is the benefit for crop i per m^3 of water used during period j, C is the extraction cost of one m^3 of water per meter of pump head; L is the actual pump head (corresponding to period j and is determined by aquifer simulation according to the distribution of extraction points) and X_{ij} is the volume of water applied to crop i during period j. The types of restrictions to be considered are pumping capacity, surface allotted to each crop, pump heads, etc.)

Fig. 2 shows the flow chart for the model where the initial conditions consider each phase of the analysis process according to the potential use of irrigation water and the depth of the water level, according to the policy that is being analyzed as one of the suggested alternatives. The linear program has two basic outputs: the activities required to maximize yield and the amount of water necessary to do so, which in turn serve as input data for the simulation model that outputs the changes in water levels. The model as a whole operates repeatedly until the entire planning horizon is covered.

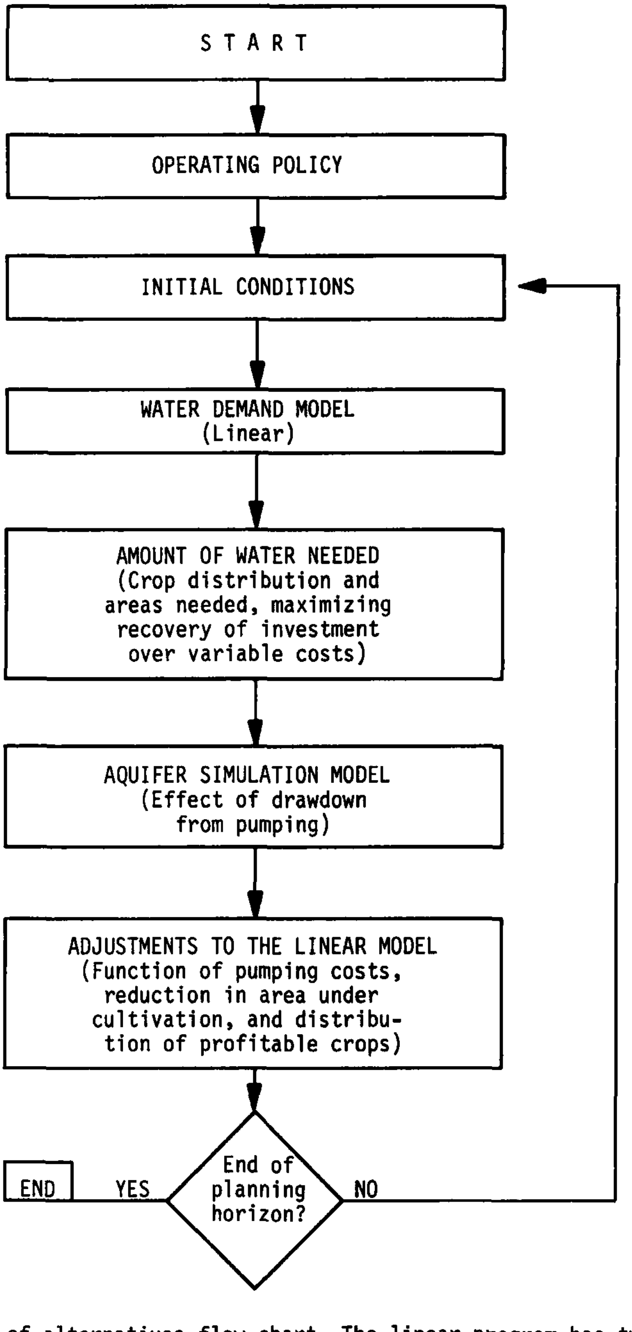

Fig. 2. Analysis of alternatives flow chart. The linear program has two basic outputs: activities and amount of water required to maximize yield, which in turn serve as input data for the simulation model that outputs changes in water levels. The model as a whole operates repeatedly until the entire planning horizon is covered.

In this way the water problem of the Hermosillo Coast is identified as a physical problem whose ultimate consequences are economic, threatening social stability, the infrastructure created during its development and the prospects of maintaining it; for this reason the restrictions imposed on the linear model were set with the purpose of keeping the region's agriculture more or less within established practice, which would lead to determination of the effects of the lowering of the aquifer's water levels and of saltwater intrusion on the net benefits obtained from agriculture.

4.5 Analysis of alternatives

The first application of the model was made considering the present conditions as maintained without any restrictions, the result being that net benefits gradually decrease from 19.67 million dollars in the first period (1974-1980) to 18.27 million dollars in the last (2019-2024), mainly attributed to progressive drawdown that causes a significant increase in pumping costs.

The situation described corresponds to a hypothetical alternative based solely on the aquifer's potential capacity to supply the required volumes of water, without causing a lowering of water levels and their collateral effects, and it gives simply a basis of comparison for the other alternatives. The effect produced in the aquifer levels for the year 2023 is shown in Fig. 3, with a theoretical maximum drop to 70 m below sea level.

A second alternative suggested would permit seawater intrusion to continue, taken as the maximum limit, which implies that the wells will cease to be used as they become affected, this situation continuing until the volume corresponding to safe yield is approximated.

Within the broad spectrum encompassed by this alternative, the following four proposals were suggested:

(1) Continue with the current procedures with the restrictions imposed by the saltwater intrusion advance.
(2) Continue with the current procedures in conjunction with a well-relocation program.
(3) Adjust the crop distribution with high-yield crops.
(4) Apply (3) with more efficient irrigation systems.

Proposal (1) provides the basis of comparison for results of the other alternatives, thus obtaining a reasonable idea of the future for the Hermosillo Coast absent supplementary water or adjustments made by the users themselves. Areas under production, extraction volumes, and relevant benefits were gradually diminished, considering the effect of seawater intrusion.

The application of each proposal requires a great amount of data and considerations that on the whole affect the use of the linear programming in

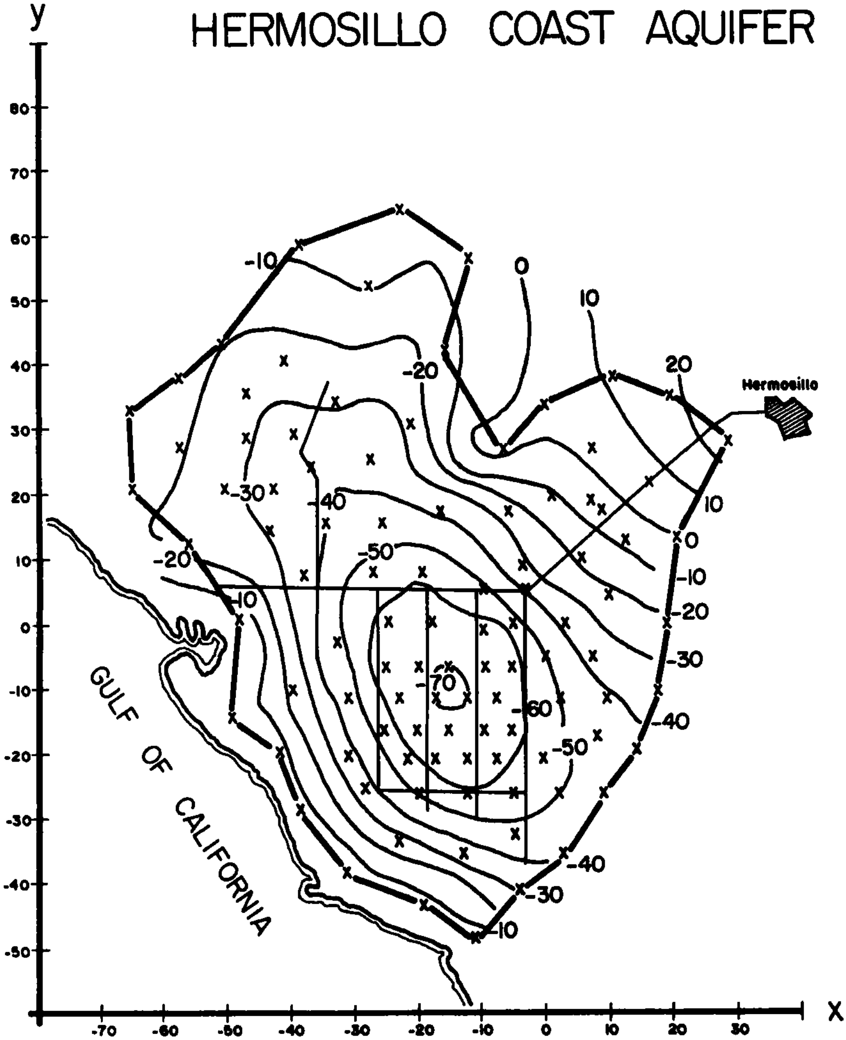

Fig. 3. Piezometric surface for the year 2023. Simulation considering hidrologic and economic failure resulting from a constant annual drawdown of 840 Mm^3 - leading to a significant lowering of the piezometric levels.

the model. Such requirements are: (1) the degree of advance of the seawater intrusion and its effect on crops, (2) the location and number of wells that will be eliminated due to salinization, (3) costs, benefits and new demands for water associated with increased irrigation efficiency, and (4) the degree of agricultural adjustment that can be achieved.

In the absence of data on the real seawater intrusion advance, four zones were defined as being affected over time (see Fig. 4), which determined the elimination of four groups of wells whose annual productive capacity is respectively 156, 174, 165, and 115 million cubic meters, achieving thereby an extraction volume of approximately 350 Mm^3/yr in a 60-year period.

The results of the application of the model to proposal (1), incorporating the restrictions of elimination of wells because of seawater intrusion, consequent reduction of area under cultivation, extraction and benefits obtained within a 60-year period, are shown in Fig. 5, together with those of the unrestricted alternative, indicating the best and the worst conditions that can occur on the Hermosillo Coast. Conversion of benefits obtained with both conditions to present values considering a 12% discount rate, gives 161.76 million dollars and 147.36 million dollars, respectively. The piezometric surface for the year 2023, as a product of this proposal, generated a moderate lowering in levels due to reduced extraction.

The other proposals were analyzed in a similar manner, various results being obtained that permitted establishing combinations leading to the definition of actions to improve irrigation efficiency and modification of crop patterns incorporating those that would result in higher yield.

Analysis of the importation of surface water was made in a similar manner, assuming a volume of 400 Mm^3/yr, taking into account the time over which such water would be available in the region, the cost of importation and modifications in the seawater intrusion advance resulting from reduced pumping and increased recharge from irrigation water return (see Fig. 6). The results of this analysis are shown in Fig. 7 and one observes that there is no 165 Mm^3 reduction in pumpage, which means a larger area may be kept under production, abandoned areas being reincorporated through the use of imported water and resulting in increased annual net benefits.

In this manner the results obtained with the model provided those in charge of water resource planning with elements needed for decision-making, among which the most important are the decision to gradually reduce extraction, change crop patterns, improve irrigation systems, and recently, the analysis of alternatives considering the use of waste water from Hermosillo for agriculture and a study on the development and planting of halophytes in the coastal zone, such as certain feed grasses resistant to high salt concentrations.

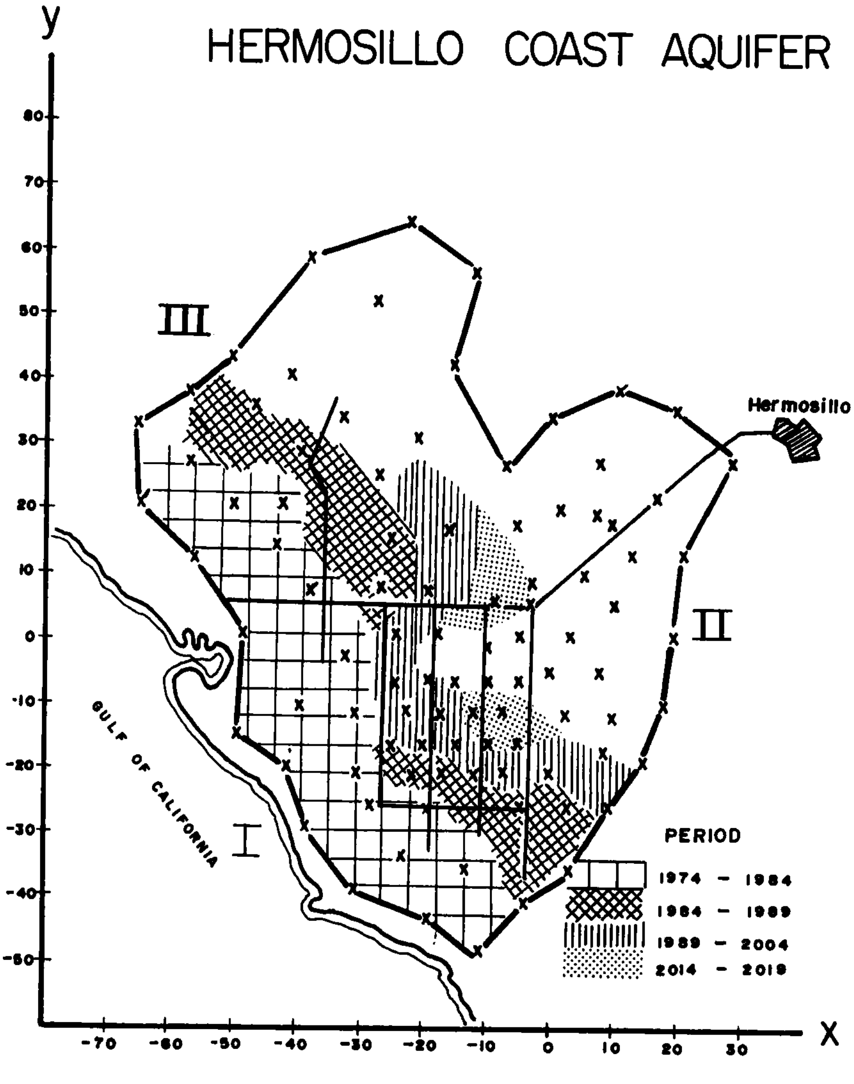

Fig. 4. Well area to be affected in each period by seawater intrusion if 1974 pumpage rates are maintained.

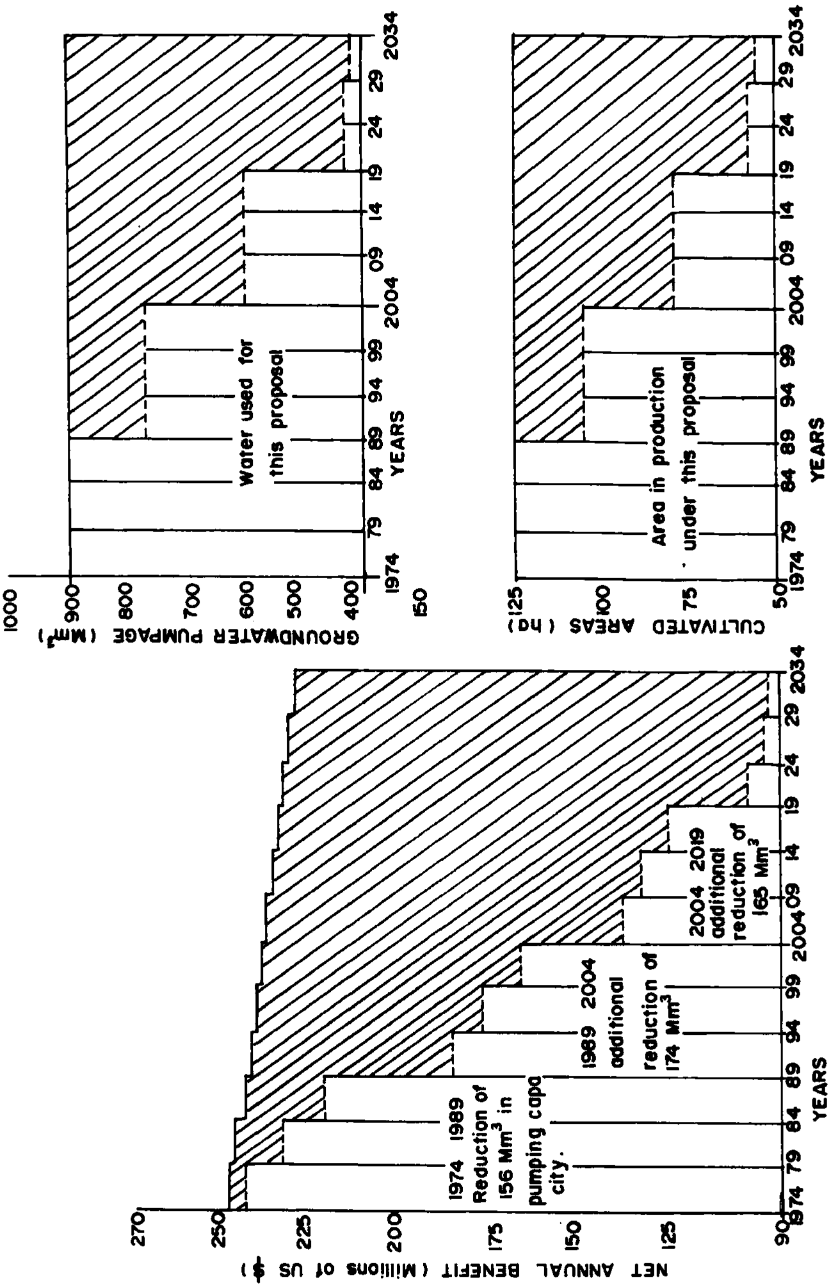

Fig. 5. Extremes within a 60 years period resulting from application of the model; the white area has incorporated restrictions: elimination of wells because of seawater intrusion, an inexhaustable freshwater supply.

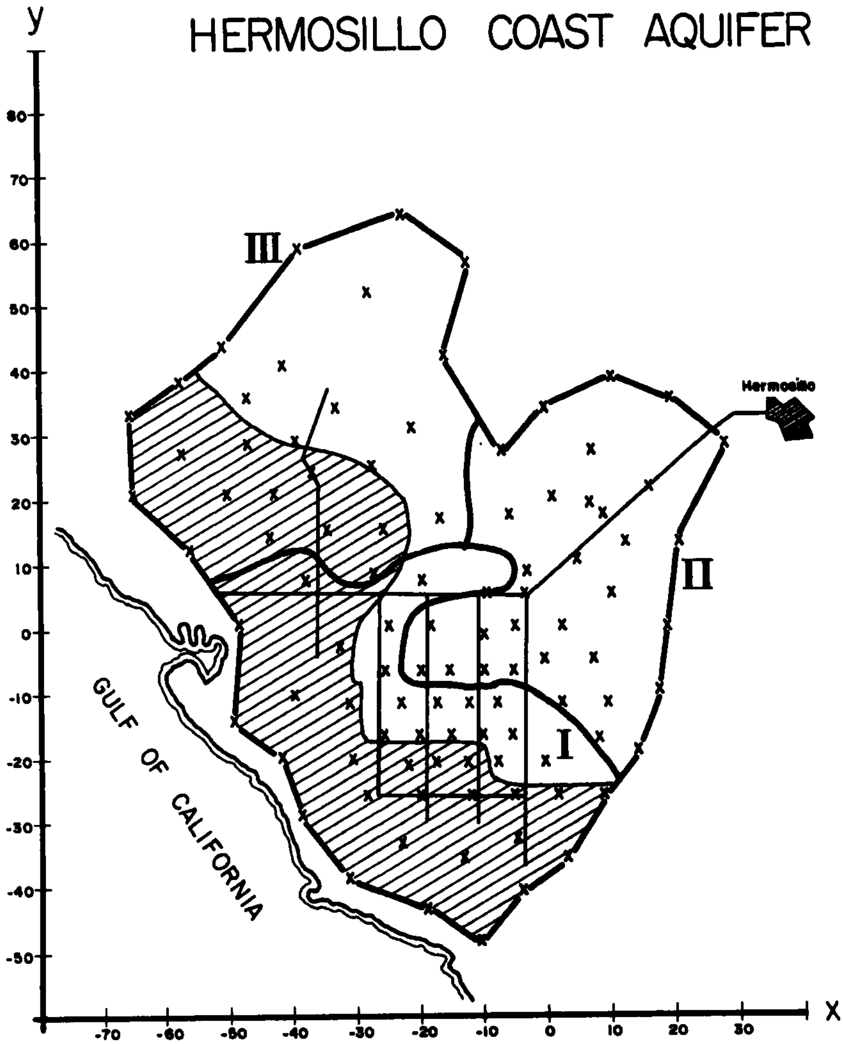

Fig. 6. Area suggested for imported surface water use (400 Mm^3/year), reduced pumping along the coast.

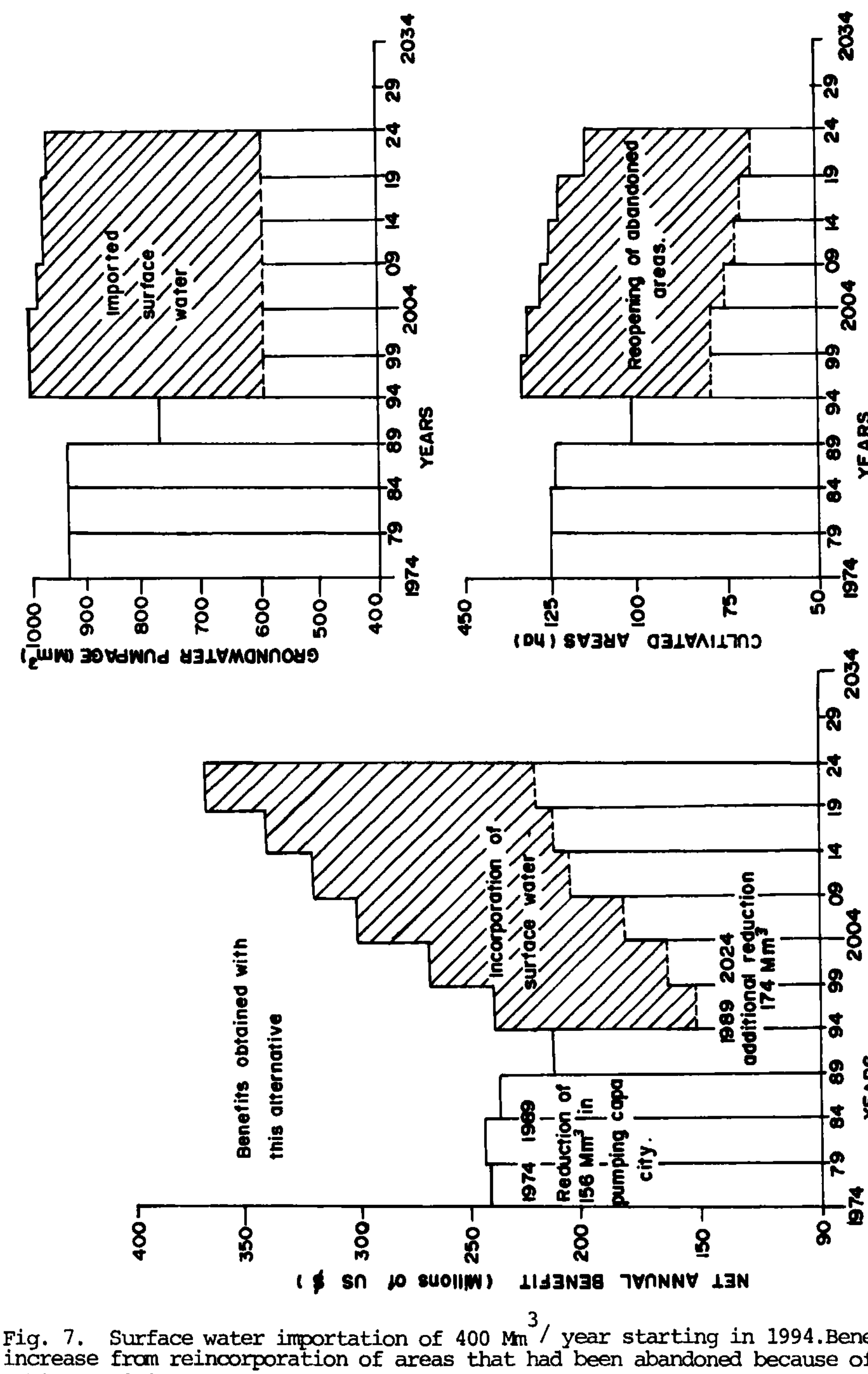

Fig. 7. Surface water importation of 400 Mm^3 / year starting in 1994. Benefits increase from reincorporation of areas that had been abandoned because of encroaching salinity. Only two of the planned pumpage reductions are implemented.

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