ECONOMIC ASPECTS OF GROUNDWATER EXPLORATION AND ASSESSMENT

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ABSTRACT

Various methods of investigation are applied to assess properties of aquifers which are relevant to their development and management. Costs and benefits of development or management are assessed, as well as the costs of investigation. A decision model is presented which is based on these cost and benefit estimates and on a priori estimates of success. The model is used to decide among three alternative policies: (1) No development/Intervention; (2) Development/Intervention without Investigation; (3) Investigation.

1. PURPOSE OF GROUNDWATER INVESTIGATIONS

A groundwater environment, or an aquifer, as part of a water supply system is either a source of water; an environment of storage; an environment for improving water quality; or it fulfills a combination of these functions.

The purpose of groundwater investigations is to improve the knowledge and information on the properties of an aquifer that are relevant to its role in the water supply system.

The main classes of water supply systems for which relevant groundwater investigations may be required, are:

(1) Rural, single well, (usually handpump) water supply systems (as described by Vernier)

(2) Reticulated supply with house connections supplied by single wells or irrigation schemes based on single wells.

(3) Reticulated water supply connected to well fields.

The benefits of water supply on a cost-effectiveness scale are higher in the last class whereas the social benefit in improving life conditions of the weak part of the population is usually higher in the first class.

Two types of aquifers (Cimino, Zoppis, Lierong) are to be considered:

(1) Discontinuous aquifers, or aquifers with highly variable properties. Success of well drilling difficult to predict.

(2) Continuous aquifers with relatively homogeneous properties over large areas. Success of well drilling less dependent upon site selection than in the previous case.

The probability of success of groundwater development as well as the chance to obtain meaningful investigation results is higher in the second type.

A second classification of aquifers, relevant to development and investigation costs, relates to their depth and lithology (loose material vs. solid rock).

The subjects of investigations are groundwater properties which are determined by the characteristics of the water supply system on the one hand and those of the aquifer on the other hand. These properties depend also on the phase of aquifer development (Mandel, Shiftan, 1981). Four phases will be considered: Exploration, Expansion, Management and Conservation, which are usually correlated with the rate of withdrawal from the aquifer (Fig. 1).

2. INVESTIGATIONS IN THE EXPLORATION PHASE

In the first phase of Groundwater Development - Exploration - the main properties that are looked for are:

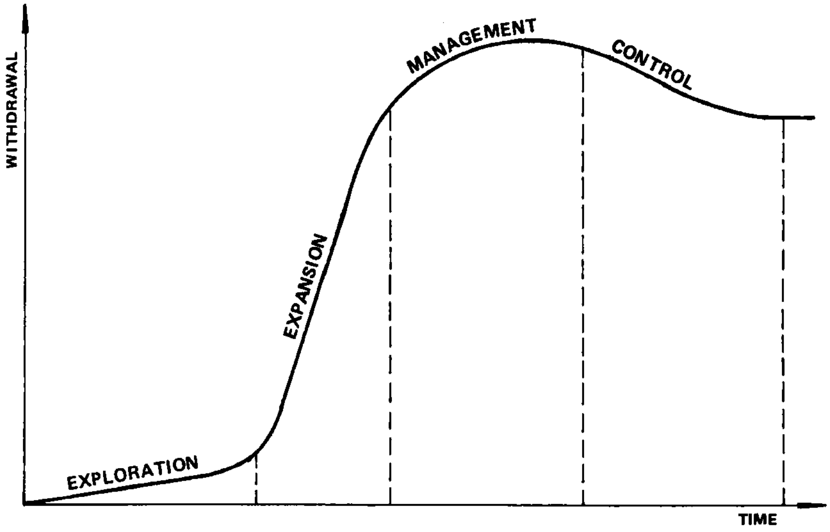
(1) The existence of aquiferous formations, their boundaries and their size (extension and depth).

(2) Yield of wells, their expected depth, depth to water table and expected water quality.

The techniques applied in this phase are:

Surface Geology - Mapping, stratigraphy, sections
Surface Geophysics - Resistivity, Seismic and other methods
Exploration Drilling

Management studies should be carried out already at this phase when groundwater is a secondary source in conjunctive use systems of surface and groundwater (Attia).



THE PHASES OF GROUNDWATER DEVELOPMENT

Fig. 1 The phases of groundwater development

3. INVESTIGATIONS IN THE EXPANSION PHASE

In this phase more wells, or well fields are brought into production and exploitation of groundwater increases. The main problems to be expected in this phase are:

(1) Selection of most appropriate well locations to assure low cost, proximity to the areas of consumptiopn and good quality of the water.

(2) Spacing of wells, in accordance with conjunctive consideration of planning and hydrological criteria.

The investigation techniques in this phase, in addition to intensifying the first phase techniques, are:

Borehole tests (well logging, subsurface geophysics)
Pumping tests
Water level maps, well hydrographs and flow net analysis
Chemical analysis and geochemical classification
Meteorological data analysis

4. INVESTIGATIONS IN THE MANAGEMENT PHASE

In this phase exploitation of groundwater reaches its limits and the main problems are related to the assessment of these limits.

Redistribution of pumping is considered in this stage (Cimino) and conjunctive use of ground and surface water is typical for this stage (Attia).

The safe yield of aquifers, variations of natural replenishment, storage coefficient, minimum regional water level, intrusion of seawater or other low quality water and land subsidence (Lierong), are properties of major interest.

Additional activities such as artificial recharge are considered and local properties relevant to the design of artificial recharge, such as seepage rate, become important.

The investigation techniques added in this phase are:

Spring and river flow analysis
Hydrometeorological models
Groundwater balance
Rainfall-runoff models

Groundwater flow models

Evaluation of exploitation and supply costs

Evaluation of water requirement and demand functions

Optimization methods for groundwater use

Field tests of seepage rates

5. INVESTIGATIONS IN THE CONSERVATION PHASE

In this phase the intensive exploitation of the aquifer and the human activities in its catchment areas endanger the quality of its water.

Reduction of exploitation and/or massive artificial recharge may be required to create hydraulic conditions that will stave off the intrusion of poor quality water or the decline of the water table to unacceptable depths.

Measures are required to control application of pollutants on the surface, infiltration of waste water and disposal of wastes.

Public intervention may be required in this phase to determine and impose the necessary measures.

Several techniques are added in this phase for assessing the rate of pollution and the efficiency of measures proposed for its control:

Geochemical study of groundwater quality
Tracer techniques: Natural
Tracer tests:
- single well
- multiple well

Studies of the unsaturated layers above the aquifer:

Seepage tests

Soil moisture logging

Seawater intrusion models

Simulation of the operation and effects of artificial recharge schemes.

6. PLAN FORMULATION

The process of hydrogeological investigation should produce the principles and design criteria for groundwater development. Therefore the investigation plan is dependent on the phase of development. The investigation plan will usually comprise the following components:

(1) Preliminary collection and review of existing data

(2) Hydrogeological mapping: surface geology, delineation of boundaries, appraisal of aquiferous properties of formation.

(3) Hydrometeorology: rainfall, evapotranspiration, soil moisture. Preparation and running of hydrometeorological simulation models to evaluate natural groundwater recharge from rainfall.

(4) Borehole and spring census: location, yield, depth to water table, water quality, total depth, elevation, lithology.

(5) Pump tests in existing wells.

(6) Precise levelling of observation wells.

(7) Surface geophysical prospecting (Cimino).

(8) Aquifer evaluation: size, replenishment areas, water level contour maps, flow directions, discharge and outlet areas.

(9) Exploratory drilling and testing for new well fields.

(10) Collection of water samples and analysis: chemical, isotopic.

(11) Groundwater balances (Cimino): replenishment, safe yield, storage coefficient, variability of replenishment.

(12) Hydrogeological (groundwater) modelling - calibration to match model responses to past and present data. 2-D flow models in the first phase of the investigation. Transport of solutes and contaminant models (2-D and 3-D) in the conservation phase.

(13) Collection of socio-economic data and their evaluation to establish the benefit criteria for optimal management of the water resources.

(14) Groundwater modelling - operational studies:

    (1) Evaluation of tentative operational management plans against given constraints imposed by the water table, flow rates from contaminated zones in the groundwater body, and by given maximum permissible concentrations of contaminants.

    (2) Finding optimal or satisfying operational policies under the above mentioned constraints, and considering additional objectives such as minimizing costs for a given target water supply or maximizing net benefits for a given product value of the water supplied.

Most of the groundwater systems in the world are already in their exploration phase and in a process of transformation to the expansion phase. Many are in transition to the Management Phase.

In the first phases of development only the first nine components will be applied. In the management and conservation phases the investigation will include also the other components (10-14).

The plan of investigation is carried out by different teams of experts and operators requiring mutual and continuous feedback of results. Special care should be given to the organization of the investigation in such a way that all the feedback channels between components and teams are ensured and that a timetable planned well in advance is strictly adhered to.

7. INVESTIGATION AND DEVELOPMENT STRATEGY

Despite the at least one, or even two orders-of-magnitude difference in cost between hydrogeological investigations and drilling, the cost of investigations is often regarded as high and the expenditure as of doubtful value. Therefore, a policy of proceeding directly to the drilling of production wells is adopted. Although in some cases natural conditions justify such an approach, in others it leads to a high incidence of failures. There is a benefit from the information gathered during drilling (provided it is carried out under due supervision), irrespective of the ultimate success or failure of the hole. It is of greatest importance, therefore, to conserve data from all boreholes, successful and unsuccessful ones alike.

The strategy may therefore be defined as the selection among one of the following policies:

(1) Investigation followed by development according to results.

(2) Development with no prior investigation and with a risk of failure.

(3) No development.

The selection is based on estimates of costs, benefits, probability of failure and requires a decision model. These topics are discussed in the following sections.

8. THE COST OF GROUNDWATER INVESTIGATIONS

The costs of investigations for groundwater exploration and their assessment relate to two main components: manpower with various levels of skill and equipment.

The performance of manpower and of equipment and their unit costs vary greatly. Little information is available in literature on costs of groundwater investigation projects. A notable exception is the chapter on exploration compiled by Custodio and Llamas (1976) which is based mostly on local information from Spain and personal experience. Papers that were submitted to the present Symposium also include such information.

The cost of manpower ranges from that for top experts to common labourers and cost of equipment ranges from that for primitive augers to highly advanced electronic equipment, laboratory costs and heavy drilling machines.

In groundwater exploration and development, a certain tradeoff can be discerned between an approach based mainly on the drilling rig as an instrument for exploration and the application of highly qualified expertise prior to, and simultaneous with, drilling. The skilled utilization and interpretation of available information, and, if necessary, its completion with regard to certain important details can result in great reductions in the expenditure for drilling, especially since substantial basic information such as geological maps, well sections, and geophysical information are often available at no or negligible costs.

Some typical costs for well drilling quoted in connection with a typical study are listed below:

		Unit costs US$/m	Typical cost of well US$
Investigation wells	up to 100 m	20	2,000
	100 to 200 m	50	5,000
	500 m	100	50,000
Production wells	up to 100 m	200	20,000
	200 to 300 m	500	50,000
	500 m	1000	500,000

Some typical costs of an investigation for groundwater exploration covering 10,000 km^2, for two years, are:

Experts:	US$300,000
Common labourers:	US$100,000
Equipment:	US$200,000
Total:	US$600,000

The per unit area (1 km^2) cost of this study is US$60. Custodio reports costs which, when updated range from 10US$ to 100US$ per km^2.

Zoppis reports on a 21,000 km^2 study for rural water supply in Chad costing 5US$ per km^2. In Mali he reports, under less favourable hydrogeological conditions, a cost of 25US$/ km^2.

The cost of an intensive surface resistivity study with 3 points per 1 km^2 is about 1000 US$/ km^2.

The costs of investigation are compared to costs of production (see next section). Such a comparison is shown by Cimino, who refers to a cost of a geophysical study of US$7,600-11,400 compared to a cost of a 250 m deep production well of US$38,000. The development to investigation/cost ratio was 3.3-5.0. Zoppis reports on ratios of 50 in the Chad study and 12 in Mali.

9. COSTS AND BENEFITS OF GROUNDWATER DEVELOPMENT

Cost estimates of groundwater development are similar to those for other civil engineering works and present problems such as: Economic vs. financial costs, market price fluctuations due to small and highly variable market volume. In groundwater development, the costs of drilling are a major element and their cost estimate may contain some elements of uncertainty such as errors in the forecast of the formations to be drilled and of depth estimates.

Benefits derived from the development of water resources are relatively easy to quantify when they are used for production processes, be it agricultural or industrial, but also here uncertainties are common concerning irrigation benefits, especially in regard of future crop yields and market prices.

Difficulties arise in the case of community water supply especially in rural areas where the willingness to pay is not a clear criterion for estimating benefits. However economic assessment is still possible through evaluation of opportunity costs such as the time saved for woman in water provision and the expected decrease of public health expenditure (Arlosoroff et al, 1987).

Benefit/cost ratios were presented at the present symposium only by Attia and are in the range of 1.25-2.9.

10. COST BENEFIT ANALYSIS - INVESTIGATION STRATEGY AND THE VALUE OF INFORMATION

Cost-benefit is one of the decision models for planning the development of a production system. The model is used for two purposes: (1) to rank development options and (2) to decide whether the development is justified or has to be rejected altogether.

In a similar manner, a model is required to rank investigation options and to decide whether the investigation is justified at all, or not.

However these two models, the development model and the investigations model are interlinked. The benefit considered in the investigation model is that of the added information.

This value can be evaluated only in the Development Model. Because of these interlinks a simultaneous solution to both models is required. This will be demonstrated in a simplified model for investigations in the exploration phase.

Due to the fuzzy nature of the underlying information such cost-benefit models are usually not applied explicitly but in the "back of the mind" of the "decision makers". In the following an explicit mathematical model will be demonstrated.

11. INVESTIGATION STRATEGY MODEL IN THE EXPLORATION PHASE

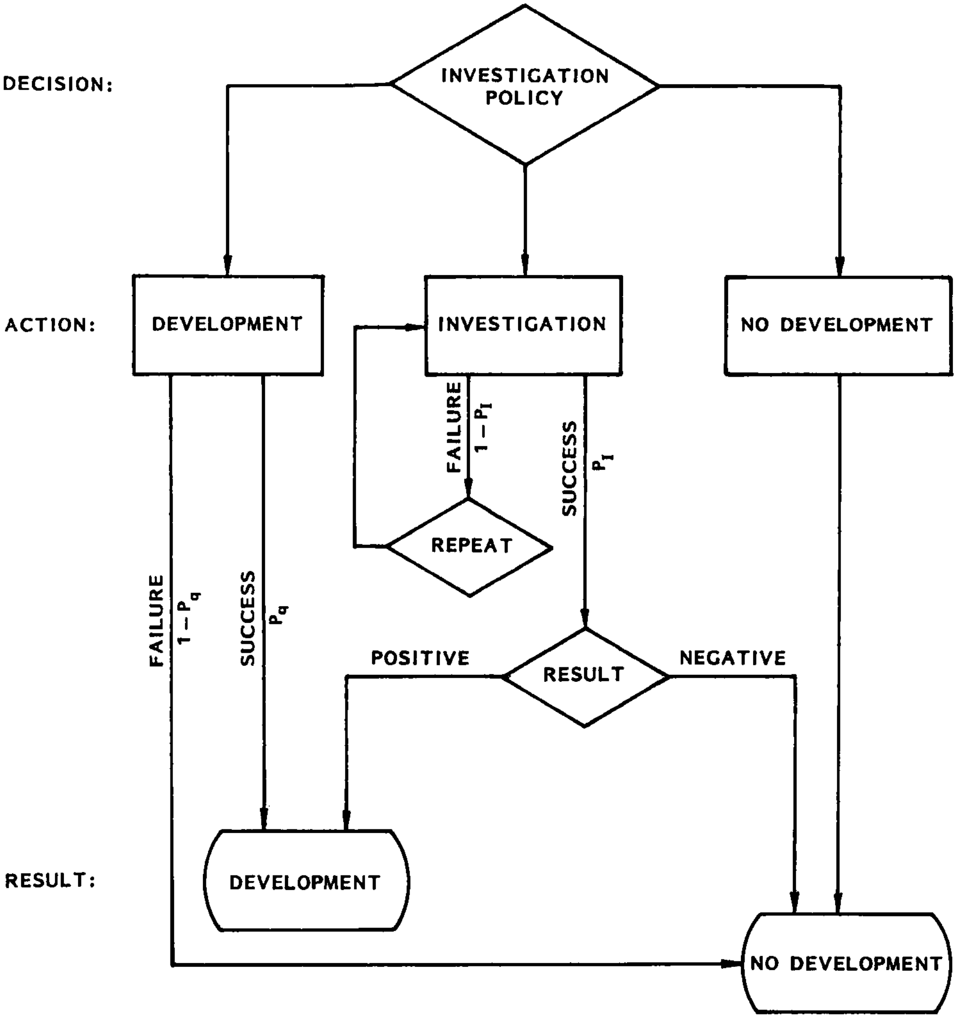
To simplify the following definitions, a Bayesian approach will be assumed, which is justified when applied to a program of multiple investigations and not to a single investigation.

The value of the unknown property may be realized on some levels with an unknown probability distribution. However let us assume that only two levels of a single property are considered: No water available (failure) with probability $1-P_q$, and water available (success) at an amount q with a probability P_q.

Zoppis reports on a success ratio of 0.95 in Chad and 0.70 in Mali. He also defines the conditions of success in terms of production rate, distance from village, and depth to water table.

The cost of the investigation is C_I and it is expected to yield complete information, i.e. to conclude positively or negatively on the availability of water. There is however also a probability $(1-P_I)$ that the investigation will fail to yield information and another investigation will be required. The mean number of investigations until success attained is $1/P_I$. P_q and P_I are a priori estimates at the time of the decision on the investigation policy.

Assume the cost of development is C_q and the benefits resulting from supplying q is B_q. The benefits are those of the public in their net present discounted value (Attia).



THE INVESTIGATION-DEVELOPMENT PROCESS

Fig. 2 The investigation-development process

Three investigation and development policies have to be compared (Fig.2):

(1) Investigation followed by development according to results

(2) Development with no prior investigation and with a risk of failure.

(3) No development.

The expected net benefits from the three policies are:

Investigation - $(B_q - C_q)\ P_q - C_I/P_I$

Development with no investigation: $B_qP_q - C_q$
No development - 0

The investigation is justified when the expected net benefit resulting from it is positive and exceeds the expected net benefits resulting from development with no investigation.

The investigation is therefore justified when:

$$(B_q - C_q)\ P_q\ P_I > C_I \qquad (1)$$

and

$$(B_q - C_q)\ P_q - C_I/P_I > B_qP_q - C_q \qquad (2)$$

Development with no investigation is justified when:

$$B_qP_q > C_q \qquad (3)$$

If all the above inequalities fail to be true than the development as well as the investigation are not justified.

Fig. 3 represents these three inequalities for some values of B_q/C_q (Benefit-Cost ratio) and of C_q/C_I (Development to investigation cost ratio), and delineates the domains of the three policies in the P_I-P_q coordinates (a priori estimates of success probabilities).

An improved assessment of these probabilities may be attained through the preliminary low cost stages of investigation.

12. RANKING OF INVESTIGATION OPTIONS

Selection of an investigation scheme among same possibilities for the same development project is by a cost effectiveness criterion - C_I/P_I. The investigation scheme with the smallest value of cost divided by its probability of success (to yield information) is selected. When the selection is among investigation schemes for different development projects the criterion for ranking will be the expected net benefit for development combined with investigation:

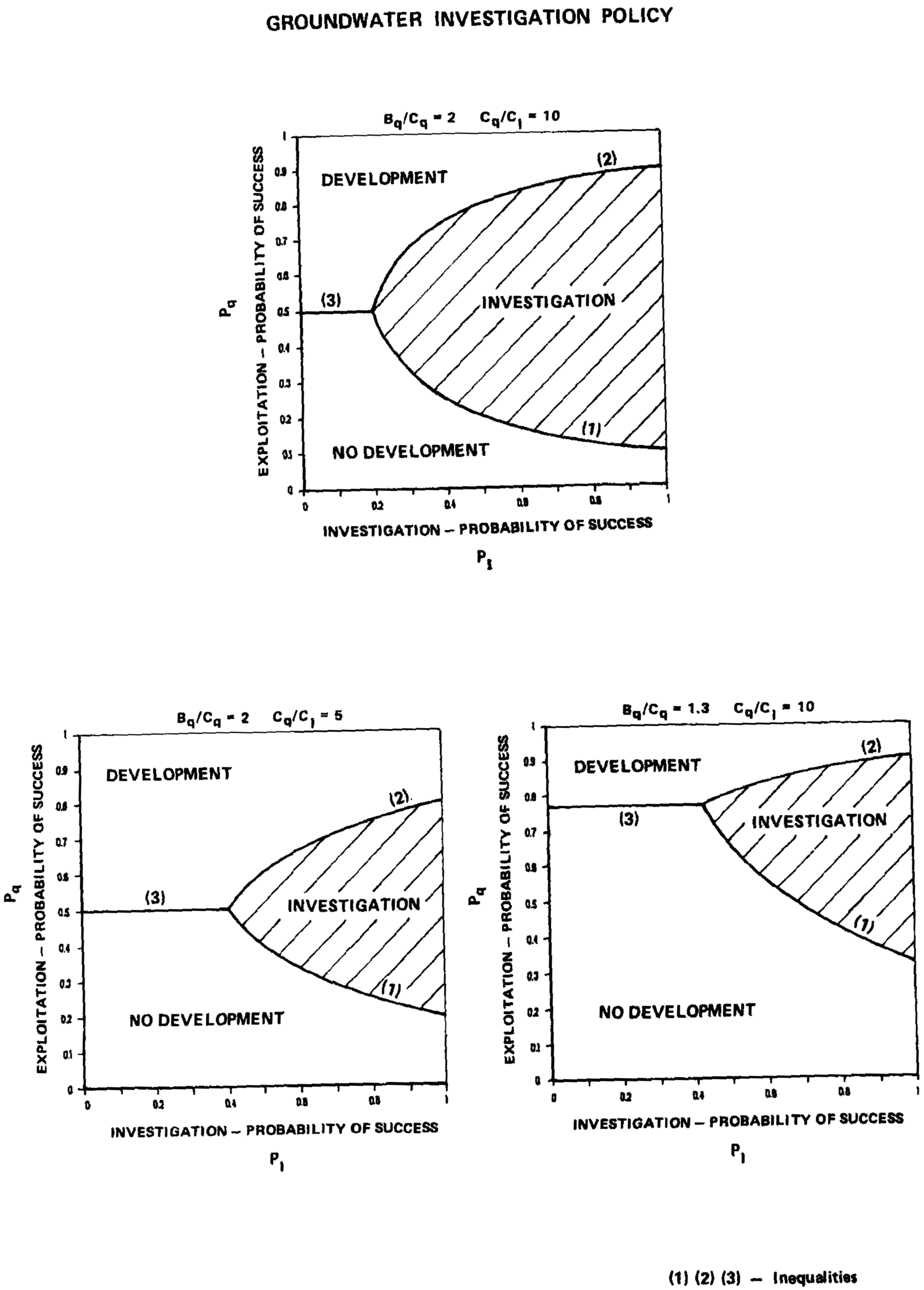


Fig. 3 Groundwater investigation policy

$$(B_q - C_q)\ P_q - C_I/P_I$$

An entirely different approach to the assessment of the value of the information consists in considering P_q itself(i.e. the probability of success in water supply) as a random variable where the investigation is aimed at decreasing its variance. No paper was presented on this approach, which seems important to improve the economic analysis of hydrologic investigations under conditions of uncertainty.

13. INVESTIGATION MODEL IN THE MANAGEMENT AND CONSERVATION PHASE

In these phases, there is no zero policy with zero benefits and costs. There is only the alternative between a policy of intervention and a status quo policy. These however, are analogous to the development versus no-development policies.

The intervention policy may involve reduction of exploitation, replacement of wells, redistribution of pumping and artificial recharge.

The status quo policy may involve damages such as increased pumping lift, deterioration of quality rendering existing wells useless, etc.

The model demonstrated for the exploration phase may be used also in these phases after the following transformations:

(1) The benefit is the difference of the expected present value of net benefits (operational benefits minus operational costs and damages) between the intervention policy and the status quo policy.

(2) The costs are the non-recoverable costs of the intervention such as: costs of new wells and artificial recharge structures, cost of installing alternative supplies, compensation to farm or well owners for being ousted from agricultural production.

(3) The probability of success P_q is the probability that the hydrologic assumptions underlying the intervention policy will be proven to be true.

After these transformations, the same model used to decide on investigations in the exploration phase as described in the last section can be used to decide on investigations in the more advanced phases.

14. FURTHER DEVELOPMENT OF METHODOLOGIES

Some simplified models for the investigation strategy based on cost-benefit estimates were demonstrated. More research is required to improve the approach to more complicated situations such as: (1) Staged investigation options with incomplete results; (2) The probability of success is not a simple binomic function and its variance is subject to decrease by investigation; (3) Non-Bayesian approaches considering risk aversion; (4) Crediting development for accruing information (learning by doing).

In the absence of reliable information, a simplified model such as the one presented in the present paper may be sufficient for many of the practical decision problems related to groundwater investigations.

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