ECONOMIC CONSIDERATIONS IN GROUNDWATER RESOURCE EVALUATION

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ABSTRACT

Basic hydrogeological exploration can be justified without recourse to economic considerations. Groundwater systems, however, provide almost limitless opportunities for investigation, as a result of their natural complexity, and beyond this initial level, sensible constraints have to be accepted. It is more relevant, therefore, to think in terms of investigation needs than investigation opportunities. Such needs must have some economic justification in terms of potential savings in groundwater resource development and management. A theoretical basis for economic analysis to determine maximum justifiable expenditure on groundwater investigation is presented, but there are often insufficient data on the success rate of uncontrolled drilling or on the disbenefits of uncontrolled exploitation to produce valid estimates. In consequence, attention is focussed upon ways of improving cost effectiveness in the use of those funds allocated, albeit rather arbitrarily, to groundwater investigation.

1 INTRODUCTION

1.1 Overall perspective

Normally, the exploitation of groundwater resources requires modest capital investment compared to that needed for the development of supplies from surface water sources.

The evaluation of groundwater resources tends, however, to require a larger proportion of the funds available for water-supply development and management, and even then results can be rather imprecise. This is especially the case in areas of complex hydrogeology.

The principal problems are associated with:

(a) difficulty in successful siting of production boreholes resulting from the geohydrological heterogeneity of many aquifers,

(b) estimation of the groundwater recharge rate and exploitable storage available for large-scale development in major aquifers,

(c) the natural occurrence of bodies of groundwater with unacceptable inorganic chemical characteristics in some aquifers.

The development of groundwater resources generally follows an evolutionary process over many years. A common situation in relatively arid regions is illustrated in Fig. 1; similar trends would occur in humid regions but the level of long-term replenishable resources would be much higher and may not be reached.

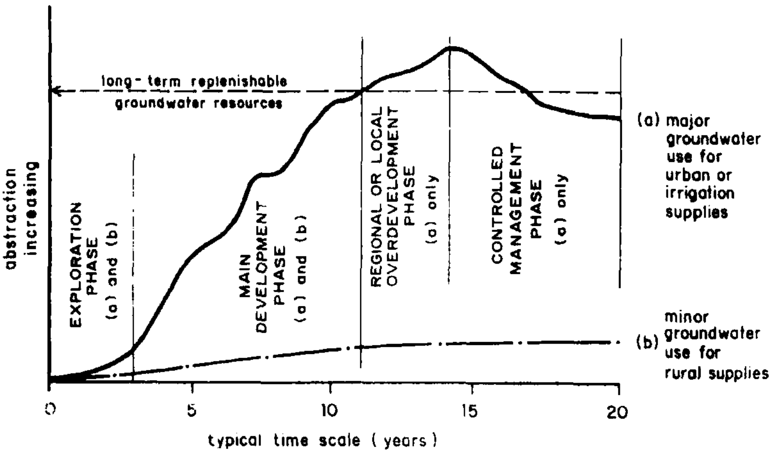

Fig. 1. Typical evolution of groundwater development in an arid region.

The decision to undertake basic hydrogeological exploration, of any given aquifer system or groundwater catchment, cannot be supported with rigorous economic analysis, but can be backed by conventional wisdom. In essence, it is not possible to establish whether investigation is justified until some investigation has been carried out.

Initial groundwater exploration is, therefore, often undertaken, financed or subsidised by government. Beyond the exploration phase, as groundwater development expands (Fig. 1), expenditure on investigation should be justified by economic considerations. It is this phase to which the present paper primarily pertains, although similar concepts are applicable in relation to investigation requirements in the management phase.

1.2 Influence of water demand on evaluation requirement

The objectives of groundwater evaluation will vary considerably with the size, location and quality of the water demand compared to the scale, distribution and status of available groundwater resources. This will determine the depth of knowledge of the local or regional groundwater system required. Although a spectrum of situations may exist, two distinct cases should be recognised:

(a) demands of very small scale in relation to the minimum groundwater resources available,

(b) demands representing a significant proportion of the total groundwater resources likely to be available.

The demand created by unreticulated rural potable water-supply and livestock watering needs is so small and dispersed as generally to require knowledge of groundwater occurrence alone, since abstraction rates are unlikely to overtax the resources of minor aquifers (Fig. 1), even those which may not have been recharged in recent history. Similar can be said of small urban or industrial water-supplies reticulated from individual boreholes, especially in the more humid regions. In this context the occurrence of groundwater is taken to include:

(a) the location and depth of hydrogeologically-productive horizons or zones,

(b) groundwater quality variations,

(c) the piezometric level and thus the order-or-magnitude of available drawdown, well yield and pumping lift.

Information on these factors will allow the prospect of successful boreholes to be assessed, development costs to be estimated and drilling site selection to be attempted.

For progressively larger and more concentrated demands, including (in increasing order) those for larger urban and industrial, mining, supplementary irrigation, major urban and large-scale irrigation water-supply, a more comprehensive knowledge of groundwater resources is required. In addition to the occurrence of important aquifers, quantitative information on such factors as their storage properties and recharge rates are required, on local or regional scale according to demand. Such information is necessary for the design of wellfields and for the management of already heavily-exploited aquifers (Fig. 1), both of which may involve large numbers of high-yielding boreholes in areas subject to complex relationships with surface watercourses or to encroachment of saline waters.

1.3 Maximum expenditure on water provision

Most activities necessitating a groundwater supply can only support a certain level of investment if they are to remain profitable. After deducting the costs of investments in all the other pre-requisites of the activity, an upper limit on expenditure for water provision is determined. In the case of such activities as industrial manufacturing, mineral extraction, agricultural irrigation and livestock rearing, an economic analysis will readily generate a reasonable ceiling expenditure for water provision. Obviously, the economic rate of return on water resources utilisation will also impose an upper limit on the funds available for groundwater investigation.

Public water-supply projects, both urban and rural, cannot be subjected to such rigorous analyses, because of the difficulty in economically quantifying their social benefits. Nevertheless, financial constraints will inevitably be imposed on the provision of water. In this case least-cost analysis of mutually-exclusive alternatives schemes of approximately-equivalent benefit will generally be used for project selection. The maximum expenditure on water provision will be defined in this way.

Thus, realistic estimates of the maximum economic expenditure for water provision can readily be reached. But the question of what proportion of this expenditure should be employed for groundwater investigation remains to be answered.

2 ECONOMIC CONSTRAINTS ON GROUNDWATER INVESTIGATION

2.1 Theoretical considerations

Groundwater investigation techniques are only justified if they increase the chances of subsequent boreholes being successful, such that the overall saving in drilling costs in the long-run is greater than the cost of investigation. Savings in operational revenue should also be considered, because they will be very significant in some aquifers. For simplicity, however, they are omitted here.

The average cost of drilling a successful borehole can be written as d/S, where d is the average production borehole drilling cost and S the success rate following the use of a given method of hydrogeological investigation. Now, if the unit cost of a method is C, we would choose method n rather than m if its incremental cost was less than the saving in drilling costs:

$$(C_n - C_m) < \left(\frac{d}{S_m} - \frac{d}{S_n}\right) \qquad (1)$$

Although it is possible to estimate d and C, few reliable data on S, corresponding to different investigation methods, exist. For a given method, S will also vary with hydrogeological conditions. However, some useful inferences can still be made (Farr et al., 1982).

Different geological environments will have a different success rate (S_o) for drilling without any hydrogeological control, that is for "wildcat" drilling; success being judged from predetermined yield-drawdown and water quality criteria. The maximum justifiable expenditure on groundwater investigation (C_{max}) will be given when S_n = 1.0, or perhaps more realistically 0.8, since it might be assumed that even the most sophisticated investigation methods will not improve the success rate to more than 80% in many instances. Thus:

$$C_{max} = \frac{d(1 - S_o)}{S_o} \quad (\text{or } \frac{d}{S_o} - \frac{d}{0.8}) \tag{2}$$

A graphical relationship between S_o and C_{max} has been established (Fig. 2) for typical drilling costs of small-diameter low yielding boreholes (US$10,000) and of large-diameter/high-yielding boreholes (US$50,000). Curves for other values of d can readily be generated.

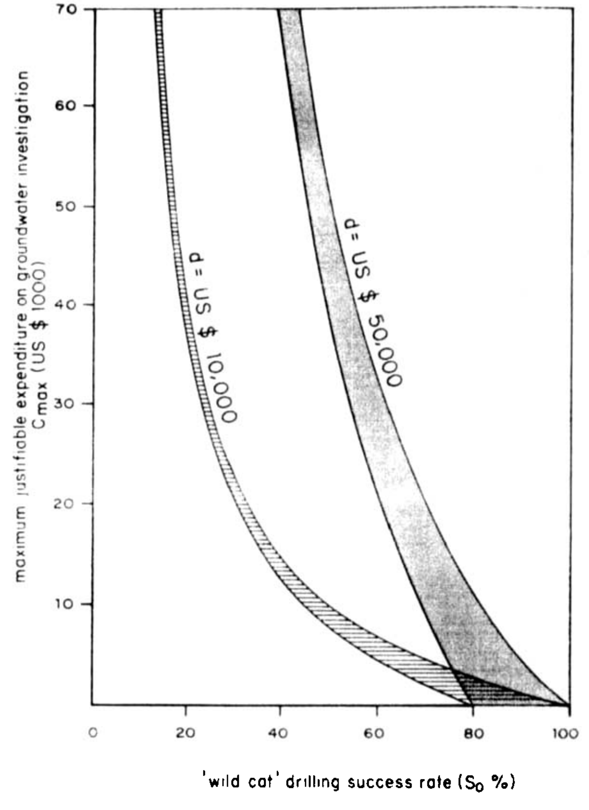

Fig. 2. Estimation of maximum justifiable expenditure on hydrogeological investigation.

The success rate that each investigation method will enjoy in a given hydrogeological environment is not known. However, the minimum success rate (S_{min}) a method would need before it could be considered can be calculated:

$$S_{min} = \frac{dS_o}{(d - CS_o)} \tag{3}$$

This gives the proportion of production boreholes that would have to be successful, after being sited with the aid of a particular method of investigation, for that method to be economically viable. Although difficult to generalise, an indication of the typical range of costs of differing methods of hydrogeological investigation (effectively suites of individual investigation techniques) is given (Fig. 3).

INVESTIGATION METHOD	C (US$ 1000/production borehole) 0.5	1	2	5	10	20	50	100	200
* Geologically supervised production borehole drilling	XXXX								
- with appropriate hydrogeological field equipment	XXXX	XXX							
- with long-traverse surface geophysics			XXX	XX					
- with short-and long-traverse surface geophysics				XXXXX					
* Full hydrostratigraphic exploration with investigation boreholes					XXXX	XXXX	XXX		
- with aquifer modelling and isotopic determinations, etc.						XX	XXXX	XXXX	

Fig. 3. Typical cost ranges for hydrogeological investigation in projects involving numerous production boreholes of 15-150 m depth.

A similar theoretical approach can be taken to the evaluation of the maximum justifiable expenditure on groundwater investigation to improve the management of existing water supplies. In this case, it would be necessary to determine the cost of negative impacts that would or might occur if management decisions were taken in ignorance of the prevailing hydrogeological conditions.

2.2 Practical situation

While this theoretical analysis forms a useful basis with which to view the economics of groundwater investigation, there are rarely sufficient data available on the success rate of uncontrolled drilling, or the disbenefits of uncontrolled exploitation, in the given hydrogeological environment, to permit a valid estimate of the ceiling for groundwater investigation. Uncertainties about the improvements in development or management efficiency, which will follow the application of a given method of investigation in a given environment, will also exist.

Moreover, groundwater investigation should be, and is often, regarded as a public good, whose benefits extend beyond the interested party, and should accordingly encouraged fiscally. It can argued that earlier development in a given area faces more difficulty than later exploitation, because once some boreholes have been drilled, and hydrogeological conditions evaluated, it will be easier to site subsequent production boreholes more successfully. Ideally, tax on later developers could be levied to recover subsidies paid to those initiating groundwater development.

In the absence of a more objective method, it is common practice to allocate for investigation an arbitrary, minor proportion of the economically-justified sum for water provision. This proportion normally should be higher than that invested in site investigation for surface water development, but in practice it varies widely in the range 2-20%.

Investigation expenditures of up to US$ 2000 are commonplace for low-yielding wells for rural water-supply and livestock rearing. In some cases, there are sufficient information on previous borehole success rates to justify such expenditure. At the other end of the scale, major groundwater development for industrial and mining enterprises with a high rate of economic return may require, and be able to justify, investigation costs of US$ 50,000 per production borehole, especially in arid regions of complex hydrogeology.

Expressed in terms of unit area, investigated, such costs are in the range US$ 100 per km^2 to more than US$ 1000 per km^2, but when viewed per unit volume of water-supply provided, however, the range is more restricted and generally in the order of US$ 100-250 per m^3/d.

Groundwater development or management decisions can be highly sensitive to prevailing hydrogeological conditions, financial constraints and economic externalities. These include situations in which:

(a) aquifers prone to rapid saline encroachment are being exploited for activities that could not tolerate an increase in water salinity,

(b) the profitability of proposed groundwater use is sensitive to energy costs, and therefore to errors in drawdown estimates, such as is the case in some agricultural irrigation projects,

(c) the net yield of schemes for conjunctive use of rivers and hydraulically connected aquifers is very sensitive to regional drawdown.

(d) groundwater abstraction may result in land subsidence or the drying-out of valued surface water features, such as springs, streams and certain marshland habitats.

In all such situations there will often exist justification to increase expenditure on groundwater investigation.

3 IMPROVING COST-EFFECTIVENESS OF GROUNDWATER INVESTIGATION

3.1 General position

In view of the fact that economic analysis is not generally likely to define a precise limit for investigation expenditure, it is considered sensible to focus most attention upon methods of improving cost-effectiveness in the use of those funds made available for hydrogeological investigation.

Although difficult to quantify in precise terms, the general position in respect of investigation cost-benefit, as judged from general observation, is probably as shown in Fig. 4. With increasing investment in investigation, a level will sooner or later be reached where the incremental benefit in terms of improved understanding of the groundwater regime begins to decrease. Moreover, as hydrogeological complexity increases, this point will generaly tend to be reached earlier.

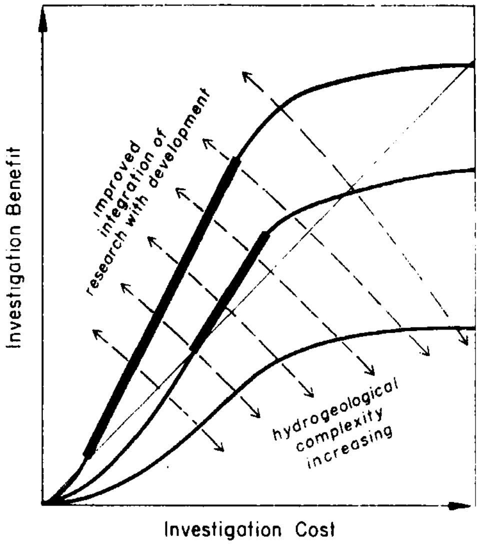

Fig. 4. Factors affecting the cost effectiveness of groundwater investigation.

3.2 Relation between investigation and development

Water-supply schemes have been traditionally considered in three rather separate stages: feasibility, design and construction. In groundwater projects these stages are more appropriately termed investigation, evaluation and development. Investment in the investigation stage is very much risk capital. Such investment can generally be reduced and phased if an integrated, flexible approach to groundwater development and management is adopted. This approach, in which the various stages overlap with hydrogeological investigation active throughout, will normally be much more cost-effective, since the probability of the investigation being successful in achieving its objectives will also be increased. High-cost activities within any investigation programme also need to be critically examined to see whether they can be reduced without compromising on data requirements (Skinner, 1983). In this way hydrogeo- logical investigation can be more readily reconciled with project economic constraints. Economically and technologically-appropriate solutions to groundwater supply problems are also more likely to evolve.

Rural water-supply programmes are often implemented in a widely-dispersed, piecemeal fashion, with boreholes and wells drilled without direct hydrogeological supervision. Little improvement is thus possible in the understanding of groundwater occurrence and thus in the selection of well design appropriate to local conditions. An integrated approach involving complete coverage of one area at a time using a number of drilling rigs under the supervision on a hydrogeologist has been shown more cost-effective (Grey et al., 1985). The concentration of drilling rigs in a single area permits direct supervision of each stage of well construction, with feedback to improve the siting and design of subsequent wells (Fig. 5). On-site decisions to abandon unpromising sites can be made at an early stage of drilling, so as to save the cost of completion of wells that would have resulted unproductive. If drilling rigs are widely scattered, this level of technical supervision would be out-of-the-question. It has proved possible at a cost as low as US$ 800-1000 per production borehole in programmes of more than 50 boreholes (Grey et al., 1985).

The careful hydrogeological supervision of production borehole drilling is a worthwhile investment at all scales, especially if the hydrogeologist is equipped to measure the basic characteristics of the formation drilled, and the occurrence and quality of their groundwater.

When this information is interpreted and acted upon directly it can result in major economies in the cost of production boreholes by:

(a) reducing or eliminating unnecessary drilling depth,

(b) selection of the appropriate well screen and installing it over the optimum depth range,

(c) mimimising or avoiding water quality problems.

In the evaluation of large-scale groundwater development prospects and management problems, aquifer recharge mechanisms and rates, and storage properties and boundaries, are key parameters, especially in the more arid regions. However, direct quantification of these parameters through short-term hydrogeological investigation presents major difficulties and results are often subject to large errors. Increasing the scale of investment in groundwater investigation does not necessarily improve these estimates significantly.

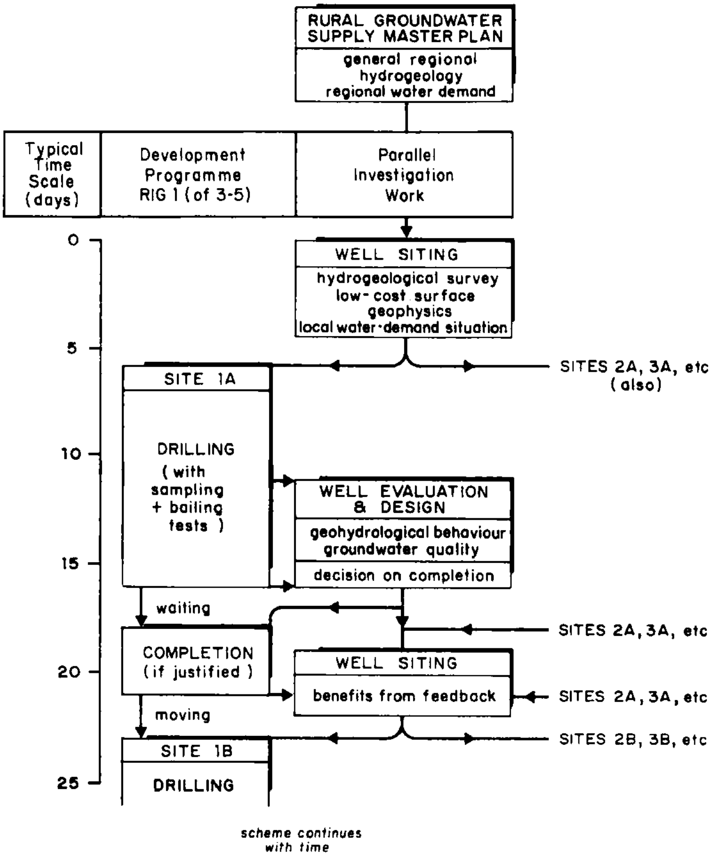

Fig. 5. Outline scheme for an integrated approach to groundwater investigation and development for village water-supplies.

It is thus strongly advisable for project design or management strategy to be sufficiently flexible as not to require radical change in the event of initial predictions proving subject to considerable error, due to wrong assumptions about recharge mechanisms and storage controls. Project design and policy formulation to achieve the required level of flexibility to accommodate initial uncertainty about groundwater recharge and storage estimates is greatly aided by use of a distributed-parameter aquifer model. While computerised numerical prediction modelling has long been used to aid development and management of groundwater resources, the critical use of models to analyse sensitivity to errors in the input parameters is less commonplace (Foster, 1987).

Projects can normally be structured to permit collection of the type of aquifer response data needed to calibrate the numerical model, and to allow time for the implementation of parallel investigation programmes to evaluate aquifer recharge and storage (Fig. 6). As the calibration of the model is

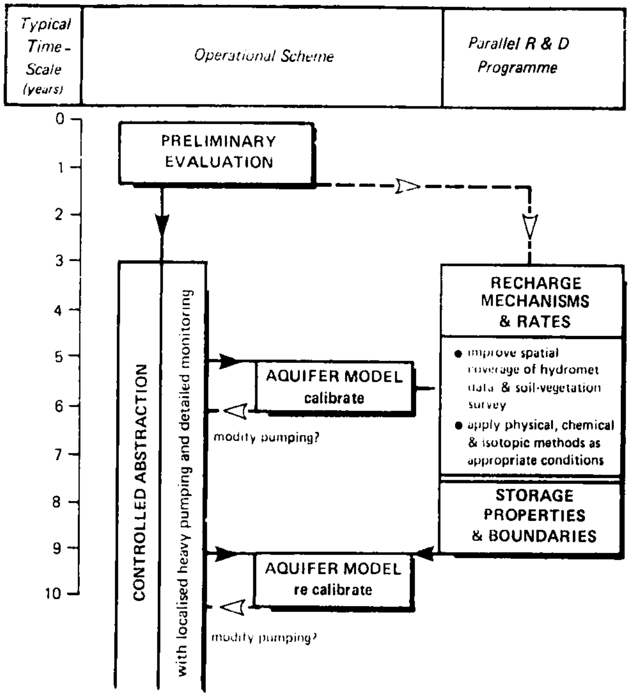

Fig. 6. Outline scheme for the integrated operational approach to groundwater investigation and development for large-scale water-supplies.

refined, so the accuracy of estimates for these parameters will improve. Moreover, such a model can ultimately be up-graded to an aquifer management model, incorporating rigorous formulation of management objectives or policy constraints through use of linear optimisation programming (Gorelick, 1983).

An essential element of this approach to groundwater evaluation is that sufficient effort goes into monitoring aquifer response. Short-term economies in this respect are likely to prove counterproductive in the longer run. In many instances significant groundwater abstraction will already exist although the aquifer response has not been monitored in sufficient detail or over a long enough period, but the same approach can be developed. In areas of complex hydrogeology such an approach will be the only practicable way to improve the reliability of groundwater recharge and storage estimates, and in many less complex situations it will often still be the most cost-effective way.

The operational approach is widely applicable, but there are circumstances in which the scope for its application will be more limited (Foster, 1987). These include situations where the minimum viable first-stage water demand is very large relative to exploitable aquifer storage, because of the need to justify major financial investment in a lengthy external pipeline to a remote water demand centre, or to construct an industrial plant for which the water-supply is required.

3.3 National groundwater data bases

In most nations the number of water boreholes drilled annually, by both public and private sector, will be expressed in hundreds or even thousands. If governments do not make adequate provision for the collection, verification, registration and archiving of the hydrogeological data from these boreholes (including an accurate record of their sites), a major and unnecessary loss of investment in that nation will have occurred, since the cost of obtaining the equivalent data by drilling investigation boreholes will be very high. Full documentation of unsuccessful water boreholes is of equal value in this context.

Moreover, if an effective statutory requirement and/or financial inducement can be devised for access to be provided in all successful boreholes for groundwater level measurement and for a tap to be installed for groundwater quality sampling, this would greatly aid national groundwater data collection at relatively minor cost and inconvenience. In some circumstances, a cumulative flow meter may also be desirable.

The periodic compilation and correlation of the data collected into various forms of hydrogeological maps and graphs is useful both to verify the internal consistency of the data base in any given area and render its data more accessible to the public.

4 CONCLUSIONS

(a) Initial regional hydrogeological exploration must be regarded as a public good and promoted without need for justification by rigorous economic analysis.

(b) Economic analysis to determine maximum justifiable expenditure on further groundwater evaluation is theoretically straightforward but sufficient data are rarely available to generate valid figures.

(c) Information on the cost of hydrogeological investigations and their success in improving the efficiency of groundwater development and management need to be systematically collected.

(d) More attention should be given to increasing investigation cost effectiveness. Close hydrogeological supervision of production borehole drilling and better integration of groundwater evaluation, development and management are the most beneficial in this respect.

(e) The economic significance of effective national groundwater data bases and water borehole archives is also stressed.

5 ACKNOWLEDGEMENTS

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