# BASIC ECONOMIC CONCEPTS APPLIED TO GROUNDWATER MANAGEMENT

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## INTRODUCTION

For many developing countries where agricultural production represents a high proportion of the Domestic Product, ground water might well have macroeconomic significance insofar as its use contributes to increasing production, income and employment, and to improving the foreign trade balance. Although this does not apply only to ground water as such, but to water in general, and indeed to the other inputs of agricultural production, there is no doubt that the required type of economic analysis of large projects based on ground water in those countries must not be the same as what a private company commissioned to carry out and run the project would produce. The induced effects of the project on income and employment, considerations on interest rates applicable, etc., cannot be excluded from the analysis, but this is a task reserved for specialised economists.

Therefore, it is undoubtedly the microeconomic aspects of production which are of interest to hydrogeologists and other professionals in this field and particularly the aspects referring to production cost. Decisions on the volume of groundwater production correspond, according to the social order, to those who manage this resource, who set the economic supply on the basis of their own cost functions and the characteristics of demand which is external to them.

Concepts such as optimum production level, production expansion processes, scale economies and optimization of the design and management of the installations, which in microeconomic theory are developed from a generic abstraction called "the firm", are expounded in this Chapter applied to a groundwater production unit consisting of a well and the auxiliary installations to place the water on the ground surface.

The Chapter is divided into two sections. The first presents some elementary concepts which the reader can study further in any basic manual of economics (Lipsey, 1963), and the second deals specifically with ground water. Continuous emphasis has deliberately been placed on concepts relating to the elements, structure and utility of the cost functions, on the conviction that these are the points which must definitively be assimilated. No place, therefore, has been given in the Chapter to the theory of cost-benefit analysis, in order to avoid excessive length, and in this respect those not familiar with the subject are referred to any of the excellent publications which apply cost-benefit analysis to the field of water (Kuiper, 1963).

## SECTION 1: BASIC ECONOMIC CONCEPTS

### 1. COST OF PRODUCTION

Let us consider a firm which manufactures a specific product by means of a certain technological process, for which it uses its installations, and certain production factors or inputs, such as labour, raw materials, energy, goods purchased from other companies, etc. The company is presumed to organise its production in a rational manner, i.e. to achieve any level of final production it uses exactly the optimum amounts of inputs deduced from its technological process.

The total cost of production of a given level of output x, during the period of time used for computation, is defined as the monetary value of all the inputs employed in the period to obtain the said amount. In the hypothesis of rational organisation of production, total cost, $C_t$, is a known function of x, supposedly continuous and derivable, consisting of two addends, $C_t = C_0 + C_v$:

a) a fixed cost, $C_0$, independent of the level of output, which the firm incurrs even when it remains inactive, made up of the charges relating to the availability and maintenance of its installations, those of its permanent staff, and other overhead costs;

b) a variable cost $C_v$ (x), which grows with x, due to the larger use of the various inputs necessary.

Figure 1 shows the usual shape of function $C_v$, setting out from the origin with a decreasing slope until it reaches a point of inflexion, after which it becomes concave. The total-cost curve is the same as the previous one, displaced upwards in the $C_0$ amount.

The variable average cost is developed from the variable cost by dividing its value by the amount of the product, $c_v = C_v/x$. Given the shape of the $C_v$ curve, the variable average cost decreases until $x = x_1$, and grows from this point onwards.

The total average cost is similarly defined from total cost, $c_t = (C_0 + C_v)/x = (C_0/x) + c_v$, its minimum value, $x_2$, being situated to the right of point $x_1$.

The average or unit costs are relevant to establish the profits or loss of the firm and to take decisions on its future level of activity, i.e. on its permanence as such and on its opportunities for expansion.

As will be seen, immediate or short-term decisions depend on the marginal cost, $c_{mg} = dC_v/dx = dC_t/dx$. In economic terminology it is common to refer to marginal cost as being the cost of the last unit produced, a simplification resulting from replacing the mathematical concept of derivative by the quotient of increments, $c_{mg} = \Delta c_v/\Delta x$, with $\Delta x = 1$, which is approximately valid when x consists of many units.

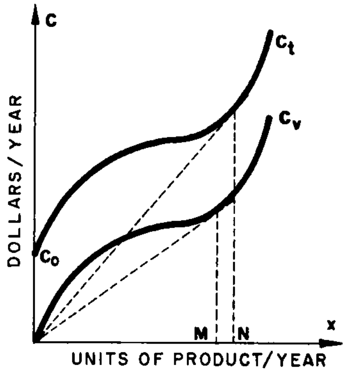

Figure 1.- Total and variable costs.

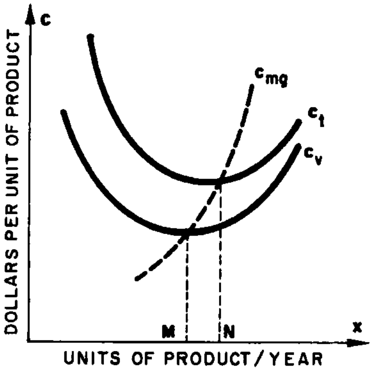

Figure 2.- Average and marginal costs.

Returning to Figure 1, the variable average cost, $c_v$ is given by the slope of the straight line joining up the origin of the coordinates with each point of the curve $C_v$, and the marginal cost by the slope of the tangent to curve $C_v$ at each of its points. Both slopes are equal when $C_v/x = dC_v/dx$, the same expression obtained when determining the minimum of the variable average cost, $dc_v/dx = 0$. Consequently, the marginal cost curve passes through the minimum of $c_v$ and the same holds for the minimum of the total average cost, $c_t$ (Fig. 2).

## 2. CAPITAL, CREDIT AND INTEREST RATE

### 2.1. Economic Concept of Capital

The term capital has several meanings in economics, all of them referring to something possessed and used by a company, an entire productive sector, or even a nation. It is of interest here to stress the strictly economic meaning of capital, defined as that set of previously produced goods applied by the company, the sector or the nation in the production processes which they undertake.

Thus, capital is a production factor and, indeed, all the factors except labour and natural resources are capital goods. Two categories of capital goods are distinguished: circulating capital, made up of goods which disappear or are extinguished in each production cycle (energy, some raw materials, semi-manufactured goods which are transformed, etc.), and fixed capital, made up of those goods which remain over several periods, which are not extinguished in the process or physically incorporated into the final product, but which undergo a loss of value as a consequence of their use and age. This category includes buildings and other infrastructure elements, as well as machinery and other movable items owned by the company. It is common to limit the use of the term capital to refer only to goods making up the fixed capital.

Insofar as it is a produced good, capital proceeds from labour, from natural resources and from other pre-existing capital goods and, consequently, in the last instance capital proceeds from an accumulation of labour applied to natural resources. However, for this type of goods to be created or produced in a society or nation not being devoted to the direct consumption of its individuals, it is necessary that some of them renounce dedicating a part of their income to acquiring consumer goods; if all individuals and organizations devoted their salaries and other income to the purchase of food, clothing, transport services, health, leisure, etc., there would be no manufacture of durable goods necessary to maintain or increase the level of production.

These renouncements of immediate consumption constitute savings, the existence of which makes it possible to create capital, known as investment.

Capital increases the productivity of labour and plays an important role in economic development, i.e., in the expansion of the production capacity of a society. It has also been seen that the basic condition of access to capital in capitalist systems consists of the existence of a significant number of individuals who have already covered their consumption needs, precisely the situation which does not occur in those societies known as "developing"; in countries with centralised or planned economies, savings can be imposed by the State, which decides on the consumer and capital goods to be produced. Owing to this crucial role of capital, it is advisable to become familiar with the ratios normally used to assess the degree of need for capital in an economic sector or for a specific project. These ratios are:

1) Capital coefficient, quotient between the monetary value of capital goods employed in production and the volume of annual production in physical units.

2) Capital-product, identical to the above, but valueing the production in monetary units.

3) Capital intensity, quotient between the monetary value of the capital goods used by a company or production sector and the number of jobs directly linked to the company or sector.

### 2.2. Credit

Credit is the name given to every operation of economic exchange in which there is no simultaneity between the moment of the provision and that of the receipt, the latter taking place after a term much longer than that required for the act of exchange itself. The goods exchanged can be of the same nature (delivery of a sum of money and subsequent repayment of the amount agreed) or different (delivery of goods against deferred payment).

Credit is the instrument which channels savings towards investment. The owners of money, directly or through the banking service, place it at the disposal of those companies who wish to purchase capital goods. Once the loan has been made, the company buys or commissions the manufacture of the desired capital, being obliged to repay the amount(s) negotiated to the lender.

It is short-term credit or commercial credit (for periods of months) that finances the purchase of circulating capital. Medium-term credit (for a few years) is used to buy capital goods and machinery, while long-term credit (five to fifteen or twenty years) is kept to finance more durable fixed capital (buildings and other fixed installations).

## 2.3. Interest and Discount Rate

The existence of credit markets, to which private savers and financial institutions go to offer money, and companies, domestic economies and the State itself go to seek funds, sets a price for the use of money. This price is known as interest, the amount of which depends on the term, the inherent risk of the business to which it relates, and the legal guarantee of the contract. The interest rate is an economic parameter on which the State deliberately acts by means of the instruments of monetary policy.

Interest as payment for the use of money is defined as a percentage rate corresponding to a certain interval of time, normally one year. If $M_0$ is the amount lent, $M_t$ the amount to be repaid after t intervals, and r the interest, the expressions linking these values are, depending on the system used:

simple interest: $M_t = M_0 (1 + rt)$
compound interest: $M_t = M_0 (1 + r)^t$
continuous interest: $M_t = M_0 e^{rt}$

Interest and discount rate are somewhat similar terms, the latter being used to up-date to the present moment the value of an amount available in future time, $M_t = M_0 (1 + r)^{-t}$ if, as is usual, the compound system is employed.

The difference between the two concepts lies in the fact that interest must be considered in financial analysis, while the discount rate is used in equivalence calculations comparing alternative projects. The rate is a value judgement based on a compromise between present consumption and capital formation from the viewpoint of the decision maker. For public investments this means the viewpoint of the people as a whole, ideally seeking to maximize total social welfare, and many opinions have been expressed on what is the best discount rate from the public's point of view (James and Lee, 1971). But in private investment decisions, the discount rate must be equal to the market interest.

In the manner in which the concept of interest has been introduced here, it would be a purely monetary phenomenon, derived from the money market. There is also an explanation in terms of real economics: companies desire to purchase capital goods because they expect to obtain profits inherent to the increase in productivity that capital implies, thus resulting in a willingness to pay for the use of other's funds. Furthermore, the level of present consumption that individuals decide to sacrifice (savings) is determined by the remuneration which they obtain as lenders. In this way interest is related to the marginal productivity of capital, i.e., to its capacity to generate additional wealth.

Consequently, disregarding the existence of different credit markets depending on the term and guarantee of the loan, and of state intervention through its monetary policy, it would have to be admitted (even if in a somewhat vague and general manner) that the market interest rate must be very much related to the potential growth of the economy based on investment. It is obvious that on a national scale, or even of the different production sectors, this potential is generally expressed in annual rates of one single digit per cent, and yet there are many countries in which the interest rates run to two digits.

This divergence is mainly due to the effect of inflation. In a country with an annual inflation of 8%, if nominal or monetary interest is 14%, the real interest would be 6%, a fact which must be remembered when setting criteria for cost estimation.

## 3. THE COST OF CAPITAL

Fixed capital is a production factor of the type which is not incorporated totally or partially into the final product, nor is it consumed or extinguished in the process, as occurs with hours of work or raw materials. However, its value diminishes over time as a result of aging, its progressive inferiority to provide service due to technological innovations, or simply because the economic activity for which it was used ceases to exist. Thus the concept arises of the useful life of a capital good as the period of time after which it is reasonable to assume that the equipment or investment is worn out or obsolete.

When a firm computes its annual production costs, it makes an annual allowance for the depreciation of each capital good. The purpose of these allowances is to build up a fund which allows the same item to be replaced at the end of its useful life or depreciation period:

$$A = \frac{C\ r\ (1+r)^n}{(1+r)^n - 1} \qquad (1)$$

A = annual allowance in case of constant depreciation; C = purchase value of the capital good; r = interest rate; n = useful life.

The justification of the value of A is based on the assumption that if the n successive annuities are placed in the financial market at interest rate r, the firm would eventually receive the amount $C\,(1 + r)^n$, an amount identical to that which it would have obtained by placing amount C from the start, instead of purchasing the capital good.

Thus, the cost of the capital is an opportunity cost, of the opportunity of profits lost when the decision was taken to devote funds to a specific investment, renouncing any other which presumably had a guaranteed yield at rate r.

The annuity of economic depreciation should not be confused with the annual amount of financial amortization of the loan which the company might have taken to buy the good being depreciated. They are different concepts, since:

a) the loan might or might not exist, depending on the financial capacity of the company, while the need for economic depreciation always exists.

b) The term of finance is usually considerably shorter than the useful life of the capital purchased. Financial amortization is a legal obligation derived from a loan contract which might be renewed during the life of the investment financed.

c) The interest rate of the loan may be lower than the current market rate, owing to governmental support of the specific economic activity involved, but market rates should be used to assess real costs.

One last point should be made relating to the use of the market interest rate to calculate the cost of capital when the economic system is suffering a significant rate of inflation. Since the market rate of interest contains the rate of inflation within itself, if the inflation rate does not vary over time, the cost of depreciation is always the result of (1), and it is not correct to up-date it each year by currency devaluation. The practice of up-dating the annuity would be correct if the real interest rate, discounting the inflation rate, were used as the value of r.

## 4. THE VALUE, COST AND PRICE OF A GOOD

Kuiper (1971) gives a very clear example to show the difference between the concepts of value and cost: "It may cost nothing to lift water out of a clear stream and drink it, while the value of doing so may be very high. It may cost a great deal to pump water to the top of a mountain, and the value of doing so may be next to nothing".

The value of a good is the monetary estimation that each individual or economic unit assigns to the satisfaction or the utility which the use or consumption of the good provides to him. More precisely, the value may be defined as the maximum amount of money an individual would pay to obtain one unit of the good. Thus, value is essentially subjective, because it depends on the individual´s system of preferences, and on the amounts possessed of the other goods.

Price is a mercantile concept which implies the existence of a market for the goods, in which it can be exchanged for money, and the price is the amount obtainable in money for each unit of the goods.

The concept of individual demand is derived from those of value and utility, and by aggregating all individual demands one can obtain overall demand for the good, defined as the amounts of the said good that buyers overall would buy per time unit at different prices (curve D of Fig. 3).

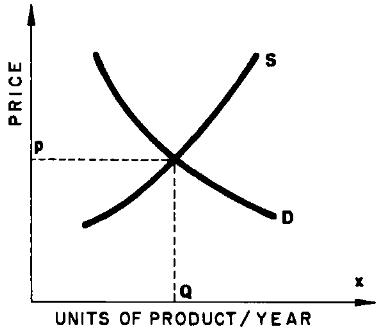

Figure 3.- Market supply and demand.

Similarly, overall supply by the companies producing the goods is defined as the amounts of the goods that the suppliers overall would produce per time unit at different prices (curve S in Fig. 3). The function of the market is to establish the balance between supply and demand which occurs for amount Q at price p.

Naturally, individual supply and consequently overall supply, is determined by the costs of the goods, i.e. by the monetary value of the inputs necessary for its production, which in turn implies the existence of prices and markets for those inputs.

It is possible to add still further to the confusion on the above concepts by considering that the prices of the input factors depend on their productivity and on the prices of the goods manufactured with them. It is not intended to end this Section with the unnecessary attempt to condense a course in microeconomic theory; for this reason, this idea will not be developed further. It has been raised to indicate that, although the price, the different values, and the different costs of a good are essentially different concepts, their respective magnitudes are related through a complex network of balances in the markets of all the goods subject to economic traffic.

## SECTION 2: ECONOMIC ASPECTS OF GROUND WATER

### 1. THE VALUE OF GROUND WATER AND ITS OPTIMAL PRODUCTION LEVEL

In this section ground water is considered from the viewpoint of its production, understanding that this has been done when the water has been mobilised for application to any activity. Consideration will not be given to its possible value as a natural resource stored in the ground, capable of future use, or kept in reserve for use in possible periods of drought.

The value of this resource as a support for an ecological environment will not be contemplated here either, which is the case of many important wetlands, nor will the utilities which by remaining in the ground it may provide to the users of the rivers into which it flows naturally, once it does rise to the river. Ground water withdrawals induce negative economic effects on other pumpers, on downstream users and perhaps on the ecological environment, generating what are known as external costs or external diseconomies. Unless administrative measures are introduced to correct these effects, these diseconomies are not taken into account by those who pump out water, as an additional cost or as a reduction in the final value of the ground water produced.

Under these premises, the uses of water which should be taken into consideration are urban or domestic, agricultural and some industrial ones. In the first case, it is a good which is applied directly for consumption. In the other two cases, water is a production factor, an intermediate good which intervenes in the obtention of another, final good.

### 1.1. Municipal Use

It is well known that demand for water by an urban community depends on the number of inhabitants, their income level, the climate, population density and other planning parameters, and on the price of purchase. Numerous studies undertaken in industrialised countries have proved that the sensitivity of demand to the price of water is very small or zero, except in residential areas where private gardens and lawns are common.

It may be stated that if the amount of water available is very small, people would be prepared to pay a very high price for it, that their willingness to pay will remain high until certain essential needs are satisfied and, that beyond an ample supply, people are scarcely prepared to pay for it.

Data are barely available to measure the value of water for domestic use, to quantify its utility in monetary units, since usually there are no free markets for water. The supply service operates under a system of public or private monopoly, with tariffs controlled by the public authorities and these tariffs are set in accordance with several criteria including that of cost.

The foregoing statement is general and objectively true. Nevertheless, situations do exist where there is a known value for the ground water destined for urban use, as in the case of operating one or several wells and selling the water under contract to the company responsible for the municipal supply; the following paragraph explains how to determine the optimum level of extraction.

## 1.2. Agricultural and Industrial Uses

In these cases demand for water is a demand derived from that for the final good produced, i.e. the value of the water depends on the price of the final good produced, on the prices of the other inputs (seeds, fertilizers, etc.) and on the proportions in which the inputs are combined.

In some special areas of a few countries there are markets for ground water, in the sense that there exists an important commercial activity relating to the water, which can be brought to different places for the irrigation of lands which do not possess water and wish to buy it. The prices in these markets reflect the value of the water in these specific areas.

If the price of water in one of these markets is p, the amount of the resource to be pumped from a specific well, W, is determined by maximising the profit function: $B(w) = w.p - C_t$, where $C_t$ is the total cost of extraction.

The condition of maximum profit, $dB/dw = 0$ yields $p = c_{mg}$, the equality between the price and the marginal cost at the optimum point, A (Fig. 4):

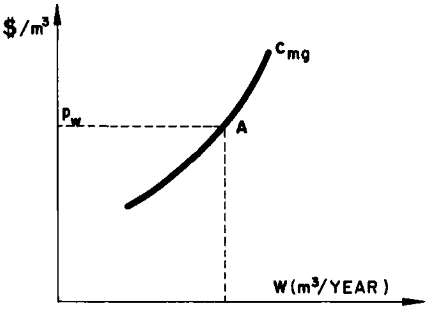

Figure 4.- Optimal production (fixed price)

It is normal practice for farmers and industrial companies to operate their own wells, extracting the quantity of water which they consider appropriate. If they were asked what value they assign to each cubic metre of water used, very few or none would present a figure. Most of them could calculate the residual profit obtained in their installations, subtracting all the costs from the revenues (labour, depreciation of machinery, fuel and energy, fertilizers, seeds, etc.), which overall may be attributed to the possession of the land and the water, and to their management as a businessman. This is why the value of the water proves indeterminate or depends on subjective criteria, and that optimum extraction cannot be achieved as simply as in the schematic manner of Figure 4.

Economic theory demonstrates that, in order to maximize his profit, a farmer who owns a piece of land must apply an amount of water per hectare such that the marginal productivity of the water is equal to the marginal cost of the water, divided by the price of the agricultural product. If F(w) is the yield or productivity function per hectare depending on the water applied, p the price of the crop, and $F'(w) = d\,F(w)/dw$, the foregoing is equivalent to:

$$F'(w) .\ p = c_{mg} \tag{2}$$

As the marginal productivity, $F'(w)$, is a function of the water applied, w, and the marginal cost of the water depends on the pumping discharge, which in its turn is a function of w and of the total surface area of cultivation, the result is that the optimum supply for a piece of land depends on its size. The value which should be attributed to water to determine the optimum level of extraction, which in the example of Figure 4 was a single and definite amount (p), is in this case a variable depending on the circumstances of each exploitation; furthermore, its determination (2) is complex, because it is necessary to know function F (w).

## 2. GROUND WATER PRODUCTION COSTS

This section describes the variables determining the cost functions of ground water using an analytic approach which allows general conclusions to be drawn which apply to all specific situations. A generic well will be the unit of analysis on the assumption that the production process concludes when the water is brought to the ground surface. Other subsequent activities, such as quality treatment, transport or distribution, are not specific to ground water and, consequently, will not be taken into consideration. The reference period of time set for the calculation of costs will be one year.

### 2.1. Fixed Costs

The following may be taken to be costs independent of the amount of water extracted:

a) Depreciation of Investments: the well pump and piping gear, engine, high tension electricity line if necessary, transformer, electricity control panel and protective housing.

The cost of these installations depends on natural factors (type of geological formations, depth and productivity of the water-bearing strata, static water level) and design factors (basically, discharge required and type of energy source). Each of these installations will have meant an investment Ii, ni being the respective periods of useful life.

If the interest rate is r, the annuity of depreciation of each one, Ai, is given by (1) and the overall annual cost will be $\Sigma$Ai.

b) Staff Expenditure. In modern installations, automation reduces the need for staff to little more than simple inspection visits by an employee of the municipal service, of the industry concerned or of the farmer himself. The economic value of the partial time of the employee used for this purpose is equivalent to an annual amount that will be denoted by L.

c) Maintenance Costs, M, to cover needs of inspection, maintenance and small repairs. These costs are usually estimated annually as a percentage of the value of the investments (2% might be acceptable as an appropriate figure).

### 2.2. Variable Cost

This corresponds to the energy used in pumping. Most electricity tariffs have a dual structure, with one addend depending on the energy consumed, and a second which is based on the power contracted; this latter should be included in the fixed costs.

If Q is the current pumping discharge h the depth of the dynamic water level, t the number of pumping hours per year, e the unit cost of energy, and R the overall power efficiency, the annual energy cost is:

$$C_v = e.Q.h.t/R = kQht \qquad (3)$$

In installations with submergible electric pumps which take energy from the grid and work in the acceptable sector of their characteristic curve, constant k of (3) is approximately 0.015e, for Q in litres per second, h in metres, e in kWh, and t in hours.

The Q and h variables are related by an expression of the type:

$$h = h_o + AQ + BQ^2 \qquad (4)$$

ho = depth of static water level; A = constant representing the transmissive characteristics of the aquifer in the well surroundings. A is not really constant; it grows with the time of pumping, but for practical purposes it is valid to state that the drawdown becomes stabilised after a short time; B = coefficient representing the efficiency of the well, which includes the part of the drawdown due to initial quadratic head losses.

Coefficients A and B can be obtained by making pumping tests. For a priori estimates, A may be assumed to be equal to the inverse of the average specific yield of the aquifer corresponding to small pumping discharges. Parameter B depends on the technology of construction of the well and normally varies between 10-6 and 10-8 day2/m5 (Custodio and Llamas, 1976).

### 2.3. Unit Costs

With the notations used, the total annual cost is:

$$C_t = C_o + C_v = \Sigma A_i + L + M + kQht \qquad (5)$$

and total average cost is obtained by dividing by the annual production.

$$c_t = \frac{C_t}{Q.t} = \frac{\Sigma Ai + L + M}{Q.t} + kh \qquad (6)$$

Substituting in (6) the value of h according to (4):

$$c_t = \frac{\Sigma Ai + L + M}{Q.t} + k\ (h_o + AQ + BQ^2) \qquad (7)$$

which is represented graphically in Figure 5 for a generic well, already built and installed, and for different values of t.

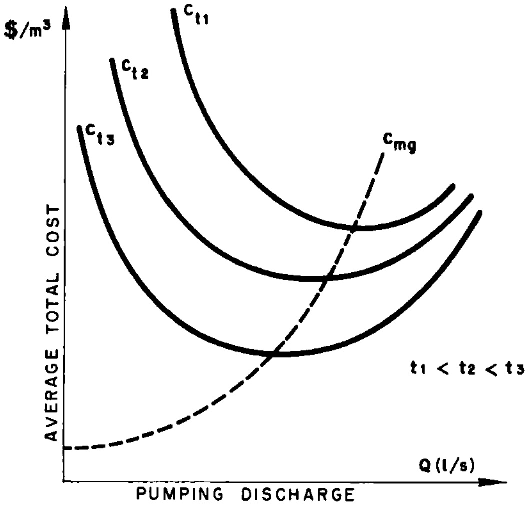

Figure 5.- Average and marginal costs as a function of discharge and pumping duration.

The marginal cost for any value of t is:

$$c_{mg} = \frac{dC_v}{d(Q.t)} = k\,\frac{d(hQ.t)}{d(Q.t)} = k\,(Q\,\frac{dh}{dQ} + h) = k(h_0 + 2AQ + 3BQ^2) \qquad (8)$$

a growing function with Q, and independent of t.

## 3. OPTIMUM PUMPING DISCHARGE

The optimum discharge for a well already built and equipped depends on the operating circumstances and three different situations are described:

a) Meeting a Specific Demand, D. In this case the price or value of the water is not relevant. The economic aim is to produce the quantity of water D with the minimum energy cost, since the fixed costs have to be borne in any case.

The energy cost, kh, grows with Q, for which reason the discharge should be as small as possible and, consequently, t should be as large as possible. The maximum value of t depends on the type of demand (continuous in urban supply systems and seasonal in irrigation and supply to tourist areas) and on the auxiliary installations in existence (storage facilities and degree of automation).

Once the maximum number of hours per annum (tmax) has been ascertained, the optimum discharge is obtained Qopt = D/tmax, and the average total cost is determined at the corresponding tmax curve, among the family of curves of Figure 5, which has been drawn in Figure 6.

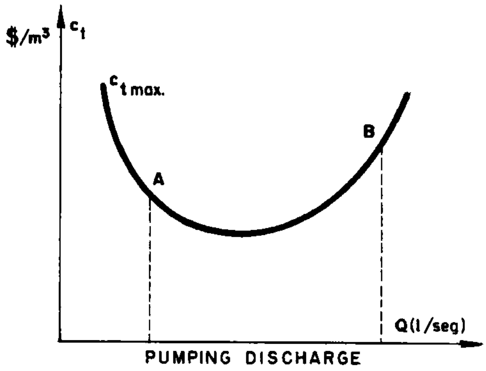

Figure 6.- Optimal well discharge (fixed demand)

If the optimum is situated on the decreasing branch of the curve (A), the well has been overdesigned for the service it has to provide. The well could satisfy higher demand at lower cost.

Situations such as the above, in which the productivity of the aquifer and the capacity of the installations are underexploited, are very frequent in agricultural wells; an association between several owners would make it possible to obtain ground water at a lower cost. The opposite case is illustrated by point B, where the discharge is excessive for the dimensions and/or equipment of the well. If the well had been properly designed, the cost of the water would be lower.

b) Sale of Water at a Given Price, p. This is the classic example of a small firm operating within a free market, included here for purely academic reasons, since markets for water are very rare.

From 1.2 of this Section it will be recalled that the maximum profit is obtained by equalizing the price to the marginal cost, thus the value of $Q_{opt}$ is obtained from

$$p = k\ (h_0 + 2AQ + 3\ BQ^2) \qquad (9)$$

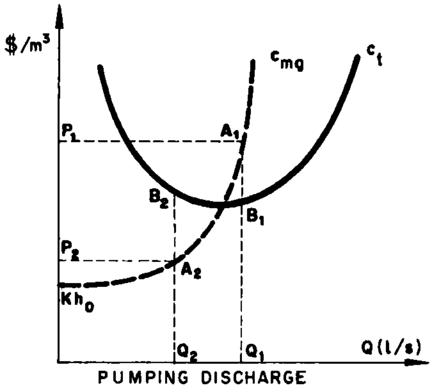

Figure 7.- Optimal well discharge (fixed price)

Figure 7 illustrates this case. For price $p_1$ the unit profit would be given by segment $A_1B_1$, and the existence of this profit encourages other businessmen to enter the market and drill new wells.

If the price was $p_2$, to the left of the minimum cost point, segment $B_2A_2$ would represent the loss per m3 suffered by the owner of the well. This price does not cover the total cost, but if it does cover the variable cost it will still be in his interest to continue pumping.

c) Production for Own Use. It has been mentioned (2) that profit maximization requires that the marginal productivity, multiplied by the price of the crop be equal to the marginal cost of the water.

$$F'(w).p = k\ (h_0 + 2AQ + 3\ BQ^2) \qquad (10)$$

If l is the area under irrigation and w the application of water per hectare to be determined

$$Q = 1.w/t_{max} \qquad (11)$$

so that theoretically there exists an optimum value of w and Q, deductible from (10) and (11).

However, farmers are seldom aware of the productivity function of their land; their normal behaviour is to set the unit application and therefore the pumping discharge. This discharge determines the cost of the water and the overall profit of the operation. If this profit significantly exceeds the normal income from the land, there will be an incentive to bring further land under irrigation and to construct new wells. Therefore, there is no economic optimization in this behaviour, and it is not easy to undertake such optimization owing to general unawareness of the productivity function.

Since the common practice consists of adopting a unit supply for the crop or combination of crops typical of each area, it is possible to optimize the size of the irrigated land on the basis of the cost of the water, making use of scale economies of production, an aspect which will be examined next.

## 4. OPTIMUM SIZE OF THE WELL; SCALE ECONOMIES

The problem of the optimum discharge for a well already constructed and equipped has been analysed, under different operating conditions, and attention has been drawn to the possibility of excessive or insufficient size in cases where the aim is to supply a fixed demand.

The problem of optimum well design will now be considered, stated as the determination of the construction features of the well and its mechanical gear, which will make it possible to satisfy the water required with the minimum production cost. Since it is not a question of costs known a posteriori but of a priori estimates on the well or wells to be constructed, it is necessary to bear in mind the random nature of the cost and productivity of a well to be drilled in an aquifer.

Indeed, the well log at a particular site is only known after the well has been drilled, and the cost of construction (diameters, pipings, filters) can be affected by the nature and thickness of the strata involved. The specific yield has a decisive influence on the energy cost of pumping and can be highly random. In a priori analysis it is necessary to use the average or expected values for those parameters which are significant for the cost, and the conclusions obtained will be more valid the less are their variances.

The conclusions of the analysis are also applicable when the intention is to drill a large number of wells to satisfy a high demand, in which case it may be expected that the real average production costs of the group of wells are determined by the average values of the statistical variables. For this reason these conclusions are particularly suitable for the economic study of planning the management of an aquifer, when considering the opportunity of intensive operation. It is in this context where the concept of economy of scale takes on the greatest importance; being an essential feature of surface water elements, it occurs to a certain extent in the case of groundwater development.

### 4.1. Specific Yield and Efficiency of the Well

It is generally agreed that there exists a linear relationship between the water level drawdown at a well and the pumping discharge up to a certain value of Q, as from which the non-linear head losses are important. Thus, the drawdown is $s = A.Q$, and the specific yield is $q_e = Q/s = 1/A$, where A is the parameter of expression (4).

The specific yield depends on the saturated thickness tapped by the well; for confined and homogeneous aquifers, several authors have deduced linear relationships between both variables, which (whether they are linear or not) can be determined by a statistical analysis of the inventory data of wells. Once this task has been undertaken, and the average depth of the static water level in the aquifer ($h_o$) is known, use can be made of the function relating the specific yield ($q_e$) to the depth of the well (d):

$$q_e = f(d - h_o) = 1/A \text{ (unconfined aquifer)} \qquad (12)$$

The parameter of efficiency, B, determines an important part of the drawdown for high pumping rates. A well in which appropriate filters have been fitted in the productive layers and in which development works have been completed will be an efficient well, with a low B value (less than $10^{-7}$ day$^2$/m$^5$). On the other hand, values of B higher than $10^{-6}$ considerably limit the yield and increase the cost of pumping.

### 4.2. Minimum Production Cost as a Function of Depth

For a determined level of demand to be satisfied by the well, D, and once the value of $t_{max}$ has been established (3.a), the pumping discharge is given by $Q = D/t_{max}$ which can be obtained with different depths of well. Different depths are successively assumed, and for each of them parameter A of expression (12) is calculated. B must be set at a value which can be reasonably attainable by the best drilling technology available.

Once the discharge and the pumping head are known, $h - h_o + AQ + BQ2$, commercial catalogues give the specifications of the right pump to be installed, its purchase price and diameter, which in its turn decides the cost of drilling. The remaining investments are also determined as functions of Q and h (pipings, transformer, power line and control panel) or are fixed (electricity line, housing, etc.).

These calculations are repeated for different depths, obtaining a curve relating the total average unit cost of the water (7) to the depth of the well, for a specific value of $Q_i = D_i/t_{max}$.

If the calculation process is completed for several values of Q, a family of curves is obtained similar to the one in Figure 8, taken from a work of the author on the Miocene aquifer of Madrid (Sánchez, A., 1986).

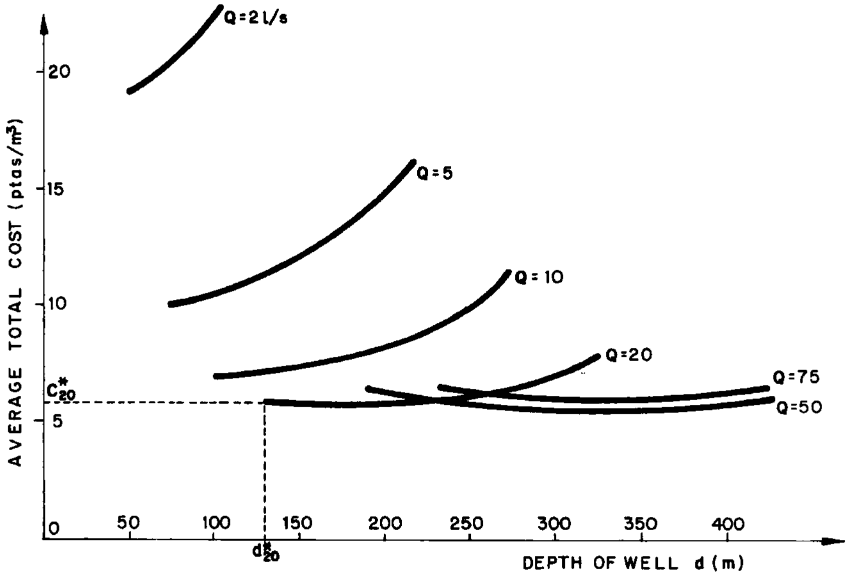

Figure 8.- Ground water cost (1985) as a function of well depth at the Miocene aquifer of Madrid ($t = 7.2 \times 10^3$ h/year, 1 \$ = 170 pesetas).

Each curve of this family has a minimum which represents the optimum design ($d^*_i$) for the well suitable to the discharge $Q_i$. The pairs of values ($d^*_i, Q_i$) determine another series of values ($c^*_i, Q_i$) which represent the minimum production cost for each Q value.

Curve $C_1$ of Figure 9 represents the minimum production costs of ground water for municipal supply in the example of Madrid, where the economy of scale can be observed which is obtainable up to flows of 30 l/s (wells of 250 m), no significant advantage being obtained from deeper wells. Curve $C_2$ is identical to the previous one, with a higher value of parameter B. Finally, curve $C_3$ is of the same type as the first, but when the water is to be used for irrigation purposes: costs are much higher as a result of the lower value of $t_{max}$.

## 5. AVAILABILITY COST OF PEAK PUMPING CAPACITY

In conjunctive use schemes of surface and ground water it is usual to assign ground water the role of reserve to cover dry periods. When the required peak

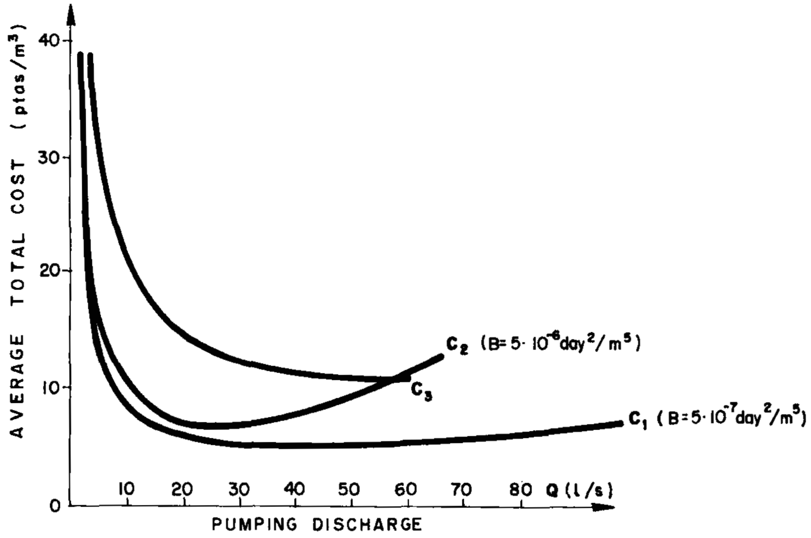

Figure 9.- Ground water minimum costs (1985) at the Madrid aquifer. Municipal ($C_1$ - $C_2$ curves) and irrigation supply ($C_3$, t = 2 x $10^3$ h/year).

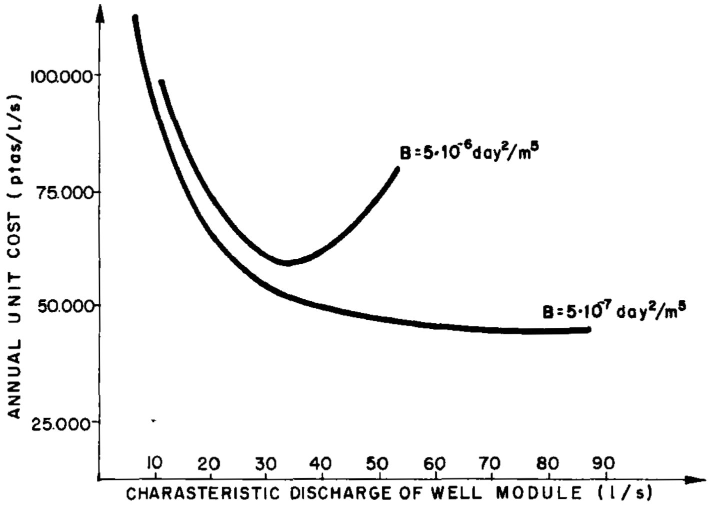

Figure 10.- Annual unit cost (1985) of peak pumping capacity at the Madrid aquifer.

pumping capacity is much higher than the average yearly rate of extraction, the availability cost of the peak is high, and it is worthwhile optimizing the design of the well module which is to provide it.

The process of determination is similar to that described in 4, with the difference that in this case only the fixed unit cost ($C_0/Q$) is calculated; for different depths of well the annual capital cost of obtaining a certain pumping capacity $Q_i$, is calculated, the minimum cost depth and related equipment are selected, the calculations for different values of $Q_i$ are repeated and the curve of minimum cost modules is determined.

Figure 10 shows the curve corresponding to the Miocene aquifer of Madrid, in which it will be seen that the pumping module must be a well of 50-70 l/s, with a depth of 300-400 m. It will be observed that if the well efficiency is low (curve $c_2$) the optimum discharge of the module is 30-40 l/s and that the availability cost of the peak is 25% higher.

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