ECONOMIC ASPECTS OF THE CONJUNCTIVE USE OF GROUND AND SURFACE WATER

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ABSTRACT

The different structure of the costs of ground and surface water and the different and complementary characteristics of both kinds of resources make it possible to solve the specific needs of water quantity and quality more adequately and economically if both resources are used conjunctively. Higher discount rates favour the inclusion of elements involving lower initial investment and generally with higher groundwater components. Lower discount rates favour a higher participation of surface water.

The external factors produced by groundwater pumping must be taken into consideration in any economic analysis. Examples of external factors are water level descents, surface water flow reduction, degradation of wetlands and ecological issues, water quality deterioration and land subsidence.

This paper discusses the economics of artificial recharge and its role in the different types of conjunctive use. Its importance is crucial in some cases and secondary or marginal in others. The amount of stored ground water in many cases is several tens or hundreds of times the mean annual groundwater recharge level. Planned overpumping allows costly projects requiring large dams or transfer structures to be postponed.

The uncertainty inherent in river flow prediction and demand variability or inadequate information of the hydrological parameters of the system can be counteracted by the flexibility in the seasonal and yearly use of ground water which conjunctive use schemes provides. In many cases this represents a kind of insurance against adverse hydrological or economic situations.

1. INTRODUCTION

Growing water needs, the constraints caused by water pollution and the cost of water development projects, including the cost of responding to social and environmental concerns, are increasing dramatically. For these reasons, it has become imperative to take into consideration all water sources and facilities in order to satisfy present and future water demands. Additional benefits will be obtained if a water resource system is planned and/or operated taking into consideration the advantage offered by the conjunctive use of ground and surface water. If the multiplicity of objectives in water planning, the different alternatives for achieving this, and the ground and surface water interrelationship seem evident, it is advisable in most situations to have recourse to conjunctive use; and not only in arid areas or those where water is scarce. Ground water management cannot exist without surface water management; and surface water cannot be managed optimally if the groundwater reservoirs are not included (Fowler, 1981).

These possibilities are far from being recognised unanimously and in fact conjunctive use has been carried out in few areas and is not a customary practice in the water resources planning agencies of most countries. Analysis of the decisions and attitudes of water specialists indicate that the majority of them favour surface water utilization. Very often groundwater resources are not taken into consideration even in regions where in-depth and reliable studies have confirmed the existence of formations whose utilization would create very positive results. This unjustified disregard of groundwater resources has been qualified by Wiener (1972) as an evidence of a deep, unpremeditated prejudice, and defined as "hydroschizophrenia" by Nace (1972) and analysed by Llamas (1974).

In some countries the responsibility for water planning has been taken over by the central government, at least when making final decisions on major projects. Large projects usually have greater financial resources available and have more favourable financial terms as well; these considerations, in addition to political motivations, tend to favour the larger more spectacular engineering projects.

The attitudes related above are due, in part, to a lack of understanding of ground water occurrence and movement. Most hydraulic engineers have limited experience in ground water studies and many planners have not had any formal education in hydrogeology, even though an appeal to increase hydrogeology studies has frequently been made (Llamas 1974, Howell and Warman 1982).

The inclusion of courses dealing with the different aspects of ground water in the water resources departments of universities, and the diffusion of technical and scientific accomplishments can co-operate to change those attitudes in the near future.

2. GROUND WATER COST STRUCTURE

The main economic difference between ground and surface water projects is that in general initial investment is much lower in ground water and on the contrary operation and maintenance costs are higher. In surface water the initial investment per unit of resulting product is usually high and the operation and maintenance cost small. The exception is that surface water treatment needs for urban uses usually require higher costs for energy and chemicals.

The classic way to compare the difference of occurrence in time between cost and benefit is by reducing this to a present value through a discount factor. The selection of the discount rate to be used in hydraulic projects has been the subject of arduous debates. A lower rate favours the projects involving a greater component of surface water. A rate which is more in keeping with the real price of money favours deferring the more costly investments for construction. For example, the present value of a dollar which will be spent in ten years time is 0.322 if a 12% discount rate is applied and 0.104 if the expenditure were to be made in 20 years. If a rate of 8% is used then the respective values would be 0.463 and 0.215; and applying a 4% discount rate the respective values would be 0.676 and 0.456. See Table I.

TABLE I
Present value of a dollar to be spent in the future

Discount rate %	12	10	8	4
10 years	0.322	0.386	0.463	0.676
20 years	0.104	0.149	0.215	0.456

Groundwater projects offer the advantage of requiring smaller investments for which reason they are a more fitting alternative for cases in which there is limited capital and high interest rates; on the other hand, as the investments involved are smaller, the risk is lower in view of the hydrogeological and marketing uncertainties involved; and as the exploitation of water can be staggered, modifying it as the demand for water develops, then unproductive investments can be reduced to a minimum. On the contrary, a scaled economy is one of the obvious, classic advantages of surface water.

In the 1950s most countries applied a socially oriented discount rate which was significantly lower than the market rate. In the 1970s a much higher discount rate was applied, as the cost of money had also increased (James and Rogers, 1976). It apparently seems that the energy crisis works against the use of ground water although, in fact, the increased discount rate compensates for the increased cost of energy (Gomez de Pablos, 1974).

Comparisons are frequently made between the cost of regulating one cubic metre of water in a reservoir and obtaining it from a well. For the sake of accuracy, the cost of transport, distribution and water treatment would also have to be taken into account, which clearly tends to favour ground water. The only cost comparison known to be made on a national level was carried out in France where the gross production cost plus water treatment of a river is 0.14 FF/m3 and only 0.09 FF/m3 for ground water (Erhard-Cassegrain and Margat, 1983). The comparison would be even more unfavourable if regulating dams were to be constructed.

Other economic aspects to be taken into consideration are the loss in the water transport and distribution networks, which is generally more significant in the case of surface water, and evaporation from the reservoirs. In the USSR, the total loss attributed to evaporation has been quoted as 10% of the total controlled volume. Loss in irrigation networks has been quoted as 16.4% in the U.S. and 75% in the Carpentras Canal in Provence (Erhard-Cassegrain and Margat, 1983). If ground and surface water are used conjunctively, the benefit of lining canals totally or partially is not evident if the infiltrated water recharges an exploited aquifer (California Department of Water Resources 1957, Morel-Seytoux et al, undated). Different alternatives must be simulated to compare their appropriateness and economic implications.

The variables affecting the cost of water pumped from a well was studied by Lopez-Camacho (1974). As a general rule the most influence factor is the annual volume of water pumped. All the other factors being equal, e.g. yield of wells, water levels, drawdown, pump efficiency ...; water costs more for irrigation purposes than for urban and industrial uses, as the former system operates fewer hours annually. In many aquifers the yield of individual wells exceeds the irrigation needs of individual plots of irrigated land. This often happens on the Mediterranean coast of Spain where it is normal to have an association of farmers owning and operating a well. This is probably also an inheritance of the need to share the risk of the drilling costs in the early days of groundwater development. It is obvious that the improvement of well construction techniques for achieving greater specific yields and the correct design of pumping and electrical installations can reduce groundwater cost.

3. EXTERNAL FACTORS PRODUCED BY GROUNDWATER ABSTRACTION

Groundwater exploitation produces external factors such as reduction in water levels, reduction in river discharges, sea water intrusion, land subsidence, wetland or ecological degradation or long term variations in water quality in irrigation areas. Piezometric decline increases energy costs and in extreme cases leads to wells being abandoned and to the need for rebuilding them. Pumping of coastal aquifers induces the advancement of the saline wedge which can cause wells to be abandoned and the consequent reduction of their economic life. In the case of overdraft, artificial recharge facilities or injection barriers have to be built. Conjunctive use, whether or not this includes artificial recharge, can help to reduce piezometric decline or seawater intrusion.

The effect of pumping on surface water flows occurs with a delay which depends on the geometry and hydrodynamic parameter of the aquifers concerned and on the location of the wells. Even in the narrow fluvial aquifers this delayed effect has been used to operate aquifers as storage elements to regulate the flow of the rivers in conjunctive use schemes when wells are pumped in low flow periods. The studies made in the aquifer-river systems of the Rivers Arkansas and South Platte in Colorado, USA, have become classics (Moulder and Jenkins, 1963; Morel-Seytoux et al, 1973, Young and Bredehoeft, 1972, Bredehoeft and Young, 1983). And in the United Kingdom conjunctive use in aquifer river systems with aquifers of relatively small dimensions is being carried out in a very strict and pragmatic way (Downing et al, 1974, Birtlees and Reeves, 1979).

Intense aquifer pumping can temporarily or permanently modify the aquifer-river relationship allowing some water volume to infiltrate through its bed and thus increase the aquifer storage. The application of induced recharge on a large scale has been suggested in the Ganges basin conjunctively with artificial recharge in unlined canals to regulate the river flow (Chaturvedy et al, 1979). Economic loss caused by land subsidence is of major importance in urban or coastal areas and minor in rural environments. As the physical process of clay consolidation is not a reversible one, land subsidence can be stopped but not alleviated if piezometric levels are raised by means of artificial recharge or decrease of groundwater pumping.

The small influence of the decisions made by an individual groundwater user on the future water level decline in his own well, and the small negative influence of his own extractions on his water costs, although not on other users', produces divergences between private and social benefits (Burt, 1964). To correct such divergencies adequate legal and administrative regulations must be drawn up.

4. WATER QUALITY PROBLEMS

Ground water is usually more saline than surface water although in some cases the opposite is true. The water imported via the Colorado Aqueduct to Southern California is saltier than the ground water from coastal aquifers with which it is recharged. In Israel water from the Kinneret Lake recharged in the coastal and limestone aquifer is more saline than ground water. Other sources of salinity are sewage waters, diffusion through the interface between fresh water and the intruded sea water and leakage increase from adjacent aquifers (Mercado 1980). Another possibility of obtaining an acceptable water quality is by mixing prior to its use.

Irrigation can increase chlorine and nitrate content in ground water. If ground water is pumped for irrigation purposes, the depression of gradients to the aquifer outlets results in a drop of water and salinity flush.

Irrigation with surface water in dry areas very often creates drainage and water and soil salinization problems which could be mitigated by groundwater pumping. The most spectacular example is the Punjab irrigation system located in the Indo alluvial plain in Pakistan where the largest concentration irrigation system in the world is located, covering an extension of 13 million hectares. Aquifer recharge as a result of excessive irrigation, and filtrations along the 65,000 km of canals, which are unlined in most cases, has produced very serious drainage and salinization problems. Over two million hectares had to be abandoned and each year this problem affects an additional 25,000 hectares (Chaudry et al, 1979). This case was studied in great detail and a proposal made to construct 30,000 wells with sufficient capacity to pump in the order of 70.10^9 m3 of water per annum. The aims of this proposal are to lower the piezometric surface and eliminate part of the salt water, thus alleviating the drainage and salinization problems.

In Soviet Central Asia an estimated 25.10^9 m3 of water are discharged annually through agricultural drainage systems in the zone under irrigation. Conjunctive use of surface and ground water has been proposed to utilize these resources (Kats, 1975).

5. ARTIFICIAL RECHARGE

Artificial recharge is an effective way to store water, reduce or stop declining piezometric levels, or protect coastal aquifers against seawater encroachment. Nevertheless it should be said that conjunctive use and artificial recharge are not synonymous, as we shall discuss later. One of the problems with artificial recharge is that very often it is costly since it requires, in addition to the recharge elements derivation, transport and sedimentation or treatment elements. Furthermore the operating and maintenance costs are usually high. It is advisable to take into consideration the possibilities of finding a cheap way to recharge water by artificial means, or by taking advantage of not deliberately planned recharge, as happens in the cases of leaking dams, unlined canals, induced recharge or incidental overirrigation (Custodio, 1986).

In the course of the artificial recharge process, the water's physicochemical and biological properties are transformed as it passes through a non-saturated zone and, as a result, bacteria, virus, organic material, heavy metals and many toxic compounds are eliminated or are greatly reduced. This method of treating polluted surface water is utilized extensively in many central and northern European countries. There also exist many instances throughout the world where ground water is recharged using reclaimed waste water (Asano 1985), and a growing interest is emerging in research to reduce pre-treatment needs. We have mentioned before that artificial recharge has also been used as a means of blending in the aquifer waters with different chemical properties.

The economic effects of raising water levels, aquifer protection against seawater intrusion and aquifer storage all need to be analysed through aquifer and water system simulation.

6. INFORMATION UNCERTAINTY AND FORECASTING

Wiener (1972) has brilliantly noted the following points concerning the need for information and the uncertainties which exist at the time of making decisions related to surface and ground water use.

In the majority of cases, stream flow represents a rapid response to climatic phenomena. Normally, the information derived from ground-water related data collected over a few years is more reliable, if properly analysed, than that provided by surface-water related data collected over a longer period of time. The inertia of the aquifers, caused by the large amounts of water stored, integrates a long period of hydrometeorological phenomena and short-term data collection can provide much better overall information.

Fluctuations in the magnitude of the flow are greater in surface water than in ground water. Mid or long term predictions of streamflow discharge cannot be made. Streamflow discharge is stochastic by nature so its behaviour can only be treated in terms of probability. Groundwater behaviour is much less erratic and more deterministic as a result of the normally close relationship between the stored water and the aquifer's average recharge.

Groundwater exploitation requires low, initial investment; however, the operational costs are high. Surface water exploitation requires a large investment, while operational costs are normally lower.

In the case of surface water, the investment required is usually indivisible, which also entails a lengthy inoperative period during the study, construction and decision making process. It may take years for the project to become actually effective in operational terms. The large investment involved also imposes greater demands on the information required. Contrary to the above, the investment required for ground water is divisible and the inoperative period much shorter. This introduces the additional advantage of its being much more adaptable to increasing water demands.

For the cases, common throughout the world, where the hydrological information is incomplete and for those where future water needs are uncertain, the considerations mentioned above are crucially important. The economic recession experienced in the last few years has had a decisive influence on reducing expected water needs in many parts of the world. Ground water can play a more important role if the water resources system is conceived dynamically and the uncertainties which exist in relation to the water resources and demand are taken into account rather than resorting to a system which is statistically conceived and structurally orientated.

In the last few years there have been some important changes in the planning and management of water resources. The utility of structural solutions has been questioned, greater interest is being shown in an optimum utilization of existing facilities rather than in investing in new ones, and in many countries the era of constructing large dams has probably come to an end (Willekee 1979). Although very few financial evaluations have been made of the results of some projects, there is sufficient evidence to question whether the results of these large construction projects have lived up to expectations or not. The problem of government subsidies for major water projects has been frequently questioned and the first step towards determining a solution should be an analysis of the various alternatives available.

7. ECONOMIC ASPECTS OF DIFFERENT CONJUNCTIVE USE TYPOLOGY

Of the different functions usually identified in a water resources system - source of water, storage and regulation, transport, distribution and water treatment - we have not analysed in this paper the aquifer as a vehicle to transport water since an aquifer is generally unsuitable for this function. The cases in which the aquifer serves as a means of water distribution are not included explicitly either, as this function is usually closely related to its role as a means of storage. Aquifers provide alternate means for water distribution and substantial savings in surface distribution systems. In previous paragrahs we have mentioned the possibilities of artificial recharge as a means of water treatment and the mixing of different kinds of water.

In addition to an aquifer´s exploitable resources, its stored water can also be utilised (referred to as the "one time" reserve) causing a temporary overexploitation.

In spite of the serious economic and social problems the overdraft of aquifers can cause, it is not necessary to rule out overdraft as a general rule. In fact, the overexploitation of ground water in California is one of the reasons for its prosperity which facilitated its economic development and consequently created the propitious conditions for carrying out other more costly projects such as interbasin transfers from areas with the heaviest rainfall in the northern part of the state (California State Department of Water Resources, 1957).

The availability of large quantities of water in the aquifers has prompted proposals for the well-planned utilisation of the aquifer´s reserves as a means of deferring costly construction projects. This has been done in Israel where such a methodology was proposed for subsequent modelling and economic optimisation (Schwartz, 1980).

In actual fact Planned Overdraft is not a separate type of conjunctive use, but rather a first stage which can be followed by successive stages of conjunctive use of one type or another. Overexploitation has also been suggested in successive stages, followed by successive surface water development and conjunctive use (Schwartz 1980), or as a permanent component during the entire planning period.

In the type of conjunctive use we have termed Alternative Use, surface reservoirs release more water in rainy periods or years and the aquifers are pumped more in dry periods. The exploitable storage capacity to be used would be made available by piezometric oscillations. In this way, an underground storage area of 37.109 m3 would become available for use in California's Central Valley with relatively small piezometric oscillations in contrast to the 27.109 m3 to be provided by surface storage (California State Department of Water Resources, 1957).

In La Plana de Castellón, on the Mediterranean coast of Spain, piezometric oscillations represent an aquifer storage of 500.106 m3, three times greater than the existing surface storage. In the Algar aquifer periodic level drawdowns represent 40.106 m3 of storage as compared to the 30.106 m3 that the Guadalest and Amadorio dams can store. Also in Spain large scale developments are possible and have been suggested (Sahuquillo, 1986).

These type of schemes require that a part of the demand can be served indistinctly by two sources and in some cases the water level oscillations can be high. When this is the case, in addition to the design and physical distribution of the different components, including wells and artificial recharge elements, the operation of the system is crucial. Optimal operation depends on the state of the system, the water stored in dams, the piezometric levels, the surface water inputs and water quality.

Improvements in mid or long term hydrological forecasting would lead to substantial economic gains in reservoir operation of conjunctive use schemes (Jaquette 1981).

Greater use of ground water can be made during drought periods. Many European countries took advantage of this in the summer of 1976. In California, it helped reduce the effects of low-water in 1976-77 to a significant extent.

Owing to the initiative taken by private industry and, to a lesser degree, government action, the effects of the drought Spain was experiencing in the early eighties were mitigated in some areas. In fact, the effects of the drought were lessened in the areas where greater utilization of ground water was made and a methodology to this effect has been proposed for subsequent application to conjunctive use of surface and ground water (Sahuquillo 1983).

When local surface waters are less important, aquifers can be used to store and distribute imported and local surface water through artificial recharge. Artificial recharge is crucial to this type of conjunctive use which we call Terminal or Lateral Ground Water Storage, as opposed to alternative use where its role is only complementary. Classic examples of this type of conjunctive use are Israel and Southern California. In this type of scheme annual variations of imported water are minimum or relatively low and in any case are less important than in the so called alternative use. Here operation is less important than the physical distribution of wells and elements of artificial recharge and water transport and distribution. The California State Department of Water Resources in the sixties developed a methodology for working on hydrological, hydrogeological, operational and economic studies for these types of systems. In these studies a large number of alternatives were simulated, also taking into account the different values of water in terms of its salinity. (California State Department of Water Resources 1966, 1971).

The Aquifer-river Systems can be considered a subgroup of alternative use. In this the aquifer-river relationship is of prime importance, also the system operation is very important, mainly of the ground water component whereas the artificial recharge is of secondary importance. With this type of conjunctive use a larger use of surface water can be obtained, giving the ground water the function of complementing the deficit in the driest years or seasonally throughout the year.

Operating ground water in this way represents an insurance against drought (Sahuquillo 1983). Bredehoeft and Young (1983) also analysed the role of the insurance the farmers of the South Platte make of ground water where they have installed a well capacity almost sufficient to irrigate the entire area, using a simulation model which links the hydrology of a conjunctive stream-aquifer system to an economic model which incorporates the farmers´ behaviour. The results of the model coincide with the well capacity actually installed. Doing this has two benefits: it maximises the expected net benefits and minimises the variation in annual income. By increasing the pumping capacity to such value, the value of flow forecast is diminished, counteracting a poor forecast by pumping more ground water. The role of reducing the unwant economic effects of uncertainty by using more ground water is discussed analytically by Tsur and Issar (1987). They provide an explicit expression for the value of using ground water in this way in terms of the marginal productivity of water, the production function and the variability of surface water.

8. APPLICATIONS OF SYSTEM ANALYSIS TECHNIQUES

The detail in which aquifer behaviour is analysed varies in the different methods. The simplest way is to consider aquifers as elements with a few aggregated parameters. The commonest way is to assimilate them to linear reservoirs releasing a flow associated linearly with a volume of water stored in the aquifer (Buras 1963, 1967, Sanchez 1983). Birtles and Reeves (1979) use multicellular nonlinear models with a few non linear cells. Usually this simplification is used in the higher hierarchical levels and very often associated with optimization methods (Schwartz 1980). Optimisation methods have been used with detailed aquifer models using dynamic programming, linear and non linear programming (Gorelick 1983).

Nevertheless, for complex systems, when the interaction between surface and ground water and when stochastic surface flow variations have to be taken into consideration, or where more than one surface reservoir exists, the use of simulation techniques is virtually unavoidable. This is particularly true in the alternative use type, or when quality problems have to be considered, and a large number of alternatives or synthetic hydrological sequences have to be simulated. In this case the eigenvalue method (Andreu and Sahuquillo 1987) is the most appropriate. Its most interesting aspect is that external actions and initial conditions are explicitly transformed for aquifers into a state vector. From this, piezometric head flows and surface-ground water interchanges are also explicitly computed to simulate conjunctive use systems.

9. CONCLUSIONS

Although ground water has very often been overlooked by planning specialists, it can offer technical and economic advantages worthy of consideration. Ground water can provide additional resources as well as the means for water storage, distribution and treatment, which can be combined advantageously with surface water resources. Likewise, ground water can provide other advantages such as its adaptability to a progressive increase in the demand for water, the possibility of temporary overexploitation as a means for deferring costly construction projects, to mitigate the effects of droughts and alleviate drainage problems. Another virtue of ground water in conjunctive use schemes is the insurance role it supplies to offset the uncertainty concerning surface flow, hydrological parameters or demand.

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