GROUND WATER EXTERNALITIES

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ABSTRACT

Ground water is a natural resource which provides the benefits inherent to its use as a final commodity or as an input to a productive process. Considering the problem of cost assessment, and disregarding the possible effects on water quality, three types of external effects can be distinguished which are not considered by individuals: a) a withdrawal of flow from the hydrological cycle; b) an energy cost induced onto the remaining ground water users, intrinsic to the boundaries and properties of the aquifer and which depends on the distribution of the wells; and c) a degradation of the potential energy of the groundwater reservoir when its reserves have been depleted beyond the optimum level.

This paper illustrates the nature of the external factors involved with simple examples and describes the opportunities for correction available to the Basin Authority.

Finally it describes the possibilities of intervention provided by the new Spanish Water Law to reduce the effects of ground water externalities, distinguishing between action on specific cases and aquifer management guidelines, to be defined in the Basin Water Plans.

1. ECONOMIC CONCEPT OF OVERDRAFT AND ITS CONTROL

A simple example will help to show clearly why renewable resources are overexploited and which factors control the process.

Let us suppose that a large reservoir exists with a uniform horizontal cross-section A into which water flows at a constant rate of R and where the natural outflow occurs at the height h_N over the datum plane (Fig. 1).

An unlimited capacity pump is installed at h_0 to extract water which can be sold at price p, while K is the unit energy cost per metre of elevation.

If there is no type of interest in the economic system to which this productive activity belongs, the value of money is independent of time and the optimal operation policy is $Q(t) = R$, $h(t) = h_N$, provided that $p > k\ (h_0 - h_N)$. If the cost of elevating from level h_N is higher than the price of the water, none will be pumped, and when they are both the same there will be no economic advantage whether any pumping is done or not.

In practice, present money is always valued more highly than future money by means of a discount rate r and if $p > k\ (h_0 - h_N)$, then the operator will feel

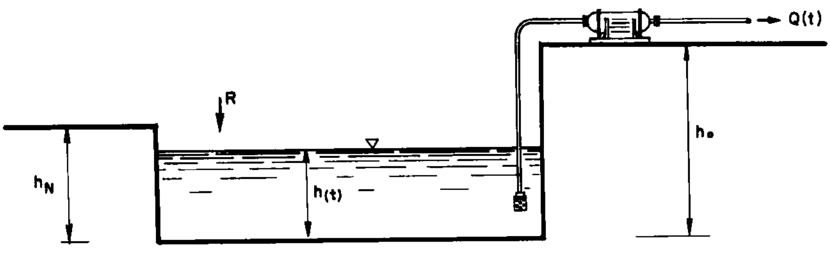

Fig. 1

encouraged to increase the rate of pumping because the initial profits are higher, though he will have to reduce it later on. The problem of maximizing the present value of his total profits is stated as:

$$\max B = \int_0^\infty e^{-rt} Q(t)\{p - k [h_0-h(t)]\} dt; \quad dh/dt = [R-Q(t)]/A \tag{1}$$

The solution can be obtained by applying variational calculus and entails two policies:

1) permanent pumping with Q = R in the position

$$h^* = h_0 + R/rA - p/k \tag{2}$$

2) instantaneous extraction in t=o of the water volume included between the initial position (whatever it was) and that of the permanent policy. Consequently, if the initial position were lower than h*, no water must be pumped until the optimal position is reached.

The optimal depth of the water, $h_0 - h^* = p/K - R/rA$, establishes the balance between the profits of the initial mining and those of the permanent policy. The water will be deeper the higher are p and r and the lower is R/A, that is, the unit recharge of the reservoir.

It can be shown that when pumping capacity is limited to Q max, the optimum policy consists of making Q(t) = Q max until the same h* position is reached and then to continue to extract the recharge R.

Let us suppose that instead of one single operator existing and producing water at a cost of $K(h_0-h^*) = p - RK/rA$, the opportunity to operate is available to many owners of pumps already installed who take their decisions independently. Each one of them will think that the other operators will go on pumping indefinitely as long as they obtain profits because no-one knows what will happen in the future. Consequently they will not stop at h* level but at a lower one, $h_0-h = p/k$. As has been shown, this operation is not economically the best and to prevent it two different solutions could be adopted, either of which should be put into practice at the moment in which temporary mining ceases and constant pumping begins.

The first solution consists of assigning the inflow R in individual quotas; if all the operators are working in identical production conditions the assignment will inevitably be arbitrary. In the opposite case, if the theory of economic optimization is applied, greater shares will be assigned to the most efficient operators, those who have a lower h_0, k, or those who benefit from a greater marginal productivity of the water. This would be equivalent to granting larger future profits to those who already obtained larger profits during the mining stage.

An alternative solution which has been proposed is to establish a unit tax on the production of value R_k/rA, because it means reducing the price of sale of the water to the point at which each operator does not go below level h^*. The problem then arises of distributing tax revenues, since it would be nonsense to return the amount paid to each one. The conclusion, therefore, is that the tax authorities should use this income in works and actions of general interest. The extraordinary operation profits of the permanent policy would then pass from the operators to the general public and, moreover, the interests of future generations would be preserved.

The example given offers certain analogies with the way aquifers are operated where one essential point is the unequal cost conditions of the users. This feature reduces the sharpness of the fall of Q from P_2 (Fig. 2), because the wells situated at higher elevations and/or in zones of lower transmissivity will progressively leave the process. After point P_3 only the best will continue to operate, which they will do indefinitely as long as the presupposed circumstances continue. The Basin Authority should impose regulatory measures at point P_1, which does not prove easy to determine analytically as a result of the varied ground surface topography, the geometry and the distribution of the parameters in the aquifer. It should, however, be noted that the general conclusions of simple analysis are at the very least indicative, and that the point of intervention by the Authority is when a unit tax of RK/rA value would stabilize the rate of pumping (a range of 0.004 to 0.25 $ per cubic metre for most aquifers in Spain).

2. INTERNAL EXTERNALITIES

In the foregoing example the water surface was always horizontal, and its fall was due solely to the fact that $Q > R$. Pumping from wells causes drawdowns at all points in the aquifer which increase with the amount extracted.

In the following paragraphs we shall admit that the behaviour of the aquifer

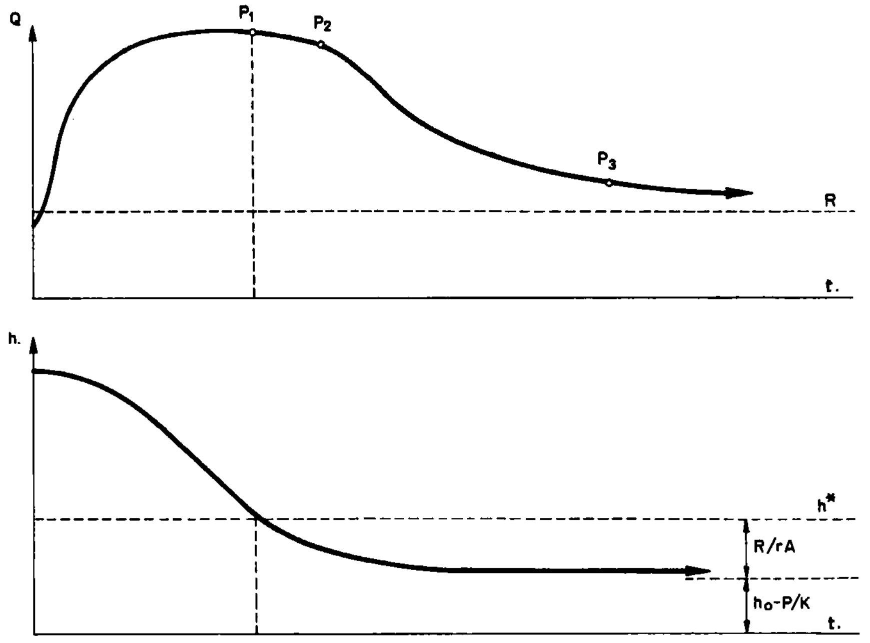

Fig. 2. Evolution of Q and h in a freely operated aquifer under the assumption of p and r = cte and with no water quality degradation

is perfectly elastic, and that the storativity is negligible so that the effects occur and are transferred immediately. Any variation in pumping patterns generates an immediate adaptation of the piezometric surface and an automatic increase in the volume of water entering from the outside, if this were necessary.

Let us suppose that N wells exist in which the natural undisturbed water levels are h_{oi}, each one of which is managed independently by an operator who sells the water at price p. The unit cost per metre of elevation is k, and the drawdown induced at point j by a unit pumping discharge in i is determined by element a_{ij} of a matrix N x N (Fig. 3). The unit cost of elevation at point i will, therefore, be

$$c_i = k\ (h_{oi} + \sum_{j=1}^{N} a_{ji} \cdot Q_j) \qquad (3)$$

The behaviour of each operator will be dictated by max $z_i = Q_i\ (p - c_i)$, the solution of which is

$$\text{marginal cost} = K\ (h_{oi} + \sum_{j=1}^{N} a_{ji} \cdot Q_j) + Ka_{ii}\ Q_i = p \qquad (4)$$

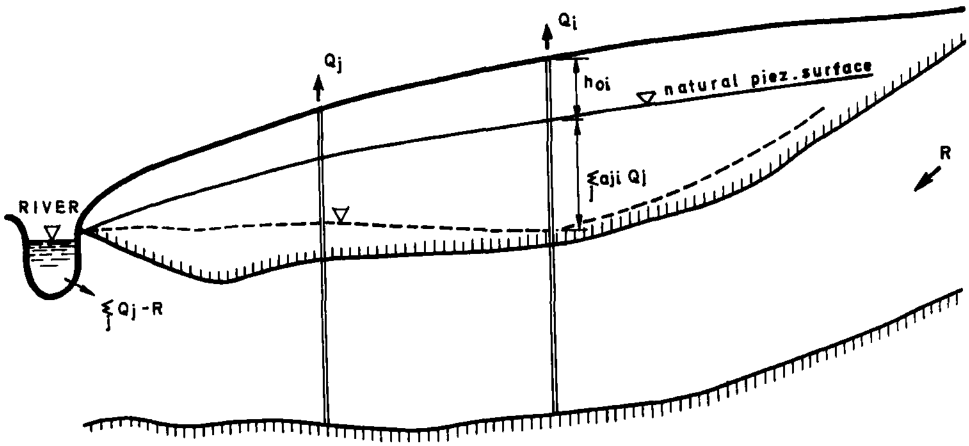

Fig. 3.- Drawdowns and river recharge induced by pumping

Fig. 3

If there were a sole owner, the problem would be stated as max $Z = \Sigma_{zi}$, which for well i is:

$$(\text{marginal cost})_i = K\,(h_{oi} + \Sigma\, a_{ji}\,.\,Q_j) + K\,\Sigma\, a_{ji}\,.\,Q_j = p \qquad (5)$$

It can be shown that centralized management leads to a lower production at all wells and to a higher overall profit, $Z^* > \Sigma \max z_i$. This is why as the difference between (4) and (5) is $\Sigma\, Ka_{ij} \bullet Q_j$, a unit tax on production has been proposed, amounting to $\Sigma\, a_{ij} \bullet Q_j$, as an instrument to correct the individualistic behaviour of operator i. Naturally, this tax represents the induced cost to the rest of the users.

If the administrative authorities collect the tax indicated from user i, it seems logical to compensate him subsequently with the amounts $ka_{ji}\ Q_j\ Q_i$, collected from users j as pumping costs induced to him. In this case, the net payment of the first would be $\Sigma\, k\ (a_{ij} - a_{ji})\ Q_i \bullet Q_j$, which may be either positive or negative. Consequently, in the final settlement some operators will receive more money than the amount already paid on account, and the remainder will not recover the tax they have paid. Considering the physical meaning of the coefficients a_{ij}, the final result could be viewed as the owners of the "worst located" wells suffering penalizations profited by the owners of the "best located" wells.

The imbursement into the Public Treasury of the entire funds collected would also be challenged, as the less favoured (larger a_{ij}) would make a greater contribution to public expenses. Finally, the allocation of the quotas resulting from the optimal solution of centralized management would also be unsatisfactory for the owners of the worse wells, because their profit would be lower than in a freely operated situation.

3. EFFECTS ON RIVER FLOW

Under natural hydrological conditions the aquifer recharge goes to the rivers in the form of springs or diffuse outflows. When the aquifer is exploited the outflow to the rivers is reduced and it can even occur that the natural direction of flow is inverted (Fig. 3).

The river water may in its turn be used for different purposes, so that an overall loss of value $\underline{c}$ can be induced on downstream users for each cubic metre detracted. The following questions are reasonable in such circumstances:

Direct problem: to maximize the overall profit of all the users, what quantity of water should be extracted from the aquifer? How should it be distributed among the different wells or groups of wells? How should the cost of river water detraction be imputed?

Symmetric problem: if it is necessary to pump a set amount from the aquifer to supply an imposed demand and we wish to minimize the overall cost of fulfilling it, how should the extractions be distributed, and how should the cost of river detraction be imputed?

3.1 Confined Aquifers

Under the assumption of elastic and instantaneous response of aquifers considered up to this point the detraction caused by each well is exactly equal to the amount of water pumped. The formulation of the problems stated above is similar to that of the previous example, and in both cases the optimal solution is the one the users would reach on their own if they considered an additional unit pumping cost which for user i is

$$\text{add cost} = \underline{c} + \sum_{j \neq i} K\, a_{ij} \cdot Q_j \qquad (6)$$

The considerations made in 2 regarding the feasibility of obtaining the socioeconomic optimum under conditions of individually-owned property also apply to this case. The correcting tax will be opposed by the owners of the worst wells, arguing that they are obliged to contribute more to the cost of river water detraction. The mere introduction of a uniform rate $\underline{c}$ will lead to an amount of water being abstracted from the river in excess of the optimum and which, combined with the assignation of the optimal quotas, would be in detriment to the output of the poorer wells, and so on successively.

The social inequity of economic optimization is a result of setting the objective of obtaining maximum profit or minimum overall cost, and this can only be achieved by strengthening the activities of the most efficient wells in detriment to the rest. Another byproduct of optimization is a lower consumption of the production factors (water from the river and energy in this case).

If the well owners operated freely, even paying a unit tax c, the amount of the water resource - and energy - used would be higher. Optimization acts as a conservation instrument for natural resources, preserving them for possible future use.

To sum up, economic analysis does not use criteria of social justice in the treatment of externalities. It simply states that public ownership of the means of production would perhaps be preferable and provides the overall economic cost of the possible decisions for the correction of externalities.

3.2 Unconfined Aquifers

Fortunately, there are very few perfectly confined aquifers. In most cases, storage plays an important role in the way pumping operations affect water levels and transfers of flow within the aquifer. The steady state response to a sustained change in pumping pattern may take years to achieve.

The influence coefficients grow in time towards their final a_{ij} values. Until these are reached, the Basin Authority does not possess sufficient evidence that corrective measures need to be taken and, furthermore, it is very likely that the value of the parameters N, K and p will also remain unstable.

Admitting that a steady pumping pattern will finally be established, it would be perfectly justified by economic theory for the Authority to establish a tax consisting of one sum to compensate the river users, another to correct the influences between wells, and perhaps a third one to avoid overdraft.

However, steady operation practices very rarely exist in water resources systems: aquifer recharge and streamflow are random magnitudes, the most important groundwater exploitation is usually seasonal, and the unit value of the river water also varies depending on its abundance or scarcity. Consequently, the time variable must be present in the evaluation of externalities. For this purpose flow models are used which simulate boundary and recharge conditions of the aquifer, its hydrodynamic parameters and the space-time distribution of the pumping (Young, R. and Bredehoeft, J., 1970 and 1972). Other more compact tools of analysis have been developed more recently, including Kernel or influence functions (Maddock, T. III, 1972) or the method of eigenvalues (Sahuquillo, A., 1983).

One important problem in the economic study of these external effects is to set value c of the unit loss to the river users, which often requires studying the remaining hydrological factors governing these uses. Alternatively, the limits of the system being optimised can be extended from the aquifer to the overall aquifer-river unit. This internalization of the external costs is the approach adopted in the conjunctive use schemes, the simplest version of which consists of detracting from the amount of water pumped a physical compensation equivalent to the amount abstracted from the river.

We shall finally indicate that as pumpings made near a river have a much greater effect on the streamflow than those further away, distance is a key variable in the assignment of pumping quotas and negative (or positive) external effects on the different groups of wells, provided the importance of the detraction lies in the fact that it takes place in a set period of the year. These ideas have been developed in Topic 4 of the Symposium and for this reason we shall simply indicate that in these circumstances of seasonality the sitings we classified earlier as "worst located" are the ones to have preference.

4. OTHER EXTERNALITIES

The most important ones are those referring to the quality of the water. Excessive and/or badly located pumping operations can lead to sea water intrusion into coastal aquifers or of brackish water into inland aquifers. The mere distortion of the natural balance between taking up and releasing of salts in the aquifer gradually leads to another equilibrium with a lower quality of the stored water.

In intrusion problems, what is ultimately of interest is not the control and prevision of the degree to which quality declines, but rather being certain that it does not decline below a minimum admissible level; the control variable of the phenomenon is piezometry. Furthermore, operational sites become useless much more rapidly than in pure overdraft processes. Other circumstances, such as the fact that waters of different quality constitute different commodities, the complexity of the physical models, lack of knowledge of the parameters involved in these models, the inapplicability of taxation systems, etc., will imply that for a long time the use of the resource will be far from economic optimization in the real treatment of these problems.

Corrective measures consist of imposing minimum limits on piezometric levels close to the coast, an objective that can be achieved by assigning maximum pumping discharges which can eventually be modified if necessary on the basis of piezometric control and maximum depths in the wells.

The fact that sea water intrusion problems do exist means that the public is not sufficiently aware of them and in part this may be due to the small number of economic assessments made during or after this sort of processes, such as the one presented to us by C.M. De la Cruz referring to the Bay of Manila or cases such as the one recounted by Tushaar Shah in the Saurashtra Region in India.

Ground water externalities can also be positive, in which case a premium should be granted to production, equivalent to the induced profit. A clear example of this type is provided by zones with drainage problems, such as the one presented by Tushaar Shah in his paper on Gujarat and many other areas in India.

A similar situation arises from using aquifers as reserve facilities against droughts, a policy which always underlies conjunctive use. In these schemes, each cubic metre of ground water extracted is equivalent to $K > 1$ cubic metre of guaranteed supply, since the $K - 1$ difference is obtained through a less conservative use of surface reservoirs.

5. GROUND WATER EXTERNALITIES IN SPANISH LEGISLATION

The Water Law in force until 1985 dated from 1879 and it scarcely paid attention to ground water. It considered ground water susceptible to private appropriation, except in two bands 100 m wide on each side of rivers, with no limitations other than a minimum distance of 100 m between wells and those derived from the general precepts of the Civil Code. One single precept, art. 23, established the prohibition that "nobody shall have the right to divert or separate public or private waters from their natural course", but the terms were so general and ambiguous that only in manifestly notorious cases could they be applied to ground waters.

It seems that the gaps in the Law were not felt until the nineteen fifties, due to the proliferation of wells in the alluvial valley of the River Segura (Murcia). Based on the aforementioned art. 23, an Order of the Government Presidency in 1959 classified as public all the waters of the alluvial aquifer, which was expressly defined; from thenceforth, the waters of the Segura Valley could only be used with State granted concessions. In 1962 a special Law was passed for the Canary Islands where detraction between users was common and a clear danger emerged of overexploitation. Facilities to use ground water were subjected to a system of authorization, after a formal requirement of a public information period to those who might be affected, but the water was still classified as private.

The drilling boom which occurred during the second half of the sixties obliged the Government to publish two Decree-Laws imposing temporary prohibitions in specific areas of Andalusia and Majorca. In 1973 a Decree provided regulations on the administrative procedures to create new wells in the Province of the Balearic Islands, and a similar Decree was issued in 1980 for the basin of the River Andarax in Almeria Province.

Several attempts were made to reform the Water Law from 1961 onwards but for one reason or another they were unsuccessful. The White Paper produced in 1971 proposed that ground waters should be considered public, and this idea became definitively strengthened as the transformations from dry farming to irrigated lands spread from the Mediterranean coasts to inland basins.

The new Water Law approved in 1985 incorporated ground waters into goods of public domain, being susceptible to private use with official granted concession; the right of an owner of a piece of land to extract therefrom up to a maximum of 7,000 m3 per annum is recognised in the Law, with the distance limits set in the Regulations.

The treatment of externalities may be summarised as follows:

5.1 Granting of Concessions

These are granted taking into account the terms of the Water Plan regarding the rational use of the basin water resources, and those of the specific hydrogeological unit, such as maximum pumping discharge distance between wells and to rivers.

All concessions are understood to be made without prejudice to the rights of third parties, who have the possibility of appealing at the public information stage. The Basin Authority may impose or propose among the conditions of the concession the payment of physical or economic compensation to the owners of other legalised facilities which prove to be affected.

Concessions may be expropriated and their conditions may be modified when this is necessary to bring them into line with the Basin Water Plan. In both cases the injured party has the right to an indemnity.

5.2 Overexploitation of Aquifers

The Basin Authority may officially declare that an aquifer or hydrogeological unit is overexploited or in danger of becoming so and a declaration of this kind produces the following effects:

a) stopping of all applications for new concessions or to modify existing ones;
b) compulsory creation of a Users Association;
c) obligation to draw up a comprehensive Plan which regulates the withdrawals from the aquifer.

The administrative definition of the concept is relatively vague, referring to the quantity of the renewable resources of the aquifer or to a serious decline in its quality. Up to the present moment, the Basin Authorities have issued four declarations of overexploitation, the formula has been applied by Decree in other areas, and a special Law has been approved for the Segura Basin which, among other measures, contains a sort of concealed declaration for the entire Basin.

5.3 Sea and Brackish Water Intrusion

The Basin Authority may declare that a zone is in the process of salinization and is thereby authorised to impose limits on extractions and to redistribute them in space.

The administrative procedures are identical to those set forth for overexploitation.

5.4 Affections Between Users

The mere variation of the water level in a well due to pumping in another is not considered an affection, but rather a reduction in the available flow, or a deterioration in its quality preventing its use for the purpose to which it was assigned. The reduction of the flow of a spring or gallery is not considered a detraction if the available remainder is equal to or larger than the amount actually used.

Affections can be reported by the concession holders and must be checked by the Basin Authority. If the check is positive, the works or installations to be made in order to ensure the pre-existing conditions must be determined, and their cost must be borne by the holder of the most recent concession. If, even by these means, the previous scale of operation cannot be restored, the possibilities open are the physical restoration of the flow, an indemnity by mutual agreement, or a revision of the most recent concession.

6. REFERENCES

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