SOME ASPECTS OF THE ECONOMICS OF GROUNDWATER CONSERVATION AND PROTECTION

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ABSTRACT

Good management practice should include measures to conserve groundwater resources and to protect them from pollution. The cost of collecting data that allows effective groundwater management is small in relation to the potential benefits. The costs incurred should form part of the overall management budget.

The benefits of pollution control are invariably intangible. Decisions about the appropriate level of control commonly involve trade-offs between two conflicting desirable benefits, for example increased agricultural production and a reduction in groundwater pollution.

Groundwater quality can only be maintained by incurring higher costs. The true costs include limitations on land-use, reduction of crop yields, treatment of wastes, and provision of sewerage systems.

Effective conservation and protection of groundwater resources can only be implemented if supported by legislation.

It can be argued that groundwater, being a vital, essential resource, with a direct bearing on the quality of life, should be conserved and protected as a social duty rather than only on the basis of economic analysis.

1 INTRODUCTION

Most engineering developments are concerned with investing in projects that generate profits but major projects often incorporate elements that do not show an obvious profit - certainly not in cash terms. These include safety, environmental aspects and the need to conform with legal requirements. Groundwater conservation and protection measures tend to fall into this category for the outcomes are intangible in the sense that, although expenditure of capital is necessary for their application, there may be no clear creation of physical assets. In terms of cost-benefit analysis they are difficult to quantify for, while the costs are definite, the benefits are elusive and subjective, representing different things to different men. However, as discussed later, this is not true for all conservation projects for a monetary value can sometimes be given to water that is conserved and this can be directly related to the cost of the conservation measures, for example in artifical recharge projects.

Groundwater conservation is concerned with good management practice, that is developing the resource at an appropriate rate and avoiding waste once it has been developed. Groundwater protection is concerned with maintaining or improving the quality of the resource but with the emphasis on maintaining quality as groundwater in its natural state is usually of high quality. The application of conservation and protection policies has a very important bearing on social aspects such as the quality of life and the state of health of communities.

Conservation of a resource becomes increasingly important once a significant proportion has been developed. As the use increases in relation to availability, decisions have to be taken about the rate of use. In semi arid or arid regions development is likely to involve mining the resource and this raises the classic resource development question of "how much for how long?". The length of time over which a resource is developed influences the economics of development and the costs of different proposals have to be compared with the benefits, which may involve the use of water for producing material goods of higher value. This is part of the decision making process and is beyond the scope of this paper which is restricted to the more basic approaches to conservation such as the cost of acquiring information necessary to manage a groundwater system effectively and hence conserve and protect the resource.

The scale of the need for conservation and protection policies is different in developing and developed countries, in urban and rural areas, in temperate and arid zones. Perhaps the need is greatest and the problem most complex in expanding urban areas which do not have a piped sewerage system.

2 GROUNDWATER CONSERVATION

Conservation policies are not specific to groundwater for they concern the use of water, especially methods for ensuring that it is used more effectively. Conservation measures include reducing consumption by various approaches, such as restricting supplies or applying a pricing policy; preventing leakage from water pipe-lines; changing land-use, for example from irrigation to dry farming; recycling water by re-use of waste water and introducing artificial recharge.

Water is a vital resource and as it becomes scarce laws are promulgated to ensure effective use. In areas where water has always been scarce distribution is controlled by local and tribal customs. Even in areas of adequate rainfall, where groundwater is regarded as a renewable resource, the total resource is finite being limited by the amount of storage in an aquifer and the average annual rate of replenishment from rainfall and seepage from surface waters. Ultimately, if the resource is not managed properly, the cost penalty of falling water levels or deterioration of water quality will limit development.

Effective management requires a legal basis. In England and Wales groundwater abstraction is controlled by a licensing system and a charge is made according to the amount of water licensed to be abstracted and the use to which it is put. Decisions about management policies regarding the most appropriate use of water can only be made if adequate data are available about the resource. Thus groundwater conservation is concerned in the first instance with collecting and interpreting data. The benefit is through the application of the interpretation to the management of the resource.

The increasing demand for water in England in the 1950s and early 1960s led to the Water Resources Act of 1963 which included provision for the collection of data through hydrometric schemes. These schemes were supported by central government funds amounting to 50 per cent of the total cost. They included the measurement and recording of rainfall, evaporation, river flow, and river quality, as well as the provision of a network of observation boreholes to monitor changes in groundwater storage and quality. The total capital expenditure approved between 1964 and 1974 was equivalent to 12 million US dollars* including 1 million dollars for groundwater networks (at 1973 values, equivalent to about 47 million and 4 million dollars at 1987 values).

Although no formal guidance was given with regard to the density of groundwater observation well networks, it was indicated that one well per 25 to 35 km^2 should be the aim in major aquifers and that one well per 100 or 200 km^2 should be monitored continuously with either an autographic or punched-tape recorder. The density required depended upon a number of factors including the areal shape of the aquifer, the extent to which it was dissected by river systems, fluctuation of the piezometric level, the risk of pollution and the use that was made of the aquifer for water supply. In actual fact the overall density of networks was one well per 27 km^2, the average density of continuously monitored wells being one per 175 km^2. The networks as established in 1974 comprised nearly 2000 wells, principally in the main aquifers of the Chalk, Triassic sandstones, Jurassic limestones and Lower Cretaceous sands.

In 1974, when the water authorities were established, responsibility for maintaining the hydrometric networks, including the groundwater networks, was transferred to these authorities. The data are collated at a national level and the Geological Survey is responsible for the groundwater observation well network (Rodda and Monkhouse, 1985). The Survey recently reviewed the archive and selected about 200 wells which could be used to monitor and assess the groundwater situation on a national basis. One well was chosen for each aquifer unit. More recently the Survey has identified about 15

*Most of the costs quoted in this paper were originally derived in pounds sterling. A conversion rate of about 1.7 US dollars to the pound has been used.

wells, the records of which are up-dated at monthly intervals so that trends that may lead to extreme events, associated with, for example, droughts, can be recognised at an early stage. Groundwater level data for the archive of 200 wells are now published annually by the Geological Survey in Hydrological Yearbooks which also contain measurements of rainfall and river flows.

The objective of the hydrometric schemes was to provide sufficient basic data for the assessment of water resources, and to monitor storage and water quality changes. As the abstraction of water from both surface and groundwater sources is now almost entirely controlled by licences granted by water authorities, efficient operation of the licensing system requires knowledge of the total resource and the consequences of developing it.

The purpose of the observation well networks is to provide a long-term measure of changes in groundwater storage. They are not dense enough and, as originally conceived, they were not intended to be suitable for the preparation of groundwater level maps or for detailed groundwater studies. They are used to forecast minimum seasonal groundwater levels and river flows, to calculate certain aquifer properties and, as groundwater resources become more extensively developed, to give a measure of long-term regional changes in groundwater storage following groundwater development.

The observation well network also provides access for sampling groundwater quality thereby providing information about long-term trends, for example, trends caused by pollution from diffuse sources such as nitrate pollution from agricultural practices. The network is not adequate, however, for pollution control. Most pollution problems are local in extent and require a dense network of observation wells to monitor the progress of pollution from a particular source, as discussed below.

The capital cost of a groundwater network is the cost of drilling the boreholes, and the provision of automatic water level recorders for about 1 in 6 sites, while the operating costs depend upon the frequency of measurement, if carried out manually, together with the interpretation of the data. To obtain an indication of the cost of such a network the Chalk aquifer in England may be taken as an example. This aquifer underlies 32000 km^2 of which 12000 km^2 are confined by Tertiary clays. At a density of 1 borehole per 30 km^2 at outcrop, and 1 per 200 km^2 in the confined area, 725 boreholes would be necessary to give adequate coverage. A typical borehole, including automatic water level recorder, costs 12000 dollars and therefore the capital cost would be of the order of 8.5 million dollars. Management and interpretation of the data would take about 6 man-months say 20000 dollars per year. (The figures are intended as a guide to the order of magnitude of costs. There are actually more than 725 wells monitored in the Chalk and many of these were drilled originally for water supply and not specifically as observation wells).

It is difficult to estimate the benefits of operating such a network. Clearly without the data it would be difficult to make decisions about operating schedules for pumping wells that were meaningful on the scale of the entire aquifer. The basic data about volumes of storage in the aquifer need to be incorporated in aquifer models and operational models of distribution systems. In the sense of providing key, basic data such networks are invaluable, for example they may provide information that indicates a modification of the pumping regime is necessary. The Chalk provides some 1255 million m^3 of water per year at a selling price of about 640 million dollars per year. This latter figure is so large in relation to the cost of the network discussed above that it could be argued that justification of the cost is hardly warranted.

Groundwater observation networks provide long-term surveillance of aquifer storage. A greater density of wells is necessary to monitor major groundwater development schemes. In the UK the design of schemes for the regional development of groundwater resources incorporates provision for monitoring the impact on the resource. This is needed not only for management but also to ensure that approval is given to proceed with the scheme and that other users of the aquifer are protected. The underlying factor is the legal basis for groundwater development now embodied in the Water Resources Act of 1963 and the Water Act of 1973.

In one major scheme in the UK, that was concerned with regulating river flow by pumping groundwater into the river as the need arose (Anonymous, 1972), three observation boreholes were drilled for each production well and many shallow, small diameter pipes were inserted to monitor the relationship between groundwater and the river system. The cost of observation wells represented 2 per cent of the capital cost of the entire scheme and between 5 and 6 per cent of the cost of production wells. Because the development involved a significant lowering of groundwater levels under drought conditions, existing wells were deepened or households were provided with a new piped water supply. The cost of such compensation works amounted to between 4 and 8 per cent of the total capital cost according to the need in individual areas. The immediate benefits of the observation well network were regional evaluation of the aquifer properties and the ability to monitor the progress of the scheme and its impact on the groundwater system. The equally important intangible benefit was concerned with public relations.

An important aspect of management is the assessment of the quantity of water that has to be kept in reserve for distribution in times of drought.

Assessments have to be made of the frequency and severity of restrictions in supply that customers expect or will accept. In England and Wales, it is considered that bans on the use of hose-pipes for garden watering will be accepted 1 year in 6 while more severe restrictions on supply will be accepted 1 year in 20 with perhaps major cuts in the use of water once a century. The judgement that is required is a fine one between developing water resources cost effectively and limiting water use in time of scarcity. These data apply to a temperate region where water is not expected to be in short supply but the decisions relating to available storage are vital for effective management and provide a yardstick against which the costs of providing a groundwater network can be judged.

In the Thames Water Authority, in England, over 1.6 million m^3 of groundwater are abstracted per day; at a value of 0.5 dollars/m^3 this represents about 0.85 million dollars per day. The authority has about 160 observation wells representing a capital cost of some 1.7 million dollars the value of two days supply of groundwater. Clearly the benefit/cost ratio of the network in managing such a system must be very high although difficult to quantify in monetary terms. There is a legal requirement to develop aquifers effectively and costs necessary for this are part of the overall cost of management. The groundwater networks represent an intangible asset that is part of the management system, involving capital expenditure but no specific monetary return.

Many countries have developed groundwater observation well networks. To give but one further example, in Cuba large investments have been made for this purpose particularly to detect and monitor the extent of saline intrusion in karstic aquifers. There are over 2500 observation wells at a density of one per 43 km^2 (Barreras Abella, 1987).

As mentioned earlier, several measures adopted for the conservation of groundwater resources can be assessed in monetary terms. These include the use of check dams to increase infiltration, the installation of drainage systems to prevent salinisation of shallow groundwater in areas that are irrigated with surface water, and the development of artificial recharge techniques.

Check dams are constructed in valleys, on aquifers, in arid or semi-arid regions to retain flood-waters and increase infiltration. The benefit can be evaluated in relation to the increase in groundwater storage (and the value of the water) against the cost of the engineering works required. The technique has been used in many parts of the world and there is a great variation in the scale of the works but the approach may be illustrated with a case study in Baluchistan by the Overseas Development Administration of the UK. The advent of electricity in the area led to an accelerated use of groundwater and previously perennial streams and infiltration galleries dried up. Increased recharge from storage behind small check or "delayed action" dams stabilised the water table and allowed increased abstraction. The details of one small scheme are given in Table 1.

TABLE 1

Economics of a scheme involving a small check dam

Height of dam	10 metres
Length of dam	560 metres
Size of catchment	25 km^2
Increase in perennial yield	30 litres/sec
Total irrigated area	8.0 km^2
Extra area irrigated	0.8 km^2
Total cost	255000 dollars
No. of beneficiary families	1665
Cost per family	150 dollars
Cost per hectare	3000 dollars
Annual return	40000 dollars
Economic rate of return	10 per cent
Life of scheme	21 years

In areas where irrigation is practised using surface water, and where groundwater is at a shallow depth, measures are necessary to preserve the quality of groundwater and prevent water logging and salinisation of the soil. Drainage by horizontal drains or wells is necessary to allow irrigation to continue.

The capital costs of engineering works necessary to conserve the quality of groundwater can be identified and expressed in relation to the total cost of an irrigation scheme. The costs of such measures can be considerable and the cost-benefit ratio needs careful evaluation. For example, the estimated cost of a programme, extending over 21 years, to reclaim a tract of land in Pakistan that had been affected by salinisation amounted to 3 billion dollars (at 1975/76 prices), an annual investment of 145 million dollars (Bokhari, 1980). The major elements of the programme indicate the scale of the problem:

Area	90,000 km^2
No. of new wells	38,000
Replacement of damaged wells	21,000
Open surface drain required	77,000 km

Despite the high costs, in countries dependent upon agriculture, the benefits of such engineering works outweigh the costs.

As groundwater development proceeds, conservation of water by artificial recharge become an important option; either surplus surface run-off or treated effluents can be the source of the water. The cost of recharge works vary widely according to the nature of the engineering works and the quality of the water. Very low costs are associated with simple techniques such as scarifying river beds to increase infiltration. Table 2 gives comparative costs of proposed basin and well recharge schemes in the United Kingdom using river water as the source. In the two cases selected, although the capital costs are similar, the unit cost of the water is higher for well recharge. The treatment costs for basin recharge are less but the costs of the works for the recharge process are higher.

The scale of the engineering works required for an artificial recharge scheme depends upon the quality of the recharge source, the method of recharge and the extent of any treatment necessary immediately prior to supply. The costs given here assume that the source of water is a relatively uncontaminated river which requires only coagulation, sedimentation, filtration, and chlorination to bring it to potable standards. This would be essential for a borehole recharge supply although, for lagoons, settlement only has often been considered to be adequate.

Lagoon recharge is somewhat cheaper than borehole recharge. Treatment costs are less when lagoons are used, although the construction of recharge facilities and the cost of land makes the actual recharge works more expensive. The capital cost of a recharge borehole expressed as m^3 per day of recharge capacity, is about half the cost of lagoons, including land. More abstraction boreholes are needed in a lagoon scheme whereas recharge boreholes can also be used for abstraction. However, maintenance works can be more readily carried out in lagoons and the life of a recharge borehole is considerably shorter than that of an abstraction borehole and, of course, of a lagoon.

Borehole recharge has a considerable advantage over lagoon recharge schemes with regard to land use and environmental impact. To recharge at a rate of 30000 m^3 d^{-1} may require 6 to 10 wells, but it would need about 15 basins, each covering 4000 m^2, assuming an average infiltration rate of 0.5 md^{-1}. The total land requirement would be about 0.2 km^2, although the water area would be only 0.06 km^2. However, it should not be overlooked that the land required for lagoons is still not particularly large. Furthermore, the water area in a recharge scheme per unit yield would be much less than for a surface storage scheme (Edworthy and Downing, 1979).

TABLE 2

Comparative costs of artificial recharge schemes in the United Kingdom

	Basin Recharge	Well Recharge
River intake	1%	1%
Pumps and pump-house	12	14
Treatment	3*	40
Pipelines **	19	20
Recharge basins	50	-
Abstraction wells	13	-
Recharge/abstraction wells	-	23
Observation wells	2	2
Unit cost of water dollars per m^3	0.27	0.32

Notes: To recharge 30,000 m^3 per day

Total capital cost of each scheme is about 10 million dollars

* Settlement only

** Recharge area about 5 km from river source.

3 GROUNDWATER PROTECTION

Groundwater protection is concerned with taking actions or decisions that will avoid pollution. It is concerned with maintaing the quality of the resource. The very nature of aquifers - large areas of permeable rocks containing a resource that is underground and out of sight - implies that legal controls to prevent pollution are essential. The basic problem is that groundwater is polluted by individuals who will not become directly responsible for their actions or are not even aware that they are causing a problem. In contrast the individual small landowner in a rural area will generally carefully site his cess-pit in relation to his well to avoid contaminating the well. It is generally true to say that attention to the protection of groundwater decreases with the scale of urban development as individual responsibility is perceived to a decreasing extent. The benefits that arise from the control of groundwater pollution are invariably of an intangible nature.

Groundwater is threatened by pollution from diffuse sources (such as nitrate pollution from fertilisers, the mobilisation and leaching of toxic metals in the soil because of acid infiltration, salinisation of irrigation systems and saline intrusion) and point sources (including waste disposal in landfills, industrial and farm wastes, and septic tanks). The problems of groundwater pollution and protection have been comprehensively reviewed by Aldrick and others (1986).

In the UK 80% of waste is disposed of in landfills but there is now also a trend towards resource recovery and recycling. It can be many times more expensive to clean-up a landfill contamination problem than to decontaminate the waste in the first place. The weakness of accepting this approach is that direct disposal of waste to a landfill is cheaper than initial treatment. More landfills are now operating as containment sites and the extraction and treatment of leachate is becoming more important. The cost of treating leachate from landfills commonly amounts to between 1 and 2 dollars per cubic metre depending upon the type of treatment.

In 1984 about 20% of the hazardous waste in the United States was disposed of in tips or deep wells. There are believed to be 10000 sites containing hazardous wastes and cleaning and rehabilitating them could cost 100 billion dollars. In 1986 the US Congress allocated 9 billion dollars for cleaning up contaminated sites over a 5 year period.

There are many examples in the literature of unfortunate incidents arising from groundwater pollution. As the scale of the problem has been appreciated, restrictions on the disposal of waste,introduced by legislation, have increased. The number of tips have consequently been reduced and as disposal techniques have become more sophisticated the costs of disposal have increased ten-fold over some 17 years; the cost of disposing of a tonne of hazardous waste in 1987 is at least 250 dollars. The cost of treating an existing hazardous waste tip by sophisticated treatment processes based on advanced technology could amount to 1 million dollars.

A significant threat to groundwater resources is leaking underground storage tanks used, for example, for storing petroleum and other chemicals as well as hazardous wastes. The leakage of 4500 litres of aviation fuel into an aquifer in the UK led to the closure of a public water supply borehole and the expenditure of one million dollars on cleaning up the aquifer and providing alternative water supplies. In many situations where groundwater has been contaminated, it will be less costly to develop an alternative water supply rather than attempt to rehabilitate a contaminated aquifer. Pollution incidents caused by leakage of chemicals and oil products emphasise the need for the careful design and specification of materials for storage tanks. In the Federal Republic of Germany all underground petroleum storage tanks must have a double wall construction and mechanisms are incorporated to prevent overfilling. Groundwater provides 70% of Germany's water needs and this partly explains attention to underground storage facilities (Moreau, 1987).

The evidence for the steady degradation of the quality of groundwater has led to legislation in a number of countries designed to protect the resource. In the UK the Control of Pollution Act, 1974, now provides an adequate basis for controlling groundwater contamination. But, because the cost of restoring a polluted aquifer to its original quality state is expensive, even if it is possible (Navarro and Soler, 1987), attention is focussing on Aquifer Protection Policies to prevent pollution occurring in the first place. This approach has been widely adopted in Europe (Headworth, 1986).

Protection policies provide guidance to planning authorities and developers by indicating the constraints they must work within to avoid groundwater pollution. It introduces the need for land-use planning over and near aquifer outcrops including:

- location and design of landfills
- control of agricultural practices
- control of disposal of sewage effluents
- implementation of regulations specifying the design of tanks for storing chemicals

Protection policies are basically concerned with defining protection zones of different widths around a groundwater source although sometimes entire aquifer outcrops are specified. The extent of the zones is to some extent subjective but based on factors such as the nature of the aquifer, rate of groundwater flow and thickness of the unsaturated zone. The innermost zone around a groundwater source, intended to give the greatest protection, commonly provides 50 days protection against microbial contamination by allowing physical, chemical and biochemical processes to reduce any contamination to acceptable levels as the water flows through the aquifer. In a sandstone the zone may be 500 m, in a fissured limestone perhaps 2 km.

To protect groundwater sources Water Authorities in the UK would like their powers strengthened to allow inspection of installations that are likely to cause pollution and to stop operations or force owners to improve conditions. In aquifer protection zones the objective is to control or prevent the use and storage of undesirable chemicals.

The above discussion has emphasised the serious, increasing problem of groundwater pollution in urban areas, the high cost of attempting to rehabilitate the quality of a polluted aquifer and the importance of taking preventitive measures to avoid pollution.

Groundwater quality monitoring networks form part of the measures necessary to protect an aquifer. Steele (1987) has summarised the major issues:

1. Why do we monitor? What are the objectives?
2. Where, when and what do we monitor?

With regard to why?, the answer is generally to measure the initial spacial variability, followed by temporal variability, and the identification of time trends. The answers to 2 depend upon the local situation but the answers determine the costs.

Groundwater monitoring networks are more densely spaced than a conventional observation well network. Wells are required to either monitor a pollution plume or provide warning of pollution up-gradient of a production well. Concern is commonly with problems in relatively limited areas, possibly a particular pollution incident or hazard. Some 10 to 20 wells, open at different depths, may be necessary to define a pollution plume from a point source, a total capital cost of say 170000 dollars. In a homogeneous aquifer, with intergranular flow, adequate warning may be provided for a groundwater source by about five or six wells arranged upgradient of the producing well, at a cost of some 50000 to 70000 dollars.

The fact that monitoring networks to identify or protect against pollution incidents have to be of greater density than conventional observation networks implies the cost are higher. The cost benefits of groundwater monitoring programmes were discussed by Wilkinson and Edworthy (1981). They pointed out that the annual costs of monitoring a single borehole (including sampling, chemical analysis, data interpretation and storage) can amount to 10% of the capital cost of the borehole. Over the life-time of the borehole the running costs represent more than the capital cost; over a life-time of 20 years it would be twice the cost. The total cost of the monitoring could then be a significant proportion of the cost of the production well it was designed to protect. In view of this it is necessary to assess the true value of the monitoring network. This must be judged by the amount of useful information it provides in relationship to the cost of providing it. The principle of the "willingness to pay for the information" has to be invoked and how the information is used for decision-making (Steele, 1987).

Applying protection policies is a form of prudent insurance allowing management decisions to be made on a technical basis. Failure to prevent the deterioration of groundwater quality can lead to:

1. loss of a water source with the consequent inconvenience together with the cost of replacement;
2. health hazards caused by degradation of quality.

The monetary value of a lost groundwater source can be evaluated from the cost of providing an alternative, but it is difficult to put a monetary value on the deterioration in the quality of life caused by a degradation in the quality of drinking water. Nevertheless, the social benefit of maintaining water quality must be the true benefit of groundwater protection policies.

Establishing and maintaining groundwater quality networks represents a minor cost in implementing a protection policy. The true tangible cost is the financial impact arising from changes of land-use, changes in agricultural output caused by a reduction in the use of fertilisers and pesticides, the costs of installing piped sewerage systems, the installation of better designed underground storage tanks (Table 3). These preventitive measures introduce significant costs that are not likely to be implemented without legally defined specifications.

In Iowa, USA, where groundwater is the state's principal source of drinking water, concern at the extent of pollution of aquifers has led to a tax on the production of pesticides and nitrogen fertiliser. Some form of taxation on fertiliser use to reduce consumption may be required more widely if groundwater is to be protected for, while the cost of applying fertiliser is less than the increase in value of the crops produced, the practice will continue. The behaviour of individuals is sensitive to financial incentives. However, studies in the UK have shown that high levels of taxation would be necessary to induce large reductions in fertiliser use. The decline in farm income would be very significant (Anonymous, 1986). Clearly any taxation proposals would involve trade-offs with agricultural productivity and have significance at national economic levels.

The capital-intensive programmes necessary for maintaining groundwater quality and preventing pollution must be paid for by appropriate charges, either taxes, or charges for the use of legally enforced waste disposal systems, or costs incurred in adhering to regulations enforcing the use of appropriate materials for underground tanks and pipes. The polluter pays principle eliminates subsidisation by taxpayers but this can only be applied, of course, if the cause or source of the pollution can be identified.

Maintaining groundwater quality is a complex technical and economic problem with many facets. The costs of preventing pollution can be evaluated, the costs of action necessary to rehabilitate an aquifer can be made but the benefits of spending this money are more difficult to identify (Table 3). Decisions can involve trade-offs between two desirable benefits, for example increased agricultural production and prevention of pollution from nitrates and pesticides, or reduced industrial costs and prevention of pollution by heavy metals. Economic evaluation is concerned with establishing the real cost of a policy, in the case considered here, the conservation and protection of groundwater. The purpose is to select the appropriate decision, the decision that gives the greatest net benefit. However, although cost-benefit analysis may be considered necessary to justify legislation that leads to the heavy capital expenditure required to protect groundwater quality, value judgements will be necessary to assess intangible benefits. But perhaps some rights should be regarded as inviolate and not subject to decisions that are based on analyses that assess the costs and benefits of simply redistributing funds. If this is accepted, the protection of groundwater, a vital national asset, must come in that category.

Although a prima facie case can be made for ensuring the protection of groundwater quality because of its value as a primary resource and the irreversible nature of the pollution process in aquifers, in reality slow, insidious pollution from multiple point and diffuse sources is likely to increase in many aquifers. In these circumstances more sophisticated treatment of groundwater will be necessary in the future and hence the cost of groundwater will increase.

If high nitrate concentrations cannot be reduced by blending waters from different sources, or by storage that allows natural denitrification or by developing new sources, then ion exchange is the most suitable denitrification treatment process available for groundwater. The capital cost of this process has been estimated to be 425,000 dollars per 1000 m^3 per day for the removal of 45 mg NO_3 per litre and the running costs are between 0.002 and 0.003 dollars per m^3 for each mg NO_3/litre that is removed (ie about 0.09 and 0.14

TABLE 3

Benefits of groundwater use and some economic factors in groundwater protection

Benefits from use of groundwater	Cost of pollution prevention	Cost of pollution
1. Good quality water	1. Treat waste before disposal	1. Develop alternative source
2. People have:	2. Design landfills efficiently	2. Rehabilitate the aquifer
a) better health	3. Control land-use	3. Treat polluted groundwater
b) better quality of life	4. Restrict use of fertilisers and pesticides	4. Provide bottled water for drinking
c) higher work productivity	5. Install sewerage systems	
d) lower medical costs	6. Store potential chemical pollutants in reliable tanks	
	7. Install quality monitoring networks	

dollars per m^3 to remove 45 mg NO_3/litre). It has been estimated that the cost of lowering nitrate levels in Britain to 50 mg NO_3/l (thereby complying with the European Communities Drinking Water Directive) would require capital expenditure of almost 350 million dollars over the next 20 years plus annual running costs rising to 17 million dollars over that time. This expenditure would be mainly incurred in eastern and central England where the total population affected is about 4½ million. It would require an increase of some 5 to 13% on the capital expenditure required for water supply in the areas affected (Anonymous, 1986).

The cost of treating groundwater contaminated with organic compounds depends upon the nature of the contaminant, its concentration and the volume of water that has to be treated. For example, treating 5000 m^3 of water per day containing 100 micrograms per litre of tetrachloroethane to reduce it to a target concentration of 10 micrograms per litre has been estimated to require direct operating costs of 0.012 dollars per m^3 for packed tower aeration, and 0.024 dollars per m^3 for granular activated carbon adsorption, with capital costs of 85,000 and 285,000 dollars respectively (Booker et al, in preparation). The usual cost of pumping and treating groundwater is 0.05 dollars per m^3.

The above discussion has been concerned mainly with developed countries but in countries that are in the early stages of developing groundwater resources, the problems are different. There the emphasis on groundwater protection is at a local level - preventing pollution in the vicinity of the well-head and ensuring latrines are sited and designed to avoid contamination of groundwater. In Malawi the quality of shallow groundwater, developed by wells only 4 to 5 m deep or by boreholes 10 to 40 m deep, is protected by a concrete apron around the well and the waste or excess water is conducted 10 m downslope from the well in a concrete drain to a soakaway. This basic protection adds 20 to 25% to the cost of drilling wells and 5 to 10% to the cost of boreholes. The benefit is the provision of water of much superior microbiological quality (Lewis and Chilton, 1984). This approach to groundwater protection has now been adopted in many countries.

4 CONCLUSIONS

It has been argued that good management practice will lead to the proper conservation of groundwater resources. Management depends upon data, particularly relating to the amount of current storage, and this must be monitored with an observation well network over a long period of time.

Establishing and operating such networks must compete for funds against other requirements and therefore an obvious benefit from the investment must be visible. It must be clear that monitoring involves more than measurement - it includes interpretation and its effect on management decisions. Nevertheless, the benefits are difficult to quantify in financial terms. They are more likely to be in the form of greater operational efficiency and goodwill from customers. There are significant cost benefits to customers if a resource is effectively managed during periods of low rainfall. Conservation of a resource for future use inevitably involves monetary penalties, such as the cost of engineering works necessary to increase recharge to aquifers.

The costs of observation well networks and conservation measures, including operational costs, usually represent a small percentage of the value of the resource or the cost of a groundwater development scheme. In these circumstances the investment can be allocated as a percentage of the value of the water supplied from the aquifer or as a percentage of the total capital cost of the scheme. The costs can be recovered as part of a direct charge for water or included in the cost of the scheme.

Emphasis on environmental problems is very biased towards surface problems which are more apparent, for example river water quality, the quality of beaches, sewage treatment and disposal, industrial and agricultural discharges. Groundwater problems are less obvious and proposals and decisions about conserving and protecting groundwater resources must usually come from experts. The general public will only be concerned about groundwater when a serious problem exists as when a pollution incident directly affects the water supply - that is interest only arises when protection has failed. The public is not generally willing to pay higher charges for conservation and protection measures unless the benefit is obvious and hence implementation requires a legal basis, enabling costs to be transferred to the water user or to the individual or organisation causing pollution through a charging system.

The extent to which an aquifer protection policy can be implemented is governed by the finance available. Quality can only be maintained at higher cost but the costs must not be unrealistic. Such an attitude when applied to groundwater protection - a hidden resource, little understood -is likely to lead to only limited funding and a continuous deterioration in quality.

Groundwater protection requires effective legislation and implementation of protective measures, for example land-use controls, adequate provision for disposal of potential pollutants, controls on fertiliser and pesticide use.

The benefits are commonly intangible but nevertheless likely to be rated very highly by individuals when expressed in terms of health and quality of life. The costs represent the cost of protecting groundwater a socially desirable duty. In more tangible terms the costs are actually significant involving limitations on land-use, reduction of crop yields, pre-treatment of wastes before disposal, or provision of piped sewerage systems. Costs are incurred through loss of production, or increased cost of production or through taxation.

The cost of dilution and expensive treatment to bring nitrate levels in the UK to below the European Communities limit of 50 $mgNO_3/l$ has been estimated to require extra capital expenditure of 340 million dollars plus operating costs of 17 million dollars per year. Perhaps it would be more appropriate to persuade farmers to use less fertiliser. A public policy provision or regulatory tax tends to lead to a loss of economic efficiency in the activity affected but it is really a question of distributing the disadvantages of a development or process amongst those who are its beneficiaries.

Conservation and protection of groundwater resources can only be implemented by a government or public authority that has authority for its actions founded in law. These concepts are more likely to be successfully applied where a unified water system provides the discipline necessary to control both water resources and quality, surface water and groundwater, waste treatment and waste disposal.

Groundwater conservation and protection are important because of environmental issues such as health care and public pressure for environmental protection and not necessarily in terms of direct market applications. Water is a commodity but it is also an environmental resource. Non-market forces will increasingly assume importance in the future as society becomes more aware of environmental impacts on health and the quality of life as standards of living improve.

Inadequate protection of aquifers could lead to the abandonment of groundwater as a source of water and could lead to the provision of bottled water. It would be a tragedy involving immense cost if this were allowed to occur. In the UK bottled water costs about 400 dollars per m^3, some 800 times the cost of the public water supply.

In the developing world conditions are entirely different. The provision of a water supply system leads to settlement, an improvement in the quality of life, a change in the environment but also the potential for pollution. In a developing country, where groundwater is just beginning to be developed at widely separated localities, there is no immediate need for conservation but protection against pollution in the vicinity of the source is essential and should be incorporated in the design. Attention should also be given to the disposal of effluents to avoid pollution. In many areas this is likely to be a more intractable problem as the size of habitations increase into urban areas.

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