

## GROUNDWATER QUALITY MONITORING SYSTEMS - MONEY WASTED?

W.B. WILKINSON and K.J. EDWORTHY  
Water Research Centre, UK

### ABSTRACT

There is some evidence to suggest that inaccurate groundwater quality data is presently being collected and archived from inadequate or badly designed monitoring systems. This not only wastes resources but possibly may lead to wrong actions being taken on the basis of false data. The paper examines such problems and proposes a simple check list that should be applied to both existing and new systems.

---

### INTRODUCTION

Over the last ten to fifteen years there has been a greatly increased awareness of the long term or even permanent damage that may be inflicted on a groundwater system due to a range of apparently acceptable activities. These may for example include effects arising from certain waste disposal, land use and water management practices. Recognition of this led to the introduction of legislation in many countries aimed at protecting underground water resources. There has also been a proliferation of groundwater quality field and laboratory studies at an international, national, regional and local level. Such investigations and the installation of the monitoring networks are costly not only in terms of the capital costs of wells and boreholes but also in the support costs for sampling, chemical and biological analysis, data archiving and interpretation. The support costs are often overlooked at the planning stage.

There is much evidence to suggest that inaccurate groundwater quality data is at present being collected and archived from inadequate or badly designed monitoring systems. This waste of money and resources is worrying in itself, but of greater concern is that wrong decisions, possibly involving substantial expenditure, may be taken on the basis of faulty data.

The more important of the many reasons why groundwater quality monitoring systems yield inadequate data are as follows:

- the objectives of the monitoring programme are not always properly defined or reviewed. In virtually every case, basic information gained in drilling the

monitoring network constitutes a large proportion of the total information available. By making the best use of the opportunity to acquire information at each stage, the amount of effort needed and hence the cost of a monitoring system can be optimised.

- the monitoring systems are installed before there is sufficient hydrogeological knowledge available on an area. The result is that the network design, choice of sampling method, selection of determinands and sampling frequency must often be suspect.
- insufficient thought is given to the collection, handling, storage, and the accuracy required for the chemical or biological analysis of samples.
- the data is either not archived at all, so that it is lost to other users, or is archived in such a way that no indication is given as to the circumstances of collection or reliability.

The geologist, hydrogeologist, water-well engineer, chemist, data manager and groundwater quality modeller may each be concerned with the interpretation of the data from the monitoring system. It is therefore important that, if possible, they each be involved at the planning stage so that they are aware of the constraints that must apply in the use of the data.

At the moment very little is understood of the way that the composition of natural recharge varies, what ambient groundwater quality might be expected to be, or what are the effects of the full range of those contaminants whose dissemination is not susceptible to control. The significance of rainfall composition in this context has been studied recently in Holland (ref. 1) and in the USA (ref. 2). Little is known of the dissemination of the less common but possibly more hazardous substances.

The object of the paper is to highlight such problems through examples. It sets down a check list to be applied to both existing and proposed groundwater quality monitoring systems so as to increase their reliability and cost effectiveness.

#### HYDROGEOLOGICAL VARIABILITY

The aim of a groundwater quality monitoring programme is to draw a picture of spatial distribution of each groundwater quality parameter and how that distribution changes in time either naturally or under man's influence. The data collected should establish background groundwater quality, detect any undesirable changes that are occurring and enable future deterioration in quality at abstraction wells or elsewhere in the system to be determined. However, the high costs of drilling, sampling, chemical analysis etc. means that only a very limited amount of data that is necessary to fully describe what may be a very complex groundwater system is available. Considerable experience and judgement is therefore necessary in designing a groundwater quality investigation if credible results are to be obtained.

An essential step, but one that is too often overlooked, is to gain as full as possible an understanding of the hydrogeological framework before proceeding with the groundwater quality monitoring programme. In most areas some data on groundwater quantity is available.

Information from areas with a similar hydrogeological setting may give a guide to scale and rate of variation. The evolution of quality with distance from the point of discharge has been defined for a number of regional aquifers (ref. 3). Areal distribution, or chemical 'mapping' is also a well-established concept (ref. 4-6). The scale of the variation established in such studies are valuable guides in the design of a regional monitoring system where starting data are sparse or even absent. Facies changes or fracture-density, or orientation, variation frequently complicates the issue but methods can be developed to assess these (ref. 7-9). The depth of the zone of circulation is a function of both of these factors as well as of the overall geological structure and topography.

It is beyond the scope of this paper to describe in detail the requirements for a hydro-geological investigation but it is worth noting the principal information that is required. The geological boundaries are likely to play an important part in controlling the flow in the system as will the boundaries between the groundwater body and surface water streams, lakes, abstraction points, and natural and artificial recharge areas. Information on the transient condition of recharge, seepage, and abstractions is also necessary. The hydraulic properties of both the saturated and unsaturated zones of the aquifer system may be required and particular attention should be paid to the flow mechanism. It may be inter-granular, through fissures or confined to high permeability stratified zones. An appreciation of the distribution of such features may also be important. For example the influence of fracturing, rock chemistry and rainfall quality has been studied by Wagner *et al.* (ref. 10) for a carbonate rock area in north Arkansas and some interesting causes of variability established.

Aquifer properties such as hydraulic conductivity and storage coefficient may be determined from pumping tests, but these are expensive to conduct and only provide information in the immediate vicinity of the test. However, if groundwater level maps can be drawn it is possible to determine regional distribution of aquifer properties by the use of models.

Sources of pollution must also be identified and attempts should be made to calculate the quantity of contaminants being produced and the rate of transport into the groundwater system. The extent by which chemical and biological reactions occur between the contaminants and the aquifer system should also be considered.

All of this information together with data on dispersivity and travel times through the aquifer system and the position of flow fronts must be woven into a

simple conceptual or perhaps a complex numerical contaminant model. The degree of refinement will of course depend on the nature of the pollution problem and the amount of data that is available. On the basis of this the first phase of the design network may be planned and executed. This will yield additional hydrogeological material as well as groundwater quality data and so a second phase may be introduced and a credible picture of the groundwater flow mechanism will thus emerge. The steps to be followed in predicting the behaviour of a pollutant in aquifer and the design of a monitoring system are shown in Fig. 1.

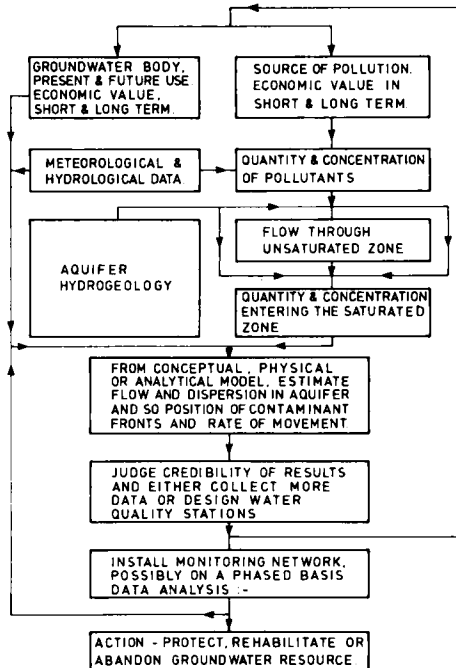


Fig. 1. Flow diagram showing the steps to be followed in predicting the movement of a pollutant in an aquifer and establishing a monitoring network.

Despite the obvious importance of understanding the flow mechanism in setting up a monitoring network, this step may be overlooked particularly during the early stages of an investigation. A simple example illustrates this.

Figures 2a, b and c show the site of a major public water supply well, located in a poorly cemented sandy aquifer. In 1973 the well water showed a relatively sudden rise in potassium, alkalinity, ammonia and odour to such an extent that it was necessary to remove it from supply. The most likely source of pollution appeared to be from a working landfill in a sand pit at the edge of the aquifer. In order to prove that the pollution was coming from the landfill boreholes were drilled at locations A, B, C, D and E (Fig. 2). Highly polluted water was found

in borehole A but only slight pollution was observed in borehole B and in boreholes C, D and E pollution was absent. Immediately after drilling the observation holes a diligent search through old records revealed sufficient groundwater levels to enable a simple flow net diagram to be drawn. This showed quite positively that the pollution from the landfill was not moving towards the abstraction well. This was being contaminated from a source to the east of the well site (ref. 11). A more careful search in the early days of the investigation may have revealed the groundwater level information and certainly the position of the observation boreholes would have been changed and the cost of the investigation could have been reduced.

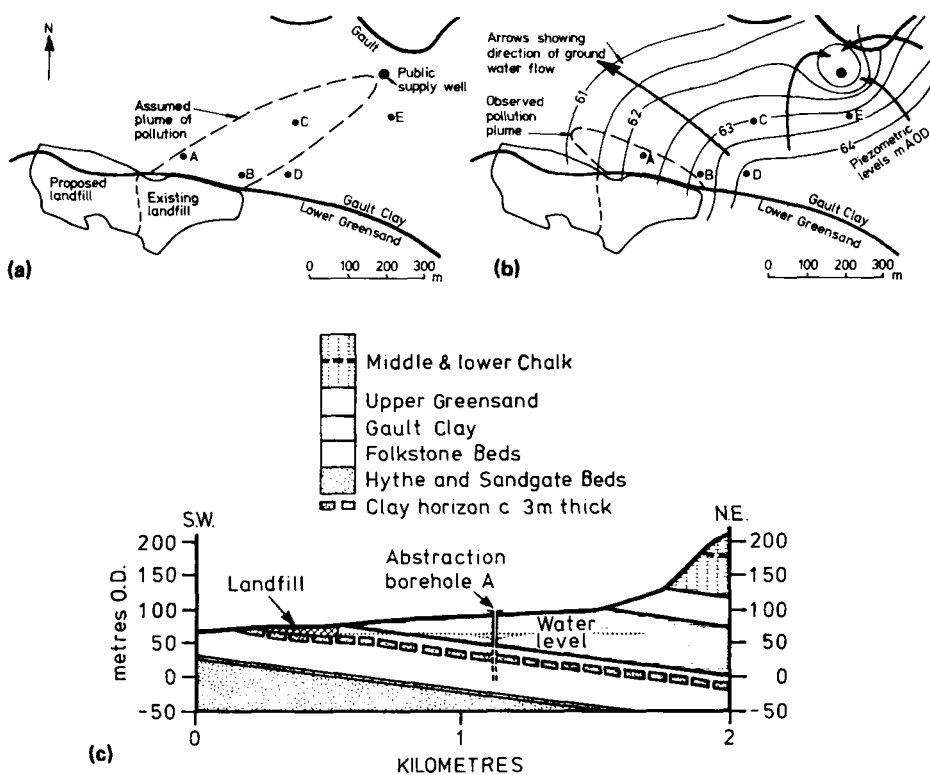


Fig. 2. Plans showing the assumed (a) and observed (b) zones of pollution adjacent to a landfill site. A geological cross-section is given in (c).

It is generally believed that the quality of groundwater changes only slowly and consequently that samples may be collected at infrequent and perhaps regular intervals. Incorrect conclusions can be reached by assuming that this always is the case. Pettijohn (ref. 12) describes such an example. Chloride-rich wastes were deposited at ground surface and in pits in an alluvial aquifer 10 m thick. The chloride concentrations between 200 and 40 000 mg/l were observed in a

number of monitoring boreholes over a period of several years. Chloride concentrations measured in August 1965, in April 1966 and 1969 showed a linear decrease indicating that the chloride would be flushed from the system by 1972 (Fig. 3). However in April 1972 the chloride concentration was 1900 mg/l and this high concentration marked the commencement of the recharge event. The example illustrates that recharge was important in understanding the amount of chloride in the system. Other examples relating temporal changes in quality to annual recharge are described by Sarma (ref. 13).

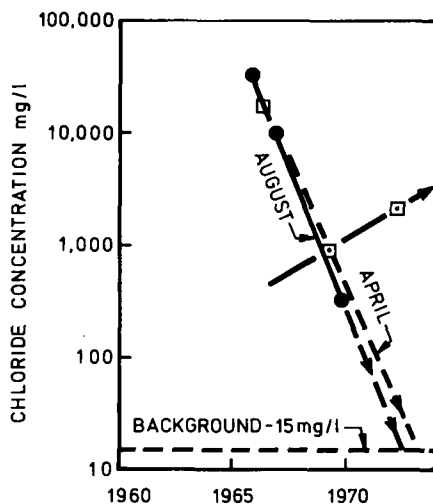


Fig. 3. Graph showing an apparent linear decrease of chloride with time (after Pettijohn, 1976).

#### COSTS AND BENEFITS

There is an increasing demand for aquifers to be used in a multiple role for water supply, waste disposal and as sources of construction material. Society should endeavour to get the best value from aquifers in relation to these competing interests. However the use of aquifers for water supply is often considered on a less than equal basis with the other needs such as waste disposal where problems are often immediate and pressing. Groundwater pollution is often a much more long term problem. A slow but nevertheless insidious decline in groundwater quality may occur. The dangers may not be recognised for many years. Once an aquifer has become polluted it may be difficult and very costly to rehabilitate and its natural recovery may take tens or hundreds of years. Furthermore, because groundwater sources have provided water of such good and consistent quality for so long, there is a tendency among water engineers towards complacency and to question the need for quality monitoring. In the UK for example there are many major groundwater sources which have no associated observation wells to warn of the onset of pollution.

Monitoring costs may appear to be high but it is necessary to compare the benefits that would result from the introduction of a monitoring system with the cost of the consequences of failing to do so. For example if polluted water enters the supply well then in an extreme case public health may be damaged or crops may be lost if the water is being used for irrigation purposes or a manufacturing process may be interfered with. Quantifying such risks is difficult but at least the nature of the risk should be identified. Other costs to be considered would be for treating the polluted water or possibly replacing the supply well by another source. These costs should be compared with the cost of pollution prevention activities such as lining or resiting a landfill, repairing leaky sewers, curtailing certain agricultural activities etc.

Monitoring costs are considered often only in terms of the capital costs of the observation boreholes. The operational commitment, possibly lasting 30 years or more, may be overlooked. The hydrogeological setting between monitoring sites varies to such a degree that it is only possible to give general guidance on costs.

The items contributing to the annual monitoring costs for a single observation borehole forming part of a larger network in the UK are given in Table 1. Capital costs for the borehole including site access and purchase, drilling, screening etc. are about £5000. If the borehole has a life of about 30 years then in simple terms there is an annual capital cost of £170. Thus the capital cost may represent only about 25% of the total and, of the other costs, the chemical analysis may be the most expensive item. It is worthwhile comparing the monitoring costs with the costs of a typical groundwater scheme. In the UK a small groundwater supply may have about four abstraction wells giving a yield of 9000 m<sup>3</sup>/h. The capital replacement cost would be of the order of £600 000. Possibly up to ten observation boreholes could be used to effectively monitor the groundwater system and over a thirty year period the capital and monitoring costs on the basis of Table 1 would equal about £120 000. This represents a substantial proportion (30%) of the replacement costs. It is therefore essential that the monitoring boreholes are properly designed and located and that the operating costs are carefully controlled if money is not to be wasted.

TABLE 1

Typical annual monitoring costs for a single observation borehole

	£
Sample collection and storage	150
Chemical analysis - one full analysis per year and limited analysis quarterly	200
Interpretation and storage of data	<u>180</u>
	530

## MONITORING AND SAMPLING SYSTEMS

For large-scale regional monitoring, pumped boreholes which effectively 'average' over a substantial volume of aquifer are superior to any other source. The very fact that samples are averaged over comparatively large intervals however means that they may be unsuitable for more detailed surveillance. Flow-cells with sensors connected in parallel with the discharge main will, if necessary give continuous pH, temperature, dissolved oxygen, and conductivity recording.

Sampling from pumped boreholes however is not without its problems. Shorter-term changes may occur as the stored water within and around the well is abstracted (refs 14-16) (Fig. 4). If this is not understood fully, false quality data may be collected leading to wrong conclusions and incorrect actions. Some of the early short-term changes during pumping are due to the effects of chemical interaction or microbiological activity occurring during stagnation of the water column within the well. Changes also often occur as the effects of delayed drainage take place (ref. 17) as the radius of influence extends, or as the inflow from the contributing aquifers adjusts to the new pressure distribution.

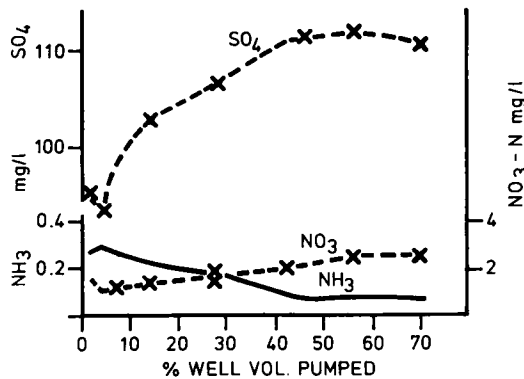


Fig. 4. Variations in concentration during pumping for three constituents of groundwater (after Colchin *et al.* (ref. 15) 1980).

Boreholes which are drilled mainly for water level measurement are normally open over a considerable depth interval. These are traditionally sampled by bailing and many virtually useless groundwater quality data have been and continue to be collected from boreholes in this way. Many types of simple bailer have been designed but these do not get over the fundamental problems (ref. 18) Pumping from such holes is often difficult because of their small diameter but is increasingly being done.

A variety of hand-operated 'thief'-type samplers are also used to obtain both single conventional samples and so-called 'depth' samples. The significance of

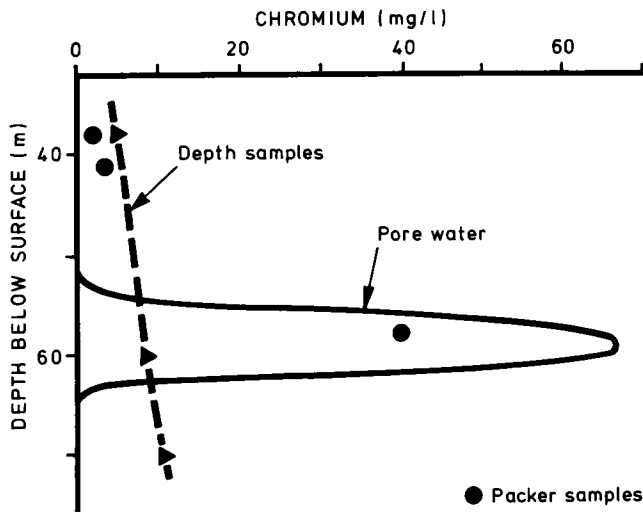


Fig. 5. Comparison of chromian concentrations collected using depth sampling, pore water samples, and packers from a borehole adjacent to a landfill site.

such samples is extremely equivocal because of stagnation effects or possibly because of substantial flow in the borehole. An example taken from a landfill site containing chromium wastes is given in Fig. 5. The existence of an open borehole distorts the natural groundwater system especially where vertical hydraulic or chemical gradients are large.

There are techniques available however which make it possible to overcome many of these drawbacks and these are:

- i) piezometer points
- ii) pore water extraction
- iii) inflatable packer sampling
- iv) 'in-situ' sampling.

Observation boreholes can be drilled and screened over selected narrow intervals but the cost of screen and blank casing may be high. A lower cost installation which also allows sampling over a selected depth interval is the small-diameter (37-50 mm) gauze-covered piezometer point or a ceramic unit. Circulation within these boreholes and access of air and light are reduced to a minimum which are definite benefits. The small diameter however makes sampling difficult particularly if the depth to the water table is large and does not allow suction sampling. Numerous variants of the piezometer installations have been developed for application in different hydrogeological conditions.

The analysis of pore water from core samples taken from the saturated and unsaturated zones of an aquifer requires the use of a destructive method of sampling but offers the most detailed information provided core recovery is good (ref. 19). The interstitial water quality can provide an essential insight into groundwater stratification, but the real significance of results can only be assessed fully when the 'fracture'-flow component is also known. In the Chalk of the UK, for example, the extremely fine grain-size of the rock makes intergranular flow virtually insignificant by comparison with the fracture component. However this is an extreme case and in poorly indurated sands and gravels which are less susceptible to fracturing, the best picture of groundwater quality conditions is given by the pore water quality distribution. The main drawback to the use of pore water from cores is that it is destructive and hence costly to carry out and even more costly to repeat. Its role is therefore limited to research.

In the oil industry sampling from between inflatable packers is widely used. The transfer of this technology in a sufficiently inexpensive form for the water industry has not been entirely successful though there are a few examples where it has been applied experimentally (ref. 20,21). At the Water Research Centre, a gas-operated ejection pump has been used successfully. The method offers a comparatively low rate of pumping which causes minimal disturbance within the aquifer and reduces the risk of drawing water past the packers.

Various in-situ suction samplers for the unsaturated zone have been developed (ref. 22-24). A similar device suitable for in-situ sampling below the water table has been successfully developed at the Water Research Centre, and several units may be sealed into a borehole at selected intervals and samples of water ejected by means of compressed gas (ref. 25). The units have been modified to allow depth-sampling from open holes.

All the methods described have been concerned with recovery of samples for chemical analysis. For microbiological analysis special sampling problems exist. In addition to the strict observance of container sterilisation procedures the error due to sampling should also be assessed in the laboratory (refs 26,27). Some of the drawbacks in using ceramic filters in piezometers or suction lysimeters for microbiological sampling also apply to certain inorganic constituents (ref. 28). Sampling for dissolved gases requires special sampling devices (ref. 29).

#### SYSTEM OPERATION

The operational aspect of groundwater monitoring can be considered in terms of

- (a) initial assessment, usually involving frequent sampling and a wide range of analysis,
- (b) long term surveillance during which the aim should be to reduce sampling and analytical costs to a minimum while meeting the objectives of the programme.

The initial assessment generally lasts for a full year. Sampling frequency must depend on the variability of groundwater quality with time. In setting up the monitoring programme the rate of variability is unknown and must be determined. Short intervals between sampling visits are therefore necessary. For most purposes monthly sampling would suffice as the rate of groundwater flow is usually very slow. This is not the case in many low specific yield aquifers however, especially those with coarse macropermeability, or where the unsaturated zone is very thin. In such situations special monitoring schedules may be required, possibly linked to major recharge or contamination events.

The selection of the determinands must depend on the objectives of the monitoring programme but often a standard 'groundwater' analysis, including the usual field determinations, will suffice. It may also be necessary to measure determinands which do not fall within the standard analysis. This will be the case particularly when monitoring a source of pollution: for example a landfill site may contain heavy metal wastes and the range of determinands would need to be extended accordingly.

On the basis of the variability established during the initial monitoring phase the appropriate long-term sampling and analytical requirements can be specified. The rule should be to go for simplicity and to minimise costs. It may be possible to reduce the number of analyses by selecting a single 'indicator' constituent for observation, or even better by making simple electrical conductivity measurements as a guide to total dissolved solids. More complete analysis should be carried out annually or even less frequently.

Where specific contaminants are known to exist these have to be identified but in many cases an 'indicator' constituent is adequate, e.g. boron may be used to identify sewage and TOC for organic contaminations.

Quarterly sampling is generally adequate for long-term monitoring. Much more frequent, or even continuous, monitoring may be needed for 'defensive' systems such as for public water supplies, or 'offensive' systems as used for the surveillance of hazardous wastes or other major sources of pollution.

Special considerations should apply to monitoring organic contaminants particularly trace organics and micro-organisms. For the former, TOC will not be an adequate indicator. Concentrations may be so low as to require GC/MS/DP techniques for initial identification though subsequent routine monitoring may be carried out using GC alone. There are special problems with micro-biological monitoring, which are beyond the scope of this paper, but systems should take into account the fact that their migration in porous or even fissured media is small. A deterioration in water quality can usually be used to indicate the risk of microbiological pollution, although virus desorption caused by rainfall recharge is an example of a possible inverse relationship between the two (ref. 30).

There are four phases in the production of groundwater quality data;

- (a) emplacement of sampler,
- (b) production of the sample,
- (c) storage of sample and preparation for analysis, and
- (d) analysis.

The errors associated with each stage are difficult to evaluate but it is clear that the cumulative error may be very large. Summers (ref. 31) has shown that significant errors can occur during analysis but when compared with those occurring elsewhere in the sampling 'chain' these are relatively small and very high accuracy in the chemical analysis would appear to be unnecessary. The cost of analysis is the main item in the operational costs and furthermore these are very sensitive to the limit of detection and the precision asked for; doubling the accuracy can more than double the cost. Despite this a specification of almost meaningless analytical accuracy is commonly requested and this represents a considerable waste of money. In any event the comparative changes or trends may be more important in monitoring than absolute values.

Too often both the choice of determinands and the frequency of sampling is decided during the first phase of the investigation and marches on unmodified. Important events may be missed because the frequency is too sparse or money may be wasted unnecessarily because of an unduly intensive programme. A continuous review of the results is needed and the programme must be periodically modified in the light of this.

#### CONCLUSIONS

All too often boreholes for sampling groundwater quality are badly designed and distributed and the data obtained is not subjected to a critical review. The simple checklist given below will help to overcome such problems.

- 1 Clearly identify the objectives of the monitoring programme. Are they designed to establish background water quality, 'defensive' monitoring (e.g. water supplies), 'offensive' monitoring (e.g. pollution sources such as landfills) or research.
- 2 Assess the economic value of the differing uses of the aquifer, e.g. water supply, waste disposal and others. Evaluate the cost penalty resulting from different courses of action and include the groundwater monitoring costs in the economic analysis.
- 3 A pre-requisite of any monitoring scheme must be to obtain as full an appreciation as possible of the geology and hydrogeology of the area. This should include an assessment of base-line groundwater quality. A conceptual picture of the spatial and temporal distribution of polluting inputs to the system must be made.

- 4 Critically evaluate existing monitoring wells in terms of their location, construction and method of sampling.
- 5 Review and modify if necessary the frequency of sampling and specification for the range and precision of the chemical, microbiological and other analysis. Examine the data storage, retrieval and dissemination system.
6. New monitoring systems should preferably be established in a number of phases so that data used in the planning of successive phases is progressively improved.
- 7 A new system should be subject to a detailed assessment over a twelve month period following its installation. On the basis of the variability established during the initial monitoring phase the appropriate long-term sampling and analytical requirements can be specified. The aim should be to go for simplicity in the monitoring system and to minimise costs.
- 8 The engineer or scientist concerned with the interpretation of the data must have sufficient confidence in it to be able to present it on a regular basis to the 'decision maker'. The data should be in an easily understood format and highlight any trends.

#### REFERENCES

- 1 C.R. Meinardi, Characteristic examples of the natural groundwater composition in the Netherlands. Proceedings of the Committee for Hydrological Research TNO Report No. 21 (1976)106.
- 2 J.A. Frizzola and J.H. Baier, Contaminants in rainwater and their relation to Water Quality Part II. Water and Sewage Works, September, (1975) pp.94-95.
- 3 L.N. Plummer, Defining reactions and mass transfer in part of the Floridan Aquifer. Water Resources Research 13:5(1977)801-812.
- 4 W. Back, Hydrochemical facies and groundwater flow patterns in the Northern part of the Atlantic Coastal Plain. U.S. Geol. Survey, Prof. Paper (1966)438-A.
- 5 E.R. Henningsen, Water diagenesis in lower Cretaceous Trinity Aquifers of Central Texas, Baylor Geological Studies, Bulletin No. 3 (1962)
- 6 F.W. Schwartz and K. Meulenbachs, Isotope and Ion Geochemistry of Groundwaters in the Milk River Aquifer, Alberta. Wat. Res. Research 15:2(1979)259-268.
- 7 D.M. Keady, Application of selected statistical methods to the study of the Chemical Quality of Water in the Woodbine Aquifers of Texas. Texas A & M University, PhD. Thesis, Dept of Geology (1970)103 pp.
- 8 O.A. Alpay, Application of aerial photographic interpretation to the study of reservoir Natural Fracture Systems. Jnl of Pet Tech, Jan (1973)37-45.
- 9 R. Stone and J. Snoeberger, Orientation and areal hydraulic anisotropy of a Wyoming Coal Aquifer. Groundwater 15:6(1977)434-438.
- 10 G.H. Wagner, K.F. Steel, H.C. McDonald and T.L. Coughlin, Water Quality as related to linears, Rock Chemistry and Rainwater Chemistry in limestone terrain. J. Env. Quality 5:4(1976)444-451.
- 11 L. Clarke and N.S. Howard, Investigations into pollution at the Clears pumping station Water Research Centre. LR 982(1980)10 pp.
- 12 W.A. Pettijohn, Monitoring cyclic fluctuations in groundwater quality. Ground Water 14:6, (1976)472-494.
- 13 V.V.J. Sarma, N.V.B.S.S. Prasad and P.R. Prasad, The effect of hydrogeology on variations in the electrical conductivity of groundwater fluctuations. J. Hydrol 44(1979)81-87.
- 14 J.M. Marsh and J.M. Lloyd, Details of hydrochemical variations in flowing wells. Ground Water 18:4(1980)366-373.

- 15 M.P. Colchin, L.J. Turk and M.J. Humenick, Sampling of groundwater-baseline and monitoring data for in-situ processes. University of Texas, Centre for Research in Water Resources: Tech. Rept. EHE78/01, CRWR - 157 (1978)121.
- 16 H.I. Nightingale and W.C. Bianchi, Well-water quality changes correlated with well pumping time and aquifer parameters-Fresno, California. *Ground Water*, 18:3(1980)274-280.
- 17 K.J. Edworthy, D.A. Stott and W.B. Wilkinson, Research into the effects of artificial groundwater recharge, Lee Valley, London, England. *Wat. Res. Bull.*; 14:3(1978)554-575.
- 18 R.F. Spalding, M.E. Exner and J.R. Gormly, A note on an 'in-situ' groundwater sampling procedure. *Wat. Res. Research*. 12:6, 1319-1321.
- 19 W.M. Edmunds and A.H. Bath, Centrifuge extraction and chemical analysis of interstitial waters. *Environmental Science and Technology*; 10(1976)467-479.
- 20 M. Price, A.S. Robertson and S.S.D. Foster, Chalk permeability - a study of vertical variation using water injection tests and borehole logging. *Water Services*, Oct. (1977)603.
- 21 C. Barber, P.J. Maris and N.C. Blakey, Borehole packers for sampling groundwater from narrow stratal intervals in Triassic sandstone and Chalk aquifers. *Water Research Centre*, LR 802, (1978)16 pp.
- 22 G.H. Wagner, Use of porous ceramic cups to sample soil water within the profile. *Soil Science* 94(1962)379-389.
- 23 R.R. Parizek and B.E. Lane, Soil water sampling using pan and deep pressure and vacuum lysimeters. *J. Hydrol* 11(1970)1-21.
- 24 W.W. Wood, A technique using porous cups for water sampling at any depth in the unsaturated zone. *Wat. Res. Research* 9:2(1973)486.
- 25 K.J. Edworthy and S.L. Brown, 'An 'in-situ' groundwater sampling device'. *Water Research Centre. Laboratory Report No 611*(1976).
- 26 De Shin Wang, J.C. Lance and C.P. Gerba, Evaluation of various soil water samplers for virological sampling. *Applied and Env Microbiology* 39:3(1980)662-664.
- 27 W.J. Dunlap, J.F. McNabb, M.R. Scalf and R.L. Cosby, Sampling for organic chemicals and microorganisms in the subsurface. U.S. Environmental Protection Agency; Report No EPA - 600/2 - 77 - 176, (1977)28 pp.
- 28 E.A. Hansen, and A.R. Harris, Validity of soil water samples collected with porous ceramic cups. *Soil Sci. Am. Proc.*, 39(1975)528-536.
- 29 E. Brown, M.W. Skougstad and M.J. Fishman, Methods for the collection and analysis of water samples for dissolved minerals and gases, U.S.G.S. *Techniques of water resources investigations*, Book 5, (1970)160 pp.
- 30 J.C. Lance, C.P. Gerba and J.L. Melnick, Virus movement in soil columns flooded with secondary sewage effluent. *Appl. Environ. Microbiol.* 32(1976)520-526.
- 31 W.K. Summers, Factors affecting the validity of chemical analyses of Natural Water, *Ground Water* 10:2(1972)12-17.