Groundwater Quality Monitoring in Relation to On-site Sanitation in Developing Countries

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ABSTRACT

Groundwater quality monitoring is considered to be an essential component of any sanitation programme where simultaneous groundwater abstraction and on-site waste disposal are proposed. The low priority currently accorded to monitoring programmes reflects inexperience of monitoring in general and consequent misconceptions about the content and benefits of groundwater quality monitoring.

The purpose of this paper is two-fold. Firstly to explain why groundwater quality monitoring is a requisite component of all pilot sanitation projects which involve on-site disposal of human excreta. Secondly, to demonstrate that it is not unrealistic to expect groundwater quality monitoring to be carried out in relation to all such pilot projects.

The resource constraints inherent in developing countries need not prohibit routine monitoring. However, it is important to define clearly the specific objectives of any monitoring programme and to design a sampling network appropriate to both these objectives and the site conditions. Monitoring must not be confused with initial assessment of prevailing conditions, nor with research studies, for which the aims, duration, technical complexity, and hence investment, are quite different.

Monitoring is a process which can evolve with increased investment to address various questions regarding the causes, nature and processes of groundwater contamination.

Keywords: Groundwater pollution; monitoring; sanitation; pit latrines.

THE CONTEXT

The real goal of the International Drinking Water and Sanitation Decade (1981–1990) is to improve public health by a reduction in water and excreta-related diseases. The first half of the Decade has seen considerable progress towards the specified goals of providing clean water and adequate sanitation for all, at least in terms of numbers of water supply and sanitation units installed. Unfortunately the anticipated health benefits have not always automatically followed improved service provision. There are two reasons for this which both reflect the lack of understanding of the relationships between excreta, contaminated water and disease. The need for simultaneous health education programmes, with an emphasis on hygiene, has been emphasized often[1] and this paper draws attention to the potential clash between the otherwise appropriate technical solutions for water and sanitation provision.

Undoubtedly groundwater provides the solution to the Decade's water supply problem whilst unsewered disposal systems, principally ventilated improved pit latrines (Fig. 1) and pour-flush latrines (Fig. 2), provide the only affordable technical solution to the sanitation problem. However, such latrines inevitably impose a pollution hazard to groundwater resources. Their performance depends primarily on the ability of the soils and rocks, in which the pits are excavated, to accept and purify the effluent. The effluent infiltrates the ground beneath the latrine pit and sooner or later percolates to the water table. To those who understand the link between excreta, water and disease, the possible consequences of constructing water wells and latrines in close proximity are obvious. Hence all on-site sanitation programmes should be monitored with regard to their effects on the quality of the underlying groundwater wherever this is used, or is likely to be used, for any purpose. Otherwise inadvertent contamination of groundwater supplies and a consequent worsening of community health may be experienced.

THE NEED FOR MONITORING

The tacit assumption fundamental to all sanitation programmes is that they will lead to an improvement in public health. Groundwater quality monitoring is necessary to ensure that this is indeed the case.

The fear of groundwater contamination by pathogen-rich effluent is in some places impeding sanitation programmes. Rather than adopt the low-cost option of on-site sanitation, authorities are continuing to advocate sewerage; the latter is much more expensive but is felt to offer a 'safer' solution.

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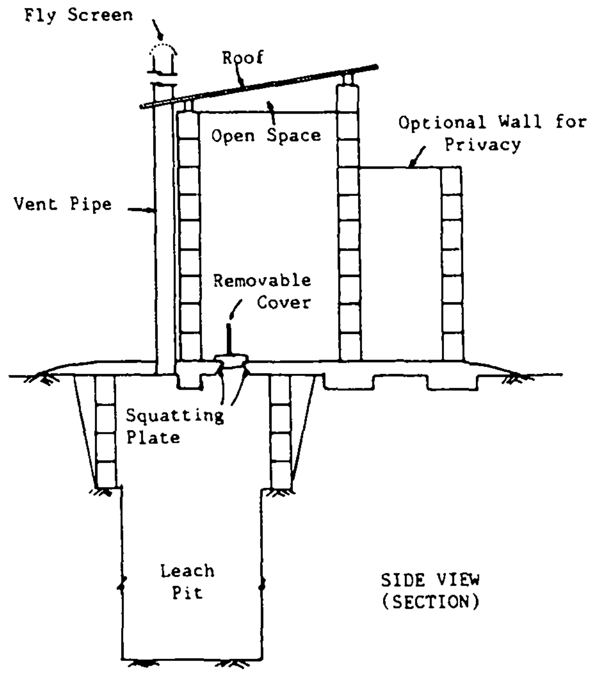

Fig. 1. Ventilated improved pit latrine
(Adapted from Kalbermatten et al, 1980[2])

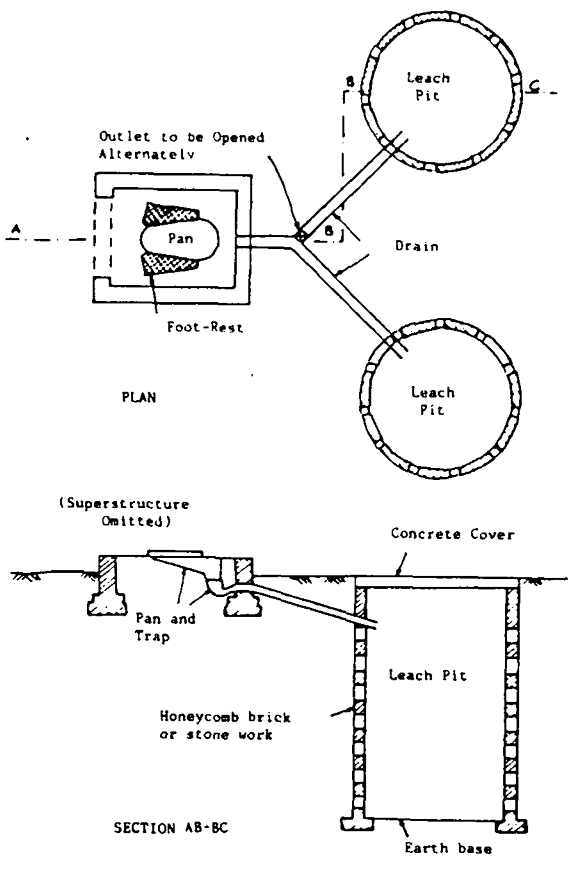

Fig. 2. Pour-flush latrine
(Adapted from Drawing No 5, Annex 2, TAG – India, 1982[3])

Yet, unless groundwaters are extremely shallow, on-site systems offer a viable alternative, provided a complementary monitoring programme is implemented.

Research studies[4] suggest that in certain hydrogeological environments, notably where fine-grained unstructured loams attain a thickness of at least 3 m above the water table, pollutant attenuation is rapid and the risk of groundwater contamination minimal. The temptation to presume that new sanitation arrangements will not cause groundwater pollution in such environments is great. However, insufficient is known about the processes of pollution attenuation under field conditions to be able to say categorically that there will be no pollution of the groundwater. Also groundwater movement is highly dependent upon local ground conditions and so pollution problems are site specific. The only way of knowing whether a sanitation installation is a potential groundwater pollution hazard, and consequently a health hazard, is by monitoring the environmental effects of the system.

Monitoring Objectives

Monitoring may be carried out with a view to detecting, predicting and preventing groundwater pollution. The initial objective is to detect and measure the environmental effects of on-site sanitation. Early detection and monitoring of contaminant travel may enable prediction of groundwater pollution. Consequently it may be feasible to prevent on-site sanitation systems from polluting groundwater sources (for example by modifying the design of the latrine or relocating water supply sources).

The effectiveness of any monitoring programme depends on the design of the monitoring network, particularly on the location of sampling points and on informed interpretation of the analytical results. These factors will vary according to the resources allocated to the monitoring programme, and broadly speaking returns will increase with investment. The limitations of the network design must always be acknowledged. For example, it will not usually be possible to predict the extent of groundwater contamination from a monitoring network designed for the specific purpose of detecting the presence of contaminants in the immediate vicinity of the latrine pit.

Monitoring programmes may be carried out for different reasons in different localities and in any one locality the purpose of monitoring may change with time. It is crucial to decide upon the precise objective of any monitoring programme so that resources can be used most effectively and results viewed in the proper context. Thus the deliberation is not whether monitoring should proceed but rather which objective the monitoring programme should aim to fulfil.

The Outcome of a Monitoring Programme

The desired outcome of a monitoring programme is to confirm the absence of pollution. Ironically a preponderance of negative results leads to a general reluctance to invest in a monitoring network. These negative results, however, offer the go-ahead for further sanitation and water supply installations throughout the hydrogeological region. On the other hand, where pollution is detected emanating from a sanitation installation, some action must be taken to ensure that water supplies remain uncontaminated and pathogen free.

The ultimate purpose of monitoring the quality of the groundwater is to ensure that potable water supplies do not deteriorate in quality unheeded and that we do not inadvertently move further away from the Decade's goal that all people should have reasonable access to an adequate water supply.

GROUNDWATER QUALITY MONITORING – A REALISTIC SUGGESTION?

In practice, routine water quality monitoring is rarely undertaken, although the idea receives nominal support. The purpose of this section is to examine why this is so, and to present a more positive stance.

Reasons for the Lack of Groundwater Quality Monitoring

Reasons proffered to explain the absence of monitoring programmes vary between admission that monitoring has never been contemplated to conviction that monitoring is unnecessary as the results are predictable. The factors which together account for an almost total lack of groundwater quality monitoring in sanitation programmes are summarized below:

(i) lack of government funding
(ii) priority given to latrine construction
(iii) unwillingness on the part of organizations to assume the responsibility
(iv) absence of formal requirement or legal obligation
(v) no experience of monitoring
(vi) lack of technical resources
(vii) absence of a reported appropriate methodology
(viii) benefits difficult to quantify nor immediately apparent
(ix) general ignorance about groundwater
(x) complacency due to apparent 'pure' quality of groundwaters

A More Positive Stance

Many of the excuses for neglecting to promote *groundwater quality monitoring* as a desirable activity commonly evolve from misconceptions about the nature of groundwater monitoring. Monitoring procedures need not be highly sophisticated; they can be simple and yet effective and need not involve great expense. The basic requirements are a monitoring network which should incorporate springs, existing pumped groundwater sources, and purpose-built sampling installations located between water supply points and sanitation units. Samples should be analysed for indicators of pollution, notably faecal coliforms, faecal streptococci and nitrate concentrations. A site investigation should be carried out to ascertain the local hydrogeology (including soil type and depth to water table), the existing water supply and sanitation arrangements, and other possible sources of pollution. The components of a monitoring network and an effective monitoring programme are described fully elsewhere[5].

The following paragraphs demonstrate that it can be feasible to conduct an effective monitoring programme even where resources are scarce:

(*a*) A monitoring network and programme should be designed according to the resources available. Expenditure can be minimized by making full use of existing resources. For instance, spare laboratory capacity may be utilized and existing wells and boreholes modified for water table observation and sampling purposes: local academic or research institutes may have laboratory facilities and staff who could carry out the field sampling programme and/or laboratory analysis of water samples.

(*b*) Monitoring can be limited to selected areas. Initially monitoring may be confined to just one or two settlements in each hydrogeological region. The total cost to the organizing authority is therefore small in relation to expenditure on the latrine construction programme. However the cost does have to be borne by a central body or local government authority rather than by individual latrine or water supply owners. Monitoring could be made a condition of central funding or aid.

(*c*) The benefits of monitoring must be seen to outweigh the costs for investment to be encouraged. These benefits are difficult to quantify but include:
   (i) increased confidence in sanitation improvement programmes as a means of improving public health;
   (ii) guarantees of safe groundwater supplies (contaminated water can be treated prior to consumption or polluted sources abandoned);
   (iii) modification to design or location of new water supply and sanitation facilities to prevent contamination of groundwater supplies.

(*d*) If, as is often the case, water supply, sanitation and public health are respectively the concern of three or more separate government departments, then one department must assume responsibility for environmental monitoring in relation to sanitation. It may choose to function in an advisory or co-ordinating capacity and sub-contract various aspects of the monitoring work to appropriate organizations.

(e) Monitoring can be conducted at different levels of sophistication: it need not demand previous experience or technical expertise. A monitoring programme can be upgraded as experience is gained: this should be borne in mind when the monitoring programme is first planned.

(f) A methodology is needed which allows resource constraints to be accommodated in the design of an appropriate monitoring network and programme. Most of the literature pertaining to groundwater monitoring is in relation to major waste disposal sites and monitoring of tip leachate where resources (money, expertise, manpower, laboratory and back-up facilities) are not significantly limited. Monitoring in the developed countries is often intensive at such sites. There is less routine monitoring from dispersed pollution sources although the problem of nitrate contamination resulting from certain agricultural practices is a topic of current research. Most monitoring methodologies are therefore inappropriate in the context of on-site sanitation programmes in developing countries. A document which outlines an appropriate methodology is now available[5].

(g) There is a need for more education about groundwater in general and in particular about groundwater movement and the behaviour of pathogens and chemical contaminants in both saturated and unsaturated soils and rocks. This education should be encouraged by in-service training and by better availability of easily understood literature.

WHAT IS 'MONITORING'?

The following section attempts to clarify what is involved in monitoring and to distinguish this activity from one-off data collection exercises and more capital-intensive research projects. By breaking down the monitoring process into conceptually more manageable tasks it is demonstrated that a low-cost monitoring programme can be effective and also that this can be up-graded to meet additional objectives.

Where groundwater is used for domestic purposes and sanitation schemes which involve on-site waste disposal are proposed or implemented, the following questions are often posed:

(i) Are existing sanitation units causing pollution of currently used water supplies?
(ii) Does on-site sanitation represent a pollution hazard?
(iii) What is the 'safe' distance between a groundwater supply point and a sanitation unit, and what are the criteria which determine that safe distance?

Although these three questions all imply a common purpose, that is to ensure that groundwater supplies do not become polluted as a result of sanitation provision, each question necessitates a markedly different type of field study. The first question can be answered by a one-off study which may be completed within, say, four to six weeks. The third question warrants carefully controlled research studies in which site conditions, especially the hydrogeology, are thoroughly examined and in which the performance of variously designed latrine pits may be tested. Monitoring primarily addresses the second question and encompasses the first: monitoring can focus on both the effect of the sanitation unit and the response of the groundwater in order to evaluate the pollution hazard of on-site sanitation.

Each of these three types of study is different in terms of its aims, focus, duration, intensity, technical complexity and observation network design. Consequently the costs and effectiveness are different for each. Table I summarizes these various aspects for each type of investigation, thereby drawing the distinction between them.

It is important to recognize these differences if expectations are to be satisfied by conducting only one type of study. The limitations of each type of study, as well as the benefits which might accrue, must be made clear at the outset. Otherwise it is unlikely that a second similar study will be initiated elsewhere.

In particular it must be realized that a short duration investigation (Table I, Column 2) is not a substitute for a proper monitoring programme. The former may not indicate the extent of groundwater pollution and it must be recognized that negative results do not necessarily mean that the aquifer is free from faecal contamination. There is no attempt to evaluate the pollution hazard of on-site sanitation nor to monitor the performance of the soil in terms of pollution attenuation, nor to assess pollution variability with time. Rather such an investigation may offer a starting point for authorities who have had little or no experience of the techniques of monitoring and who are therefore uncertain how to proceed with a comprehensive monitoring programme.

The Monitoring Process

Monitoring is a process whereby a sequence of questions can be solved. A comprehensive monitoring programme attempts to establish the following:

(a) the background groundwater quality
(b) the nature of the pollution hazard, both the chemical and microbiological threat
(c) the general directions of pollution movement
(d) the extent and three-dimensional shape of the pollution plume
(e) whether a steady-state has been attained or whether pollution is still spreading
(f) whether there is any explicable variation in pollution with time, due for example to seasonality of climate or latrine usage.
(g) pathways of pollution, such as may be afforded by fissuring in soils and rocks (see also (k))
(h) velocities of groundwater flow and pollutant travel
(i) cause(s) of pollution in relation to the design and usage of the sanitation unit, for example, hydraulic loading

TABLE IA. Three Types of Investigation: Characteristics

Type of investigation	Monitoring programme[5]	One-off short duration investigation[6]	Research project[7]
Aims	to monitor spread of contaminants	to assess current contamination of water supplies	(a) to establish pollution processes and rates for different soils and rock types. (b) to evaluate leach pit design.
Focus	(a) sanitation units (b) groundwater sources	groundwater sources	(a) aquifer (b) sanitation units
Duration	permanent: minimum 3 yrs	temporary: 1–3 months	long-term
Intensity of activity	low	high	initially high, decreasing with time.
Study area (minimum)	2 km^2	urban: 0.5 km^2 rural: all water supplies	local: defined by project objectives
Observation network components (minimum)	i) rain gauge ii) permanent groundwater level observation boreholes iii) protected & purpose-built groundwater sampling points	i) 3 temporary observation boreholes ii) existing protected, pumped sources iii) temporary groundwater sampling points	as for monitoring but higher density of sampling points
Pollution indicators monitored (in order of priority)	faecal coliforms faecal streptococci nitrate chloride temperature electrical conductivity ammonium nitrate iron others as appropriate	faecal coliforms nitrate faecal streptococci chloride electrical conductivity (temperature)	faecal coliforms faecal streptococci nitrate chloride others as appropriate

(j) other possible sources of pollution
(k) details of site conditions, especially the hydrogeology, including, for example, details of soil and rock textures, structures and moisture content (see also (g))

This breakdown of the monitoring process suggests it should be possible to implement a monitoring programme in three stages. The first stage aims to determine the nature and extent of any pollution. The second step is to determine the mechanisms, or process, of groundwater pollution and the third is to identify the cause, or causes, of pollution. Table II summarizes the aims and possible outcome of each monitoring phase.

TABLE IB. Three Types of Investigation: Costs and Effectiveness

	Monitoring programme	One-off short duration investigation	Research project
Degree of sophistication	medium	low	high
Costs	medium	low	high
Application of results	extrapolated to hydrogeologically similar regions	*cannot* be extrapolated to other sites	ultimately enabling pollution prediction in all environments
Benefits	• pollution identification • pollution prediction • remedial action enabled • improved planning and design of sanitation and water supplies	• detection of contaminated water supplies • immediate effective intervention • need for monitoring highlighted	• understanding of polluting process • improved sanitation design • improved guidelines for sanitation programmes.

TABLE II. Three Monitoring Phases

Stage	Purpose	Questions addressed (see page 298)	Resultant action
I	To determine NATURE and EXTENT of pollution	a–d	Identify polluted water supplies – prevent use of source, or treat. Identify sources under threat of imminent contamination – monitor supplies closely.
II	To determine MECHANISMS or PROCESSES of groundwater pollution.	e–h	Identify hydrogeologically similar zones. Modify usage of latrines. Possibly modify water supply sources (e.g. deepen boreholes).
III	To identify the CAUSE(S) of groundwater pollution	i–k	Modify latrines and/or water supply design. Eradicate other sources of pollution. Transpose results to other sites with same ground conditions.

It is quite possible to initiate a monitoring programme to satisfy the requirements of phase I only. Once this level of monitoring has been established some of the other constraints on monitoring (listed previously) may be removed; for example an awareness of the value of monitoring and familiarity with the basic techniques may lead to a desire on the part of those involved to extend the monitoring programme to include phase II and ultimately phase III.

As the monitoring study increases in complexity so it should provide a more thorough understanding of the processes and causes of groundwater pollution. As far as possible the benefits should be proportional to investment for each phase. If additional investment needs to be disproportionately high, for example to accommodate sophisticated sampling equipment or more skilled personnel, then it may be unrealistic to expect this to be done routinely; rather the study may be enhanced and treated as a research project.

CONCLUSIONS

Unsewered sanitation offers the only affordable technical solution for improved waste disposal in many parts of the developing world and it is not the intention of this paper to discourage the use of on-site sanitation systems. Indeed, in some hydrogeological environments the capacity of the soil to attenuate microbiological pollution suggests that much more use might be made of such systems.

The message of this paper is rather to proceed with caution and continually check that on-site sanitation systems are not causing the groundwater to be contaminated. Groundwater quality monitoring is essential for the protection of groundwater and is not beyond the means of the developing countries. Monitoring programmes and networks can be designed within the resource constraints wherever sanitation facilities are introduced or upgraded.

To be effective, groundwater quality must be monitored from the outset of any sanitation programme. The developing world cannot afford to follow the example of the developed world where groundwater pollution has so often been a prerequisite for monitoring exercises. Groundwater offers the only real solution to the problem of the world's water supply, and the quality of this valuable resource must be preserved.

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DISCUSSION

Mr M. F. G. Archer (Howard Humphreys & Partners) asked what were the main objectives of monitoring? Were they to build up data for design purposes or to monitor outgoing conditions to indicate the need for action to be taken to reduce or avoid pollution? He wondered if there was not a pressing case for much more research to be carried out so that the siting and design of sanitary facilities might be more properly carried out to ensure minimum pollution potential. He wondered if we could even end up with computer models to enable designs to be carried out with little site investigation.

Mr R. B. Armstrong (Southern Water Authority) said that relief organizations such as WaterAid aimed to install facilities in communities on the basis that these would enable the people to help themselves. Even if monitoring facilities were included, were the local people sufficiently expert to be able to interpret the results?

It seemed to Mr Armstrong that the responsibility for monitoring programmes should rest with those in charge of the water supplies rather than those installing latrines. An understanding of the local hydrogeology was important if the monitoring programme was to achieve any benefits, and it was more likely that this understanding would be confined to those who looked after water supply.

Mr J. Chandler (Southern Water Authority) asked what action the author foresaw if monitoring revealed a problem in a third world village. He also wondered if it would be better to concentrate resources on protecting water supplies and providing piped water. He asked what the author's priority would be for spending aid money?

Dr I. Fox (Southern Water Authority) asked whether, in the situation of a poorly co-ordinated monitoring programme administered by reluctant officials and carried out by technicians using imprecise field test kits, the author would feel that there was a danger of misinterpreting the source of any detected pollution, given that background data on water quality would probably be lacking.

Mr K. Guiver (Southern Water Authority) asked whether it was the best tracers possible that were proposed as part of the monitoring, insofar as mention was made in the paper of faecal coliforms and nitrate concentrations. Tracers should, if possible, be closely associated with the source of pollution being monitored, should travel maximum distances from the source of pollution without modification, and there should be no secondary source of the tracer to confuse the issue when they were found. The tracers should also be easily measured. With regard to faecal coliforms, it seemed highly likely that there would be other sources around monitoring boreholes, from which they might be detected. Nitrates could also arise from secondary sources and in particular from the application of any fertilizers. Was it not possible that ammonia would be a better tracer, whilst recognizing that aerobic soil conditions and the presence of the correct bacteria would convert that ammonia to nitrate as it moved away from the pollution source?

It also seemed that there would be a danger in the monitoring proposals if the analyst regularly found zero concentrations of the tracers, and thus tended to lose interest in the whole scheme intended to alert the authorities to the movement of pollutants towards water supply boreholes.

Mr S. Puri (Binnie & Partners) asked who, in the author's experience, would be responsible for installation of acceptable monitoring wells, collecting the data from them, analysing it, and then taking appropriate action.

Mr J. Wild (Binnie & Partners) said there had been a lot of discussion about guidelines on distances between wells and latrines. A more important aspect was the depth between the base of the latrine pit and the groundwater table. It was also important to be aware of the likely seasonal fluctuation of the groundwater table.

Author's Reply

The author, in reply to Mr Archer, said that the immediate objective of monitoring was to anticipate contamination of water supply sources and so prevent consumption of contaminated water. This was achieved by positioning sampling wells between sanitation systems and groundwater sources, bearing in mind the groundwater gradient which determined the direction of groundwater movement. Closer monitoring of ground pollution adjacent to latrine pits might suggest conditions in which design modifications were desirable. A piecemeal approach to latrine installation might mean that this second type of study was the more appropriate.

Ms Ward agreed with Mr Archer that there had so far been very little research relating leach pit design with performance. The prerequisite for the application of model results in the form of a classification of hydrogeological environments in relation to pollution risk was currently lacking. Until that was resolved, pollution problems and their solutions remained site specific, hence the need for more monitoring.

In reply to Mr Armstrong, the author said that people were responsive to the need for monitoring and were willing to take an active part so as to ensure clean water supplies. There was not a dearth of skilled personnel everywhere: local colleges, public health and medical departments might have spare capacity. Field kits made the determination of indicators relatively simple. The problem came back to funding of not only the capital costs but also the running costs of a monitoring exercise.

Currently few bodies accepted responsibility for monitoring the general quality of either surface or groundwater, although the quality of water supply sources might be tested by a water supply or health department. Although some might prefer the 'polluter should pay' principle, the reality of piecemeal sanitation development whereby the population might install their own latrines without reference to a central agency, made it impractical to suggest otherwise. However, in pilot areas, short-term responsibility might fall on the latrine programme. (This also partly answered the question from Mr Puri).

Ms Ward said in answer to Mr Chandler, that appropriate action depended upon the relative quality of alternative water sources and upon the extent of the problem. In the short term, disinfection of the source or boiling water for drinking and food preparation were effective temporary solutions; the latter required intervention in the form of health education. The source of pollution, meanwhile, needed to be confirmed and if possible eradicated. In the long term, supply sources might need to be relocated and supplies reticulated.

In reply to Mr Chandler's other two questions, the author said that since ultimate aspirations were for piped water supplies with multiple in-house connections, it might be that the best technical solution was to accept groundwater pollution and to import and reticulate water from an unpolluted distant source. In this context, aid money should be allocated to packages which combined water supply improvement, sanitation provision and health education: sanitation was ineffective if not used!

Replying to Dr Fox, Ms Ward said that a walk around the area would often reveal many possible sources of contamination; it should not be presumed that on-site sanitation was necessarily the cause of detected pollution. A monitoring network must be carefully designed with this in mind, and background values were required. If, for example, monitoring commenced some time after the installation of latrines, the background values must be obtained from sampling points up-gradient of the sanitation system.

Field test kits were adequate for detecting significant changes in concentration of the specified pollution indicators. Laboratory-based determinations entailed more complicated procedures for sample collection, storage and transportation.

The author said, with regard to Mr Guiver's comments, that faecal coliforms and nitrate concentrations were indicators of faecal contamination. They were relatively easy to determine using field kits. Increasing the number of determinands also increased the cost of routine monitoring. If results were positive, and especially if concentrations were found to be increasing with time, then it might be necessary to analyse for other constituents, such as ammonia or nitrite, in order to prove the source of contamination where this was not apparent from field conditions. Field studies suggested that on-site sanitation would always result in elevated nitrate levels in shallow groundwaters. So, unfortunately, it was extremely unlikely that zero concentrations would be recorded for long.

In answer to Mr Puri, Ms Ward said that her reply to Mr Armstrong had partly covered this question. In India there were State Boards for Prevention and Control of Water Pollution. They were only now beginning to monitor certain surface waters routinely and were focusing on industrial effluent position. With current arrangements it was likely that installation of monitoring wells, data analysis, and subsequent action would be shared between three different government departments, e.g. groundwater, public health, water and/or sanitation, respectively. Responsibility would be dictated by the source of funds.

With regard to Mr Wild's comments, the author said that the most significant factor in reducing microbiological pollution was the residence time of micro-organisms in the unsaturated zone. Research studies suggested that a depth of 2–3 m of fine-graded unstructured soil between the bottom of the leach pits and maximum groundwater levels was adequate to minimize microbiological pollution to acceptable levels. However, due to the natural heterogeneity of soils and the frequency of fissuring and preferential flow paths, this guideline should be followed cautiously. Detailed examination of sub-surface materials should precede a latrine construction programme. Once pollutants reached the water table they would travel in the direction of the groundwater flow much more rapidly. That brought into question the concept of a safe spacing of wells and latrines.