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The pollution hazard to village water supplies in eastern Botswana

W. J. LEWIS, BSc, MIWES*
J. L. FARR, MSc†
S. S. D. FOSTER, BSc, MICE, MIGeol, FIWES†

Concern about groundwater pollution has been aroused by observations in many village water supply boreholes of nitrate concentrations far in excess of recommended limits. A hydrogeological and hydrochemical study in the environs of a selected borehole, aimed at evaluating the causes and mechanisms of pollution, is described. Pit latrines are shown to cause a major build-up of nitrogeneous material in the surrounding soil and weathered rock, from which nitrate is leached intermittently by infiltrating rainfall. Moreover such installations can also present a risk of groundwater pollution by faecal bacteria. The study illustrates the need for integrated planning, based on a sound appreciation of local hydrogeological conditions, when developing low-cost village water supplies and sanitation, if serious new public health hazards are to be avoided.

Introduction

Water supply situation in eastern Botswana villages

During the past few decades there has been a steady improvement in public health throughout eastern Botswana, effected by the drilling of water-supply boreholes,[1] the introduction of low-cost sanitation and the elimination of the use of surface watercourses. Similar conditions exist in the rural population centres of many developing countries, and are the target of the United Nations' development programmes for the 1980s.[2]

2. Groundwater is normally the safest source of untreated potable water in developing countries, but regular monitoring of chemical and bacteriological quality at individual water-supply boreholes is frequently beyond the capacity of local professional and financial resources.

3. Recently many important villages in eastern Botswana were found to have polluted groundwater. A sampling and analytical programme[3] showed the nitrate concentrations in most public water-supply boreholes within urban limits to exceed World Health Organisation drinking water standards: below 100 mg NO_3/l preferable and above 200 mg NO_3/l unacceptable. In certain instances concentrations were grossly in excess of these levels. The problem has been shown to be persistent and widespread.

4. The potential health implication for infants of ingesting excessive nitrate

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* Formerly Geological Survey Department, Botswana, now Loughborough University of Technology.

† Geological Survey Department, Botswana, and Institute of Geological Sciences.

concentrations in drinking water has been a topic of continuing medical attention[4–9] and the possible effects on adults of high nitrate intakes over long periods is a subject of growing medical concern.[10] The presence of high groundwater nitrate concentrations, if derived from organic sources, may be associated with intermittent bacterial pollution and would normally warrant careful monitoring.

Geohydrological setting of eastern Botswana

5. Over most of eastern Botswana the Kalahari sand cover, which mantles the remainder of the country, has been removed by erosion and pre-Cambrian basement formations exposed. Minor aquifers are developed in the weathered zone and/or in the underlying fractured/jointed bedrock. Groundwater movement takes place almost exclusively through any open fissures, which may be sparse because of infilling by clayey weathering products. Groundwater levels are usually relatively shallow (less than 30 m), aquifer transmissivities low (less than 50 m^2/d) and borehole yields small (less than 2 l/s), but with deep cones of pumping depression.

6. Eastern Botswana has an average rainfall of about 500 mm/a and, with thin, albeit clayey, soils and frequent bedrock exposures, diffuse groundwater recharge occurs fairly regularly in most wet seasons (November–March). The region is hilly and there is substantial runoff in (locally influent) ephemeral streams. There are few perennial streams, fed by groundwater discharge.

7. In most areas the chemical quality of unpolluted groundwater is good and the total dissolved solids and chloride concentrations are relatively low.

Scope of research

Methods of investigation and objectives

8. The study was aimed at establishing the causes and mechanisms of pollution of village water-supply boreholes, and at considering possible remedial action. It involved a detailed evaluation of the factors controlling water and pollutant movement in the unsaturated and saturated zones around a selected water-supply borehole.

9. Three investigation/observation boreholes, at 15–25 m radius from the water-supply borehole (Fig. 1), were drilled to about 10 m below the water-table using power augering and air-flush cored rotary or hammer percussion techniques. They were lined with perforated plastic casing and developed by pumping until their discharge cleared. Soil samples were collected at every 0·5 m. A series of auger holes for sampling the soil and weathered rock was also drilled.

10. The main methods of investigation were

(*a*) test pumping of the water-supply borehole, using the existing plant, at a constant rate of 1 l/s, groundwater levels being measured and electrical conductivity/temperature logs run
(*b*) chemical and bacteriological analyses of water samples collected from the saturated zone
(*c*) nitrate and chloride analyses on soil samples
(*d*) chemical tracer experiments.

The timing of the investigations is shown in Fig. 2; most of the analytical work was performed in a field laboratory.

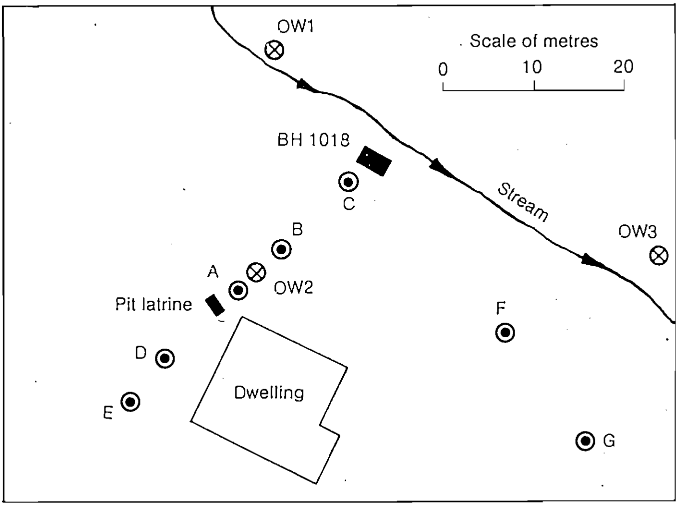

Fig. 1. Detailed site plan

Groundwater conditions in study area

11. Borehole BH 1018 (Fig. 3) was in a major village with a population of about 20 000, had a nitrate concentration of more than 500 mg/l and, until 1977, was the primary source of water for a nearby hospital.

12. The study area is in an embayment of an escarpment (Fig. 4) of Waterberg sandstone and shales and is underlain by talus and weathered Basement Complex granite gneisses. Soils are dark, clayey, 0–3 m thick and grade downwards into weathered rock. The area is transected by a stream which rises in the Waterberg hills and is impounded by a small dam about 150 m upstream of BH 1018. The stream is gaining in its upper reaches, base flow being maintained for some of the year, but in the study area it apparently becomes losing.

13. Pumping test analysis shows the weathered granitic aquifer to have a transmissivity of only 15–20 m^2/d with a storage coefficient of up to 0·01. Some natural or induced recharge from the adjacent stream is present but its proportion must be minor or intermittent because it could not be detected as a boundary in the pumping test.

14. The direction of regional groundwater flow is away from the escarpment, in common with that of the surface drainage, but because of the low aquifer transmissivity is of only small magnitude. The hydraulic conditions and low pumping rate will limit the flow frontage intercepted by BH 1018 to within 100 m of the borehole.

15. A survey of potential pollution sources within a 100 m radius of BH 1018 was made. About one in four households has a pit latrine (a popular and growing form of low-cost sanitation in Botswana), which is normally shared.

16. The area surveyed had 30 pit latrines used by about 200 people. The nearest pit latrine to BH 1018 was 25 m distant (Fig. 1), hand-dug to about 2·5 m deep and floored by weathered bedrock with the local water-table 3·0 m

below its base. It was constructed before the water-supply borehole. Additionally, although outside the 100 m radius of BH 1018, there are about 300 people at the hospital, some of the effluent of which enters the reservoir impounded by the dam; this reservoir overflows into the stream which flows past BH 1018.

Groundwater quality in saturated zone

Hydrochemical

17. The electrical conductivity logs showed the presence of groundwater stratification in observation boreholes OW1 and OW2, with abrupt increases from about 800 $\mu\Omega^{-1}$ to more than 2000 $\mu\Omega^{-1}$ at 6 m and 8 m depth respectively. The groundwater in OW3 had a uniform conductivity of 800 $\mu\Omega^{-1}$. On pumping, the lower conductivity water was depleted and the stratification quickly disappeared. Various pumped and depth samples were collected for full chemical analyses. These analyses (Table 1) confirmed the observation (Fig. 5) and showed the deeper, higher conductivity, layer to be comparable chemically

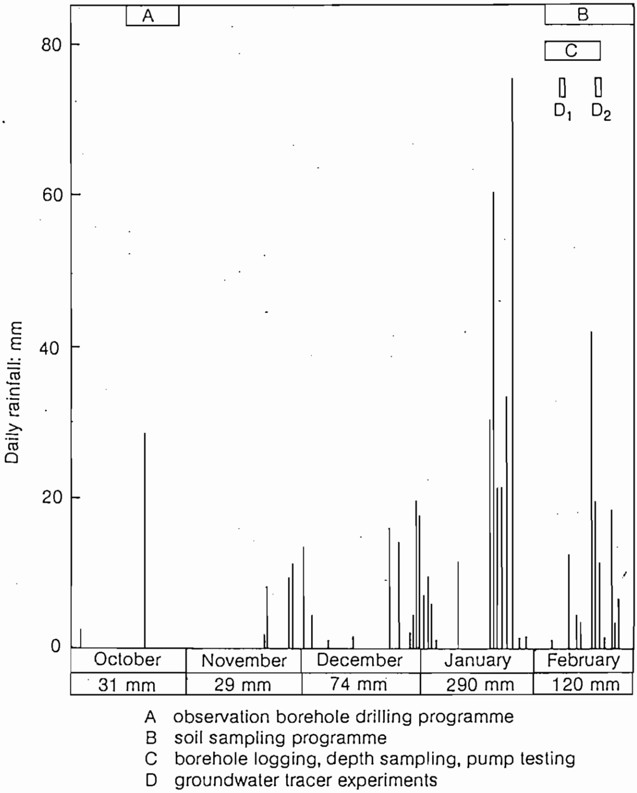

Fig. 2. Timing of field investigations during wet season of 1977–78

Fig. 3. General plan of study area

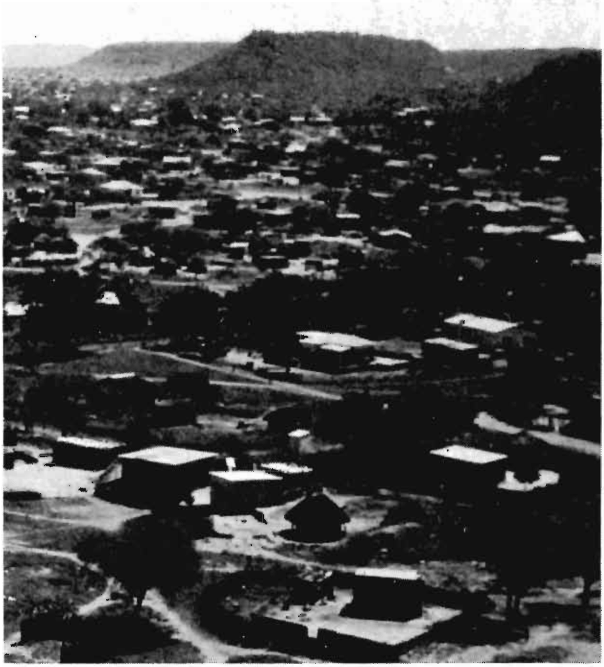

Fig. 4. Settlement pattern in study area

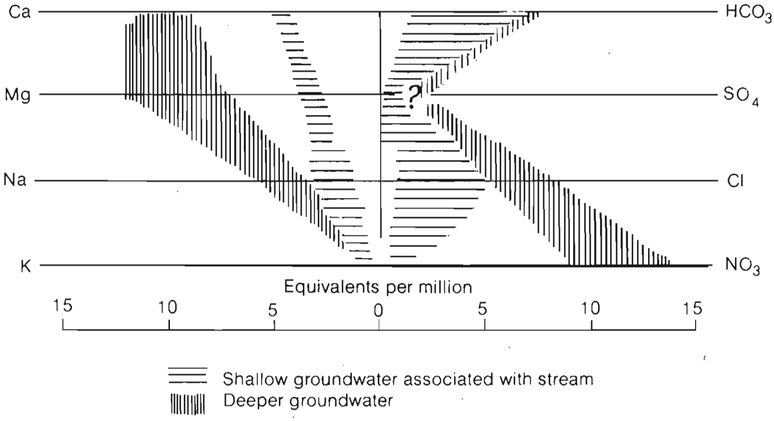

Fig. 5. Stiff diagram summarizing groundwater chemistry

Table 1. Full chemical analyses of groundwater samples

Sample (depth)	BH 1018 (pumped)				Stream (surface)				OW1 (4 m)		OW1 (10 m)		OW2 (6 m)		OW2 (10 m)		OW2 (22 m)		OW3 (6 m)	
Date	21.10.77		3.2.78		21.10.77		3.2.78		2.2.78		2.2.78		2.2.78		2.2.78		2.2.78		2.2.78	
Electrical conductivity.	2450		2800		1085		335		880		2340		1070		2550		2350		960	
pH	8·1		6·5		8·0		8·1		7·3		7·0		7·4		6·3		6·5		7·5	
Units	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l	mg/l	m eq/l
HCO_3	321	5·26	396	6·49	222	3·63	105	1·72	491	8·05	500	8·20	172	2·82	222	3·64	340	5·57	78	1·28
Cl	238	6·73	294	8·29	145	4·08	35	0·99	35	0·99	190	5·36	177	4·99	276	7·79	278	7·84	100	2·82
SO_4	80	1·67	93	1·94	38	0·80	28	0·58	26	0·54	—	—	—	—	81	1·69	—	—	22	0·46
F	0·7	0·04	*	0·00	0·6	0·03	*	0·00	*	0·00	*	0·00	*	0·00	*	0·00	*	0·00	*	0·00
NO_3	614	9·90	874	14·11	16	0·26	39	0·64	51	0·83	568	9·16	37	0·60	600	9·78	680	10·97	284	4·63
NO_2	*	0·00	0·6	0·01	*	0·00	0·5	0·01	*	0·00	0·2	0·00	61	1·33	15·0	0·33	7·6	0·17	0·1	0·02
Sum of anions	1254	23·60	1658	30·84	422	8·80	207	3·94	603	10·41	—	—	—	—	1194	23·23	—	—	484	9·21
K	2	0·04	2	0·04	22	0·55	17	0·44	36	0·92	34	0·87	20	0·51	7	0·18	8	0·21	4	0·10
Na	144	6·28	102	4·44	85	3·68	19	0·83	26	1·13	99	4·31	77	3·35	91	3·96	101	4·39	39	1·70
Ca	174	8·69	240	11·98	41	2·06	30	1·50	100	4·99	180	8·98	80	3·99	230	11·48	230	11·48	90	4·49
Mg	122	10·03	150	12·34	25	2·09	12	0·99	44	3·62	88	7·24	28	2·30	100	8·23	100	8·23	28	2·30
NH_4	*	0·00	0·1	0·01	*	0·00	0·3	0·01	0·1	0·01	0·1	0·01	3	0·17	*	0·00	0·1	0·01	*	0·00
Sum of cations	442	25·04	494	28·81	173	8·38	78	3·77	206	10·67	401	21·41	208	10·32	428	23·85	439	24·32	161	8·59
Ionic balance	−3·0%		+3·4%		+2·4%		+2·2%		−1·2%		—		—		−1·3%		—		+3·5%	

* Not determined.

with the water supply from BH 1018, and the lower conductivity layer to resemble stream water in certain respects. The latter similarity must reflect the presence of influent seepage from the stream, but the fact that lower conductivity groundwater was rapidly depleted suggests that the seepage must be small and perhaps intermittent.

18. The deeper layer appears to be representative of groundwater in the general area. It is heavily polluted with nitrate (invariably exceeding 500 mg/l) and also has high chloride, sodium, calcium and magnesium concentrations. The samples from borehole OW2, which was adjacent to the pit latrine, also contain high concentrations of nitrite and some ammonium.

19. In the nitrate-rich groundwater, the increased calcium and magnesium content is not balanced by a proportionate increase in bicarbonate, but more likely by nitrate itself. This is probably due to nitrate being leached from the soil-weathered rock in an acidic form, and hence dissolving some of the carbonate present. There is a good correlation (a coefficient of 0·92) between excess $Ca + Mg$ $(—HCO_3)$ and NO_3 when they are expressed as equivalents; analyses of samples pumped from other water-supply boreholes in the same village were used when this hypothesis was tested.

Bacteriological

20. Samples were collected from the water-supply borehole and from the observation boreholes for bacteriological examination; taps and a depth sampler were sterilized by flaming in methanol before sampling. Total and faecal coliform counts were made on each sample in the field laboratory using a standard membrane filter technique.

21. *Escherichia coli* occur in enormous numbers in the excreta of man and animals and their presence in water is indicative of recent faecal pollution. However, they cannot be used as a quantitative measure of faecal pollution nor of the presence of pathogenic micro-organisms. The philosophy is that if faecal contamination of water is present, then pathogens may also be present. Other coliform organisms are more widely distributed in nature and may gain access to water from non-faecal sources, e.g. soils and plants.

22. The bacteriological tests (Table 2) showed gross faecal pollution in observation boreholes OW1 and OW2; there were lower *Escherichia coli* counts in BH 1018 and OW3. Nevertheless, the water supply from the former would be classified as suspicious to unsatisfactory because the sampling was very limited.

Table 2. Bacteriological tests on groundwater samples

Sample (depth)	BH 1018 (pumped)		OW1 (10 m)	OW2 (pumped)	OW2 (6 m)	OW2 (10 m)	OW3 (pumped)
Date	26.10.77	10.2.78	3.2.78	26.10.77	3.2.78	3.2.78	26.10.77
Escherichia coli/100 ml	9	1	200	13	350	80	2
Total coliforms/ 100 ml	*	127	500	*	1000	500	*

* Not determined.

There had been little previous bacteriological examination of village borehole water supplies in Botswàna. Regular measurements or routine monitoring, especially during and after heavy rainfall, are required to establish the extent and regime of bacteriological pollution at any given site.

23. Since the work described here was done, a preliminary study of the pollution of borehole water supplies by faecal bacteria has been carried out in the same village; the results are alarming.[11] Gross faecal pollution has been found to be general, frequently pathogenic species have been identified and, in certain instances, these appear to be strains which are resistant to many common antibiotics.

Contamination of soil and unsaturated zone

24. The mobile field laboratory was equipped with a refrigerated centrifuge with special bucket liner assemblies for extracting pore fluid from geological samples. It was used in the determination of the nitrate and chloride content of soil and weathered rock. A modification to the normal centrifuge method[12] incorporating an elutriator was developed because low soil moistures did not generally permit the recovery of sufficient pore fluid. Known small volumes (15–20 ml) of deionized water were added to soil samples (of about 150 gm) after they had been packed in the centrifuge liners; recovery of the elutriate was 30–80%. Experimental recovery of solutes which were added artificially to samples suggests that the error introduced by this method of sample handling does not exceed ±20%.

25. The samples of elutriate were stoppered and refrigerated until they were analysed in batches for chloride and nitrate by argentiometric microtitration and the colorimetric sodium salicylate method respectively. The results were expressed in terms of milligrams of leachable ion per kilogram of moist sample (ppm by weight). The soil NO_3—N content determined may include other nitrogen species present in the soil and oxidized by the elutriation/centrifugation technique; this possibility is considered in the interpretation of the results.

26. The locations of the seven auger holes A–G used for soil sampling are shown in Fig. 1; four additional auger holes H–K were drilled in and outside the village at sites remote from all potential pollution sources to determine background concentrations. High concentrations of NO_3—N and Cl (10–2000 and 10–400 ppm respectively) were found in the soil samples from auger holes A–E, which were drilled close to the pit latrine, whereas the samples from auger holes F and G, which were about 40 m distant, recorded only background concentrations (2 ppm NO_3—N and 4 ppm Cl). The highest NO_3—N and Cl concentrations were in general immediately above the rock head (Fig. 6); the higher concentrations found around auger hole E are probably due to preferential drainage.

27. Nitrate is a stable ion; it is generated from oxidizable forms of nitrogen by infiltrating rain-water and leached from soils during the wet season. Assuming a field bulk density of 1·3, the total mass of readily oxidizable nitrogen in a column of soil reaching from the surface to the rock head for the sites in the immediate vicinity of the pit latrine (auger holes A–E) has been calculated to be 0·1–0·5 kg N/m^2. This shows that the contaminated soil zone, which extends at least 15 m either side of the pit latrine, represents a major source of nitrate contamination to groundwater supplies.

28. The nitrogen content of human excreta is believed to be about 5 kg/man per year; thus the total nitrogen discharged to the soil within 100 m radius of

water-supply borehole BH 1018 (discounting the hospital further upstream) would be 1000 kg N/year. Assuming a mean nitrate content of 600 mg/l for this borehole and that, when in use it operated throughout the year for five hours a days at 1 l/s, the discharge would represent about 900 kg NO_3—N/year.

Groundwater tracer experiments

Unsaturated zone

29. The transit time between the pit latrine and the adjacent observation borehole (OW2) was measured by the injection of 20 l of lithium chloride solution (approximately 2500 mg Li/l) into the pit latrine during the pumping test in February 1978. After injection, samples were collected regularly from the observation borehole throughout the subsequent 20 hour period. Lithium was chosen because it is a safe, mobile ion, and its background level of occurrence is very low.

30. The first sample collected from borehole OW2 had a concentration of lithium of more than five times the background level (Fig. 7). Subsequent samples showed a steady decrease in lithium concentration and after about nine hours the concentration was at its normal level. Most of the tracer thus reached the water-table in less than 25 minutes; as the bedrock between the pit latrine and borehole OW2 (Fig. 6) was fissured, recharge took place rapidly. The experiment thus demonstrated the high risk of faecal bacterial contamination of groundwater via pit latrines.

Saturated zone

31. The transit time between boreholes OW2 and BH 1018 was determined by the injection of 2 l of the concentrated lithium chloride solution and monitoring appearance of the tracer by frequent sampling (Fig. 7). During the first 200 minutes the lithium concentration in the discharge from BH 1018 remained

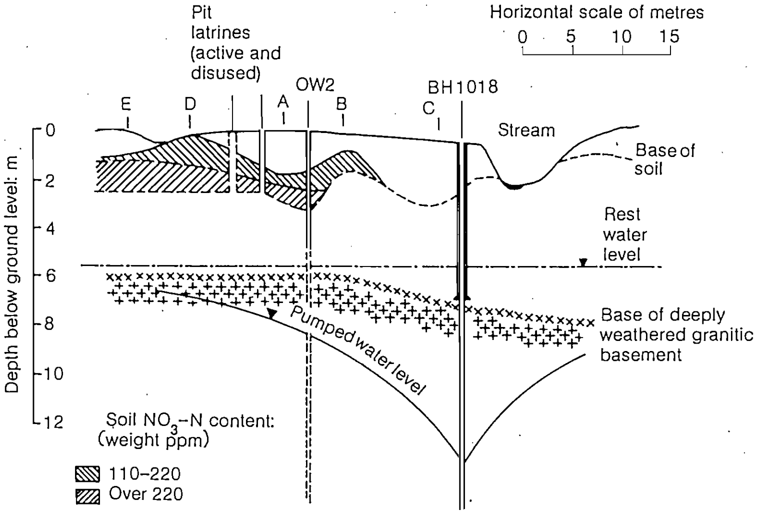

Fig. 6. Hydrogeological section of study area

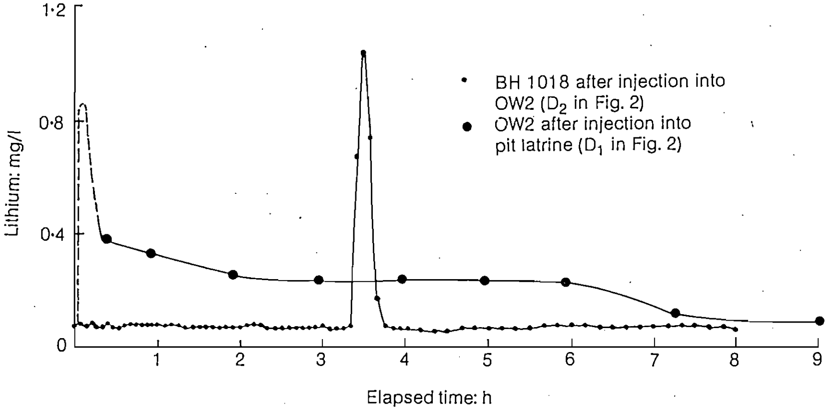

Fig. 7. Results of groundwater tracer experiments

at 0·08 mg/l; it peaked at 1·05 mg/l in the sample collected after 210 minutes and dropped to 0·08 mg/l again after 230 minutes. A sample taken from the observation borehole after completion of the test showed that there was still a plentiful supply of lithium in the water at depth, suggesting that the flow of the tracer out of the borehole had occurred only at isolated fissure-flow horizons. The total transit time from the pit latrine to the water-supply borehole was thus less than 235 minutes: a further demonstration of the pollution hazard involved.

Conclusions

32. The study clearly establishes the serious groundwater pollution hazard represented by pit latrines in hydrogeological environments such as those widely encountered in eastern Botswana. This hazard has two distinct components

(*a*) rapid transport of faecal bacteria to the water-table before natural elimination can occur
(*b*) major build-up of nitrogenous effluent in the surrounding soil and weathered bedrock, from which high nitrate concentrations are leached.

If pit latrines and water-supply boreholes are closely associated in this type of hydrogeological environment a potentially grave risk to public health results. Intermittent heavy contamination of the water-supply by faecal bacteria can be anticipated and nitrate concentrations considerably in excess of the absolute World Health Organisation limit (100 mg NO_3/l) may occur. For these reasons groundwater, which is normally the safest and most viable source of potable water in developing countries, must be managed with sound hydrogeological understanding if serious new health hazards are to be avoided.

33. All soils and unconsolidated strata appear to remove 90% of bacteria within the first 1–2 m of water movement in the unsaturated zone, almost regardless of the initial bacterial loading, because of mechanical filtration and biological elimination.[13–15] They thus represent an effective waste water treatment system. However, any bacteria reaching the saturated zone may move substantial distances down any hydraulic gradient, normally in a thin sheet close

to the water-table.[16–18] As viruses are smaller than bacteria, it is generally believed that those strains that can resist changes in environment may be more persistent and mobile in groundwater systems.[18–20]

34. In bedrock fissure-flow formations, bacteria and viruses can be especially mobile.[21] A serious outbreak of infectious hepatitis in a small town in the USA has been attributed to rather similar conditions to those described in this Paper.[22] Even in low-transmissivity basement aquifers like those in eastern Botswana, in which natural mass movement is very slow, relatively rapid groundwater flow without significant bacterial filtration may take place at certain horizons over radial distances of at least 25 m and up to perhaps 100 m, given the steep hydraulic gradients imposed during pumping. In the absence of hydrogeological data, it has been recommended that the distance between a properly-constructed shallow well and a pit latrine founded in deep soil should be at least 30 m.[18,23]

35. There are many small—mostly ephemeral—streams in villages in eastern Botswana. They normally generate some influent seepage, because frequently they flow directly on weathered bedrock, and when they pass close to water-supply boreholes they represent an additional bacterial and chemical pollution hazard; however, they are unlikely to have high nitrate concentrations. In general it is inadvisable to site new water-supply boreholes close to such watercourses.

36. The most realistic long-term solution is the progressive relocation of public water-supply boreholes in unpopulated areas with reticulation to standpipes in the villages and chlorination of any remaining doubtful sources. Such a policy is now gradually being implemented in eastern Botswana. However, it must be recognized that small-scale chlorinators are unlikely always to operate effectively in developing countries. Source protection must, therefore, form the primary counter-pollution measure. Pollution protection areas should be established, as a priority, around all new water-supply boreholes.

37. To eliminate direct pollution an area of at least 5 m radius around boreholes should be fenced to exclude people and animals from entering and paved so as to direct surface drainage away from the borehole. Solid lining tubes should be effectively grouted at the surface and taken to a depth below the zone of seasonal water-table fluctuation.

38. To reduce pollution via the aquifer certain restrictions should be enforced over a much larger area; these include a ban on the construction of pit latrines, septic tanks and so on (and, therefore, effectively on habitation), the storage of chemicals and oil, and the location of livestock pens. The size of this area should be dictated by local groundwater conditions (e.g. aquifer transmissivity, hydraulic gradient, groundwater flow regime, the presence of any confining strata and thickness of the soil and unsaturated zone). However, in practice adequate hydrogeological data and expertise may not always be available. Although far from ideal, it is considered that the pollution hazard would be greatly reduced in the groundwater conditions normally encountered in eastern Botswana by the establishment of pollution protection zones of 200 m radius around each water-supply borehole.

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