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Low-technology sanitation affecting groundwater quality

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INTRODUCTION

Groundwater is increasingly being used in developing countries for potable water supplies, as it is usually the cheapest and safest source. It is commonly derived from large numbers of simply-designed boreholes and dug wells exploiting relatively shallow unconfined aquifers, which may be vulnerable to pollution from the land surface. Sanitation is often being improved at the same time, by the construction of latrines or simple wastewater stabilisation lagoons, sometimes with effluent reuse for irrigation in arid regions. The impact of such schemes on groundwater quality has received only limited investigation, although in certain hydrogeological conditions they can present potential pollution hazards. This paper presents the principal results from detailed field investigations beneath a low-technology wastewater reuse scheme in Peru, and discusses their relevance to the aquifer types and different hydrogeological conditions which occur in Africa.

WASTEWATER REUSE SCHEME, LIMA AREA, PERU

Background and hydrogeological setting

Lima is situated on the extremely arid coast of Peru where rainfall is almost negligible, and groundwater from the alluvial aquifer is a major source of potable water supply. The sediments are mostly highly permeable, unconsolidated sands and gravels, which are recharged by rivers from the Andean Mountains and their associated irrigation schemes. The aquifer is overdeveloped, with groundwater levels currently falling at 2-4 m/a, and the acute shortage of water resources is leading to the recycling of wastewater for agricultural production.

The San Juan de Miraflores wastewater reuse scheme was constructed in 1964 and is located on the outskirts of Lima. It comprises a series of 21 simple, unlined, stabilisation lagoons excavated in the sand, each only 2m deep with a design retention time of 5-10 days. The complex receives 360 l/sec domestic sewage from neighbouring low-income housing areas, about half of which passes through the lagoons. The effluent and remaining raw sewage is used to irrigate 400 hectares of cultivated land and woodland at average rates of 5-10 mm/d. The area is underlain by highly permeable sands, and there is significant leakage from beneath the lagoons (10-20 mm/d) and excess irrigation beneath cultivated land (average 5mm/d) which recharges groundwater. The unsaturated zone is 20-30m thick.

Research Investigation

Eight cored boreholes were drilled in 1984/5 in the bases of specifically drained lagoons and beneath cultivated land irrigated with effluent, to investigate the water quality in the unsaturated and saturated zone of the underlying aquifer (ref.1). Sand samples were centrifuged at 3000rpm to extract pore-water for chemical analysis, and replicate samples were cultivated directly for microbiological analysis. Some of the boreholes were completed with slotted lining tubes to allow subsequent groundwater sampling, and unsaturated zone suction samples were installed in others to monitor the quality of infiltrating water.

Table 1. Water Quality at San Juan de Miraflores Wastewater Reuse Scheme

determinand	raw sewage	unsaturated zone pore-water beneath lagoons (below 5 m)	secondary lagoon effluent	unsaturated zone pore-water beneath arable land (below 5 m)
EC (uS/cm²)	1080	991	1050	1245
Cl	115	182	116	168
Total N	46	10	31	21
NH_4-N	29	8	20	0.6
NO_3-N	<0.1	1.7	<0.1	20
SO_4	240	29	231	196
Ca	302	45	318	121
Mg	80	17	69	26
Na	64	90	61	85
K	15	20	15	14
P (total)	4.4	nd	3.3	nd
P (soluble)	3.1	bdl	1.4	0.9
TOC	170	5.5	110	5.5
ABS detergent	1.6	2.0	1.7	0.3
Fecal coliform	10^{7-8}	20	10^{5-6}	10^2
Fecal streptococcus	10^{6-7}	10	10^{4-5}	10^2
Salmonella	10^{3-4}	bdl	10^{0-1}	bdl
Human Rotavirus	10^{3-5}	bdl	10^{2-5}	10^4

chemical analyses expressed in mg/l except EC in μS/cm²
microbiological concentrations expressed per 100 ml or as equivalent
bdl below detection limit

Unsaturated zone profiles

The raw sewage and lagoon effluent are quite saline (table 1) and their character controls the quality of water in the unsaturated zone. Chloride profiles under cultivated land show the effect of evaporative concentration (fig.1), a mass balance calculation giving the recharge as about 5 mm/d.
Nitrogen in the raw sewage and effluent is in the organic and ammoniacal form. Under the lagoons ammonium concentrations are similar to those in raw sewage in the top 2m, but decrease steadily with depth by adsorption on clay mineral surfaces, and are very low beneath 10m. The cation exchange capacity appears to have reached saturation in the surface layers and this will advance down the porewater profile with time. The presence of ammonium with only low levels of nitrate confirms that conditions in the unsaturated zone are anaerobic as expected. The nitrogen load reaching the water table is quite low at present. Under cultivated land ammonium is negligible as soil aeration between flood irrigation events promotes oxidation to nitrate. Excess nitrogen to crop requirements is applied, and about half (400kg N/ha/a) is leached in the excess irrigation water. The nitrate concentrations are high in relation to the WHO guidelines for potable supply (10mg NO_3-N/l).
Sulphate profiles have much lower concentrations than raw sewage due to precipitation of sulphides or bacteriological sulphate reduction, particularly in the anaerobic environment in the sewage sludge at the lagoon base.
Phosphate is not very mobile and is precipitated as calcium phosphate at the base of lagoons or adsorbed beneath them.
Detergents used in Peru are mainly relatively non-biodegradable alkyl benzene sulphonate (ABS) which was detected at quite high concentrations beneath lagoons and at lower though significant levels beneath cultivated land.
Fecal pathogens and indicator organisms decrease by one or two orders of magnitude as they pass through the lagoons. Infiltration through the basal sludge results in further elimination by mechanical straining and adsorption; nevertheless high concentrations of both bacteria and viruses penetrate into the upper part of the unsaturated zone (fig.2). There is rapid elimination within the top 3m and populations below this depth are generally below the detection limits. Beneath cultivated land irrigated with waste water, populations of fecal indicator bacteria are as high in the surface layers despite lower incident concentrations in secondary effluent. Irradiation and dessication between irrigation events lead to die-off, but although they decrease rapidly over the top 3m, there are positive counts of these and the hardy human rotavirus throughout the profiles right down to the water table at 20-25m depth. The reduced elimination, when compared with the situation beneath lagoons, is probably because of the lack of a sludge mat at the infiltration surface. The ineffectiveness of an unsaturated zone of fine-to-medium sands of this thickness in eliminating these micro-organisms is surprising. The pathogenic bacteria salmonella appears to be rapidly eliminated rapidly in all the unsaturated zone environments.

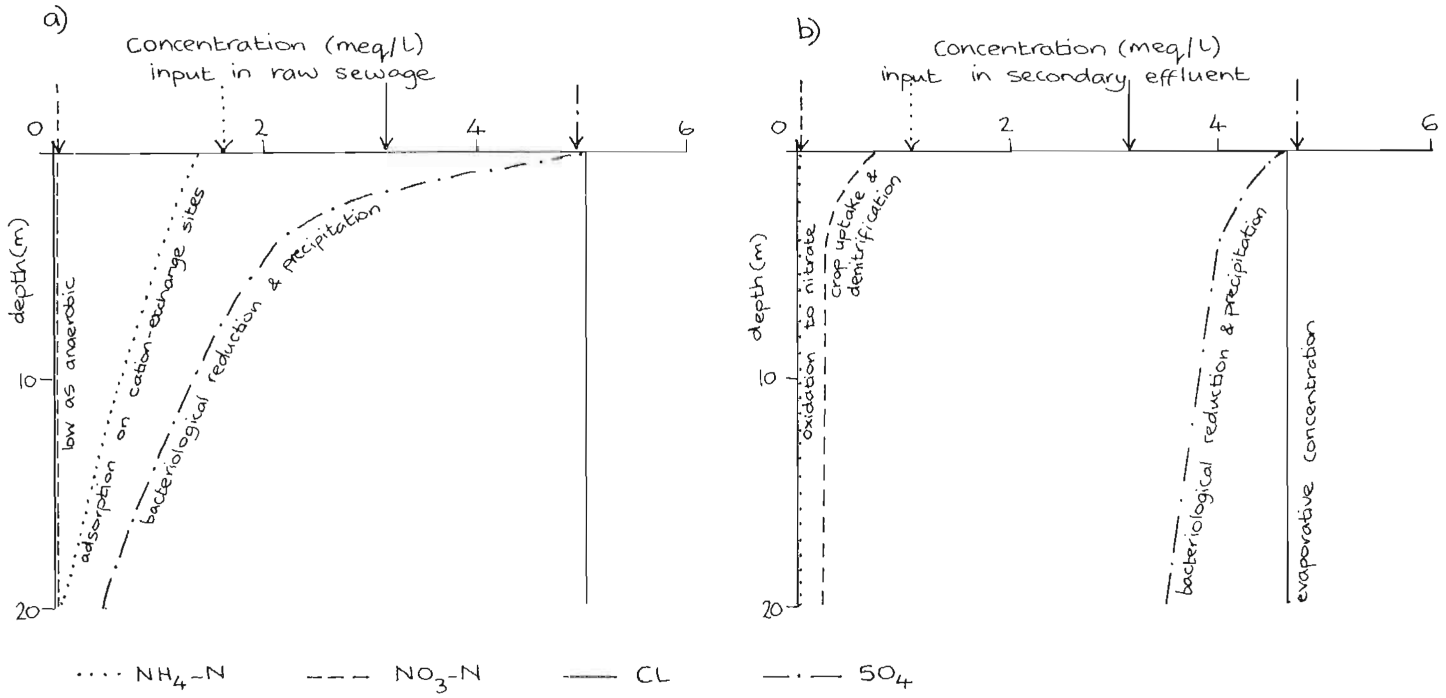

Figure 1: Generalised form of unsaturated zone chemical profiles
a) beneath wastewater lagoon b) beneath cultivated land irrigated with wastewater

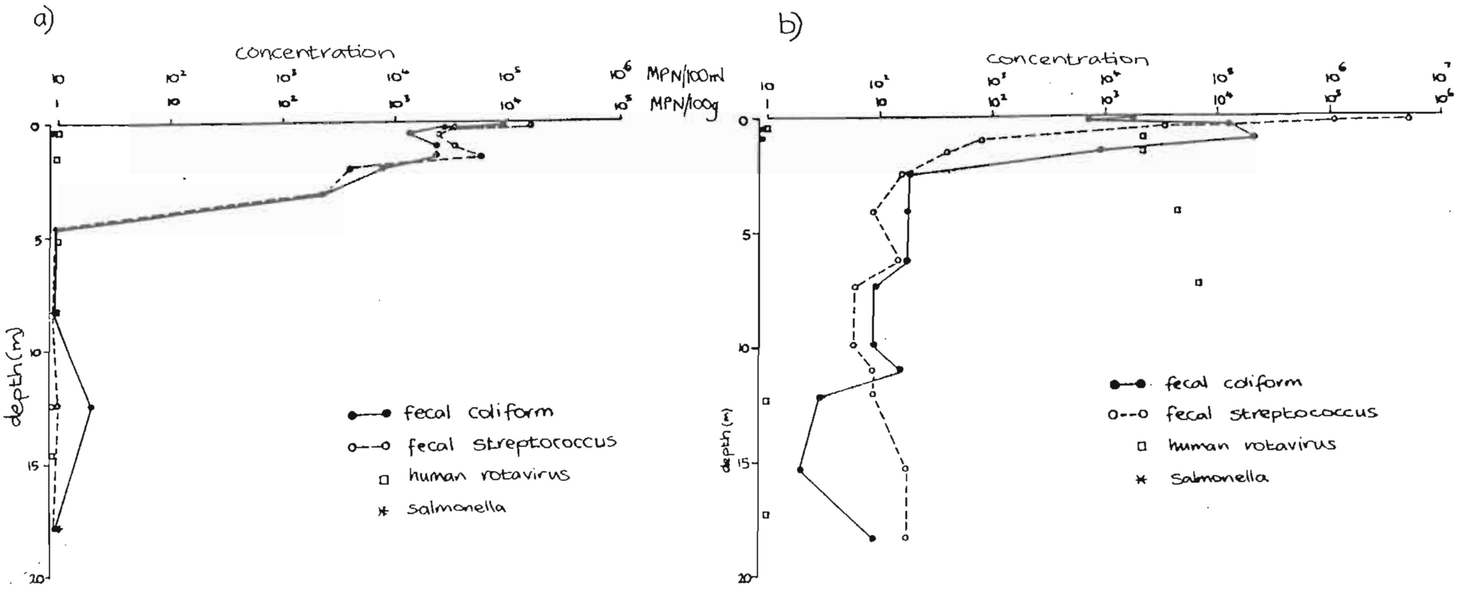

Figure 2: Fecal pathogens and indicator organisms in the unsaturated zone

a) beneath wastewater lagoon

b) beneath cultivated land irrigated with wastewater

Saturated zone

Fecal pathogens and indicator organisms were detected at relatively high levels (up to 10^3/100 ml) in groundwater samples bailed from the investigation boreholes, confirming the evidence of incomplete elimination despite a thick unsaturated zone of unconsolidated sands.

Trace organics migration and attenuation in groundwater systems is very uncertain, but many soluble compounds are believed to be retarded by adsorption and the more readily degradable compounds will probably be eliminated. TOC concentrations of up to 9 mg/l observed in groundwater beneath the lagoons and cultivated land are a gross indicator of organic pollution. Detailed organic analysis of 4 groundwater samples showed generally low levels of polycyclic aromatic hydrocarbons, phenols, polychlorinated biphenyls and the common halogenated solvents with most compounds being below detection limits. However elevated levels of the solvent 1,1,1, - Trichloroethane (up to 58 µg/l) and hydrocarbons (up to 160 µg/l were detected.

DISCUSSION

Groundwater Pollution Threats

The soil and unsaturated zone are an effective wastewater purification system, and are clearly an important first line of defence against aquifer pollution. The relatively slow water movement allows substantial reduction or removal of most of the unwholesome components in domestic wastewater by adsorption, filtration, precipitation or exchange processes, especially in the upper metre or so. The contaminants are further attenuated on reaching the water table, by dilution from regional groundwater flow. Nevertheless wastewater reuse schemes can, and do pose a threat of aquifer pollution from certain nutrients, dissolved salts, pathogens and trace organics. Groundwater recharge from such schemes will not be potable, and even where there is dilution from regional groundwater flow there will be a local need to restrict the use of groundwater to purposes other than domestic supply. The containment of polluted water by interception in drains or scavenger boreholes, although desirable, would be expensive. Close care needs to be taken in siting new reuse schemes, and to avoid siting potable water supply boreholes in the near viscinity.

There will also be a risk of groundwater pollution by the same contaminants from unsewered latrines or septic tanks, although often to a lesser degree because of lower loadings on the aquifer, but the problems will be more widespread. The nitrogen compounds will tend to be rapidly converted to nitrate beneath latrines because the conditions will generally be aerobic. Nitrate contamination will thus be almost inevitable, except where the groundwater system is naturally anaerobic allowing denitrification. Although this presents a less immediate hazard than any pathogens reaching the water table, it will be a persistant problem, especially in arid areas without significant regional groundwater flow (ref.2).

Effect of differing hydrogeological conditions in Africa

The aquifer type is important, unconfined aquifers being vulnerable to pollution from the land surface, whilst for semi-confined and confined conditions the risk is negligible.
The nature of the soil and strata determine the effectiveness of the purification, the greatest attenuation occurring in fine-grained, unconsolidated sediments with high clay contents. The clay-rich surface layers of the weathered basement aquifer for example, which is widespread over many regions of Africa, offer considerable protection against groundwater pollution. The unconsolidated sediments of the younger alluvial basins in Africa would be generally less effective in pollution protection, and more comparable to the Peruvian sands described above. The pollution risk will increase both with the coarsening of the material and the degree of consolidation and fissuring, as the flow velocities could be several orders of magnitude higher (ref.3). The greatest risk, particularly of fecal pollution, is where there is only a thin soil cover over a fissured non-porous bedrock aquifer, for example some volcanic lavas with major cavities and fissures. It should be noted that the upper 2m of the soil profile is biologically the most active and contains the greatest concentrations of pathogen-antagonistic microbes (ref.4); this important barrier is normally removed during latrine construction.
The thickness of unsaturated zone will control the time-lag and degree of purification attained before reaching the water table; obviously this will be least where the water table is shallow. The worst situation arises where latrines discharge directly into groundwater, and the practice of digging them as deep as possible regardless of hydrogeological conditions should be discouraged.
The excess rainfall affects the extent of leachate dilution. In coastal Peru, the rainfall is negligible and the quality of the infiltration beneath cultivated land irrigated with wastewater is controlled by the quality of the latter and the irrigation regime. In the more humid areas of Africa, the recharge would be diluted by excess rainfall resulting in lower salinity.
The aquifer thickness and flow regime affect the potential for dilution in the saturated zone.
The unsaturated zone permeability increases with moisture content, so if there is heavy artificial loading (e.g. beneath lagoons or pour-flush latrines) or high intensity rainfall the flow velocity increases, and the opportunity for pathogen elimination is greatly reduced.

CONCLUDING REMARKS

It is clear that low-cost sanitation schemes can have a detrimental effect on groundwater quality, the depth to the water table and the character of material in the unsaturated zone being the main controls on the degree of penetration of pathogens and biodegradable organics. The extent of dilution from regional groundwater flow, local recharge and effluent liquids (in pour flush latrines) control the final concentrations of nitrate, chloride and persistent trace organics in groundwater (ref.4). Water and pollutant movement in the unsaturated zone is complex, and the risk of groundwater contamination is much greater under some hydrogeological conditions than others. The normally accepted minimum separation of 15m between excreta disposal units and a groundwater supply source may therefore be over-cautious in some situations yet inadequate in others.

Those responsible for planning sanitation schemes need to recognise that a potential pollution hazard exists, and to be aware of the importance of groundwater for potable supplies. It would be desirable for low-cost sanitation and groundwater supply programmes to be planned on an integrated basis, with careful designs to minimise the aquifer pollution.

ACKNOWLEDGEMENTS

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