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Nitrate in groundwater and N circulation in eastern Botswana

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Abstract Nitrate pollution due to deep leaching from pit latrines has caused water supply wells in eastern Botswana to exceed health limits concerning nitrate. It was deduced from the estimated intake of salt and protein by the population that, as an average, about 10 percent of the human nitrogen excretion is leached to the groundwater. This fraction was also found in southern India, where on-the-ground excretion is customary. The nitrogen circulation in general in the savanna ecosystem is not appreciably affected in spite of a large livestock density. Overall nitrate leaching is in the order of 1.5 kg N/ha/y, similar to that in another semiarid area in southern India. However, in India, there seems to be a more diffuse areal leaching from agriculture as well as from villages.

Measures to minimize the nitrate leaching could be to plant deep-rooted trees adjacent to pit latrines or to use latrines that separate the urine from the faces for a more near-surface infiltration facilitating plant uptake. Measures to minimize leaching will also lessen the rick for bacterial pollution of the groundwater.

Key words Groundwater — Nitrate — Latrines — Nitrogen cycling

Introduction

Nitrate in excess of health limits has appeared in several village water schemes in Botswana (Lewis and others 1980). This report deals with the nitrate pollution from the perspective of the general nitrogen circulation in the investigated area. The report presents a comparison of three cases of nitrate pollution in groundwater where the resulting concentrations are of similar magnitude but where the causes are different. Countermeasures will have to be designed accordingly.

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Geographical characteristics

The main features of the investigated area around the village of Mochudi in eastern Botswana are given below. The results are compared with two other case studies, one from a similar climatic zone in southern India and one from the humid zone in Sweden.

Mochudi, Botswana

Eastern Botswana has a rainfall of about 500 mm. About half of the precipitation falls in the period December–February, while June, July, and August are very dry. The mean annual temperature is 21°C. The area investigated is 170 km^2 and includes the villages of Mochudi, Morwa, Bokaa, Pilane, and Rasesa, 40 km northeast of Gaborone. The rocks are precambrian granites and proterozoic sandstones, siltstones, and claystones. The groundwater in the area occurs in fractures and joints. The overlying soils are Ferric Luvisols, Ferric Arenosols, and Regosols (FAO-UNESCO classification).

The vegetation is a tree and shrub savanna with *Croton gratissimus* on rocky sites and *Acacia erubescens* and *Terminalia sericea* on sandy soils in the lower portions of the terrain. The cultivated area is less than 20 percent. The population density is 180 inhabitants/km^2. The livestock amounts to about one head of cattle and two goats or sheep per hectare.

Areas used for comparison

The Coimbatore area, in Tamil Nadu in southern India, recieves 500–800 mm of rainfall. The southwest monsoon comes during June to August, while the northeast monsoon is active during October and November. The mean annual temperature is 27°C. The underlying rocks are precambrian gneisses an charnockites in which the groundwater occurs in fractures and joints. The soils in the area are Alfisols, classified as Rhodustalfs, with smaller areas of Vertisols, classified as Chromusterts (USDA Soil Taxonomy). The Rhodustalfs are approximately equivalent to the Ferric Luvisols of the Mochudi area in Botswana. The area is cultivated except for habitations and wasteland with shallow soil. The crops cultivated are sorghum, millet, cotton, groundnut, and pulses. The tree and bush vegetation is synantrophic, restricted to a few species, palmyra palm (*Borassus flabellifer*) and mesquite (*Prosopis juliflora*), which occupies most wastelands and invades land left fallow for a few years. The population density is high, about 300 inhabitants/km^2 at the time of the investigation (Jacks and Sharma 1982). The livestock consisted of 0.9 cattle and 0.9 goats or sheep per hectare.

The humid area in southwestern Sweden (Andersson 1986) has a precipitation of about 800 mm, evenly distributed over the year, and a mean annual temperature of 8°C. The soils are sandy Cambisols. Most of the area is cultivated. The main crops are barley, wheat, and potatoes. The population density is on the order of 20 inhabitants/km^2 and the livestock amounts to about one head of cattle per hectare. The tree coverage is restricted to curtains along some streams and roads.

Materials and methods

The study has mainly utilized existing data from the Department of Water Affairs in Gaborone, Botswana. Some complementary analysis for soil nitrogen and nitrate in water was carried out. Literature values were used for nitrogen fixation rate and groundwater formaton rate. Field work mainly aimed at verifying the deductions from the data bases and the literature surveys.

Nitrate pollution

Groundwater data were available at the Deparment of Water Affairs and the Geological Survey starting from the early 1960s when the village water schemes were started. The average nitrate content during the first decade was very low, below 1 mg/l, but rose during the 1970s and exceeded the health limits during the first half of the 1980s (Fig. 1). The wells were drilled in the villages or were gradually encroached upon by the settlements. The latter half of the 1980s saw a decrease of the average nitrate concentration as well fields were constructed away from the villages and the most contaminated wells in the villages were closed. The population increased during the period by about 40 percent.

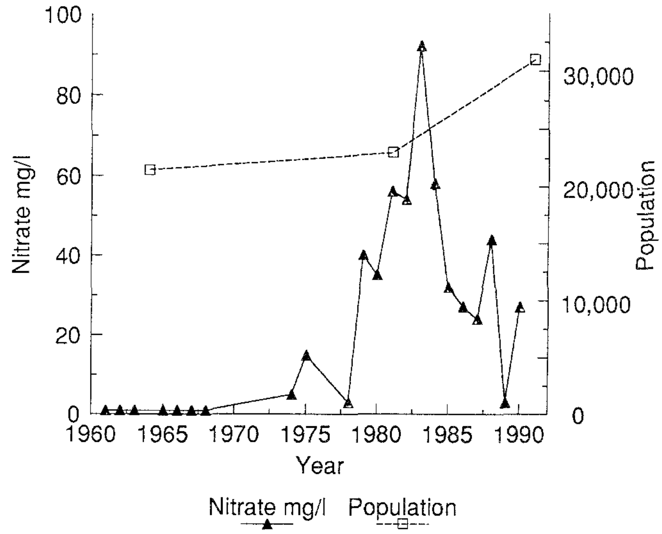

Fig. 1. Nitrate contents in water supply wells in the Mochudi area, eastern Botswana

From the pollution history, it is evident that the settlements themselves have polluted the wells. Presently high nitrate groundwaters occur in the village of Mochudi and in wells eastwards along a major faultline. The contents of nitrate in wells in the village of Mochudi are in excess of 100 mg/l and 50–100 mg/l along the fault line.

Goundwater pollution by pit latrines has been recorded by Lewis and others (1980). The introduction of pit latrines has been very successful in Africa and in Botswana in particular, in contrast to the very moderate acceptance met with in India. The use of pit latrines has spared the population from several types of infectious diseases such as gastroenteritis of various types and parastic infestations such as hookworm.

If the intake of salt and protein by the population is known, chloride can be used as a tracer to estimate the fraction of nitrogen lost in deep leaching to the groundwater. The intake of salt in various communities ranges from 50 mmol to 250 mmol/pd (Stamler and others 1991). By comparison with the consumption by comparable groups in neighboring countries and after consulting the Family Health Division of the Ministry of Health, we estimated the intake of salt at 150 mmol/d or 9 g NaCl. The protein consumption was assessed at 80 g/d after considering the consumption of comparable groups in the region (Maletnlema 1992) and again consulting the Family Health Division.

In Fig. 2 nitrate content is plotted versus chloride for a number of water supply wells in the area investigated. From the chloride values are subtracted 10 mg/l, which is considered to be a background value coming from atmospheric deposition. The lowest chloride concentrations in groundwater in the Mochudi area are around 10 mg/l, which is compatible with the 0.4 mg/l of chloride recorded

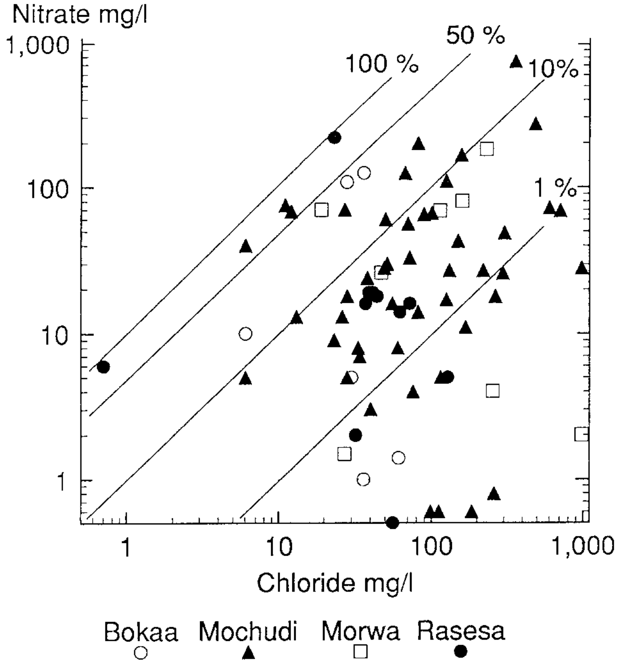

Fig. 2. Nitrate concentrations as a function of chloride in village wells. Diagonal lines denote fractions of leaching from human excretion assuming a daily intake of 9 g common salt and 80 g of protein. From the chloride values are subtracted 10 mg/l representing atmospheric deposition

in rainwater by Gieske (1992). Considering the above deduced intakes of chloride and protein-nitrogen, lines have been drawn for different fractions of deep leaching of the nitrate. There is naturally a wide variation, but seldom more than 50 percent is leached and, on an average, just below 10 percent of the nitrogen seems to reach the groundwater. Jacks and Sharma (1982) estimated the fraction of leaching in Indian villages to range in a similar interval where squatting on the ground in the outskirts of the hamlets was the common way of excretion. While ammonia volatilization and plant uptake may prevent most of the nitrogen from being leached in India, there is probably quite an efficient denitrification in the pit latrines. Most latrines are dug in the loamy Luvisols with impeded drainage, which should favor denitrification. If the fraction of leaching could be reduced, more of the existing wells could be used for water supply in a future with growing water scarcity. A way of achieving this would be to plant deep-rooted trees adjacent to pit latrines allowing the recovery of the nitrogen into biomass. As this would also reduce the water flux blow pit latrines, it would also lessen the risk for bacterial pollution. Another option is latrines that separate urine from feces and to infiltrate the urine near the soil surface allowing plant uptake.

Nitrogen budget

To put the groundwater pollution in perspective, we decided to synthesize a nitrogen budget for the area, assessing

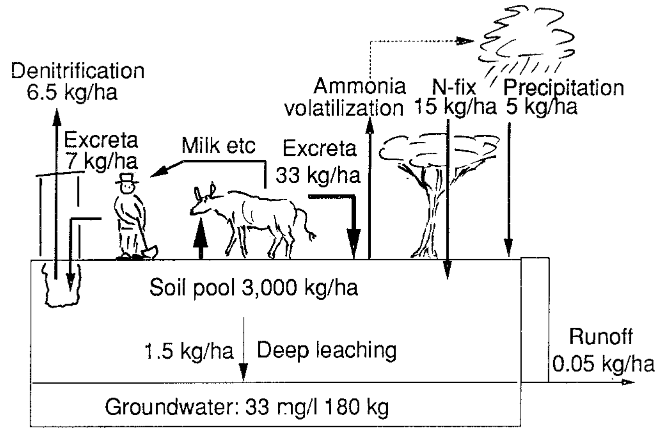

Fig. 3. Tentative nitrogen budget for the savanna ecosystem in the Mochudi area. Fluxes are expressed in kilograms of nitrogen per hectare per year and pools in kilograms of nitrogen per hectare

fluxes and pools from existing and measured data. The data are summerized in Fig. 3.

Nitrogen inputs

Gieske (1992) measured 0.45 mg/l of nitrate in rainwater in eastern Botswana, which means about 2 kg/ha/yr of wet deposition. Ammonium and dry deposition would add up to a total deposition of approximately 5 kg/ha/yr.

The symbiotic nitrogen fixation is important in the savanna ecosystem. The estimates vary from about 10 to 30 kg N/ha/yr depending on the management (Wild 1989). Acacia species are abundant in the studied area. The higher figure is given for grazed savanna. Assuming 20 kg/ha/yr for the 72 percent of the area that is savanna, this gives an overall fixation rate of about 15 kg/ha/yr.

No inorganic fertilizers are used in the small scale cultivation practiced in the area.

Internal fluxes

The above estimated protein intake of 80 g/person/d would give an age and sex adjusted intake of 68 g/d, adding up to close to 4 kg N/person/yr. This gives an overall input of 7.1 kg N/ha/yr. Jacks and Sharma (1982) give a figure of 7.6 kg N/ha/yr for the area in southern India. The protein intake is lower, but the population density is almost double that in Botswana.

A very sizable amount of the primary production goes to the livestock herds. Gandar (1982) estimated that cattle consumed over 20 percent of the primary production in a savanna in northern Transvaal. Granberg and Parkinson (1988) give a stocking rate of about one head of cattle per hectare for the nearby Kweneng N district. This is a high figure, but observations of land degradation and even desertification (Government of Botswana 1989) does show that the carrying capacity is exceeded. One head of cattle and a couple of smaller animals per hectare may be a reasonable stocking rate. The daily need of protein for a sebu cattle is on the order 450 g (Pratt and Gwynne 1978). This means about 70 g of nitrogen in daily excretion. The smaller animals are browsers, eating a relatively protein-rich matter (Pratt and Gwynne 1978). Thus the per head excretion of the smaller animals is considered to be the same as for humans. The total figure for nitrogen in excreta from the livestock is thus 33 kg/ha/yr.

The leaching from the soil zone to the groundwater can be calculated by knowing the mean concentration of nitrates in the groundwater and by using a reliable groundwater recharge rate. The recharge rate has recently been assessed by Gieske (1992) through several methods in eastern Botswana. A reasonable mean deduced from his figures seems to be 20 mm/yr, close to the figure of 30 mm arrived at by Jacks and Sharma (1982), in a similar climatic environment. The mean content of nitrate in monitored wells after 1984 is 33 mg/l ($N = 42$) or 7.5 mg/l of nitrate N. This may be on the high side as sampling probably was directed towards problem wells and even now a majority of the wells are situated in the vicinity of the villages. Accepting the figure yields a leaching of 1.5 kg N/ha/yr.

Losses

Runoff is seasonal or occasional. The Metsemothlaba river, draining most of the area, has a measured runoff of 4 mm (Government of Botswana 1989). Nitrate-N contents in this river and the Ngotwane river measured by the authors was 0.8 mg/l. Other reported values for runoff water range from 0.8 to 1.4 mg/l. Thus, runoff may lead to losses of 0.03–0.06 kg N/ha/yr.

Denitrification in upland sites is likely to be small, with a low soil moisture even in the wet season. Denitrification may occur in the groundwater-fed discharge areas of the Metsemothlaba river and its tributaries, explaining the discrepancy between leaching losses to the groundwater and runoff losses (Fig. 3).

Volatilization of ammonia from animal dung and urine may be important. Tolsma and others (1987) have studied the accumulation of nutrients near borewells used for watering of the herds. Nutrients from urine and dung was accumulated within 100 m from the waiter point. While phosphorus is found in 80-fold concentratons as compared to distant sites, the increase in nitrogen is only three-fold. This indicates that volatilization is a major loss, accelerated by the trampling of the ground, destroying grass and herbs. Volatilization of ammonia seems to be the main process balancing the inputs to the soil.

Pools

The content of nitrogen in four composite samples of surface soil 0–10 cm near Bokaa was 450 ppm. Tolsma and others (1987) found 420 ppm in Kgatleng. In nine samples from Mochudi subsoil, 10–30 cm, Ernst and Tolsma (1989) found 280 ppm N. Extrapolating the nitrogen content to zero at 1 m depth and using the density of 1.5 kg/dm^3 gives a soil pool of about 3000 kg/ha.

The aquifer thickness of the sandstone in the area is 40–60 m, and the storage has been estimated at 550 mm, or equivalent to one years' precipitation, as deduced from data by Keller 1(988). The resulting nitrogen pool is 180 kg/ha. Given a recharge rate of 20 mm (Gieske 1992), the turnover rate of the groundwater is on the order of 30 years.

Conclusions

Nitrate leaching in the Mochudi area turns out to be due to pit latrines. These are largely beneficial, saving the population from several types of infections such as gastroenteritis of different kinds, hookworm, etc. The pit latrines do not promote increased nitrate leaching when compared to the on-the-ground excretion in southern India. The soils in the Mochudi area are poorly drained Luvisols and should promote denitrification in the latrines. In Table 1 the major fluxes of nitrogen in the Mochudi area are compared with those in another semiarid site, Coimbatore, and finally those from the humid site in southern Sweden. It is notable that the contents of nitrate in the groundwater are quite similar in spite of other differences.

It is remarkable that there is no general leaching of nitrate from the large amount of livestock, especially as this occurs in Coimbatore where there are fewer animals. One possible explanation is the presence of shrubs and trees in Botswana that are deep-rooted due to the seasonal moisture deficit. In Coimbatore most of the area is either fallor or under agricultural crops.

The high leaching in the Swedish site is mainly due to a long wet period after the growing season with ploughed fields left bare during autumn and winter.

Table 1. Annual fluxes of nitrogen in eastern Botswana, southern India, and southwest Sweden

Area	Precip. (mm)	Fertilizer (kg/ha)	Animal dung (kg/ha)	N fixation (kg/ha)	Leaching (kg/ha)	Nitrate in groundwater (mg/l)
E. Botswana	500	0	33	15	1–2	33
S. India	600	20	32	10–20	2–3	40
SW Sweden	800	100	33	small	25	40–60

Recommendations

A way of avoiding nitrate leaching from the pit latrines may be to plant deep-rooted trees adjacent to the latrines. The trees would be expected to extract both water and nutrients from the subsoil. The trees should thrive well, as their phosphorus requirement should be well covered. Phosphorus deficiency is otherwise a normal feature in the savanna land (Ernst and Tolsma 1989). Using latrines that separate urine and faces is another possible countermeasure. Improvements in the water quality will come slowly as the annual recharge is small and the groundwater turnover rate is on the order of decades. However, the water resources in Botswana are scarce and it is essential to recover an acceptable water quality in as many existing wells as possible.

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