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Urbanisation effects on groundwater chemical quality: findings focusing on the nitrate problem from 2 African cities reliant on on-site sanitation

Aidan A. Cronin, Alfred W. Hoadley, James Gibson, Ned Breslin, Fatoumata Kouonto Komou, Louis Haldin and Steve Pedley

ABSTRACT

By 2010 Africa's urban population will have grown to over 420 million with on-site sanitation the predominant excreta disposal option. The use of on-site sanitation has important public health benefits but can result in large faecally derived loadings of nitrogen and chloride to groundwater resources. Nitrate is of particular concern, with elevated concentrations linked to potentially serious health problems. N and Cl can derive from natural sources so it is important to quantify the additional impact of human activities. Several authors have used empirical relationships between nitrate and chloride concentrations to assess the extent to which excreta influences groundwater quality. However, these relationships have assumed fixed loadings from excreta. Relationships between N and Cl have been extended here by adding country-specific estimates of average annual per capita nitrogen and chloride content of, and loading from, excreta. The results are compared with groundwater monitoring results from two very different mid-sized African cities (Timbuktu, Mali and Lichinga, Mozambique) where the vast majority of residents use on-site sanitation and are dependent on the subsurface water for drinking purposes. The results illustrate the impact of urbanisation on groundwater quality. They are compared with data from other African cities to allow the calculation of a general nitrate and chloride relationship for unsewered African urban areas. Potential interventions to help arrest rising nitrate levels and so provide a public health benefit are also examined.

Key words | Africa, ecological sanitation, faecal nutrients, nitrates, urban groundwater, urine diversion

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INTRODUCTION

By mid-2007, for the first time in human history, the majority of the world's population will be urban dwellers. As with Asia and Latin America, Africa has been undergoing rapid urbanisation and it has been estimated that some 430 million of an anticipated 1 billion African population will be living in cities by 2010, a significant increase on the 300 million people inhabiting African cities in 2000 (UN-HABITAT 2003). The vast majority ($>60\%$) will be living in towns with less than 500 000 inhabitants. Rapid urbanisation typically results in densely populated areas that lack adequate infrastructure and have poor hygienic conditions. This is especially true in smaller towns that generally have fewer resources available to them than do the larger capital cities. Dramatic increases in urban populations are already impacting on water supply and distribution systems. This can be seen in East Africa where the number of hours of service provided by piped water systems has dropped and queuing times at community wells have increased over the last 30 years (Thompson *et al.* 2001). The high rate of urbanisation and inadequate resources in such areas has meant that pit latrines are the principal sanitation option available. This will most likely

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remain the case for dense urban populations in African cities for the foreseeable future.

Groundwater is a vital source of drinking water in African towns and cities, but this resource often has been compromised by the combined use of aquifers as a repository for human waste (Taylor *et al.* 2004; Cronin *et al.* 2006). Previous research has generally focused on microbiological contamination from on-site sanitation in African towns (e.g. Howard *et al.* 2003; Cronin *et al.* 2004). However, degradation of chemical water quality can also impact on health, especially as a result of nitrate contamination associated with on-site sanitation. This has often been neglected in past studies of water quality in urban areas.

Nitrate concentrations in excess of drinking water quality guideline values, defined by the World Health Organisation as >10 mg/l NO_3 (as N), can result in methaemoglobinaemia (blue-baby syndrome) in children (Comly 1945). This occurs when nitrate in the stomach of infants is reduced to nitrite. The nitrite is then able to oxidise haemoglobin to methaemoglobin which is unable to transport oxygen around the body (WHO 2004). There is also substantial evidence collected from animal experiments that carcinogenic N-nitroso compounds are found in the stomach and intestinal tract following chronic ingestion of elevated nitrate (Nomura 1996). In addition, there are claims that high nitrate concentrations can lead to spontaneous abortions (e.g. Grant *et al.* 1996) though no study relating to this topic can be regarded as definitive (Schubert *et al.* 1999). Nitrates in soil and groundwater are typically derived from the microbial degradation of organic nitrogenous material such as protein to ammonium ions that are then oxidised to nitrite and subsequently to nitrate by aerobic chemolithotrophs (Hounslow 1995). Typical strategies for reducing excess nitrate in drinking water supplies in developed countries has been either to blend high nitrate waters with lower concentration waters or to remove it by a treatment process such as ion exchange. Neither are viable low cost options that are generally available in sub-Saharan Africa. Hence, prevention of excessive N loadings to aquifer systems used for water supply is the optimal control option. No health-based guideline value is proposed for chloride in drinking water though concentrations in excess of about 250 mg/l can give rise to detectable taste in water and so this is regarded as the maximum allowable guideline value (WHO 2004).

Despite the public health implications of faecally derived chemicals, these parameters have often been omitted from groundwater quality monitoring programmes in developing countries. Taylor *et al.* (2004), reviewing available geochemical data from urban areas in sub-Saharan Africa, found fewer than 10 studies that included urban groundwater nitrate and chloride concentrations and concluded that the quality of groundwater in urban areas of sub-Saharan Africa has been the subject of very few detailed studies and rising nitrate concentrations have been identified as a concern in North African countries such as Morocco (Abouzaid & Echihabi 1995).

Several authors have derived and employed empirical formulae (Equation (1); Foster & Hirata 1988) to predict the concentrations of nitrate and chloride in groundwater beneath unsewered urban areas in Latin America and South East Asia (e.g. Foster & Hirata 1988; Morris *et al.* 1994; ARGOSS 2001) based on a simple mass balance calculation, i.e. the total faecal loading on a typical one hectare plot divided by the total recharge volume entering that hectare:

$$\text{Concentration of N or Cl (mg/l)} = 1000aAF/(0.365AU + 10\mathrm{I}) \quad (1)$$

where a = unit mass of N or Cl excreted per person per year (assumed by these and subsequent authors as 4 and 2 kg, respectively), A = population density (persons per hectare), F = proportion of N oxidised and leached into the subsurface; typical values proposed have been 0.2–0.6 (Walker *et al.* 1973; Kimmel 1984), U = non-consumptive portion of total water use (litre per person per day) and I = natural rate of rainfall infiltration (mm per year).

However, application of assumed N and Cl loading values for all countries and development settings does not take into account variations in diet between countries and their effects on N and Cl loadings to the subsurface. Hence this study attempts to further develop and improve the inputs to such formulae, as well as extending them to urban settings in Africa. More detailed investigations of this type of relationship are necessary as they require continuous refinement and field testing for justification (Van Ryneveld

& Fourie 1997). In addition, the authors examine the state of groundwater quality and sanitation management in two mid-sized African cities (Timbuktu, Mali and Lichinga, Mozambique) where the vast majority of residents draw their drinking water from underlying aquifers but also use it as a receptor for on-site sanitation systems. This was done in order to understand the impact of urbanisation on groundwater quality, to postulate what this means for the long term health of communities and as an opportunity to extrapolate the results to other unsewered city areas with standard monitoring programmes. The ultimate aim is to allow recommendations to be made for specific interventions for prevention and treatment where required.

BACKGROUND

The two case study cities (Figure 1) represent very different African urban area settings; some key parameters are compared in Table 1.

Lichinga, Mozambique

Lichinga is the capital city of Niassa, Mozambique's largest and least developed province. Niassa is almost entirely underlain by crystalline basement characterised by plateaux formed during several erosion cycles with local inselbergs and mountainous areas. Many parts of the extensive plateaux are underlain by deeply weathered rocks. The basement complex is dominated by gneiss and a gneiss–granite–magmatite complex that forms part of the Mozambique Metamorphic Belt (Ferro & Bouman 1992). This crystalline basement landscape has led to complex local drainage patterns with many local swamps and rivers that are often used for drinking water purposes. High failure rates in drilling are common and yields are seldom in excess of $1.5\,l\,s^{-1}$ although higher yields may be realised in areas of fracturing and along dykes. The majority of people in the urban areas of Niassa abstract water from unprotected, unlined traditional wells or surface water. A piped water system does exist, but it serves only a small percentage of

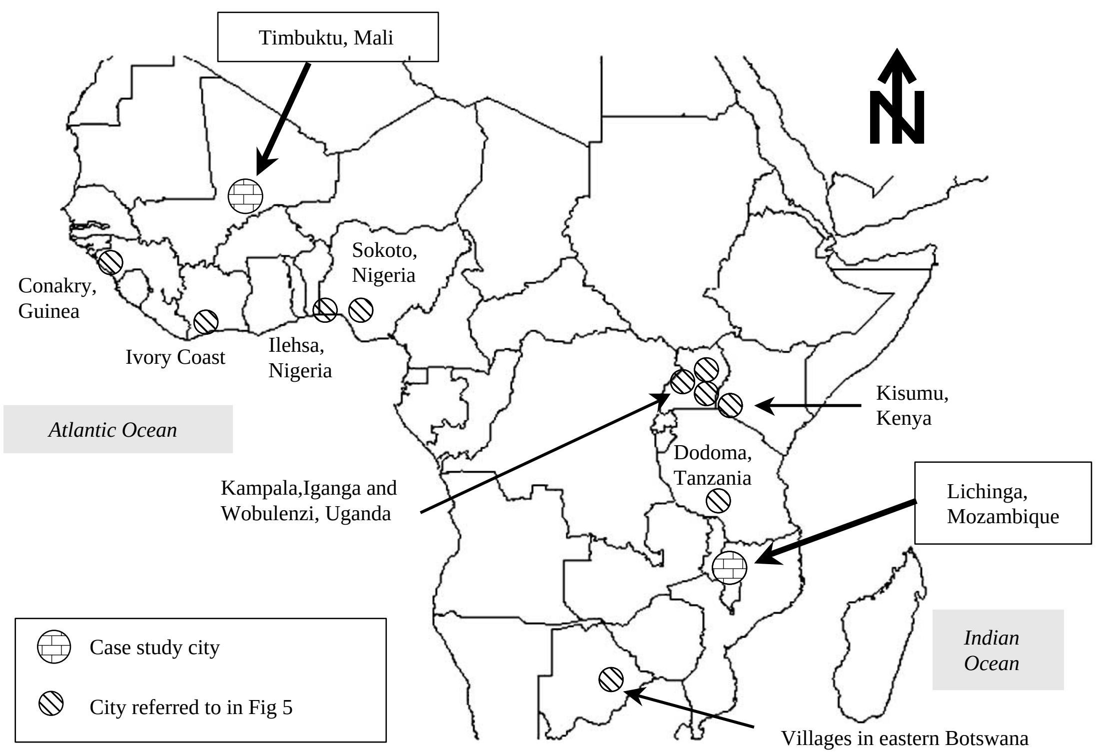


Figure 1 | Map showing location of the two case study towns along with the locations of other cities with median urban geochemical values cited in Taylor et al. (2004) and shown in Figure 5.

Table 1 | Comparison of key parameters for Timbuktu, Mali and Lichinga, Mozambique

	Timbuktu	Lichinga
Country	Mali	Mozambique
Co-ordinates	16°46′N, 3°00′W	13°18′S, 35°15′E
Town area	~880 ha	~12,500 ha
Population	~38 000	~100 000
Average rainfall	230 mm yr^{-1} (June to Sept.) with high variability.	1120 mm yr^{-1} (mainly Oct. to April)
Geology	Quaternary clay–sand alluvium, eolian sand and eluvium; situated at northern edge of the Sahel and the southern edge of the Sahara desert	Crystalline basement complex
Water supply	Traditional shallow to deep dug wells. Drilled and dug wells to depth increasing from 3 m near the Niger River to over 35 m 45 km from the River and fitted with Mark II handpumps.	Small piped system but mainly traditional shallow hand dug wells; improved windlass wells, Afridev handpumps, rope pumps, local swamps and springs
Sanitation types	Pit latrines (traditional and improved) and seepage pits in urban areas. Latrines are rare in rural areas except at schools and health centres.	Pit latrines (traditional and improved) and some ecological sanitation and septic tanks

the population and is generally unreliable, which increases the pressure to use local groundwater. Traditional shallow hand-dug wells are, on average, 8 m deep (52 wells measured as part of this study) with an average depth to water of 5 m (from 93 measurements). The most common handpump used on public protected and lined wells is the AfriDev, though many are currently in a state of disrepair. The province receives over 1,100 mm of rain per year, mainly during the wet season (November to April). Latrine coverage rates vary from 60–90% from a survey of two towns in Niassa, though the vast majority of these are traditional latrines that are not considered adequate provision under the national sanitation policy (WaterAid Mozambique 2004). Rural sanitation provision is much lower than this. Ecological Sanitation (ECOSAN) toilets are increasing in popularity and are designed to reuse some of the nutrients in human waste after storage for a sufficient period to ensure pathogen die-off. There are two types of ECOSAN toilet in use in Niassa, the Fossa Alterna and the Arborloo. The Fossa Alterna uses two partially lined permanent shallow pits with one moveable latrine slab. The slab is moved alternately between pits, the first pit being emptied only when the second pit is completely full. The Arborloo (Morgan 2005) sees a young fruit tree planted on the site of a full latrine pit and formalizes a practice that has been in evidence in Niassa for decades (Breslin 2001).

Timbuktu, Mali

Timbuktu is a city of just under 40 000 population located in Mali at the northern edge of the Sahel and the southern edge of the Sahara desert (Figure 1). Here the savanna begins to transform into semi-desert and desert, giving rise to extensive sandy areas. The geology consists of Quaternary deposits that include clay–sand alluvium, eolian sand and eluvium (United Nations 1988). The city is situated about 12 km north of the Niger River as the river begins its wide bend from a north-easterly to a south-easterly direction of flow. Rainfall, which occurs between June and September, is on average ~230 mm per year, but is highly variable. Shared human and animal use of watering points, and to some extent water containers, is a common feature of life in the semi-desert savannas of the northern region of Mali. Dug wells with a surrounding wall are traditional, often rigged with a pulley and rope to facilitate raising and lowering of an open bucket, often powered by a mule or camel. The water table depth from ground surface increases steadily with distance from the Niger River, from 3–6 m near the river to 13–17 m in Timbuktu, and to 35 m in Agouni 31 km north of Timbuktu during the dry season; water levels rise about 2 m during the rainy season in Timbuktu. Water within the city is supplied from three municipal boreholes located in the southwest section of the city, north of the Niger River. It is distributed within the city to public standpipes and house connections. However, traditional wells and wells fitted with India Mark II pumps remain in use within the city as well as in communities lying outside the city. Latrines are not common features of life in the desert outside of settled areas. Human wastes within the city are disposed of to cesspits serving individual houses.

METHODOLOGY

Analyses

Chemical analyses (NO_3-N, Cl) in Lichinga were carried out on-site using a Palintest Photometer Model 5000 (Palintest UK) with all analytical tests checked against corresponding standards at the time tests were run. Each sample transmission reading was checked three times and, if transmission readings varied by more than 2% the test was repeated. In Timbuktu, nitrate was tested using a Hach colour comparator Model NI-12 and NitraVer 5 reagent within a range of 0–50 mg/l as N. Nitrite was tested within a range of 0–0.5 mg L^{-1} as N with NitriVer 3 reagent. Temperature and electrical conductivity were measured at the study sites using a Palintest Micro 500 Conductivity meter (Palintest UK). This meter measures up to three different ranges (0–199.9 μS, 0–1999 μS and 0–19.99 mS with associated resolutions of 0.1 μS, 1 μS and 0.01 mS); accuracy is quoted at ± 1%. The measurement range for temperature is 0–80°C, with 0.5°C accuracy and 0.1°C resolution.

In Lichinga, sampling was carried on three to four occasions for 74 wells (serving high numbers of users) that were chosen to represent different well types and to provide a spatial spread. Also single samples were taken from a range of other wells ($n = 159$). All sampling was undertaken between April 2002 and August 2004. Additional samples were also preserved and returned to the UK for a complete suite of analyses where cation analyses were carried out using a Perkin-Elmer Optima 3300DV ICP-OES and Cl, TON, NO_2-N; NH_4-N analyses were carried out using a Skalar SAN++ Analyzer (automated colorimetry). Water quality sampling in the Timbuktu region was undertaken during one dry season and during one rainy season between September 2002 and May 2003 as part of a wider water quality sampling programme at 94 wells in 55 communities in the Timbuktu and Gourma Rharous Circles in northern Mali. Samples were taken from a total of 31 wells located north of the Niger River and within 35 km of Timbuktu, including 14 wells within, or very near to, the immediate Timbuktu urban area and the latter form the focus of this paper (e.g. Table 2).

Estimation of country-specific nitrogen values in excreta

The amount of nitrogen in food is linearly correlated with its protein content and so by comparing food statistics with detailed excreta measurements in Sweden this relationship was determined to be a factor of 0.13 (Jonsson & Vinneras 2004; Jonsson *et al.* 2004). This relationship allows the calculation of N in excreta in local diets, assuming a similar relationship and assuming similar proportions of food wastage. Protein content of food supply per capita is available for each country in the world through databases maintained on-line by the Food and Agricultural Organization (FAO), so providing a simple and quick way of estimating nitrogen content in excreta. These data make it

Table 2 | Electrical conductivity in groundwater in the three distinct zones identified in and around the Timbuktu urban area: the urban area of Timbuktu itself, the zone outside the town but potentially having higher values than surround wells and then the other wells beyond this zone

	Urban area (μS cm^{-1})	Zone of increased conductivity (μS cm^{-1})	Other (μS cm^{-1})
No. of samples	29	12	28
Minimum	221	145	126
Maximum	2010	640	313
Median	1055	466	196

possible to estimate total and per capita food supplies available for human consumption in terms of quantity and, by applying appropriate food composition factors for all primary and processed products, also in terms of caloric value and protein and fat content. Per capita consumption values are derived by dividing the quantities of food available, as determined by the FAO, by the total population actually partaking of the food supplies during a certain time period.

RESULTS

The impact of urbanisation on groundwater quality

It was assumed for both case study areas that nitrate forms all of the inorganic nitrogen because of the low values of ammonium and nitrite ions measured at the same time (<1 mg/l N), though one sample from Timbuktu had a value greatly in excess of this (5.0 mg/l NO_2-N). A wide range of NO_3-N and Cl values were measured in both Lichinga and Timbuktu (Table 3), which makes the differentiation of anthropogenically affected groundwaters from those affected solely by natural geochemical processes more difficult. However, the effects of human waste on groundwater nitrate levels can be seen clearly in Figures 2 and 3 which show much higher concentrations in the urban areas of both Timbuktu and Lichinga, respectively, compared with the surrounding rural areas.

Natural values of electrical conductivity of groundwater in Niassa are generally less than 500 μS cm^{-1} and higher values observed in urban areas are interpreted to represent anthropogenic influence. Temporal differences can be seen at individual wells (e.g. N values in Figure 3) though the mean electrical conductivity varied only from 155 μS cm^{-1} to 175 μS cm^{-1} from dry to wet season, respectively; the median increased only from 129 μS cm^{-1} to 134 μS cm^{-1}.

Conductivity levels observed in wells located to the south and east of the Timbuktu urban area varied between 126 and 313 μS cm^{-1} (Table 2). Within the Timbuktu urban area itself, conductivity increased to between 348 and 2010 μS cm^{-1} (median 1140 μS cm^{-1}, mean 1228 μS cm^{-1}), decreasing to an average of 461 μS cm^{-1} (median 466 μS cm^{-1}) in well waters sampled north of the Timbuktu urban area. Nitrate concentrations (mean 26.9 mg/l, median 27 mg/l) in well waters sampled within the Timbuktu urban area varied substantially, as can be seen in Figure 2, but were not detected outside of the urban area save at specific wells, most likely subject to contamination. As in Mozambique, the electrical conductivity results from all wells sampled in northern Mali tended to be lower during the dry

Table 3 | Summary of all and urban only groundwater nitrate and chloride concentrations (mg/l) from the study areas in Mozambique and Mali

	Mozambique		Mali	
Field measurements	**Nitrate as N**	**Chloride**	**Nitrate as N**	**Chloride**
Total number of samples	180	180	163	147
WHO guideline (mg/l)	11.2	250	11.2	250
Maximum conc. (mg/l)	20.0	83	48.1	2700
Minimum conc. (mg/l)	<0.1	<0.1	<0.1	<0.1
Median conc. of all samples (mg/l)	2.3	7.6	<0.1	56
Median conc. of urban samples only (mg/l)	5.6	13.5	35	500
Calculated values (mg/l) from Equation (1)	2.3–7	9.5–19	41–123	104–208
N:Cl (mg/l) ratios (from calculated values)	Lichinga: 0.3–1.9		Timbuktu: 0.5–3.0	

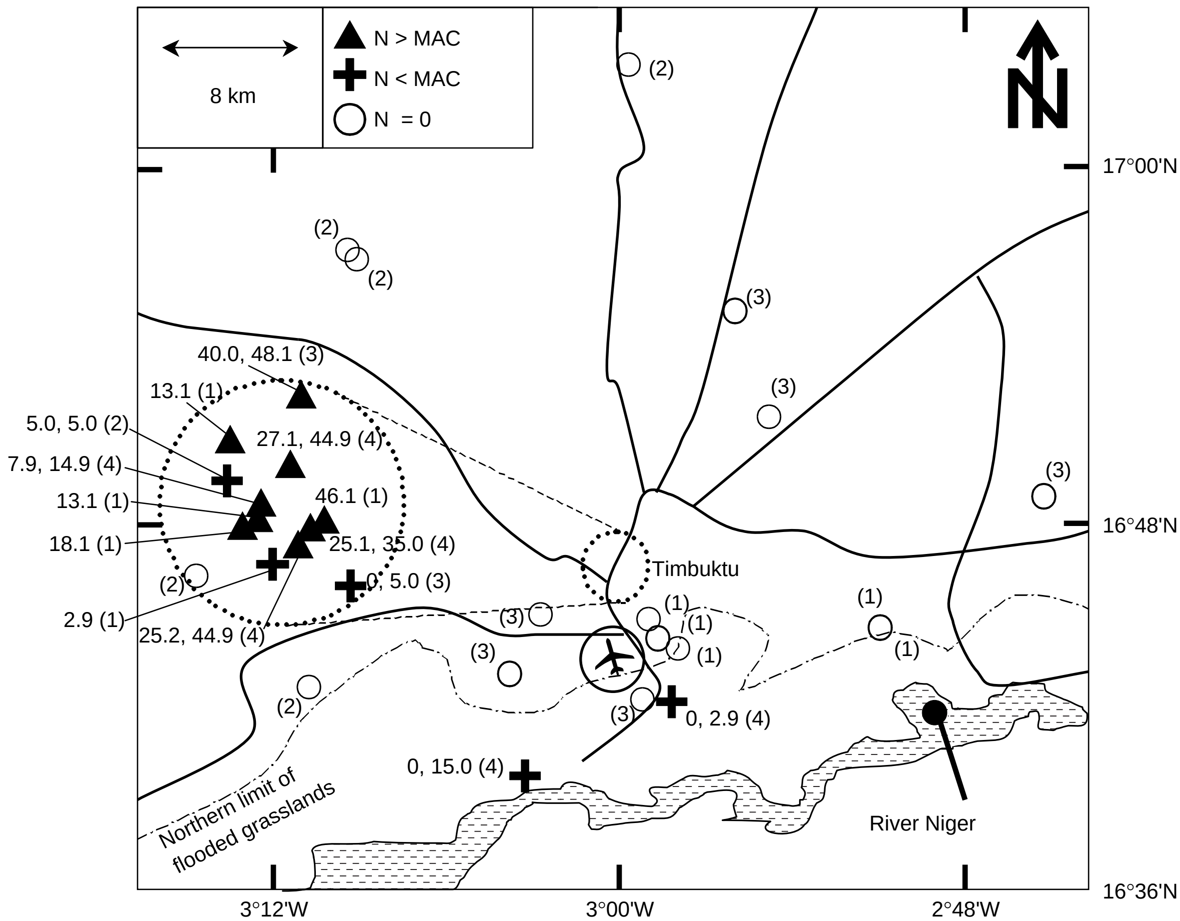


Figure 2 | Plot of median nitrate values (below and in excess of the WHO guideline Maximum Allowable Concentration (MAC) in Timbuktu and surrounding rural area (2002–2003). The town centre is circled (and expanded to facilitate presentation). The solid black lines indicating the road network. Temporal variation is illustrated by displaying the minimum and maximum nitrate values (mg/l as N) at available wells; the number of sample points is given in brackets after the values. The map is based on digital charts of the world developed by Environmental Systems Research Institute, Inc. (ESRI) from US Defense Mapping Agency data.

season than during the wet season (dry season mean conductivity 441 $\mu S\ cm^{-1}$, median 220 $\mu S\ cm^{-1}$; wet season mean conductivity 585 $\mu S\ cm^{-1}$, median 236 $\mu S\ cm^{-1}$), but the difference was not statistically significant ($P_1 = 0.2297$, $P_2 = 0.4593$ by the Mann–Whitney test).

Nitrate and chloride groundwater concentration estimation

Annual per capita N and Cl loadings from excreta for the case study cities (Table 4) were calculated using the method of Jonsson & Vinneras (2004). This method yields N to Cl ratio ranges quite different from those previously assumed using the standard values for N and Cl of 4 and 2 kg per capita per year, respectively (Foster & Hirata 1988). Recharge values are also needed to estimate concentrations of the solutes in groundwater. Little research to estimate recharge has been undertaken in the Niassa region of Mozambique. A figure of 10% of average annual precipitation between 1995 and 2002 (1120 mm at climate station location 13.3° S, 35.2° E, altitude 1365 m) was assumed for this study as this is a typical value for such crystalline aquifers (ARGOSS 2001). Community water usage was estimated in and around Lichinga and Mandimba towns by interviewing 84 families that were randomly selected. This study gave an average per capita usage of 23 l/person/d in small village to rural areas, but usage was less where longer distances of travel to collect water were required in the Mandimba villages. Water usage in Lichinga town itself varied from 30–50 l/person/d.

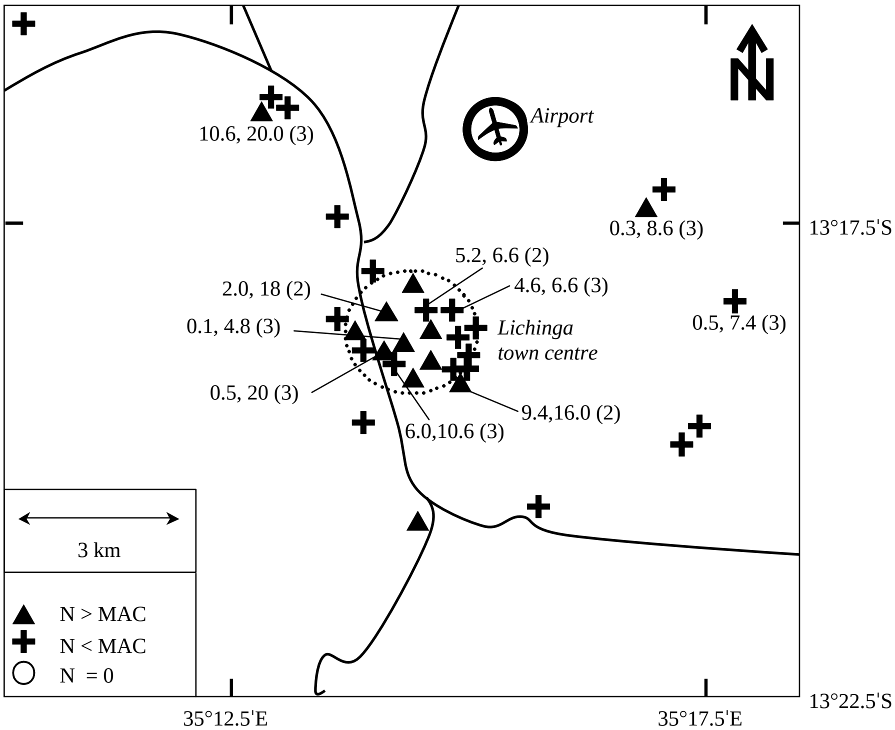


Figure 3 | Plot of median nitrate values (below and in excess of the WHO guideline Maximum Allowable Concentration (MAC) in Lichinga and surrounding rural area (2002–2004). The town centre is circled and the solid black lines indicating the tarred road network. Temporal variation is illustrated by displaying the minimum and maximum nitrate values (mg/l as N) at available wells; the number of sample points is given in brackets after the values. All wells without these values were sampled on one occasion only.

These values were applied to the formula of Foster & Hirata (1988) given in Equation (1), i.e. $a = 1.82$ for nitrogen and 1.5–3.0 kg per capita per year for chloride (from Table 4), $A = 8$ persons per ha (from Table 1), $F = 0.2–0.6$ for NO_3^- and 1.0 for Cl, $U = 50$ litres per capita per day and $I = 112\,\text{mm yr}^{-1}$.

The estimation of concentrations for the Timbuktu urban area is more difficult than for Lichinga as no accurate water usage statistics are available and recharge estimations are very difficult due to the variability in rainfall and the arid conditions. However, the values used are $a = 3.0$ for nitrogen and 1.5–3.0 kg per capita per year for Cl (from Table 4), $A = 43.2$ persons per ha (Table 1), $F = 0.2–0.6$ for NO_3^- and 1.0 for Cl, $U = 30$ litres per capita per day (estimated from observation) and $I = 15$ mm per year (from BGR/UNESCO (2004), though recharge rates in arid areas can vary widely). The calculated concentrations and resulting N:Cl ratios (as meq/l) from both sites are incorporated into Table 3.

DISCUSSION

Study areas

The calculated nitrate and chloride concentration ranges for Lichinga correspond well with the median measured

Table 4 | Calculation of country-specific nitrogen loading and resulting N and Cl value ranges

Country	Total protein (g per person per day)[1]	Total N (kg per person per year)[2]	Total Cl (kg per person per year)[3]
Sweden	98	4.6	1.5 to 3
Mozambique	38.7	1.8	1.5 to 3
Mali	63.3	3.0	.5 to 3

[1]Average daily protein values 1998–2002 (g per person) from FAO (2005).
[2]The amount of nitrogen in food is linearly correlated with its protein content. Hence, by employing protein contents of faeces available from the FAO, the nitrogen content of the excreta can be calculated (Jonsson & Vinneras 2004).
[3]Normal chloride losses are about $4\,\text{g}\,\text{d}^{-1}$ in a non-salt-free diet though Cl intakes of up to $12\,\text{g}\,\text{d}^{-1}$ from food alone have been reported (WHO 2004).

concentrations, which are towards the middle of the calculated range (Table 3). The calculated upper and lower N:Cl ratios (as calculated from Table 4) are included in a graph of sampled N versus Cl values (Figure 4). The majority of urban points plot between the calculated ratios. Figure 4 also highlights the effect of urbanisation on the measured values and shows several wells exceed WHO guidelines on N values. The wide range of spatial and temporal concentrations reflects the range of flowpaths, the proximities of wells to latrines, the degree of oxidisation of reduced nitrogen to nitrate and the amount of seasonal rainfall as well as the length of the rainy season. The temporal variations in N will also be affected by contamination being washed into poorly protected wells after the rains (Cronin *et al.* 2006) and the median value is used to take all of these factors into account.

Timbuktu and its immediate surroundings offer an ideal site for the study of the impact of wastes on the chemical quality of groundwater in and around urban areas as the city's arid zone setting means that its surrounding area is sparsely populated. Conductivity values and chloride concentrations in groundwater outside the immediate urban area and to its south were low and nitrates were not detected save in two wells adjacent to surface water sources and subject to local pollution where very low nitrate concentrations occurred in occasional samples. In contrast, within the immediate Timbuktu urban area, conductivity and concentrations of chloride and nitrate are increased significantly, reflecting pollution from cesspits and solid waste. In particular, elevated nitrates were demonstrated in all wells within the Timbuktu urban area (Figure 2) with concentrations up to 48 mg/l as N. The median concentration of nitrate in the urban samples was in excess of WHO guideline values (Table 3) and 22 of the 29 samples exceeded the guideline value. Higher conductivity values north of the Timbuktu urban area may suggest a wider influence of the urban area, although increases in salt concentrations originating from natural sources cannot be ruled out.

Ratios of nitrate-N to chloride (in meq/l), determined for well water samples from the Timbuktu urban area, varied widely but were generally lower than the calculated values in Table 3, though the higher values did fall within the range of calculated values (Table 5). This possibly

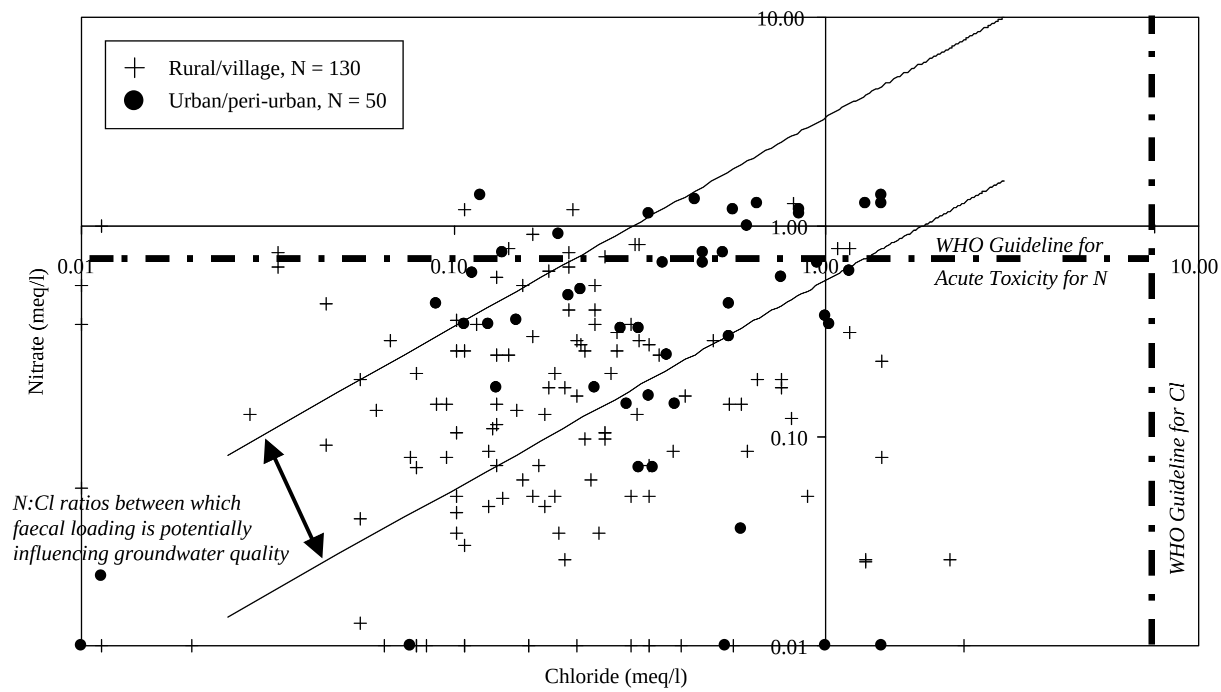


Figure 4 | Plot of Nitrate versus Chloride (meq/l) for all samples taken in Lichinga. The elevated values are principally from urban areas (circle markers) with the majority of points plotting inside the upper and lower limits of NO_3:Cl ratios, as calculated from Table 4, and shown by the two parallel straight lines. For reference, the WHO maximum guideline values for N and Cl are shown by the broken lines.

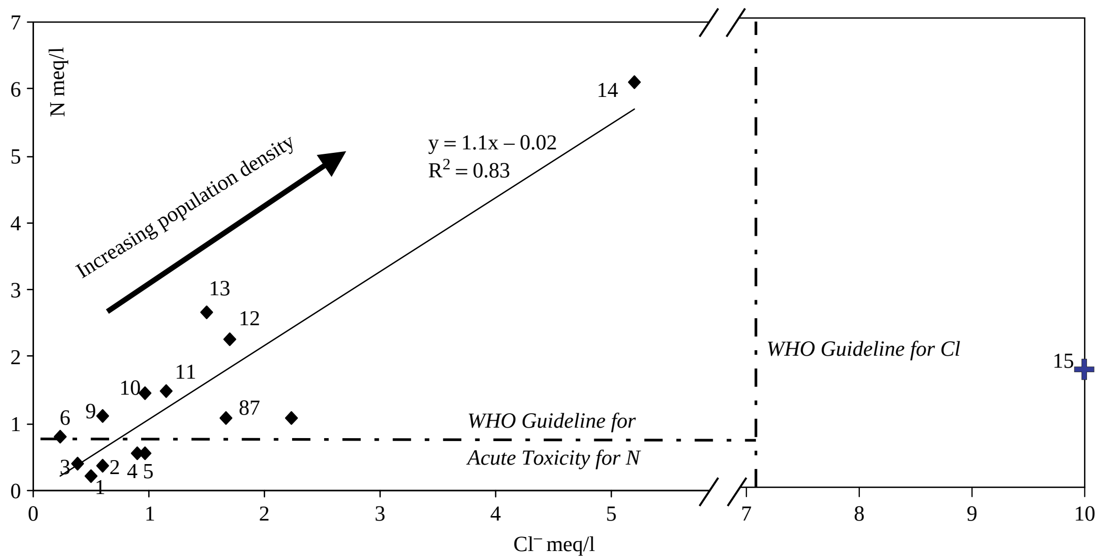
Table 5 | A comparison of N:Cl ratios (in meq/l) for the wells inside the Timbuktu urban areas with wells outside this area that had detectable N concentrations

	Timbuktu urban area	Other wells positive for nitrate
No. of samples	21	23
Minimum	0.05	0.01
Maximum	0.79	1.12
Median	0.12	0.11
Mean	0.18	0.20

reflects uncertainty in the input values used in Equation (1). It is noted also, however, that in some locations in Mali (although not in the immediate Timbuktu urban area) natural chloride concentrations are very high (2700 mg/l or 76.2 meq/l), resulting in extremely low N:Cl ratios. Furthermore, denitrification could contribute to a reduction in the ratio in this urban area.

It is interesting to compare the results from Lichinga and Timbuktu with other African urban areas to assess whether the results from these two studies can inform N and Cl comparisons for future groundwater monitoring studies. Figure 5 presents the median values from Lichinga and Timbuktu along with other available urban monitoring data and city values cited by Taylor *et al.* (2004). The resulting trendline ($R^2 = 0.83$) for the N:Cl as meq/l ratio gives a value of 1.1. This approximate ratio is less dependent on population density, unlike the actual solute values. Hence, values from other African unsewered cities may be plotted on a similar graph to assess the extent to which faecal loading is adversely affecting groundwater quality.

The limitation of this method, however, has been demonstrated by some localised results from northern Mali where local background chloride concentrations were elevated (most probably due to groundwater dissolution of halite) or where inputs to Equation (1) may be suspect and this is why the Timbuktu point is so far from the



Ref.	Town	Ref	Ref.	Town	Ref
1	Wobulenzi	Tindimugaya, C., (2000)	9	Ivory coast	Faillat (1990)
2	Kampala (low density)	Barrett *et al.*, (1998)	10	H. Mosquee, Conakry	Gelinas *et al.*, (1996)
3	Lichinga	Case study	11	H. Mosquee, Conakry	Gelinas *et al.*, (1996)
4	Iganga	Barrett *et al.*, (1998)	12	Bonfi, Conakry	Gelinas *et al.*, (1996)
5	Ilehsa	Malomo *et al.*, (1990)	13	Bonfi, Conakry	Gelinas *et al.*, (1996)
6	Sokoto	Uma (1993)	14	Villages, E. Botswana	Lewis *et al.*, (1982)
7	Kisumu	Pedley *et al.*, (in prep)	15	Timbuktu	Case study
8	Kampala (high density	Barrett *et al.*, (1998)			

Figure 5 | Median Nitrate and Chloride (meq/l) concentrations for all cities shown in Figure 1 with number labels referred to in the adjoining table to allow individual city identification. Timbuktu urban median value (10, 1.9) is shown but not included in the ratio calculation. For reference, the WHO maximum guideline values for N and Cl are shown by the broken line.

trend-line. In addition, denitrification may have played a role in decreasing the N:Cl ratio in Mali. The above N:Cl ratio of 1.1 suggests a typical N value in excreta of 2.2 kg per person per year if the leaching factor is assumed to be 0.4 and the chloride loading is taken as 2 kg per person per year. This value for per capita nitrogen excretion compares much better with the average annual N loading value of 2.6 kg per person per year calculated from the FAO protein consumption statistics (Table 6) than the previously proposed empirical value of 4 kg per person per year. It should be noted also that the data plotted in Figure 5 suggest that median nitrate concentrations exceed WHO Drinking Water Guidelines (WHO 2004) in over half of the towns for which groundwater quality data are available.

It is not surprising that the estimated N concentrations in excreta are lower in these African countries than the often quoted 4 kg per person per year, as the latter may be more suited to Northern Hemisphere diets (Table 4). Typical diets in Mozambique and Mali are heavily dependent on low protein, cereal foods (i.e. millet, sorghum, rice, maize, wheat) though high protein beans are very popular in Niassa. In Mali, cereals are reported to account for 74% of the energy in the diet (Barikmo *et al.* 2004). Table 6 highlights the differences in nitrogen excreta loading even among African countries. Of course, there may be considerable variation in consumption among individuals and regions depending on diet, supply and even geographical differences in nutrient content for the same cereal (e.g. Barikmo *et al.* 2004). There are a number of other factors that influence the resulting concentrations of N and Cl in groundwater under urban areas. These include the quantity of solutes in the waste loading, which depend on waste composition and population density, the volumes of water recharging into the aquifer derived from precipitation and from domestic water use in the area as well as solute natural background levels (Van Ryneveld & Fourie 1997). Population density is often difficult to measure in urban African settings with frequent expansion and population density increases due to migration from rural to peri-urban and urban areas. Estimating recharge in urban areas is extremely difficult in all cities, regardless of location or development status (Cronin & Lerner 2004). The increase in impermeable area in an urban region changes the surface and groundwater hydrology (Lerner *et al.* 1990). Hence, infiltration and direct recharge often decrease, resulting in increased surface runoff though this may be compensated for by localised recharge from soakaways or storm drains and latrines. To better estimate urban recharge volumes, detailed measurements of both components of the recharge, i.e. urban-influenced natural recharge as well as urban discharge, would be required.

Table 6 | Calculated protein and nitrogen loading in excreta for inhabitants of cities shown in Figures 1 and 5 and based on FAO (2005)

	Average protein for years 1998 to 2002 (g per person per day)	Nitrogen (kg per person per year)
Nigeria	61.8	2.9
Ivory Coast	52.4	2.5
Guinea	50.3	2.4
Uganda	54.9	2.6
Mali	63.3	3.0
Mozambique	38.7	1.8
Kenya	57.1	2.7
Botswana	67.2	3.2
Average	53.6	2.6

Timbuktu (and the neighbouring region of Mali north of the Niger River) is fortunate in that good quality groundwater is available from municipal wells located outside the area influenced by urban groundwater contamination. This water is distributed within the city itself but by providing more public standposts where wells are currently in use, and extending the distribution system to serve the outskirts of the city, the potential hazard of ingesting high nitrate groundwater could be reduced.

Interventions to address elevated nutrient values

As stated in the introduction, on-site sanitation will continue to be the predominant form of sanitation in peri-urban and urban Africa for the foreseeable future. The rapid rate of urbanisation and the high capital and maintenance costs associated with conventional sewer networks means that such systems are often not viable options, at least for the near future (Drangert & Cronin 2004). If this is the case, however, it must also be accepted that on-site sanitation will add nitrogen loadings to the subsurface in the range of 2.2–2.6 kg per person per year. This has been shown to result in nitrate concentrations in excess of WHO guidelines in many towns, especially those with higher population densities (such as those cited in Figure 5). Interventions are required if it is desired to reduce nitrate concentrations in drinking water to meet international standards and so diminish the associated health risks. Neither treatment, which is costly, nor control by blending, are practical options in sub-Saharan urban areas.

One potential intervention to reduce the nitrogen loadings to underlying aquifers would be to intercept the bulk of the nitrogen load to latrines. Urine contributes by far the largest proportion of nitrogen (70–90%) in human waste, the split depending on the digestibility of the food consumed, with digested nutrients leaving the body via urine and undigested matter leaving via faeces (Jonsson & Vinneras 2004). The high N content of urine suggests that urine-diverting toilets represent a potential mechanism by which to achieve the separation and removal of nitrogen from latrines (e.g. Drangert & Cronin 2004). However, diverted urine then has to be utilised in a controlled manner, otherwise it can infiltrate and create a localised high-concentration N source. Application of diluted urine to plants as a source of water and nitrogen following separation of the urine offers a potentially productive way to achieve this. Typical N uptake, depending on loading rates and crop type, can be in the range of 68–90% (Prajapati & Gajurel 2004). Assuming 80% of N is excreted with urine and two thirds of the urine N is utilised by irrigated plants then of the ~2.6 kg N excreted per person per year, ~0.5 kg will enter the latrine as faeces and 2.1 kg will be excreted with urine, of which 1.4 kg can be used for plant growth. The remaining 0.7 kg N in the effluent of the plant fertilisation process, if infiltrated to the subsurface, will bring the total N loading to 1.2 kg, or about half of the normal loading entering via the pit latrine. This option could alleviate groundwater pollution while at the same time increasing crop yields and, indirectly, nutrition levels. Though work is on-going in this area, further research is needed to ensure such projects can significantly reduce N loadings to the subsurface in an acceptable manner and avoid point sources of high-concentration N. These simplified calculations demonstrate that urine diverting toilets and subsequent plant fertilisation could prove an appropriate technical intervention to reduce nitrate loadings to groundwater in much of sub-Saharan Africa, especially where water is scarce.

CONCLUSIONS

Monitoring of groundwater quality in Timbuktu and Lichinga, together with results from other reported urban groundwater studies from Africa, have shown that urbanisation has led to elevated nitrate and chloride concentrations in groundwater and that on-site sanitation is the likely cause. Previously derived empirical relationships using N:Cl ratios have employed excessively high source N values in excreta. These have been based on Western rather then typical African diets. A simple method for measuring country-specific N values in excreta, based on readily accessible FAO data, has been used to calculate loading values for Timbuktu and Lichinga. The average N excretion loads derived in this way for African urban areas was approximately 2.6 kg per person per year. The median results from groundwater monitoring in Lichinga were compared with those from other published studies and from this it was deduced that the approximate N:Cl ratio (in meq/l) for urbanised areas affected by on-site sanitation tended towards 1.1. This ratio could be used in future studies for comparative purposes with other urban African areas though care must be exercised when high background concentrations are encountered, as is the case in Timbuktu. While population density affects absolute solute concentrations, the ratio remains approximately constant. Ratios calculated for Timbuktu and other sites in northern Mali differed substantially in some locations because naturally occurring background chloride concentrations are high.

To manage the risks associated with nitrates in groundwater originating from on-site sanitation, it is proposed that urine-diverting toilets could be used to reduce N loading to the subsurface by over 50%, provided it was done in association with properly managed cultivation. Such an option could increase crop yields and nutrition levels and thus aid poverty alleviation. Though work is on-going in this area, further research is needed to ensure that such projects would lead to reductions in N loadings and not result in poor urine management with subsequent infiltration becoming point sources of contamination. In the future, other threats to groundwater chemical quality in African urban aquifers also need to be recognised, principally from organic chemicals and others linked to various urban activities. However, as Taylor *et al.* (2004) point out, their influence on urban groundwater chemical quality has yet to be established due to the lack of appropriate analytical equipment and due to a lower level of industrial development in sub-Saharan cities. Poor enforcement of environmental regulations compounds this problem.

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