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Research article

Nitrate pollution of groundwater by pit latrines in developing countries

Michael R. Templeton [1,] *, Acile S. Hammoud [1], Adrian P. Butler [1], Laura Braun [1], Julie-Anne Foucher [1], Johanna Grossmann [1], Moussa Boukari [2], Serigne Faye [3] and Jean Patrice Jourda [4]

1 Department of Civil and Environmental Engineering, Imperial College London, London, United Kingdom SW7 2AZ
2 Département des Sciences de la Terre, Université d’Abomey-Calavi, Cotonou, Bénin 01 BP 4521
3 Département de Géologie, Université Cheikh Anta Diop, Dakar, Sénégal PO Box 5005
4 Département des Sciences et Techniques de l’Eau et du Génie de l’Environnement, Université Félix Houphouët-Boigny, Abidjan, Côte d’Ivoire 22 BP 582

* **Correspondence:** m.templeton@imperial.ac.uk; Tel: +44-207-594-6099.

Abstract: Pit latrines are one of the most common forms of onsite sanitation facilities in many developing countries. These latrines are suitable as a means of isolating human waste, however, conditions within pits often lead to nitrification of the contained waste. In areas with a near-surface aquifer, the potential for nitrate pollution arising from pit latrines cannot be ignored. In this study, site visits were made to three densely populated, peri-urban areas near three West African cities (Dakar, Abidjan, Abomey-Calavi) to gather relevant information about the latrines in use and the soil and groundwater underneath the sites. Modelling was then conducted to demonstrate the potential for nitrate pollution of the groundwater from the latrines in such settings. The depth from the bottom of the pits to the water table was considered as 5, 10 or 30 m, to represent the range of aquifer depths at the study sites. Nitrate half-lives ranging from 500 to 1500 days were considered, and time scales from 6 months to several years were modelled. The results highlighted the high likelihood of nitrate pollution of groundwater reaching levels exceeding the World Health Organization guideline value for nitrate in drinking water of 50 mg/L after as short a period as two years for the aquifer situated 5 m below the pits, when considering moderate to long nitrate half-lives in the subsurface. Careful siting of latrines away from high water table areas, more frequent pit emptying, or switching to urine diversion toilets may be effective solutions to reduce nitrate passage from pit latrines into groundwater, although these solutions may not always be applicable, because of social, technical and economic constraints. The study highlights the need for more reliable data on the typical nitrate concentrations in pit latrines and the nitrate half-life in different subsurface conditions.

Keywords: nitrate; groundwater; latrine; sanitation; pollution; modelling

1. Introduction

Many low-income countries are still striving to meet their Millennium Development Goal (MDG) for access to improved sanitation, and the construction of basic pit latrines is a common strategy that is being implemented to achieve this goal. A pit latrine typically consists of a dug pit approximately 2–3 m deep and 1–2 m^2 in surface area, with the walls often lined with concrete blocks or bricks to prevent pit collapse, and with a slab and superstructure over the top of the squatting hole [1]. Lined pit walls are typically left un-mortared below the top 0.5 m [1], to allow the liquid fraction of the waste to infiltrate into the surrounding soil, leaving mainly the solid waste in the pit. However, both the liquid and solid fractions of the waste contain nitrogen, e.g. urea in urine and various forms of organic nitrogen in feces, and the biodegradation of the waste within the pit (and indeed other forms of onsite sanitation, e.g. septic tank soakaways [2,3]) often leads to nitrification of this nitrogen-containing waste, i.e. the formation of nitrate.

Nitrate is persistent and mobile in the subsurface, difficult to remove, and poses serious health concerns if it enters drinking water. The World Health Organization (WHO) has set a guideline concentration for nitrate in drinking water of 50 mg/L based on these health concerns [4]. Therefore, pit latrines may represent a serious risk to those who rely on nearby groundwater as a source of drinking water supply, especially in areas with high water tables that approach the level of the pits. Ironically therefore, regions that have met their MDG for access to improved water supply might see regression in this metric if this potential nitrate pollution arising from onsite sanitation facilities is overlooked.

This study aimed to highlight the importance of this issue by conducting modelling to represent the potential for nitrate contamination of groundwater in three low-income, peri-urban areas of West Africa with relatively high water tables. As is often the case when working in developing countries, data were limited or completely lacking for some of the key parameters of relevance to nitrate transport in the subsurface, therefore the intention of the study was not to estimate precisely the actual nitrate concentrations in the aquifers in these areas, but rather to gauge the likelihood of the nitrate levels in the affected groundwater exceeding the WHO guideline for nitrate in drinking water [4] and to estimate the time scales over which this pollution occurs.

2. Materials and Method

2.1. Site visits, data collection and estimation of parameters

Site visits were conducted to the peri-urban areas surrounding Dakar, Sénégal, Abidjan, Côte d'Ivoire, and Abomey-Calavi, Benin in the summer of 2014 to collect relevant information for the subsequent modelling. Each of these areas is characterized by high water tables, which ranged from between 5 and 30 m below the bottom of the pit latrines and are used for drinking water supply. Some of the necessary information was already available from previous hydrogeological studies which were conducted by the in-country university partners on this research [5,6], including soil hydraulic conductivity and information about depth to water table and aquifer thickness. Other information had to be collected first-hand, including an estimate of the number and dimensions of the pit latrines and the number of users per latrine. For the purposes of the subsequent modelling, a representative model sub-area was considered which was based as much as possible on the values observed through the three site visits and the previously collected information. The modelled aquifer area was 250,000 m^2, with aquifer dimensions of 1000 m in length by 250 m wide and 4 m depth. The latrine density was estimated as one latrine for every 50 m^2, and the area of each pit latrine was observed to be approximately 2 m^2, which sums to a total latrine area of 10,000 m^2. It was determined through an informal survey of the inhabitants that there was an average of 10 users per latrine. The water flux from the pit latrines was estimated as 0.002 m^3/m^2/day based on anecdotal reports of the pit usage and filling rates. The soil moisture was assumed as 0.2 and hence the pore velocity was 0.01 m/day. The longitudinal dispersivity was set at 2 m. The retardation coefficient for nitrate was assumed to be 1, reflecting the high mobility of nitrate [7,8,9]. Hydraulic conductivity data for the soil types, in the study zones, which are a mix of sand and clay, was collected from previous studies [5,6], and an average value of 7.43 m/day was used in the model. The groundwater recharge rate was estimated as being between 0.001 and 0.002 m^3/m^2/day (i.e. between 360 and 720 mm a year) and the hydraulic head gradient was estimated as ranging between 0.01 and 0.02.

There was no data for the nitrate concentration in the bottom of the pits in the study area, and there is very little data on this in the literature. However previous studies have estimated that each person excretes between 7.9–12.5 g/day of nitrogen [10-14]. To simplify the modelling, it was assumed that there was no other input of nitrate besides from the pits, e.g. none from surface runoff. A value in the middle of this range of 10 g/day per person was considered. Assuming 2.5 litres of urine per day and that 60% of the nitrogen in the waste is converted to nitrate [15], this resulted in an estimated nitrate concentration within the pit of 2400 mg/L. It should be noted that the results discussed below (and plotted in Figures 2–4) are directly scalable to this assumed value for the nitrate concentration in the bottom of the pit, therefore the results could be easily translated if a more reliable estimate of the actual concentration can be obtained, e.g. through pit sampling. Given the sensitivity of this and subsequent calculations to the value that is used for the nitrate concentration in the bottom of the pit, future studies should aim to collect data for this parameter in different settings, e.g. different regions, pit designs.

A range of nitrate half-lives have been reported in the literature, and the decay of nitrate will depend on factors such as the biological activity of the soil matrix and the nitrate sorption properties of the soil type. Since no data was available for the nitrate decay rates in the particular soils of the sites in this study, a range of half-lives were considered in the modelling to cover a range of cited values in the literature, from 500 to 1500 days [16,17].

2.2. Modelling approach

In order to provide quantitative assessment of the impact of nitrate from pit latrines on groundwater, a combined modelling approach was used. This comprised an analytical solution for steady-state reactive transport through the unsaturated (or vadose) zone, which was then used as the input to a groundwater mixing model. This approach was selected as it combines sufficient complexity to incorporate the key processes with necessary simplicity due to the lack of detailed field data. More detailed attempts have been made to simulate the problem of sludge disposal, e.g. [18,19]. However, these use the numerical model HYDRUS [20] and require detailed site data to characterize soil hydraulic properties. In contrast, a highly simplified approach has been developed by the British Geological Survey for assessing risk to groundwater from on-site sanitation. However, this does not explicitly consider the effects of denitrification and is used for local-scale assessments (i.e. at the scale of an individual borehole) [21,22].

The standard advection-dispersion-reaction model [23] (Equation 1) was therefore used to estimate the transfer of nitrate into the subsurface, from the bottom of the pit to the top of the water table, using the parameters described in section 2.1.

$$\frac{\partial C}{\partial t}=\frac{d_L v}{R}\frac{\partial^2 C}{\partial z^2}-\frac{v}{R}\frac{\partial C}{\partial z}-\frac{\lambda}{R}C \qquad (1)$$

where, C is the concentration of nitrate in unsaturated soil (g/m^3) (which is equivalent to [mg/L]), d_L is the longitudinal dispersivity (m), v is the mean pore water velocity (m/day), R is the retardation coefficient (> 1 where sorption present), λ is the linear decay coefficient (1/day), which is related to the half-life by $T½ = \log(2)/\lambda$ (days).

For uniform conditions, with a nitrate concentration at the base of the pit latrine of C_0, then the concentration C_{pw} at a depth z_w, the depth of the water table below the base of the latrine, is given as:

$$C_{pw}=\frac{C_0}{2}\left[\frac{\left(\exp\left(vz_w\right)\left(1-\gamma\right)\right)}{2vd_L}erfc\left(\frac{z_w-v\gamma t}{2\sqrt{vd_L t}}\right)+\frac{\left(\exp\left(vz_w\right)\left(1+\gamma\right)\right)}{2vd_L}erfc\left(\frac{z_w+v\gamma t}{2\sqrt{vd_L t}}\right)\right] \qquad (2)$$

where [24]:
$$\gamma=\sqrt{1+\frac{4\lambda d_L}{v}} \qquad (3)$$

The solution was implemented in Matlab©.

A water flow balance and nitrate mass balance were then conducted to estimate the dilution of the nitrate by the aquifer volume and the resulting overall concentration in the aquifer (C_{ao}) after different elapsed times.

Water flow balance: $Q_{ao}= Q_{ai} + A_r\cdot q_r + A_p\cdot q_p$ (4)

Nitrate mass balance: $Q_{ao}\cdot C_{ao}= Q_{ai}\cdot C_{ai} + A_r\cdot q_r\cdot C_r + A_p\cdot q_p\cdot C_{pw}$ (5)

$Q_{ai}=W\cdot H\cdot K\cdot i_i$ (6)

where Q_{ai} is the inflow into the aquifer (m^3/day), Q_{ao} is the outflow of the aquifer (m^3/day), C_{pw} is the nitrate concentration reaching the top of the water table (obtained from the advection-dispersion-reaction model, in g/m^3), C_{ao} is the nitrate concentration in the aquifer outflow (i.e. the ultimate goal of the model, in g/m^3), C_{ai} is the nitrate concentration in the aquifer inflow (assumed to be zero), C_r is the nitrate concentration from surface runoff (assumed to be zero), q_p is the water flux from each pit latrine (0.002 m/d), q_r is the groundwater recharge rate (m^3/m^2/day), A_p is the total surface area of all the pit latrines (m^2), A_r is the surface area of aquifer recharge (m^2), W is the width of the aquifer (m), H is the height of the aquifer (m), i.e. the effective mixing zone, K is the hydraulic conductivity (m/d) and i_i is the hydraulic head gradient. This is represented schematically in Figure 1.

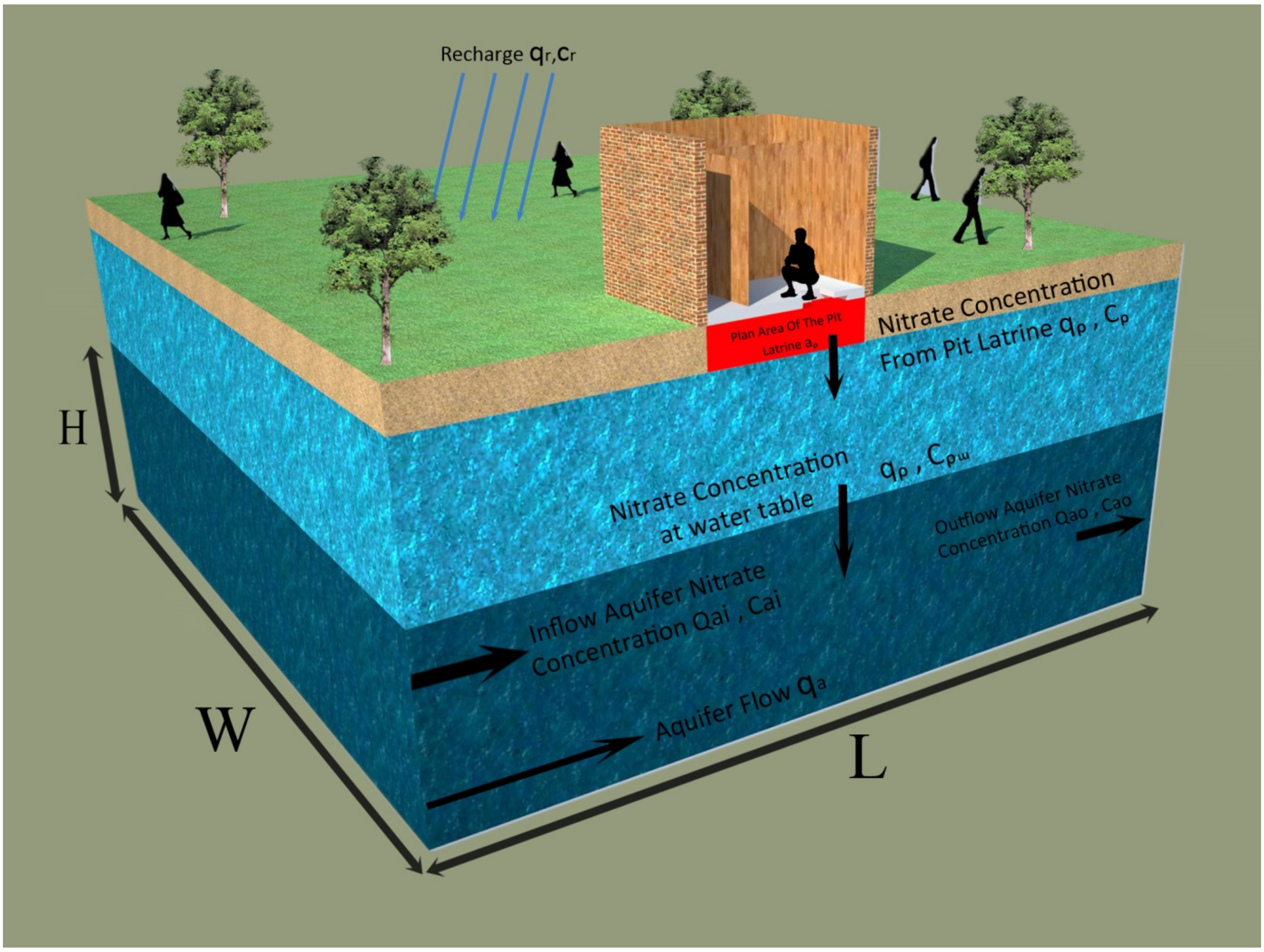

Figure 1. Schematic representation of the model parameters. The light blue zone represents the unsaturated zone and the dark blue zone represents the aquifer.

3. Results

The nitrate concentrations in the subsurface region between the bottom of the pit latrines and the water table based on the advection-dispersion-reaction model are summarized in Figures 2 to 4, considering depths from the bottom of the pits to the water table of 5, 10, and 30 m, respectively, over different time scales, ranging from 6 months up to 50 years. A range of C_{pw} values entering at the top of the aquifer, from 500 to 1500 mg/L, were then considered in the subsequent water flow and nitrate mass balance calculations, to capture the range of C_{pw} values that would occur over time under these different depth and half-life assumptions (Figures 2–4). For these flow and mass balance calculations, two hydraulic head gradients (0.01 and 0.02) and two groundwater recharge rates were considered (0.001 and 0.002 m^3/m^2/day), to represent the estimated ranges of these parameters across the study sites. The resulting C_{ao} values are tabulated below (Table 1).

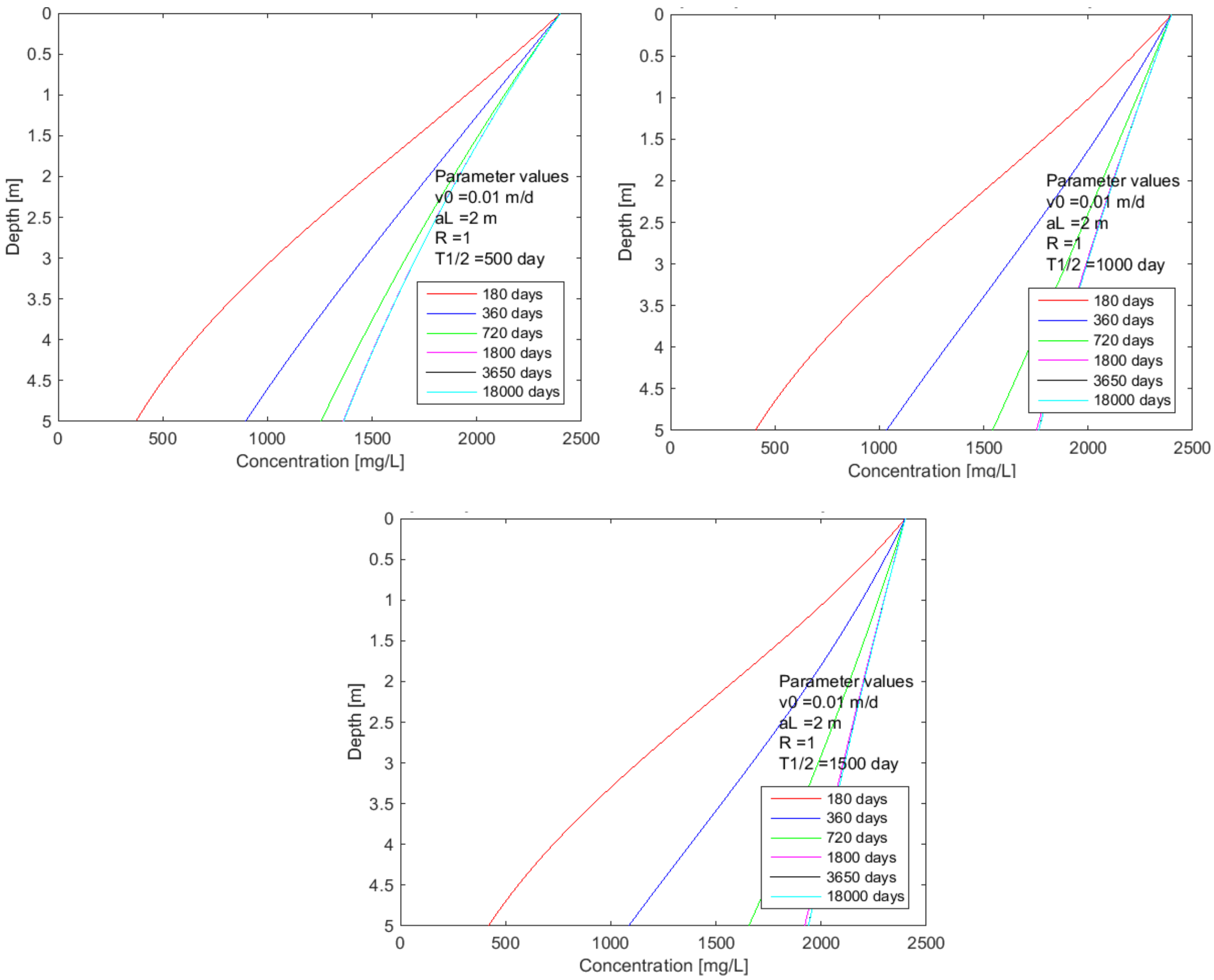

Figure 2. Depth-dependent nitrate concentrations at specified times, considering a depth from the bottom of the pits to the water table of 5 m, with nitrate half-lives assumed as 500 days (top left), 1000 days (top right), or 1500 days (bottom).

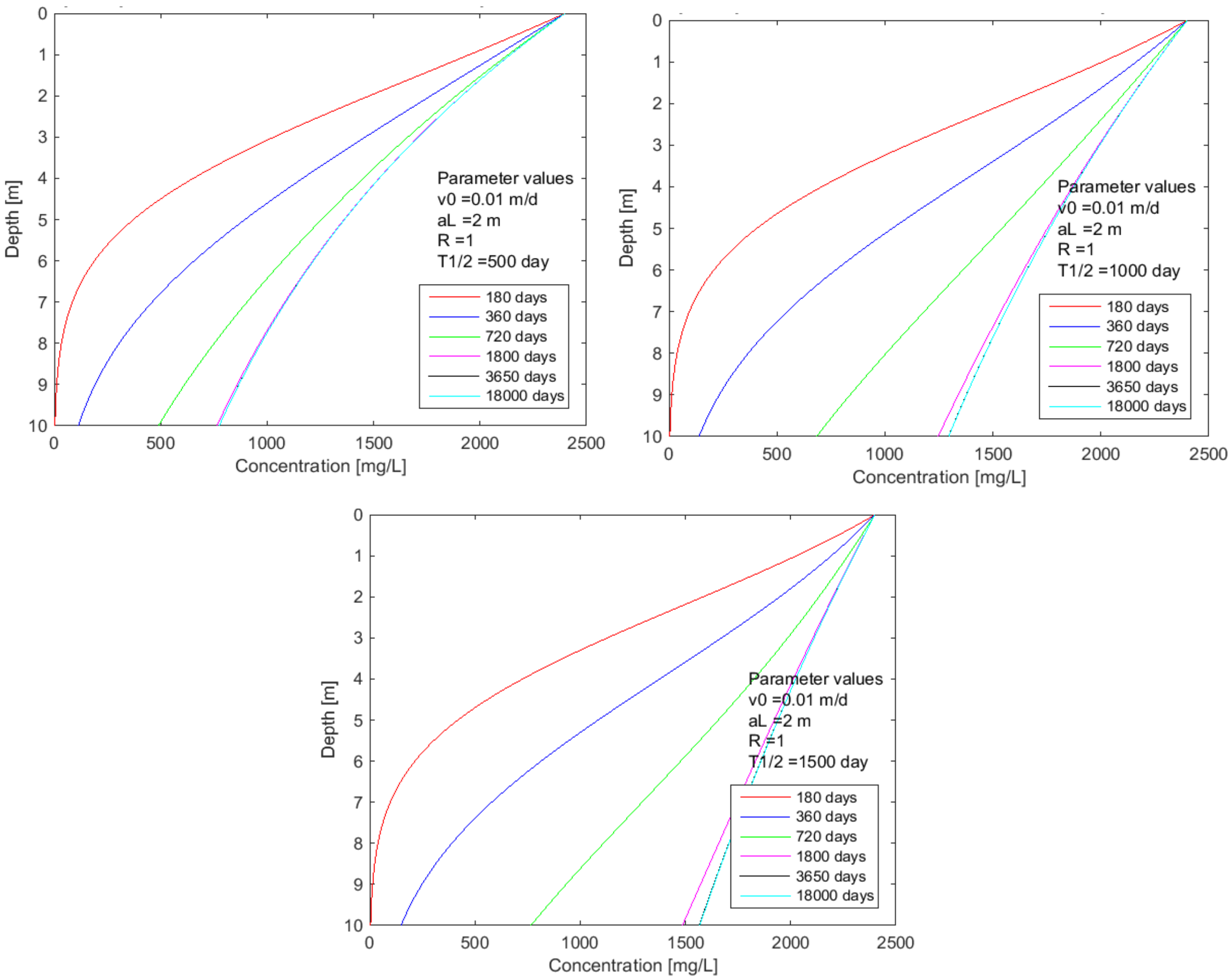

Figure 3. Depth-dependent nitrate concentrations at specified times, considering a depth from the bottom of the pits to the water table of 10 m, with nitrate half-lives assumed as 500 days (top left), 1000 days (top right), or 1500 days (bottom).

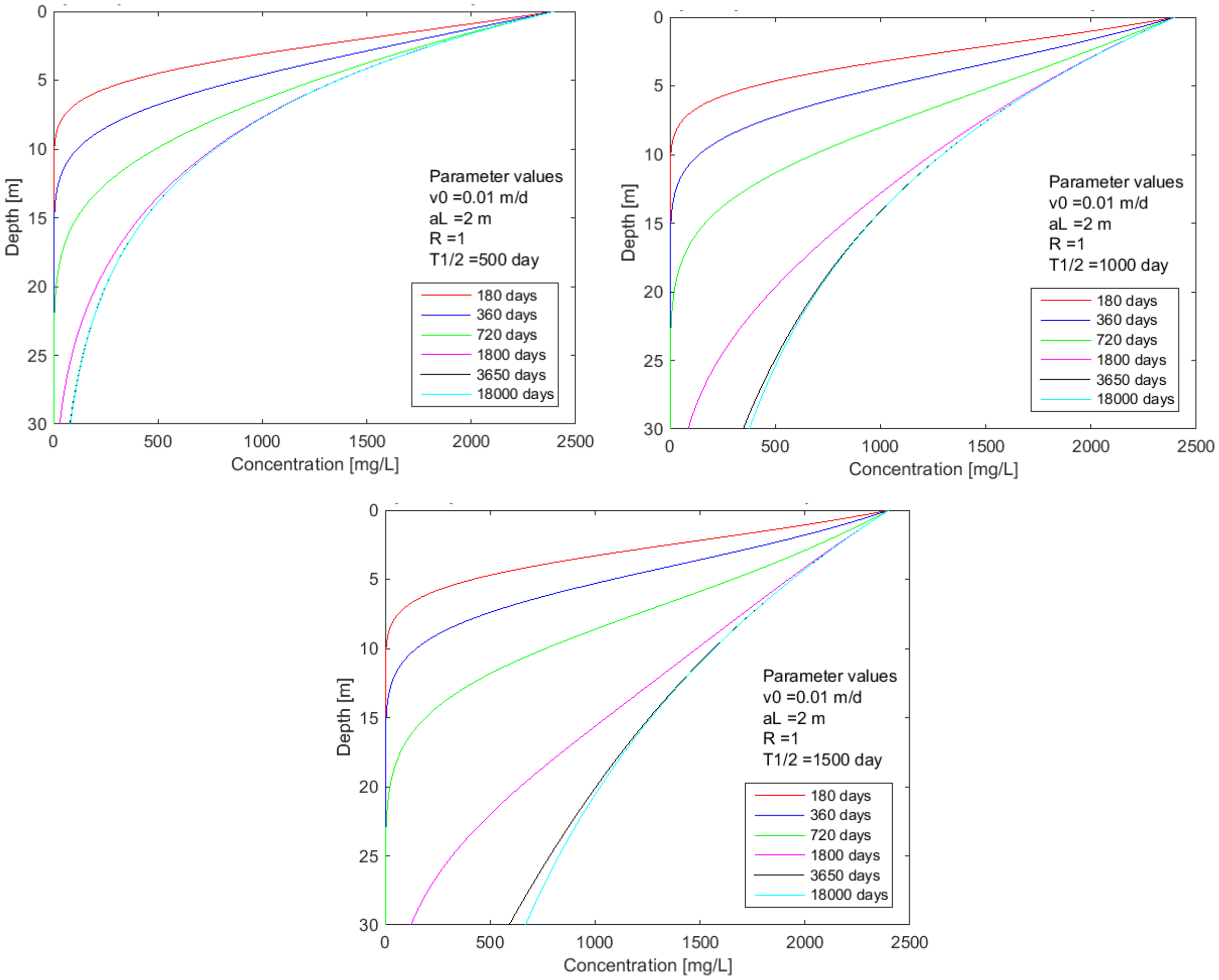

Figure 4. Depth-dependent nitrate concentrations at specified times, considering a depth from the bottom of the pits to the water table of 30 m, with nitrate half-lives assumed as 500 days (top left), 1000 days (top right), or 1500 days (bottom).

Table 1. Resulting nitrate concentrations in the aquifer (C_{ao}, mg/L), for different C_{pw} values and hydraulic head gradient (i_i) and groundwater recharge (q_r) assumptions.

C_{pw} (mg/L)	1500	1500	1250	1250	1000	1000	750	750	500	500
i_i	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
$q_r = 0.001$ m^3/m^2/day	87	72	73	60	58	48	44	36	29	24
$q_r = 0.002$ m^3/m^2/day	51	45	42	37	34	30	25	22	17	15

4. Discussion

Considering a ‘best case’ condition in this study, i.e. the maximum groundwater recharge rate (0.002 m^3/m^2/day), the highest hydraulic head gradient (0.02), and the shortest nitrate half-life (500 days), it would take over 50 years for the nitrate concentration in the aquifer to exceed the WHO guideline value for nitrate in drinking water of 50 mg/L, even for the shallowest distance from the pit down to the groundwater level of only 5 m (based on when the nitrate concentration at 5 m depth reaches 1500 mg/L in Figure 2, top left). However, the calculation is very sensitive to the nitrate half-life, and this time to exceed the WHO drinking water guideline for the 5 m depth-to-water-table case would be reduced to only two years for the moderate nitrate half-life condition of 1000 days (based on when the nitrate concentration at 5 m depth reaches 1500 mg/L in Figure 2, top right) and to even less than two years for the longest nitrate half-life condition of 1500 days (based on when the nitrate concentration at 5 m depth reaches 1500 mg/L in Figure 2, bottom). It should be noted that a commonly cited recommendation is that pit bottoms should be no less than 2 m from the groundwater level [1], while in this study the nitrate concentration penetrating to the groundwater was significant event at a depth of 5 m below the pit (except when assuming the shortest nitrate half-life). Even the 10 m depth-to-water-table case would reach the WHO drinking water guideline after approximately 5 years if the longest nitrate half-life is assumed (based on when the nitrate concentration at 10 m depth reaches 1500 mg/L in Figure 3, bottom).

The groundwater recharge rate also has a significant influence on the resulting nitrate concentrations in the aquifers, with the nitrate concentration in the aquifer increasing by approximately 60–80% when the recharge rate was halved, with all else staying the same (Table 1).

There was very little historical nitrate concentration data for the aquifers in the study locations, though relatively recent nitrate data from a well-sampling study for the Beninese study site ranged range between 0.5 to 140 mg/L [5]. The approximate ranges of contamination estimated through the modelling in this study (Table 1) fall within the field-measured range of values, which was encouraging, especially given the uncertainty regarding the concentration of nitrate in the pits and the nitrate half-life in the subsurface, as discussed earlier.

There are several potential mitigating actions that could be put in place to reduce this risk of groundwater pollution, though these may not always be suitable based on local social, technical and economic constraints. Probably the best solution is to avoid building latrines in areas with high water tables in the first place, however this is a luxury that cannot always be accommodated in booming urban areas, where the poorest people often are relegated to undesirable lands that are most prone to groundwater flooding.

For pits that are already constructed in high water table areas, more frequent emptying of the pits would at least reduce the accumulated mass of waste that leaches nitrate into the subsurface. The two years needed for the aquifer with water table 5 m below the pits to reach the WHO drinking water guideline value, explained above, may be shorter than the typical time interval between pit emptying for many households [1], for example. In that case, however, the decision on the final destination of the emptied waste [25] would also need to take careful consideration of the groundwater pollution risk, e.g. if the waste is to be dried offsite or spread on agricultural land as biosolids in areas with similarly high water tables.

Another possible solution is to change the latrine design to one that better prevents nitrate contamination. One option is to encourage the use of urine diversion toilets, which would reduce the passage of urea into the pits, however this would require significant user buy-in to be successful, both financially and from an acceptability standpoint. Also, a common recommendation for high water table areas is to build latrines on mounds rather than dug into the ground [1], although the results of the modelling in this study suggest that adding a few extra meters of depth between the pit and the groundwater level is unlikely to have a significant effect in terms of delaying nitrate penetration to the groundwater level, especially for the most shallow water table cases (e.g. water table < 5 m below the pits).

Research into novel means of achieving denitrification within a pit latrine, such as the addition nitrate-adsorbing materials to the bottom of pits or practical methods for enhancing biological denitrification in the subsurface around pits, should also be conducted. However, any such newly developed denitrification methods should be low-cost, robust to changing conditions, long-lasting, and should not require ongoing user intervention nor maintenance, which are challenging constraints.

5. Conclusions

This study has highlighted the risk posed by pit latrines to groundwater quality in terms of nitrate pollution, specifically in low-income, densely-populated peri-urban areas with only basic forms of onsite sanitation and high water tables. At a water table depth of 5 m below the pit bottom and making best case assumptions about groundwater recharge and other influencing factors, the model aquifer in this study would have reached nitrate levels approaching the WHO guideline value for nitrate in drinking water (50 mg/L) in under two years, if a conservative (i.e. moderate to long) nitrate half-life is assumed. Groundwater recharge rate was also identified as a particularly influential parameter on the resulting nitrate concentrations in the model aquifer in this study. There is a need for more data on the typical nitrate concentrations in pits and the nitrate half-lives in different subsurface conditions.

Careful siting of latrines and appropriate pit design and management are especially important in areas with high water tables. It is hoped that the modelling approach presented here may be useful for those working in other low-income regions to similarly estimate their risk of nitrate pollution and to highlight site-specific data needs for sanitation planning.

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Conflict of Interest

There are no conflicts of interest to declare.

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