

Review Paper

Multi-date trends in groundwater pollution from pit latrines

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ABSTRACT

This paper provides a multi-date review of trends in groundwater pollution from pit latrine sanitation structures using global, regional and South African cases. The paper focuses on three parameters which are microorganisms, nitrate and phosphorus, which are aligned with the challenge of waterborne diseases, and generally linked to poor water quality, and inadequate sanitation and hygiene. Poor sanitation and hygiene open up transmission routes for ingestion of faecal matter, which as at 2018 continue to pose risks of diarrhoea, opportunistic infections, and consequent malnutrition. These challenges currently account for approximately 1.7 million deaths annually, of which more than 90% are in developing countries, which have low sanitation coverage. While pit toilets are the generally preferred form of sanitation technology for developing countries, most provide evidence of the interconnectedness between the structures and groundwater pollution. The mechanism of pollution is generally indicated to be seepage of polluted pit latrine leachate into groundwater. This specific type of microbial and chemical routing from toilets into the environment increases the prevalence of diseases. These diseases usually result in high mortality for developing countries. Therefore, this review has highlighted the need to minimize pollution of groundwater from pit latrines, thereby contributing towards sustainable water quality management.

Key words | groundwater pollution, hygiene, microbial pollution, phosphorus and nitrate, pit latrine, sustainable water quality management

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INTRODUCTION

Worldwide, previous and current works have focused on disseminating the risks of waterborne diseases, which are generally linked to poor quality water, and inadequate sanitation and hygiene (Dzwairo 2005; Confalonieri & Schuster-Wallace 2011; Douagui *et al.* 2012; World Health Organization/United Nations Children's Fund (WHO/UNICEF) 2013, 2017; Khan *et al.* 2017; Debela *et al.* 2018). These diseases are highlighted as the major cause of illness and death (Batterman *et al.* 2009), with figures currently being reported as more than 90% as at 2018 (Milledge *et al.* 2018). Over three million children under the age of five die

each year globally due to environment-related diseases, such as diarrhoeal and acute respiratory illness, with acute diarrhoeal diseases being the major cause of morbidity and mortality in developing countries (Molla *et al.* 2014). WHO/UNICEF (2017) concurred that microbial contamination of drinking water remains a universal concern, with a disproportionate number of deaths, occurring among the poor and the vulnerable (Landrigan *et al.* 2018).

Consequently a large proportion of these diseases affect developing countries, which have low sanitation coverage (Nsubuga *et al.* 2004; Tiberghien *et al.* 2011; Milledge *et al.*

2018). Lewis *et al.* (1980) noted that diseases which are related to the use of polluted groundwater result in high mortality especially in developing countries. Hence drinking water sources such as unprotected dug wells can become contaminated from ingress of spilt water, excreta, etc. (Hynds *et al.* 2013). WHO (2005) recommended lining these wells with concrete and fitting windlasses in order to reduce contact with hands and containers, as this water is usually used directly without treatment (WHO 1995; Douagui *et al.* 2012). For bores, WHO (2011) recommended encasing them to a reasonable depth, and sealing the boreheads in order to prevent ingress of surface or shallow groundwater.

The most common and widespread health risk associated with drinking water from contaminated sources is microbial contamination (Khan *et al.* 2017), the consequences of which impact negatively on human health, sadly where water quality data suggests that levels of water quality compliance are low in many developing countries (WHO/UNICEF 2017).

On a technical note, groundwater is connected to other water sources which rely on that aquifer (Bricker *et al.* 2017) and it feeds shallow wells, rivers, boreholes and springs. However, if a groundwater aquifer is polluted, it becomes very difficult and complicated to clean it up to acceptable quality. Thus an objective to keep the groundwater safe from pollution is especially important for rural and, in some cases, peri-urban populations of developing countries, especially because many studies and country profiles distinguish environments as either urban or rural (Hui & Wescoat 2018).

Rural and sometimes peri-urban communities are exposed to waterborne diseases and their complications, mainly as a result of inadequate or poor performance of specific types of sanitation (Hynds *et al.* 2013; WHO/UNICEF 2017; Debela *et al.* 2018). Diseases may include campylobacteriosis, shigellosis and cholera, among many others (Genthe & Seager 1996; Batterman *et al.* 2009; WHO 2011). Related diseases have been reported in Khan *et al.* (2017), for example diarrhoea, intestinal infections, dysentery, hepatitis, typhoid fever, vomiting and skin diseases. For rural populations in developing countries, which in Africa are estimated to be 70 to 80% of the countries' populations (Dzwauro 2005) and about 60% for Africa as a whole

as at 2018 (<http://www.worldometers.info/world-population/africa-population/>), on-site sanitation systems like pit latrines and groundwater mainly from shallow wells, are widely used.

If on-site sanitation technologies are applied to unsuitable geological settings (Lewis *et al.* 1980; Aller *et al.* 1987), like sandy collapsible soils, structural failure may result (Dzwauro 2005). The example of a sinking latrine, as provided in Dzwauro (2005), indicates that soils within the vicinity of a collapsing pit are inevitably exposed to faecal pollution while the users run the physical danger of falling into the collapsing latrine.

A major concern though, when using both groundwater and pit latrines within the same system boundary, is the impact of leachate from the pit (faecal matter) on quality of the groundwater. In light of this challenge, the current paper provides a multi-date review of trends in groundwater pollution from pit latrines using the paper by Dzwauro *et al.* (2006) (using Ward 14 of Marondera District, Zimbabwe) as a pivot paper for selected earlier and later published studies on groundwater pollution from pit latrines. These papers range backwards from 2006 down the timeline to 1921 and forwards from 2006 up the timeline to 2018.

Ward 14 has Plutonic and Precambrian geological formations on an E. Kalahari Precambrian Belt. Its soils are well-drained Ferralic Cambisols, while at a local scale, Dzwauro *et al.* (2006) reported that the area's drainage is influenced by numerous faults, the north/north-east and north-east trending sets being the two outstanding ones. These geological formations together with soil types, among other biogeochemical parameters, influence the area's groundwater hydrogeology, which consequentially affects the structural stability of pit latrines. Pit latrines are the predominant form of sanitation in Ward 14.

Hence, for this multi-date review, the first objective was to systematically document selected temporal (time-specific) impacts of pit latrines on groundwater quality, using three parameters: namely microorganisms, nitrate and phosphorus. This objective also included evaluating available literature that focused on the significance of testing for nitrate during groundwater quality assessments. The second objective was to analyse the relationship between sanitation and disease incidence using the same three parameters: i.e., microorganisms, nitrate and phosphorus.

A way forward was then suggested based on pollution trending, sanitation and disease relationships. Finally, the use of pit latrines was justified in view of methodologies like the DRASTIC ((D)epth to water table, net (R)echarge, (A)quifer media, (S)oil media, (T)opography slope, (I)mpact of the vadose zone and hydraulic (C)onductivity of the aquifer) and modified DRASTIC/GIS (Geographical Information System) protocols (Aller *et al.* 1987; Babiker *et al.* 2005) as well as freely available Food and Agriculture Organization of the United Nations (FAO) soils' databases for various global regions. Conclusions were drawn regarding adapting pit latrine technologies to vulnerable geologies and sensitive environments. This is especially in light of the global sanitation shortfall to the year 2015 (2015 was the original baseline for measuring success against Millennium Development Goals) and beyond using the Joint Monitoring Programme (JMP) Proposal sanitation targets to the year 2040 and also to the decade's earlier Sustainable Development Goals (SDG) 2030 targets 6.1 and 6.2. The paper advocates that latrines are envisaged to contribute towards increased coverage in low income countries, thus the need to continue to provide literature and suggest technological alternatives that could enhance stability of the structures as well as provision of barriers between a pit toilet base and groundwater, in order to enhance minimization of pollution.

MULTI-DATE TRENDS IN GROUNDWATER POLLUTION

It has been recognized that on-site sanitation systems like pit latrines can potentially pollute groundwater resources (Abu Amr & Yassin 2008; Debela *et al.* 2018). This scenario does not support the overall goal of Integrated Water Resources Management principles, which is to maintain water quality and related vital ecosystems (Dzwaïro *et al.* 2010). Indeed, centrality of water to well-being is one of the greatest challenges to improved quality of life (Acho-Chi 2001). Thus care should be taken, where practical, to protect groundwater (WHO 2011) which, in many instances, is consumed without treatment (Douagui *et al.* 2012).

Diseases which emanate from consuming contaminated water compromise human health in that limited numbers of

water points can be accessed by large numbers of people, who may all be exposed to the waterborne disease-causing organisms. The disease can easily and rapidly affect many people in a relatively short space of time (WHO 2011). It is crucial then, to develop a clearer appreciation of pollution trends as these can inform prevention actions which are required to protect the water resource (Ferguson *et al.* 2012; Hynds *et al.* 2013; WHO/UNICEF 2017). The following sections discuss groundwater pollution trends from pit latrines using the variable choice set microorganisms, NO₃⁻ and phosphorus. These variables represent microbial and nutrient pollution.

Microbial activity contribution towards groundwater pollution

Investigations relating to the nature and thickness of soils and rocks of the zone which is permanently unsaturated, which occurs below the base of an on-site sanitation structure, have gained attention in groundwater pollution studies (Lewis *et al.* 1980; Kristian Stevik *et al.* 2004; Lutterodt *et al.* 2009; Toze *et al.* 2010; Graham & Polizzotto 2013; Wuta *et al.* 2016). Therefore, pollution prevention and impact mitigation measures target this particular soil layer and the activities taking place therein. Of major interest are studies on pathogens, which are a class of microbial pollutants of interest in studies on groundwater pollution by on-site sanitation (Lee *et al.* 2011; Debela *et al.* 2018). It is noted that various combinations of transport mechanisms may influence pathogen transport in groundwater. During their transit through unsaturated soil profile and groundwater systems, processes including starvation, predation, adsorption, filtration and dilution occur collectively to reduce the microbial load (Rusinga 2004). In reviewing the works related, using a multi-date approach from as far back as 1921, it is also noted that the term 'faecal coliforms', which has been used in previous studies, unless specifically stated, is currently more appropriately called thermotolerant coliforms. Examples of papers in which this term has been used are quoted in this paper (Paruch & Mæhlum 2012; Frank *et al.* 2018; Lunestad *et al.* 2018) since it has been established that some environmental coliforms can sustain the temperature (44–44.5 °C) that has been used for detecting faecal coliform. However, in the current multi-date

approach, the term specifically used in each reviewed paper was kept as is, whether faecal or thermotolerant coliforms, in order to maintain the integrity of the research papers.

Thus, using multi-date trending from very early studies, Caldwell & Parr (1937) detected faecal coliform 10 m away from a newly constructed pit latrine which had penetrated the water table. However, within three months of using the latrine, the soil clogged, which resulted in improvement of the soil filtration mechanism. It was also noted that pollutant dispersion was considerably curtailed as a result of establishment of this clogged zone. Subsequent related multi-date papers are summarized in Table 1. On the other hand, the pivotal paper by Dzwaïro *et al.* (2006)'s outstanding conclusion was that it was generally risky to abstract water from within 25 m lateral distance of an unlined pit latrine for this particular study site.

As far as the author could establish, no other study had and has been done in this particular setting in order to assess impacts of pit latrines on groundwater quality using the parameters indicated. The value of Dzwaïro *et al.* (2006) has also been shown by its citations within the field of research. Thus, its use as a pivot paper by the same author who could attest to the authenticity of the findings in Dzwaïro *et al.* (2006). Additionally, the 25 m conclusion provided a new set-back distance to the generally accepted 30 m for Zimbabwe, although it could be suggested that the 5 m difference would offer a buffer distance for pollution.

Discussions of review papers after 2006 include that by O'Lunaigh *et al.* (2012), who performed extensive percolation studies using on-site effluents in Ireland in order to determine the capacity to attenuate *Escherichia coli* bacteria and spiked bacteriophages. The paper discussed the interactions of microorganisms with soil profiles, especially the profile around and in contact with the microbial organisms. Results showed that the greatest *E. coli* removal in the subsoil occurred within the first 0.35 m of unsaturated subsoil for all effluent types considered in the study. Finally, Back *et al.* (2018) also referred to the pivotal paper (Dzwaïro *et al.* 2006) and strongly highlighted the policy issues that are required for any groundwater pollution protection measures in developing country settings.

Similar multi-date trends were done for the other sections, where data was available. Next, studies on pit

latrines and groundwater pollution, but targeting particular soil types, were reviewed in the succeeding sections using Dzwaïro *et al.* (2006) as the pivot paper for earlier and later studies. For example, Allen & Morrison (1973), showed that fractured bedrock especially promoted injection of pollutants directly into the groundwater system. Later, research by Hearne *et al.* (1992), which was done in Colorado, quantified the vulnerability of shallow groundwater supplies that were overlain by fractured bedrock that offered very minimal resistance to transportation of leachate towards groundwater, resulting in little (12%) microbial removal (Hearne *et al.* 1992).

On the other hand, the *biomat* layer naturally forms a protective barrier that is approximately 0.3 m away from application of a microbial pollutant. Its main purpose is to provide conditions that promote predation and scavenging to occur in order to kill or reduce the effluent's microbial load within, for example, a soil matrix. The soil matrix's characteristics contribute markedly towards mobilization of microorganisms and nutrients within specific environments like the pit of a latrine as well, or unsaturated and saturated soil zones (Beal *et al.* 2006; Jeong *et al.* 2011; Martínez-Santos *et al.* 2017). Therefore, mitigation measures against groundwater pollution could target and manipulate the soil matrix properties in order to retain or destroy microorganisms before they reach the groundwater resource.

Nitrate contribution towards groundwater pollution

Nitrogen transformational/conversional mechanisms are biochemical pathways which even as recently as 2018, have been depicted as two pathways represented by conversion of ammonia to nitrite and then nitrite to nitrate (Murphy *et al.* 2009; Rajagopal & Béline 2011; Cheng *et al.* 2013; van Kessel *et al.* 2015; Isobe *et al.* 2018). Lately, the nitrogen pathways have been shown to consist of many other unknown but very beneficial pathways and species, including archaea, depending on the environmental conditions. A detailed account and understanding of current biochemical knowledge and gaps of nitrification, is presented in Lancaster *et al.* (2018).

Additionally, a crucial recent discovery is the comammox bacteria, which carry out complete nitrification from ammonia to nitrate in one step (van Kessel *et al.* 2015;

Table 1 | Summary of the multi-date trends for microbial activity contribution towards groundwater pollution

Year	Authors	Title	Microbial activity
1921	Kligler	Investigation on soil pollution and the relation of the various types of privies to the spread of intestinal infections	documented the relationship between pit latrines and the spread of waterborne infectious diseases
1937	Caldwell & Parr	Ground water pollution and the bored hole latrine	detected faecal coliforms 10 m away from a newly constructed pit latrine which had penetrated the water table
1938	Caldwell	Studies of subsoil pollution in relation to possible contamination of the ground water from human excreta deposited in experimental latrines	noted maximum vertical and lateral travel distances of 1.8 m and 0.6 m, respectively, in a sandy permeable soil
1950	Subrahmanyan & Bhaskaran	The risk of pollution of ground water from borehole latrines	a sandy soil with less than 0.001 hydraulic gradient restricted the groundwater velocity to a maximum 0.9 md^{-1} , with a bacterial survival period of 4–7 days, which allowed 8 days' travel time between a pollution application point and a water withdrawal point
1954	Butler <i>et al.</i>	Underground movement of bacterial and chemical pollutants	discussed the interactions of microorganisms with soil profiles, especially the profile around and in contact with the microbial organisms
1957	Baars	Travel of pollution, and purification en route, in sandy soils	tests which were done seven months after the end of a camping season detected no faecal indicator microorganisms at depths greater than 1.3 m but showed that bacteria might infiltrate to cover some distance into the soil
1958	Krone <i>et al.</i>	Movement of coliform bacteria through porous media	attributed reduction of <i>Escherichia coli</i> to possible soil clogging and microbial predation, using sandy columns
1972	Lance	Nitrogen removal by soil mechanisms	while nitrite is readily oxidized to NO_3^- , ammonium ions may be converted to NO_3^- depending on availability of oxygen
1973	Allen & Morrison	Bacterial movement through fractured bedrock	fractured bedrock especially promoted injection of pollutants directly into the groundwater system
1974	Ziebell <i>et al.</i>	Use of bacteria in assessing waste treatment and soil disposal systems	within 0.30 m of a clogged zone, there was reduction of bacterial communities that resided underneath and to the sides of a septic tank's seepage beds
1980	Lewis <i>et al.</i>	The risk of groundwater pollution by on-site sanitation in developing countries	documented several studies which related to separating out of bacteria at the soil infiltration surface
2000	Chidavaenzi <i>et al.</i>	Pit latrine effluent infiltration into groundwater: the Epworth case study	using seasonal variation, this research found out that pit latrine contents leached downwards and down-slope for distances which varied with season and soil type
2004	Pang <i>et al.</i>	Estimation of septic tank setback distances based on transport of <i>E. coli</i> and F-RNA phages	predation was noted to be important for microbial attenuation while the paper also provided figures regarding microbial attenuation and transport mechanisms in pumice sand aquifers
2005	Dzwauro	Assessment of the impacts of pit latrines on groundwater quality in rural areas. A case study from Marondera District, Zimbabwe	this research reported microbial and chemical lateral travel distance, up to 25 m away from a pit latrine, for a localized sandy study area in Marondera District, Zimbabwe

(continued)

Table 1 | continued

Year	Authors	Title	Microbial activity
2006	Love <i>et al.</i>	Impacts on groundwater quality and water supply of the Epworth semi-formal settlement, Zimbabwe	the density of pit latrines at a study location was established to contribute to pollution of groundwater from coliforms and NO ₃ ⁻
2006	Dzwauro <i>et al.</i>	Assessment of the impacts of pit latrines on groundwater quality in rural areas: A case study from Marondera district, Zimbabwe	it was generally risky to abstract water from within 25 m lateral distance of an unlined pit latrine for this particular study site
2009	Cey <i>et al.</i>	Influence of macroporosity on preferential solute and colloid transport in unsaturated field soils	acknowledged that groundwater flow influenced pollutant travel
2011	Confalonieri & Schuster-Wallace	Data integration at the water–health nexus. Current opinion in environmental sustainability	data integration at the water–health nexus
2012	O’Luanaigh <i>et al.</i>	The attenuation of microorganisms in on-site wastewater effluent discharged into highly permeable subsoils	discussed the interactions of microorganisms with soil profiles, especially the profile around and in contact with the microbial organisms
2018	Back <i>et al.</i>	Risk assessment to groundwater of pit latrine rural sanitation policy in developing country settings	strongly highlighted the policy issues that are required for groundwater pollution protection measures in developing country settings

Lancaster *et al.* 2018). A number of these known and unknown complex nitrogen transformation mechanisms also occur within the soil matrix that is in contact with pit effluent. They occur as feedback mechanisms for pathogen and other contaminant degradation as well as to support nutrient bioavailability for microbial and plant growth. Specifically the discovery of comammox bacteria means that the nitrogen cycle is now depicted differently than previously understood and presented. For groundwater pollution nutrient and microbial interactions, these pathways within the shallow soil matrix are impacted by the groundwater flow, which is influenced by, among major parameters, elevation. Thus geological profiling subsequently affects the hydro-chemical profiling of the shallow soil matrix and near-surface groundwater in that pollutants and other constituents tend to follow flow pathways from higher to lower altitude, although most of a pit latrine’s activities occur generally within a bottom depth of 3 m maximum, depending on technology used. It would then be inferred that Zimbabwe would drain from the Central Highveld towards the northerly and southerly direction, with additional influence of the regional geological fault lines that are a result of tectonic contact (Figure 1).

The study area (Ward 14) of the pivot paper would then appear to be potentially part of a general lower-lying accumulation area relative to its eastern surrounding areas that have higher elevation.

Structurally, studies have concluded that septic tanks and seepage pits expose groundwater to NO₃⁻ pollution (Woodward *et al.* 1961), with quantification by Walker *et al.* (1973) concluding that 7.5 kg of this pollutant reached groundwater per year, for a family of four people. Additionally, in eastern Botswana, widespread and severe NO₃⁻ contamination of shallow groundwater supplies was attributed to pollution from pit latrines (Hutton *et al.* 1976). Further, Brooks & Cech (1979) found out that groundwater pollution occurred to a large extent in rural areas of Texas (USA), where background NO₃⁻ concentrations in the unsaturated zone ranged from 0–1 mg NO₃⁻ as N/kg.

Additionally, both Robertson (1979) and Lewis *et al.* (1980) reported on groundwater pollution from NO₃⁻ in a densely populated but low income residential area in Delaware, USA. According to Lewis *et al.* (1980) the nitrate that was detected in the groundwater was in excess of 135 mg/L NO₃⁻-N. It was concluded that pit latrine effluent containing nitrogenous material was the cause of the water pollution. A study by Stenström (1998) in sandy Botswana soils traced NO₃⁻ contamination of wells from pit latrines, to a maximum distance of 100 m. However, seasonal variation, which has an obvious influence on pollutant movement, was not captured in this study, although Chidavaenzi *et al.* (2000) later concluded that pit latrine contribution to groundwater nitrogen content was significant in the dry season. Chidavaenzi *et al.* (2000) attributed the significant nitrogen content in

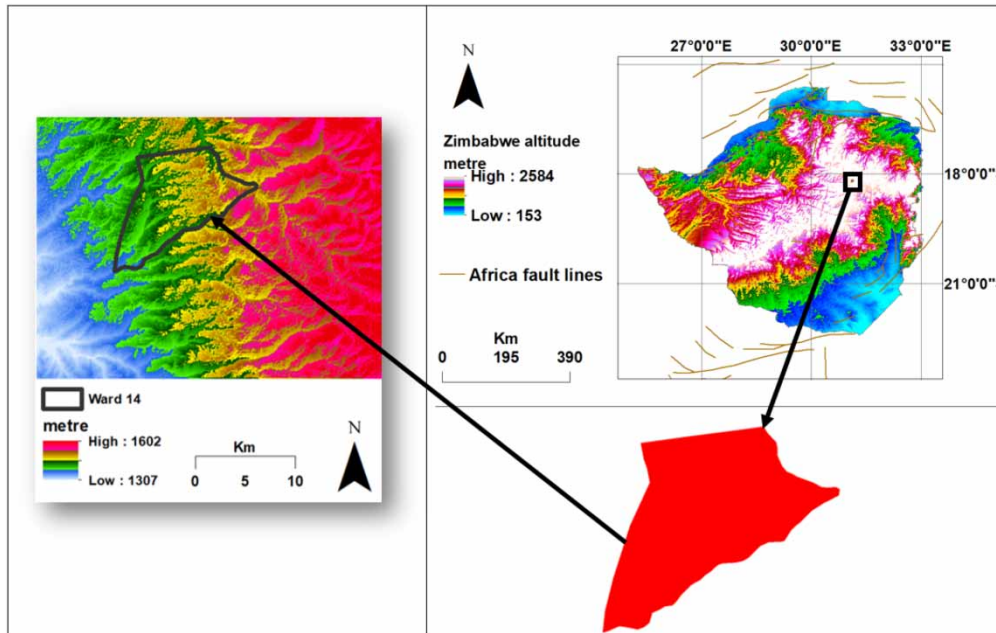


Figure 1 | Zimbabwe and Ward 14 altitudes and positions of the continental fault lines. GIS Platform: ESRI ArcGIS 10.3. Source of data: Freely available internet shapefiles including SRTM, <http://srtm.csi.cgiar.org/SELECTION/listimages.asp>.

the dry season to low or moderate removal of nitrogen due to diminished groundwater recharge.

Pollution of shallow groundwater from NO_3^- is problematic in areas with high densities of pit latrines (Lewis *et al.* 1980; Chidavaenzi *et al.* 2000; www.ircwash.org) and where there is moderate to low rate of removal of nitrogen as well as recharge of the groundwater (www.ircwash.org). In areas where the concentration of natural NO_3^- in groundwater is low ($<2 \text{ mg NO}_3^- \text{-N}$), and where there is no use of agricultural fertilizers, elevated levels of NO_3^- may indicate faecal contamination (Lewis *et al.* 1980). On the other hand a pit latrine could leach about 20% total nitrogen into groundwater in an alluvial soil matrix (Nyenje *et al.* 2013). However, nitrate–nitrogen for all sampling points in the pivot paper (Dzwauro *et al.* 2006) ranged from 0.0 to 6.7 mg/L, which was within the 10 mg/L WHO guidelines. This result was consistent with that for thermotolerant coliforms (which were reported as faecal coliforms) in the same paper, specifically for position tw10.

In Ghana, Anornu *et al.* (2017) reported on a study that was carried out to determine the sources of groundwater nitrate contamination and also to ascertain the potential human risk from exposure to nitrate contamination in the

Upper East Region by using an integrated hydro-chemical and isotopic technique. Two of the conclusions reached indicated that the nitrate source was predominantly human and animal waste while the risk of ingesting nitrate contaminated water was found to be non-carcinogenic (Anornu *et al.* 2017).

In summary, microbial processes which oxidize ammonium to NO_3^- generally also promote nitrogen mobility as NO_3^- , which may end up polluting groundwater. This movement was also reported by Templeton *et al.* (2015) in Mukate *et al.* (2017). The study indicated that elevated nitrate content (above the WHO guideline value), which was attributed to pit latrines, extended to an aquifer depth of 50 m within a short period of time.

Phosphorus contribution towards pollution

In the review which led to this current paper, a multi-date approach was also used where phosphorus trending was carried out as one of the objectives. Regarding phosphorus contribution to groundwater pollution, it should be noted that while most soils contain low concentrations of inorganic phosphorus, a large proportion is complexed with

soil minerals. This contributes to the low mobility of this chemical (Woltersdorf *et al.* 2016). Additionally, NO_3^- , K^+ and PO_4^{3-} are responsible for soil and water salinity as well as nutrient enrichment (Woltersdorf *et al.* 2016). Thus, phosphorus adsorption/desorption and precipitation/dissolution equilibriums control the chemical's mobility and bioavailability in soil. This equilibrium depends on pH, concentration of anions that compete with phosphate for ligand exchange reactions, and concentration of metals that can co-precipitate with PO_4^{3-} (Hinsinger 2001).

Additionally, a study by Jacks *et al.* (1999), indicated that phosphorus was conservative as it remained immobilized in the residues of a pit latrine if the water table occurred below the base of the pit. A fraction, though, could leach together with pit contents into the mineral soil around the bottom of the pit latrine. Tirivarombo (2001) noted that phosphorus was mainly lost through sedimentation by a mud-water interchange process which deposited it into the sediment. Further, a study by Nyenje *et al.* (2013) reported that less than 1% total phosphorus leached into groundwater in an alluvial soil type, a result which supported the general conservative nature of phosphorus.

In another study (Whalen & Chang 2001) at the Lethbridge Research Centre in southern Alberta, Canada, it was shown that there were elevated extractable and total phosphorus concentrations at soil depths of up to 1.5 m. This was unexpected for a calcareous clay loam. In the same study area but using a different soil structure, Lutwick & Graveland (1978) in Whalen & Chang (2001) had earlier concluded that phosphorus adsorption capacity was related to clay content, cation exchange capacity, and ammonium acetate-extractable calcium and magnesium. The same report further noted that silty clay-loam soils allowed for 236 to 950 mg P/kg adsorption for soils up to 1.5 m deep. It was estimated that soils with a clayey textured soil could receive annual applications of 40 kg P/ha for 120 to 153 years before that soil could become saturated.

James *et al.* (1996) concluded that extractable organic phosphorus in the surface soil layers decreased to background levels within two to three years after application was terminated. This time range provided ample time for phosphorus to reach groundwater in favourable environments. Indeed, Eghball *et al.* (1996) demonstrated that phosphorus from beef excreta could move through high

calcium carbonate soil layers to eventually reach groundwater, especially in areas with shallow water tables.

The pivot paper by Dzwaïro *et al.* (2006) did not report on this parameter; however, Indraratne *et al.* (2009) concluded that long-lasting phosphorus enrichment could pose an environmental threat, long after application ceased. Jalali & Naderi (2012) demonstrated, in an experiment, that a combination of acid rain and calcareous sandy loam soils encouraged pollution of groundwater from phosphorus. Phosphorus transformations towards its thermodynamically stable phase favour neutral to alkaline environments (Wang *et al.* 2011), conditions which discourage phosphorus movement in the soil structure.

Therefore, although phosphorus has been shown to be generally stable in the soil matrix, specific conditions might mobilize it to end up raising the nutrient content of groundwater. Interaction of surface water with the polluted groundwater may end up causing algae blooms, and if not mitigated against, eventually cause eutrophication in the surface water. Phosphorus is thus a limiting factor in aquifer systems because it is relatively immobile in comparison to the more mobile NO_3^- counterpart (Rivett *et al.* 2008) during algal blooms.

RELATING SANITATION TO DISEASE INCIDENCE

Pollution contribution from microorganisms

Microbial agents are a major cause of death in developing countries (Lewis *et al.* 1980; Foppen & Schijven 2006; WHO 2011; Molla *et al.* 2014), some of which are as a result of ingesting water contaminated by faecal matter (Lehloesa & Muyima 2000). Much earlier on, Kligler (1921) had documented the relationship between pit latrines and the spread of waterborne infectious diseases. This was done using field studies on a variety of soils using pit latrines that were one to three years old. The study concluded that properly constructed pit latrines were unlikely to cause the spread of bacterial intestinal infections because of the rapid die-off rate of pathogens that colonize excreta.

In Bangladesh, Knappett *et al.* (2011) sought to establish the association between the local population, latrine density, latrine quality and concentrations of faecal bacteria and

pathogens in pond water. It was noted that ponds which directly received latrine effluent exhibited highest concentrations of faecal indicator bacteria. Human waste was polluting drinking water and subsequent use consequently caused persistent diarrhoeal diseases in rural South Asia (Knappett *et al.* 2011). Drinking water should not contain faecal indicator organisms (WHO 2011; WHO/UNICEF 2017).

Pollution contribution from nitrate

As indicated in the latest WHO guideline (WHO 2011), excess nitrate/nitrite is mentioned as one of the chemicals of greatest health concern in some natural waters. Sources would include on-site sanitation structures if these are extensively used in an area, where NO_3^- seepage into groundwater could occur. This might then lead to potential health problems for humans and animals if they consume this water (Love *et al.* 2006; Mukate *et al.* 2017). A negative feedback mechanism of increased NO_3^- -N concentrations in groundwater is eutrophication when the groundwater discharges into surface water. For NO_3^- , the WHO drinking-water guideline (WHO 2011) suggests an upper limit of 11 mg/L as NO_3^- -N, the figure depends on conversion of NO_3^- to nitrite (Johns & Lawrence 1973; Douagui *et al.* 2012).

Epidemiological evidence for associating dietary NO_3^- to cancer is, however, insufficient. Nitrate, though, appears to competitively inhibit iodine uptake, with the potential to affect the thyroid. Douagui *et al.* (2012) cautioned of a 'possibility' of human gastric cancer while Zhang *et al.* (2013) indicated that long-term exposure to 2 to 4 mg/L in drinking water, could 'possibly' cause bladder and ovarian cancer. Kent & Landon (2013) described the link between nitrate and cancer as an 'association between certain types of cancer and NO_3^- concentrations'. Cave & Kolsky (1999) reported that NO_3^- and nitrite had been 'suggested as possible carcinogens'. Thus researchers have thus far tended to be cautious when reporting nitrate health risk for cancer. This is because of lack of a clear cut cause-effect relationship between nitrate and cancer.

However, Cave & Kolsky (1999) associated high NO_3^- levels in drinking water with methaemoglobinaemia in infants of less than three months of age. Baurès *et al.* (2013) also noted that children were at risk of methaemoglobinaemia.

Occasional cases of methaemoglobinaemia were reported in some adult populations, though (WHO 2011). Earlier research by Shual & Gruener (1972), however, failed to identify high methaemoglobin levels among children who were exposed to NO_3^- levels of between 50 and 90 mg/L and who represented 6% of the infants' population. As at 1973, cases of methaemoglobinaemia which could be linked to consumption of water containing NO_3^- concentrations above those recommended, were unavailable in Australia (Johns & Lawrence 1973).

It should be stressed that it is not automatic, if high NO_3^- concentrations are experienced in a groundwater resource, to link the problem to pit latrines or some other on-site sanitation system; investigations should be conducted to establish the source. This approach may minimize the risk of prematurely excluding pit latrines as a sanitation option. For example, Cave & Kolsky (1999) made a comparison to rather be exposed to high nitrate-containing groundwater than to water that might be polluted with pathogens from exposed faecal matter, which inevitably would result in sickness or death.

Pollution contribution from phosphorus

Although elemental phosphorus is very toxic and can bioaccumulate, phosphates, which are formed from elemental phosphorus, can exist as orthophosphate, metaphosphate and organically bound phosphate. The *ortho* forms are produced by natural processes and are also found in sewage while poly forms are used in boiler water treatment and in detergents.

Organic forms of phosphates occur in nature where they function in vital geochemical cycling. These organics might also point to possible breakdown of organophosphate pesticides in nature. Organic phosphates can exist as particles in aqueous form or as loose fragments, or be incorporated into aquatic organisms. However, phosphates are not toxic to people or animals unless they are present in very high levels. Digestive problems could then occur from extreme exposure through ingestion. If that water feeds groundwater, then consumers of the groundwater might become exposed to cyanobacteria toxins (Tian *et al.* 2013). This is a knock-on effect which, however, does not reflect direct injection of phosphorus-containing pit latrine effluent into groundwater.

Additionally, in a study that focused on surface water (Su *et al.* 2015), the link between cyanobacterial blooms and microcystins was highlighted as a threat to human and animal health. The same paper reported on an incident that occurred at a hemodialysis centre in Caruaru, Brazil, in 1996, where it was concluded that microcystins-contaminated water could cause hepatic disease or death (Su *et al.* 2015).

Interaction among the three parameters versus choice of affordable low-income sanitation technologies

Despite the challenges with technology, pit latrines are the sanitation technology of choice in low income areas and in developing countries where drinking water sources that are easily available for these environments are mainly shallow wells and boreholes (groundwater). It is generally accepted to allow at least 2 m of sandy soil that will act as an active pollution barrier between the base of a pit latrine and the water table, if the pit latrine base does not sit in a water-saturated soil zone. The combination of water and sanitation technologies for these developing and low-income communities presents a challenge to governments that are obligated to universally provide safe drinking water to all basic sanitation. The problem is that pit latrines generally pollute groundwater unless the hydro-geochemistry discourages leachate movement. Additionally, studies of nutrient interaction with groundwater are necessary as they are specific and the more field data gathered for these specific studies, the better the evaluation of different settings for appropriate sanitation technologies. For example Nyenje *et al.* (2013), which acknowledged the research by Dzwaïro *et al.* (2006), assessed dissolved nutrient loads and the processes (which are driven by microbial interaction) likely affecting them in aquifers underlying a domestic solid waste dump and a site with two pit latrines in an unsewered low-income urban slum in Kampala, Uganda. Results indicated that approximately 2–20% of total N and less than 1% of total P mass input was lost to groundwater from the pit latrines, indicating an advantageous retention of pollutants within the soil matrix, thereby reducing leaching into the groundwater.

Nevertheless, it should also be noted that, as was concluded by Luh *et al.* (2017), sanitation technology choice

cannot be disassociated from climate-related hazards, which should be incorporated into local settings. Additionally, in South Africa, Hartley (2000) developed a protocol to ensure that when making decisions and designing sanitation systems, the process should be done in such a manner as to match the local environment, in addition to factoring in user acceptance, cost, and density of similar technologies within a specified radius of the area. The hydro-geochemistry of the environment cannot be the only deciding factor yet cost in many cases has been used when selecting on-site systems, over more appealing waterborne or other systems.

It is thus suggested that as an available alternative procedure, the DRASTIC protocol by Aller *et al.* (1987) is a simple methodology that can be applied with relatively minimal demand on data. The approach can incorporate regional geologic zones (these are freely available on the internet) factors and weights to assist with calculating the DRASTIC index which delineates the groundwater pollution potential. The overall assessment process quantifies vulnerability of groundwater resources and thereby guards against inappropriately located or designed sanitation systems. Therefore, where funding allows, DRASTIC can be combined with geographical information systems to enhance groundwater assessment potential of the methodology (Babiker *et al.* 2005).

On the other hand, pit latrine design should reflect geological variations, especially where assessments of what may or might not work as mitigation measures to pollution from pit latrines have been done on a case by case representation of hydro-geochemical process groupings. The reason is that although pit latrines are recognized to cause groundwater pollution (Cave & Kolsky 1999; Dzwaïro *et al.* 2006; Graham & Polizzotto 2013; Tillet 2013; Debela *et al.* 2018), in some instances infrastructural development prioritizes their use against prevention of diseases. An example is where pit latrines were the technology of choice for improving access to sanitation in order to mitigate against trachoma (Rotondo *et al.* 2009). Since pit latrines might be the only option for faecal containment in some low income environments, disease prevention versus potential for groundwater pollution may stir debate regarding country roadmaps towards the 2040 JMP proposal for sanitation targets (Maestu *n.d.*) and the 2030 SDG targets 6.1 and 6.2

(WHO/UNICEF 2017), seeing that 2015 sanitation targets were not achieved for specific countries.

CONCLUSIONS

Pit latrines are the world's chance of increasing sanitation coverage for the majority of the global population who still lack access. It is already of great concern that 2015 sanitation targets were not met (2.3 billion (10⁹) people still lacked even a basic sanitation service – aligns with SDG 1.4) while 892 million people worldwide still practised open defecation (aligns with SDG 6.2), low-cost on-site sanitation technologies could be the practical and feasible route to climbing the sanitation ladder. Sadly, a significant global population without sanitation live in rural areas, where the levels of open defecation are high. In noting that the sanitation target for 2015 was missed, and as part of the JMP proposals provided in Maestu (n.d.) (<https://sustainabledevelopment.un.org/content/documents/3929maestu.pdf>), one of these indicates that global trends are now targeting 2040, where everyone is expected to use adequate sanitation when at home. This approach does not negate the targets as stated in the Global SDGs, the sanitation proposals of which are also listed in Maestu (n.d.), together with the associated water proposals.

Additionally, researchers have provided calculations to design on-site sanitation systems including pit latrines, in order to minimize pollution impacts on groundwater. These include providing 1.5–2.5 m of a soil layer beneath the base of a pit latrine and if the base is thin soil, to artificially increase the soil thickness. These models which provide designs to construct low pollution-impact systems are available and should be promoted if the sanitation gap is to be tackled in any way significant especially in low-income communities. With statistics showing that with the exception of Australia and New Zealand, no SDG region is on track to achieve universal basic sanitation by 2030, the pace is just too slow to meet SDG targets to 2030. The saddest reality is that global data indicates that access to basic sanitation is actually decreasing in one out of seven countries.

This multi-date paper has discussed two critical objectives which aimed to place pit latrines on the global arena

for debate as well as stir forward thinking, towards meeting sanitation SDG targets especially in developing countries. Overall, this review should sensitize interested and affected parties to the challenges of providing sustainable sanitation, which will contribute towards sanitation coverage figures towards 2040 (according to the JMP proposals) as well as the decade earlier to 2030, according to the SDG target that advocates for 'leaving no one behind'. Any techno-enviro-socio approaches to enhance sanitation coverage should still not compromise on groundwater quality, water coverage and human health for all.

A re-designed and improved pit latrine technology is thus required for vulnerable environments like hard rock, fissured bedrock, high-water table and sandy soils, etc. This focus should be taken up as a global pit latrine protocol recommendation but with local adaptation depending on local settings. It is encouraged that investment into higher end-of-pipe technologies should make latrines safe, both as barriers of disease pathways and as safe containments of faecal matter.

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