

Faecal contamination pathways of shallow groundwater in low-income urban areas: implications for water resource planning and management

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ABSTRACT

Shallow groundwater is vulnerable to faecal contamination, especially in low-income urban areas where use of on-site sanitation facilities is high. This paper explores statistical relationships between potential factors influencing contaminant pathways (i.e., variables) and observed faecal contamination of shallow groundwater, represented by nitrate concentrations and counts of *Escherichia coli* (i.e., response function) in a small, growing town in Uganda over dry and wet seasons in 2018 and 2019. A statistically significant ($p = 0.004$) multiple linear regression model from dry-season *E. coli* counts in 2018 identifies medium sanitary risk levels and modes of construction as significant pathways ($p = 0.01$). Water source depth (< 20 m) and proximity (> 10 m) to a pit latrine were also significant ($p < 0.05$) in both hydrogeological formations. No significant linear regression models were established for NO_3 during both seasons due to low pH and rapid infiltration velocities; inconsistent sample timing during the wet season impaired the significance of the statistical models of *E. coli* counts. We show that modes of construction of water sources and pit latrines play key roles in determining the quality of the shallow groundwater in urban environments. Greater emphasis is therefore required to improve the functionality and sustainability of on-site water sources and pit latrines.

Key words: contamination, faecal, nitrate, pathways, shallow groundwater

HIGHLIGHTS

- Majority of the developing countries still depend on shallow groundwater.
- Shallow groundwater systems are prone to faecal and chemical contamination where the use of on-site sanitation systems is common.
- Several pathways influence the bacteriological and chemical quality of shallow groundwater systems.
- Pathways were ranked in their order of statistical significance.

INTRODUCTION

Debate continues about the best strategies for the management of shallow groundwater systems, which remain a common source of water for domestic use in low-income countries because of lower capital costs of construction, especially when constructed by local artisans (Van Steenberg & Luutu 2012). Shallow groundwater systems are prone to faecal and chemical contamination (Lorentz *et al.* 2015; UNICEF 2019). Previous research has shown that a number of factors, representing pollutant pathways (e.g. depth of the well, mode of construction, type of well, distance to the nearest on-site sanitation systems (OSS), geology, water-source ownership, sanitary risk levels), can facilitate the mobility of faecal and chemical contaminants to and within shallow groundwater systems (Allevi *et al.* 2013; Tumwebaze *et al.* 2013; Sorensen *et al.* 2015; Abanyie *et al.* 2016; Lapworth *et al.* 2017; Back *et al.* 2018; Nayebare *et al.* 2020). Use of different numerical methods, such as water quality index (WQI), computational image processing, geographical information system (GIS) methods, and machine learning methods, has been used before for water quality assessment (Haghiabi *et al.* 2018) in addition to field and laboratory analyses.

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Here, we apply a multiple linear regression model to evaluate relationships between observed groundwater quality (i.e., response variable) and a series of explanatory variables representing potential contaminant pathways. The goal is to inform better planning and prioritisation of resources for sustainable and effective management of shallow groundwater resources within the depth of 30 m. Research to date has tended to focus on potential sources and factors that exacerbate faecal and chemical contamination rather than investigating dominant pathways/factors. The generalisability of much published research on these issues is challenged by uncertainty, inhibiting efforts to better plan and manage shallow groundwater resources. Motivated by the United Nations (UN) Sustainable Development Goal (SDG) 6, which aims at sustainable and universal access to safe water and sanitation by 2030, there is still urgent need to address water safety problems related to shallow groundwater especially in low-income countries where the dependence on shallow groundwater systems remains high. This paper seeks to better characterise the impact of different pathways/factors on faecal and chemical contamination of shallow groundwater systems. The results will help highlight key risks by ranking their significances, from which communities, local authorities, and policy makers can base their interventions for effective and sustainable management of shallow groundwater systems. First, we review factors (potential pathways) that have been implicated in the contamination of shallow groundwater in most conurbations.

Depth of the well

Research has consistently shown that well depth influences the quality of shallow groundwater. Cases of faecally contaminated shallow wells have been reported by a number of studies; for instance, in the quantification of microbial contamination in private drinking-water supply systems in Virginia, [Allevi *et al.* \(2013\)](#) revealed that 91% percent of the *Escherichia coli* (*E. coli*) found in contaminated groundwater systems were sampled from shallow wells. In the Estes Park Valley of Colorado (USA), 71% of the shallow wells (<60 mbgl) tested positive for total coliform ([Gonzales 2008](#)). Further, in the shallow coastal aquifer of southwestern Nigeria, microbial contamination decreases with depth ([Aladejana *et al.* 2020](#)). [Hamutoko *et al.* \(2016\)](#) note that shallow water-table depths decrease the residence time for microorganisms to reach the aquifer when they are introduced on the land surface. Screen intake depth of a well is widely considered to be a reliable predictor in determination of faecal and chemical contamination risk level of shallow groundwater systems.

Mode of construction

It has been observed that appropriately constructed and maintained water sources (protected, grouted and sanitary sealed), designed to minimize an ingress of surface water into the well, are effective in reducing contamination risk ([Danert *et al.* 2020](#)). The mode of system construction such as hand digging or drilling can determine the type of exploited aquifer (shallow/deep aquifers and/or consolidated/unconsolidated rock), thus governing raw groundwater quality supplied to the public ([Pieper *et al.* 2016](#)). [Back *et al.* \(2018\)](#) demonstrated that lack of protective wall correlated with observed microbiological contamination incidence, which was exacerbated by increased human and livestock activities close to inadequately protected boreholes. In contrast to hand-digging, narrow-diameter drilling can allow for effective sanitary sealing to inhibit recontamination of the well and aquifer. Research by [Wallender *et al.* \(2014\)](#) found that ineffective design, maintenance, or location of private wells and septic systems contributed to 67% of reported disease outbreaks from groundwater contamination from 1971 to 2008, while studying contributing factors to these, associated with untreated groundwater throughout the United States.

Distance of water source to source of pollution

Existing research recognises the critical role played by the source and location of the faecal and chemical contaminants such as the position of OSS in relation to the water source. [Allevi *et al.* \(2013\)](#) found a significant relationship between faecal and chemical contamination and a distance of within 0.5 miles (0.8 km) of livestock operations. [Abanyie *et al.* \(2016\)](#) observed decreasing contamination with increasing distance from pollution sources in Bolgatanga Township of Ghana. In a related study in Malawi, [Back *et al.* \(2018\)](#) established that a distance of less than 10 m from a pit latrine to the water source increased the risk of contamination.

Source ownership

Surveys such as that conducted by [Taylor *et al.* \(2009\)](#) and [Kayiwa *et al.* \(2020\)](#) have shown that poor community hygiene has been significantly correlated with faecally contaminated shallow groundwater systems. [Tumwebaze *et al.* \(2013\)](#) noted that communal systems face challenges associated with their operation and maintenance and they are commonly unsanitary with high risk scores ([Engström *et al.* 2015](#); [Nayebare *et al.* 2020](#)). The water

source systems are among the causes of some of the diarrhoeal disease especially in children below 5 years of age (Atu *et al.* 2016). Although more studies have focussed on the quality of public drinking water systems, privately owned water sources have been found to lack well construction and location standards along with routine water quality testing (Swistock *et al.* 2013) and have also for some reasons been implicated for some of the diarrhoeal disease (Wallender *et al.* 2014). Therefore, defining which systems are more susceptible to faecal and chemical contamination in terms of ownership is important for better water source management by policies and authorities.

Hydrogeological environment

Previous research comparing different hydrogeological environments has found that the vulnerability of different hydrogeological environments to pollution varies (Morris *et al.* 2003). The commonly applied empirical model, DRASTIC (Aller *et al.* 1987), which is based on geological, hydrogeological and hydrological characteristics that impact contaminant transport and attenuation processes. The model explicitly recognises the role of local geology (in which water sources are sited) plays in defining groundwater flow hydrodynamics (Pieper *et al.* 2016). Local geological characteristics such as macropores, karst features, and fractures influence groundwater contamination (Swistock *et al.* 2013; Wallender *et al.* 2014; Islam *et al.* 2016). Morris *et al.* (2003) highlights the vulnerability of unconfined weathered basement and major alluvial sediments for example, as being moderate to high.

Sanitary risk level

High sanitary risk scores of water sources have been associated with poor water quality (Howard *et al.* 2003; Taylor *et al.* 2009; Sorensen *et al.* 2015). Unsanitary environment is the source of faecal and chemical contaminants especially where there are human and animal faeces. High scores of sanitary risks to the quality of groundwater-fed sources in Kampala were significantly correlated with observed contamination from faecal sources (Taylor *et al.* 2009). Engström *et al.* (2015)'s risk factor analysis suggested that on-site hygiene was significant during the assessment of the prevalence of microbiological contaminants in groundwater sources and risk factors in Juba, South Sudan.

Water source type

In this study, source type was considered in terms of whether it was a protected or unprotected water source. The findings of Ercumen *et al.* (2017) suggest that the dominant contamination route for shallow groundwater was short-circuiting at the wellhead while they were assessing the risk of microbial contamination using sanitary inspection. Conversely, protected springs are termed improved water sources compared to their counterparts, the unprotected springs, which are unimproved water sources (WHO 2015). Unprotected springs are prone to contamination from surface runoff, animal and bird droppings, including all kinds of human waste. For instance, residents in Kampala, Uganda, reported that water from unprotected springs was 'very dirty' (Nastar *et al.* 2019). In a related study of water quality in Lukaya, a small town in Uganda, unprotected springs demonstrated gross faecal contamination (Nayebare *et al.* 2020).

Many of the above listed pathways are exacerbated by seasons, which is reflected in the different levels of faecal contamination of water sources during wet and dry seasons (Rajankar *et al.* 2013). Reported are high levels of faecal contamination during the rainy season, although this has been envisaged to be at the onset of the rainy season (Taylor *et al.* 2009; Wallender *et al.* 2014; Joon 2016) and within 48 hours after the rainfall event (Howard *et al.* 2003; Kulabako *et al.* 2007). In tracing enteric pathogen contamination in sub-Saharan African groundwater, Sorensen *et al.* (2015) realised that an onset of the wet season increased the amount of DNA within the groundwater system. Assessment of the association of the pathways with faecal and chemical contamination during both dry and wet seasons was explicitly considered.

Study area

Lukaya is located in Kalungu District of central Uganda on the equator between latitudes 0°6' and 0°11'S and longitudes 31°49' and 31°56'E (Figure 1). The total land area defined by the town council is 57 km² with a population density on inhabited land (38 km²) of ~640 inhabitants per km² and population growth rate of 3% per annum (PDP 2017); remaining land (19 km²) is occupied by wetlands adjacent to Lake Victoria. Rainfall in the region occurs throughout the year, although it is characterised by two wet seasons with heavier rainfall from March to May (MAM) and September to November (SON) and, with less rainfall from December to February and June to August (Figure 1) (rainfall data collected over three years 2017–2019, obtained from Ministry of

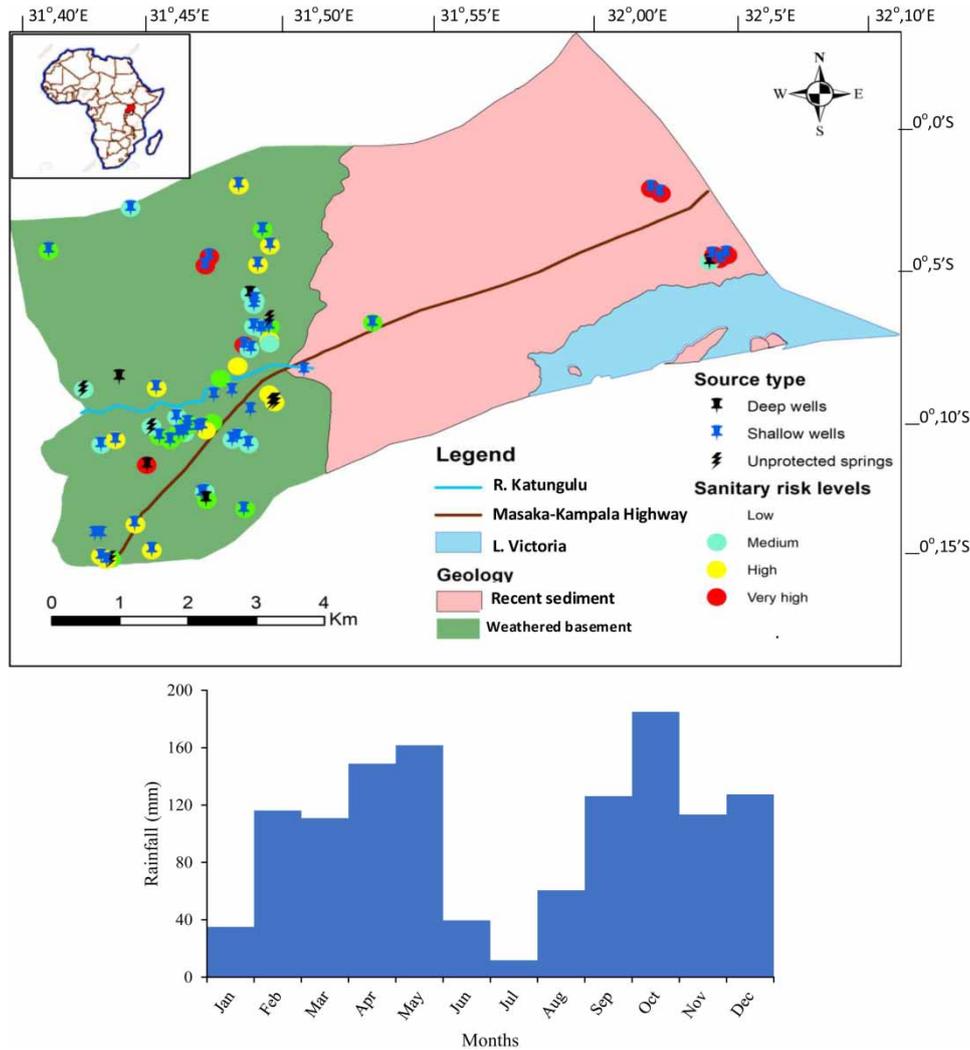


Figure 1 | Location map showing the regional geology and water source sample locations with their sanitary risk levels. Inset figure shows the variation in the average monthly rainfall from 2017 to 2019 for a rain gauge station located in the neighbouring District, Masaka.

Water and Environment). Monthly minimum and maximum temperatures range from 13 to 17 °C and 18 to 39 °C, respectively (rainfall field data collected between 2018 and 2019) and estimated potential evapotranspiration ranges from 1,350 to 1,750 mm year⁻¹ (Nwra 2013).

Water and sanitation systems

In Lukaya Town, people depend on groundwater primarily from shallow aquifers using wells that are equipped with hand pumps and unprotected springs. Although the majority of the hand pump wells are communal, ~23% are privately owned. A tiny minority (<1%) of inhabitants is connected to a piped water system that is supplied by a borehole managed by National Water Sewerage Corporation (NWSC). Sanitation facilities comprise partially lined, elevated pit latrines due to the shallow water table (0.5–5 m bgl) in low-lying areas. Other sanitation facilities include ventilated improved pit latrines, urine-diverting toilets and flushing toilets discharging into septic tanks (Nayebare *et al.* 2020). The town possesses neither a sewer network nor a wastewater treatment facility so faecal effluent is entirely contained in the shallow subsurface using on-site sanitation. Emptying of sanitation facilities is done by either digging another pit or transferring of the faecal matter to another pit (focus group discussions (FGD), February 2017).

Physiography, geology and hydrogeology

The town lies primarily within a lowland plain that is the result of down warping during the Late Quaternary in the Upper Nile Basin associated with inter-rift tectonics (Taylor & Howard 1998). Depositional features which

developed along valleys on the plateau and on the margins of Lake Victoria influence hydrology of local Rivers Katonga and Katungulu, which flow into Lake Victoria. Mean elevation over the most eastern part of the town exceeds the mean lake level of 1,134 m above sea level (m asl). The western part of the town is on relatively higher ground with an average elevation of 1,238 m asl.

The regional geology of Uganda is dominated by crystalline basement rocks, which constitute 90% of the land area, and are covered by a thick layer of weathered saprolite material (Taylor & Howard 2000). These form major aquifer systems within the weathered (saprolite) and fractured Precambrian crystalline basement rocks with shallow wells having yields generally between 0.1 and 3 L/s (Taylor *et al.* 2004). This study determined transmissivity of ~11–25 m/day. In Lukaya, for example, saprolite aquifers are the main systems which are supplemented by Recent sediment aquifers (see location of wells, Figure 1).

MATERIALS AND METHODS

Guided by the research hypothesis that associations between the different pathways and quality of shallow groundwater exist, we evaluated whether any of the variables (i.e. source type, geology, distance from the nearest pit latrine, depth of the well, mode of construction, water source ownership and sanitary risk level) correlated linearly with the response variables (nitrate, *E. coli*) and, to what significance levels. Basing on the Null hypothesis (H_0), which states that 'no relationship exists between two variables under consideration', the results were to guide on whether the Null hypothesis was to be accepted or the Alternative hypothesis (H_1), in which a relationship exists. Employed data in this paper were drawn from field research from 2015 to 2020. A pragmatic assessment approach was used to assess the pathways potentially controlling shallow groundwater contamination arising from surrounding OSS. Fixed variables such as well depth, geology, mode of construction, source ownership and distance to the nearest OSS were recorded once during the study whereas dynamic variables such as risk levels, *E. coli* counts and NO_3 concentrations were collected on a monthly basis for one year and their median values were used in the model analysis. Multiple regression model analysis was employed to evaluate the significance levels of the different variables.

Statistical analysis

Data description

Throughout this paper, the term variable is used to mean factors that influence the contamination of shallow groundwater systems. The variables used in the statistical analyses have been described in order to better understand their origin and meaning. Tables 1 and 2 give the descriptions and basic summary of the different independent and dependent variables. The identification of relationships between faecal contamination and predictive factors used the entire available dataset on water sources collected during the study ($N = 44$ (dry) and $N = 50$ (wet)). The analysis aimed at identifying the predominant factors potentially associated with faecal and chemical contamination. The dependant variables, *E. coli* counts and NO_3 concentrations were determined in the water samples collected from different water sources on a monthly basis during the study period.

Multiple linear regression

Multiple linear regression (MLR) is a statistical technique that uses several explanatory variables to predict the outcome of a response variable. A MLR model describes linear relationships between explanatory (independent) variables and a response (dependent) variable. The model uses dependent variables as continuous numbers and independent variables as continuous or binary. The model assumes the regression model is linear, data are normally distributed, homogeneity exists in residuals variance, and there is no perfect multicollinearity. MLR is represented by Equation (1) (Lilja 2016)

$$y_i = \beta_0 + \beta_{1xi1} + \beta_{2xi2} + \dots + \beta_{pxip} + \epsilon \quad (1)$$

where:

$i = n$ observations,

y = dependent variable

xi = explanatory variable

β_0 = y-intercept(constant)

β = slope coefficients for each explanatory variable

p = the n^{th} estimated regression coefficient

ε = the model's error term (residuals).

Table 1 | Description of the variables used in the statistical analysis

Variable	Description
Well depth	The depth of 20 m bgl defined the boundary between deep and shallow groundwater wells. The decision was based on the field observations and discussions with well owners and key informants. During the drilling activity, the shallow aquifers existed between ~8 and ~15 m bgl whereas hand dug wells were reported to have been dug to a depth ranging between 15 and 30 ft bgl (~5–10 m). All springs were considered as shallow wells.
Mode of construction	The mode of construction included hand dug, drilled and protected and/or unprotected springs. Some construction methods facilitate the placement of sanitary seals whereas a protected spring prevents direct ingress of surface water especially after rainfall events.
Type of water source	Type of water source was defined based on common characteristics such as protected or unprotected. Therefore, well types were protected or unprotected spring.
Distance to the nearest OSS	A spatial distance of 10 m from the water source was considered following the WHO (1997) guidelines of sanitary inspection. Therefore, a distance of <10 m between water sources and OSS was considered unsafe compared to that >10 m.
Geological formation	Geological formation has been categorised as Weathered basement and Recent Sediments. The two different geological formations have different lithological characteristics implying different hydrodynamic properties. For example, AGROSS (2001) gives vulnerability levels of different hydrogeological environments with their associated pollution levels whereas Morris <i>et al.</i> (2003) highlights the vulnerability of unconfined weathered basement and major alluvial sediments for example, as being moderate to high.
Source ownership	Water sources were subdivided into privately owned and communal water sources. In this study, communal water sources are not necessarily managed by public/private service. The privately owned water sources exist majorly in individual and/or institutions' compounds whereas communal ones are located in accessible points where all community members have access to them.
Sanitary risk	During water sample collection over the study, sanitary inspections of the water sources were carried out based on WHO (1997) inspection guidelines. These were averaged and categorised as low, medium and high-risk levels.

Table 2 | Summary of the pathways and water sources including categories and percentages

Pathways/variables	Categories	Water source counts (n)	Percentage (%)
Water source type	Shallow well	40	80
	Deep well	4	8
	Unprotected spring	6	12
Geology	Weathered basement	38	76
	Recent Sediments	12	24
Distance to the nearest pit latrine	<10 m	10	20
	>10 m	40	80
Well depth	<20 m bgl	44	88
	>20 m bgl	6	12
Mode of construction	Drilled	11	22
	Hand dug	33	66
	Protected spring	0	0
	Unprotected spring	6	12
Water source ownership	Communal	38	77
	Private	12	23
Sanitary risk level	Low	13	26
	Medium	22	44
	High	15	30

The model output coefficients table includes the coefficients for the regression equation (model), tests of significance for each variable and R squared value. For a binary variable, the coefficient only applies for the group coded as 1. The estimate column in the coefficients table gives the quantities of each independent variable in the regression model. The R^2 can only be between 0 and 1, where 0 indicates that the outcome cannot be predicted by any of the independent variables and 1 indicates that the outcome can be predicted without error from the independent variables. However, R^2 value increases with the number of independent variables so it is better to use the adjusted R squared value especially when comparing models with many variables. The test of significance p -value ranges from '0' to '1' where 0 means no association/correlation whereas 1 means perfect association/correlation. The regression model was developed using R statistical soft-ware, version 3.6.3 (2020-02-29).

RESULTS AND DISCUSSIONS

Summary statistics

The first set of analyses examined the impact of seasonality to the quality of water. Table 3 summarises observed *E. coli* counts and NO₃ concentrations of water samples collected over the dry ($N = 44$) and wet ($N = 50$) seasons for the year 2018–2019.

Table 3 | Summary statistics of the dependent variables as per the analysed water samples of the two seasons

Dependent variables	<i>E. coli</i> × 10 ³ (cfu/100 mL)		NO ₃ (mg/L)	
	Dry	Wet	Dry	Wet
Minimum	0	0	0	0
Mean	45	4	17	29
Median	6	0	7	19
Maximum	319	95	168	259
Standard deviation	79	15	32	42
WHO (2015)	0	0	50	50
Number of samples (N)	44	50	44	50

Of the analysed samples, 75% ($n = 33/44$) and 42% ($n = 21/50$) tested positive for *E. coli* and ~4.5% ($n = 2/44$) and ~16% (8/50) had NO₃ concentrations above Cotruvo (2017) guidelines during the dry and wet seasons respectively. The dry season is with median and maximum values of 6×10^3 and 319×10^3 cfu/100 mL *E. coli* counts and 17 and 168 mg/L NO₃ concentrations, respectively. The wet season, however, gave median and maximum values of 0 and 95×10^3 cfu/100 mL *E. coli* counts and 19 and 259 mg/L of NO₃ concentrations, respectively.

Table 3 reveals that *E. coli* counts observed during the dry season were generally higher than those observed during the wet season, which is inconsistent with previous studies reporting an increase in microbial counts during the wet season (e.g. Wallender *et al.* 2014; Sorensen *et al.* 2015; Joon 2016). The high *E. coli* counts during the dry weather in this study are attributed to the greater accumulation of faecal matter at the land surface and less-diluted, faecally contaminated recharge. Nayebar *et al.* (2020) observed that ~68% of the households (HHs) had grey water and HH waste including children's faeces most times, indiscriminately disposed of in open spaces around HHs, resulting in ponding. Some studies have noted, however, that high levels of *E. coli* counts are pronounced within 48 hours after the rainfall event (Howard *et al.* 2003; Kulabako *et al.* 2007). Low microbial counts during the wet season are presumed to result from dilution caused by infiltrating rainwater from more regularly flushed land surfaces. Joon (2016) identified high micro-organisms concentrations at early rainfall events of the wet season in Northern Thailand where contaminants were flushed into shallow wells, after which the quality improved as the wet season progressed. This is consistent with Taylor *et al.* (2009), whose findings indicated ephemeral contamination after heavy rainfall events of >10 mm/day. Like the existing body of research on seasonal NO₃ concentrations, this study established higher contaminant levels of the water sources above WHO (8/50) during the wet season compared to the dry season (2/44). There is oxidation likely of organic nitrogen due to relatively high levels of oxygen by the recharge in addition to the relatively conservative nature of nitrates in well aerated shallow groundwater over long distances. These high levels of NO₃

concentrations originate from waste dumps from domestic and animal wastes, fertilizers and the oxidation of ammonium from faecal matter where there exists high density of OSS.

Multiple linear regression

After testing for multicollinearity, all the variables were fit for the progressive regression analysis. Table 4 presents the model results of both dry and wet seasons of *E. coli* counts whereas Table 5 presents those of NO₃ concentrations respectively.

Table 4 | Model results of *E. coli* counts during the dry and wet seasons (August 2018 and May 2019)

Variables	Dry season					Wet season				
	Estimate (%)	Std. error	t-value	p-value	Level of significance	Estimate (%)	Std. error	t-value	p-value	Level of significance
(Intercept)	-45	0.29	-1.55	0.13		997	11.62	0.86	0.40	
Geology, Weathered basement	-18	0.12	-1.50	0.14		150	9.09	1.66	0.11	
Distance to the nearest pit latrine >10	38	0.17	2.20	0.03	*	175	7.42	0.24	0.82	
Depth of the well >20	15	0.24	0.64	0.52		199	5.18	0.39	0.70	
Source type, Shallow	40	0.17	2.33	0.03	*	-1306	6.23	-2.10	0.04	*
Water source ownership, Private	10	0.13	0.79	0.43		-653	5.12	-1.27	0.21	
Risk level low	5	0.16	0.31	0.76		-600	9.97	-0.60	0.55	
Risk level medium	135	0.42	3.24	0.003	**	-684	15.96	-0.43	0.67	
Mode of construction, Hand dug	64	0.22	2.95	0.006	**	619	7.89	0.78	0.44	
Mode of construction, Unprotected spring	52	0.28	1.90	0.07	.	040	9.70	0.04	0.97	

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

Multiple R²: 0.54, Adjusted R²: 0.37, p-value: 0.0042 (dry).

Multiple R²: 0.24, Adjusted R²: 0.00, p-value: 0.4538 (wet).

The significance codes indicate for example, with a significance level of 0.05, we can be 95% sure that the variable is significant.

Table 5 | Model results of NO₃ concentration during the dry and wet seasons (August 2018 and May 2019)

Variables	Dry season					Wet season				
	Estimate (%)	Std. error	t-value	p-value	Level of significance	Estimate (%)	Std. error	t-value	p-value	Level of significance
(Intercept)	-1,526	28.54	-0.54	0.59		-996	39.057	-0.26	0.80	
Geology, Weathered basement	925	23.57	0.39	0.69		894	32.26	0.28	0.78	
Distance to the nearest pit latrine >10	2,856	17.06	1.68	0.10		2,839	23.34	1.22	0.23	
Depth of the well >20	1,486	12.18	1.22	0.23		1,027	16.67	0.62	0.54	
Source type, Shallow	-2,108	17.38	-1.21	0.23		091	23.79	0.04	0.97	
Water source ownership, Private	1,217	12.46	0.98	0.34		437	17.05	0.26	0.80	
Risk level low	-178	23.01	-0.08	0.94		-1,972	31.49	-0.63	0.53	
Risk level medium	-439	36.19	-0.12	0.90		2,649	56.56	0.47	0.64	
Mode of construction, Hand dug	1,399	21.67	0.65	0.52		850	29.65	0.29	0.77	
Mode of construction, Unprotected spring	898	27.43	0.33	0.75		458	37.53	0.12	0.90	

Multiple R²: 0.17, Adjusted R²: -0.13, p-value: 0.8533 (dry).

Multiple R²: 0.11, Adjusted R²: -0.22, p-value: 0.9769 (wet).

The model p -values from the wet season of *E. coli* counts ($p = 0.454$, Table 4) and nitrate ($p = 0.853$, Table 5), as well as p -values from the dry season of nitrate ($p = 0.977$, Table 5) show that the model was not statistically significant. No relationship between the variables could be statistically explained by these models. One major theoretical explanation for the failure to establish significant linear regression models for NO_3 are the reducing conditions prevailing in the studied shallow aquifers, inferred from low pH and associated with decomposition of organic carbon, likely faecal matter. A related research study conducted by Nyenje *et al.* (2013) in Bwaise, Kampala, revealed that the bulk of N leached to groundwater was in the form of NH_4 due to Mn-reducing conditions. 60–70% of the nitrogen in faecal sludge is organic (i.e. bound to carbon) (Hemkend-Reis *et al.* 2008). In areas with rapid statistically extreme velocities within the subsurface (Taylor *et al.* 2004a, 2004b) and low pH occasionally exceeding 6 (Shi *et al.* 2018) nitrification in the subsurface is inhibited. Extreme flow velocities limit attenuation processes that promote nitrification. As in other studies where filtration is poor, high faecal microbial levels can occur even when nitrate concentrations are low (Haruna *et al.* 2005; Goepfert & Goldscheider 2011). Consequently, nitrate may not be an ideal response variable to identify seasonal changes in groundwater quality but may well reflect the impact of long-term loading of faecal matter that has undergone nitrification to nitrate (e.g. Thiaroye aquifer in Dakar).

Similarly, the wet season *E. coli* model was not statistically significant. It has been noted that groundwater quality deteriorates most within 48 hours after a rainfall event (Howard *et al.* 2003; Kulabako *et al.* 2007), after which dilution takes place thus lowering the counts and contamination peaks twice a day from 10:00 to 14:00 hours and at around 20:00 hours, likely due to the periods of high use of the OSS (Ekklesia *et al.* 2015). As sampling did not consistently occur within 48 hours after rainfall events, this factor may explain why no trend could be identified in the statistical model.

As can be seen from the data in Table 4, *E. coli* counts in the water samples during the dry season indicated that the model is highly statistically significant, $p = 0.004$ and more than 50% ; that is, ~54% ($R^2 = 0.54$) of the variations can be explained by the model containing the considered variables (pathways). Statistically significant in the table are distance to the nearest OSS, source type (shallow), risk level (medium) and mode of construction (hand dug wells) with p -values of 0.035, 0.026, 0.003, 0.006, respectively. Although in Table 4 the mode of construction (unprotected spring) was not statistically significant, it contributed more than half (52% estimate) to the quality of the shallow groundwater systems. The model equation (Equation (2)) obtained from the estimate column therefore is:

$$E. coli \text{ counts} = -44.6 + (38.4 * \text{distance to the nearest pit latrine}) + (40.0 * \text{source type, shallow}) + (134.6 * \text{risk level, medium}) + (64.2 * \text{mode of construction, hand dug}) \quad (2)$$

From the equation therefore, it can be observed that a <50% change in the distance to the nearest OSS and source type (shallow wells), would cause a change in the *E. coli* counts in shallow groundwater. However, closer review of the Table 4 results shows that the relationship between the *E. coli* counts and distance to OSS does not follow the normal trend of <10 m from OSS (WHO 1997). That is, distances of water sources beyond 10 m from pit latrines still caused shallow groundwater contamination and these were the majority (80%) during the surveys (Table 2). The high statistical significance association of the mode of construction (hand dug) ($p = 0.006$) and *E. coli* count levels in the water samples stems from the improper well design, which does not allow for proper and appropriate sanitary sealing. Pieper *et al.* (2016) noted that the mode of system construction determines the source depth and aquifer, which, in turn, govern the raw groundwater quality being supplied to the public in addition to location and placement of sanitary seals. It is clear that hand-dug wells are sunk in the shallow aquifers, which are prone to contamination. Although commonly high sanitary risk levels have been associated with poor water quality (Howard *et al.* 2003; Sorensen *et al.* 2015), the correlation of medium sanitary risk levels with poor shallow groundwater quality ($p = 0.003$) is likely to be exacerbated by focused recharge in areas covered by low permeable zones such that contaminants from far sources other than the immediate surrounding environment enter into the aquifer or water source through some pathways such as broken aprons (MacCarthy *et al.* 2013; Lapworth *et al.* 2017). Additionally, poor structural integrity such as broken aprons provide short circuits (macropore flow) such that there is a short residence time for any attenuation process to act on the contaminants. The statistically significant association between shallow water sources and *E. coli* contamination indicated by this study ($p = 0.026$) has been noted by Gonzales

(2008), Allevi *et al.* (2013) and Aladejana *et al.* (2020). This association likely results from the short residence time for microorganisms to reach the aquifer when they are introduced on the land surface (Hamutoko *et al.* 2016), resulting in a lack of attenuation of contaminant flows. The association of *E. coli* counts with distance of OSS beyond 10 m from the water source ($p = 0.04$) is an indication that other factors such as mode of pit latrine construction (lined/unlined) and structural integrity of both water source and OSS could be the causal factors of the association. For example, during data validation, it was observed that only 24% of the pit latrines were lined, most of which were >10 m from the sampled water sources. In addition, in the preliminary study in the area involving sanitary risk levels of OSS, it was observed that many of the high risk levels (77%) originated from poor structural integrity (Nayebare *et al.* 2020).

Although the model was not statistically significant for *E. coli* counts during the wet season, the source type, shallow, was statistically significant ($p = 0.043$). Research has indicated that shallow groundwater quality deteriorates mostly within 48 hours after the rainfall (Howard *et al.* 2003; Kulabako *et al.* 2007), after which dilution comes into play. Ekklesia *et al.* (2015) also noted diurnal variations in faecal contamination levels whereby faecal contamination peaks twice a day from 10:00 to 14:00 hours and at around 20:00 hours were likely due to the periods of high use of the OSS. There are high chances that the samples that were collected shortly after the rainfall events (within the 48 hours) and/or during the contamination peak had elevated *E. coli* counts. During the wet season, many of the water sources are flooded, as observed by the lead author during field surveys. Flooding coupled with an unsanitary environment are presumed to be the causes of the correlation between the variable (shallow well, Table 4) and the *E. coli* count during the wet season.

CONCLUSION

A multiple linear regression model was developed to explain relationships between potential contaminant pathways and observed quality of shallow groundwater in a rapidly growing town in southern Uganda. The results show statistically significant relationships between *E. coli* counts in shallow groundwater and distance to the nearest OSS, source type (shallow), risk level (medium) and mode of construction (hand dug wells) during the dry season. Risk level and mode of construction (hand dug) play a major role in the quality of the shallow groundwater during the dry season. During the wet season, the model analysis for *E. coli* count was not significant probably due to random sampling that did not capture the events when the groundwater quality deterioration is expected to be high. Similarly, the model analysis was not statistically significant for NO_3 concentration as an indicator of faecal contamination for both the wet and dry seasons due to limited capacity for nitrification as a result of low pH and rapid infiltration velocities. Improvement of structural integrity of both water sources and OSS; for example, engineering headworks such as cracks on the aprons and proper sanitary sealing of the water sources and lining of pit latrines should be encouraged.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by The Royal Society (UK) and the UK Department of International Development (DFID) under the AfriWatSan Project (ref. AQ140023). We also acknowledge the critical support of Lukaya Town Council as well as field assistants Ms Rita Nakazibe, Mr Robert Sesanga and Ms Susan Kigozi, who assisted in the execution of field surveys and and laboratory analyses.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 12 September 2021; accepted in revised form 29 October 2021. Available online 9 November 2021