Physics and Chemistry of the Earth 144 (2026) 104485

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

# Groundwater contamination and public health burden in an emerging urban settlement: A mixed-methods assessment from Charlton Park, Gweru, Zimbabwe

Oshneck Mupepi, Tererai Kundishora, Roberta Mavugara *

*Department of Geography, Environmental Sustainability and Resilience Building, Midlands State University P.bag,9055, Gweru, Zimbabwe*

ARTICLE INFO

*Keywords:*
Emerging residential areas
Water borne diseases
Faecal contamination
Human health risk
Groundwater
Urban planning

ABSTRACT

In developing cities, urbanisation often overtakes the provision of water and sanitation services, forcing residents in emerging settlements to rely on untreated groundwater. This poses severe, yet poorly quantified, public health risks. The study assessed groundwater contamination and associated public health issues in Charlton Park residential area in Gweru, Zimbabwe using a convergent parallel mixed-methods study. Water samples were collected from accessible groundwater sources ($n = 8$) and subjected to microbiological analysis for faecal coliforms. Additionally, a household survey ($n = 40$) was administered. Data was triangulated with key informant interviews, focus group discussions, and clinical records. Statistical analysis included Kruskal-Wallis, Mann-Whitney U, and Spearman's correlation tests. Water quality analysis revealed 87.5% exceeded World Health Organisation faecal coliform guidelines. A significant negative correlation was found between latrine proximity and coliform levels ($\rho = -0.81$, $p = 0.015$). Major pathways of water contamination were seepage from inadequately lined septic tanks, discharge of human waste and leachate from open domestic waste dumps. Clinic records showed a disproportionate burden of disease among children, with a case distribution ratio of 1.67 compared to adults. This study provides empirical evidence that groundwater in unserviced and emerging urban settlements is a major pathway for faecal pathogens, directly impacting community health with unmistakable inequalities. Given these findings it is critical to ensure that service delivery precedes urban settlement. The study proposes a Socio-Hydrological Intervention Framework (SHIF) to mitigate contamination and its associated health burdens. It offers a phased, actionable model transferable to similar contexts across Zimbabwe.

## 1. Introduction

Groundwater contamination from organic waste threatens health risks of communities in developing countries, where groundwater is the main source of water (Onipe et al., 2020). Water is essential to ensure good health for human beings as confirmed by the United Nations' report on supporting the global Sustainable Development Goal (SGDs) 3 and 6 for good health and well-being and clean water and sanitation respectively (Sunny et al., 2021). Groundwater contamination has become a major global challenge and concern in recent decades due to poor sanitary condition as a result of high population growth (Mukherjee and Singh, 2020). By 2025, an estimated 67% of the global population will encounter water scarcity and related health problems if the current lack of effective groundwater contamination monitoring persists (USAID, 2019). The world's groundwater resources are facing unprecedented pressure from the converging impacts of population growth, urbanization, and over-extraction (Gleick and Cooley, 2021). As such, actions are essential to safeguard groundwater quality and sustainability, ensuring a resilient water future for all (Carriço et al., 2020).

In Southeast Asia (Indonesia), only 20.1% of the population has access to piped water whilst the majority rely heavily on groundwater for drinking. However, the quality of this groundwater is poorly understood which raises concerns over health and safety risks for residents (Kazama and Takizawa, 2021). The quality of groundwater has been compromised by anthropogenic activities (Kirschke et al., 2020; Makaya and Maphosa, 2023). In 2019, 89% of drinking water sources in Syria tested positive for *E. coli* contamination, resulting in 59 638 confirmed cases of infectious diarrhoea (Kazama and Takizawa, 2021). The situation in Syria has been worsened by ongoing conflicts which make groundwater monitoring and decontamination in the region nearly impossible.

* Corresponding author.
*E-mail address:* robertamavugara@gmail.com (R. Mavugara).

https://doi.org/10.1016/j.pce.2026.104485
Received 15 December 2025; Received in revised form 25 February 2026; Accepted 29 April 2026
Available online 30 April 2026
1474-7065/

Countries in sub-Saharan Africa are not spared from the ramifications of contaminated groundwater. In Ogbomoso, Nigeria a study found evidence of bacterial contamination in the form of faecal coliform, which suggested that the water may not be safe for human consumption (Igboama et al., 2022). They further assessed that microbes from onsite sanitation systems such as pit latrines and septic tanks are the main contributors to groundwater contamination posing serious threat to public health (Igboama et al., 2022). In South Africa, a comprehensive analysis of groundwater quality from borehole and household wells revealed widespread contamination and potential health risks (Masindi and Foteinis, 2021). The findings highlight the urgent need for indicated monitoring and management of groundwater sources to protect human (Masindi and Foteinis, 2021). Groundwater pollutant load has become a pressing concern, as it leads to a range of gastrointestinal illnesses such as vomiting and constipation and other health problems (Kirschke et al., 2020). Subsurface water has long been regarded as a readily accessible and reliable source of freshwater for various human needs and the environment, but due to the growing concern of organic wastes related groundwater contamination, it makes it an unreliable and unsafe source (Pradhan et al., 2023).

Recently, the scope of groundwater contamination has expanded beyond traditional microbial and physicochemical parameters to include a growing range of “Contaminants of emerging concern”. These contaminants include radionuclides, microplastics, polycyclic aromatic hydrocarbons (PAHs), bisphenol A (BPA), and polychlorinated biphenyls (PCBs). Studies have detected microplastics in treated water, raising concerns about bioaccumulation and chronic exposure (Rahim et al., 2025; Gyimah et al., 2024). BPA contamination, often linked to plastic degradation and landfill leachate migration, further complicates groundwater quality monitoring frameworks, especially in settlements without engineered waste containment systems. Similarly, PCBs and PAHs, usually associated with poor waste management and industrial activity, are increasingly found in groundwater in rapidly urbanising areas (Odewade et al., 2025). Moreover, both geogenic and anthropogenic radionuclides have gained renewed attention regarding environmental risk over the past five years (Olatunji et al., 2023).

While these emerging contaminants demonstrate the growing complexity of groundwater safety worldwide, evidence from low-income settlements indicates that faecal contamination from on-site sanitation remains the most urgent public health threat (Sekgobela et al., 2023; Ng’andwe et al., 2025). In contexts characterised by shallow aquifers, high settlement density, and inadequate sanitation planning, microbial contamination often outweighs chemical exposure risks. Situating this study within this broader contamination landscape enhances its relevance. This study recognises emerging global threats whilst empirically emphasising the primary exposure pathway affecting vulnerable populations in informal settlements.

In Zimbabwe, groundwater contamination has become a serious health concern since the early 2000s, with larger cities like Harare, Bulawayo and Gweru being the most affected, especially in their emerging high-density residential areas with poor sanitation and improper disposal of organic wastes (Matsa et al., 2021a,b).The prolonged water crisis from all water sources has exacerbated risks to public health, as witnessed by the 2024 cholera outbreak, which claimed 71 lives in Harare and 26 in Gweru (Ministry of Health and Child Care, 2024). In Amsterdam Park, Harare, researchers found that rapid urban growth resulted in increased organic solid waste which is not being properly disposed leading to groundwater contamination through leachate percolation (Maruta et al., 2023). Residents of Amsterdam Park experienced health issues like diarrhoea, stomach problems, and typhoid fever due to contaminated groundwater (Maruta et al., 2023). Charlton Park in Gweru is among the high-density residential areas struggling with inadequate and unreliable water supplies, forcing residents to rely on wells and boreholes, which are often directly contaminated by human and animal waste. Against this background, this study sought to:

a. Identify and characterise the primary groundwater sources utilized by residents of Charlton Park.
b. Determine the microbiological quality (faecal coliform count) of these groundwater sources and assess compliance with WHO drinking water guidelines,
c. Analyse the relationship between sanitation infrastructure (specifically latrine proximity) and groundwater contamination levels.
d. Evaluate the associated public health burden by triangulating self-reported health data with clinical records, with a focus on differential impacts across age groups.
e. Develop a stakeholder-informed and evidence backed framework to reduce groundwater contamination and its associated health risks in emerging urban settlements such as Charlton Park.

Whilst studies have reported on water quality issues in several developing countries and the Zimbabwean context, to the best of our knowledge, few have provided a comprehensive and actionable step towards tackling it. Given the emphasis on provision of clean water and sanitation as emphasized in Sustainable Development Goal 6 as well as Zimbabwe's National Development Strategy 1, it is imperative to study comprehensively the status of groundwater quality and it's impacts on the population in emerging residential areas. This study stands out by providing a novel framework that stakeholders and responsible authorities can put into action to address groundwater contamination.

## 2. Study area

The study was conducted in the city of Gweru which is the provincial capital for the Midlands Province of Zimbabwe (Fig. 1). Gweru city has a population of 161 294 of which 74 434 are males and 86 860 are females (ZIMSTAT, 2022). The city blends urban development with agricultural activities contributing to its economy for example cattle ranching and household farming to improve their food security (Chaminuka et al., 2021; Kusena et al., 2022).

The coordinates of Gweru District are "-19.4657°S, 29.8124°E″ with an elevation of 1424 m (4672 feet) above sea level. The district receives an average annual precipitation of 660 mm and high temperatures of 28.89 °C. Gweru City is 168 km from Bulawayo and 280 km from Harare along the major Harare-Bulawayo road. Gweru straddles across diverse soil types like black basalts, red loams and sands with high drainage capacity that allows contaminants to enter groundwater at a fast rate. The city of Gweru lies on a watershed, which stretches from Rusape to Bulawayo and is at an altitude of about 1422 m. The municipal area is bisected by numerous streams most of which drain into the Gweru River a tributary of the Gwayi River. The region is mostly affected by south-east prevailing winds which are dominant in summer from August to November with a mean speed in the range of 8.0 to 9.3 knots.

The topography of the Gweru district is predominantly undulating, characterised by gentle to moderate slopes that promote surface runoff. Settlement peripheries including Charlton Park are characterised by uneven micro-relief with localised steep gradients which accelerates lateral transport of contaminants from sanitation facilities, waste dumps, and unprotected soils towards shallow groundwater systems. This topographic profile, combined with the permeable soils, increases the vulnerability of shallow wells to rapid faecal infiltration, especially in areas lacking engineered drainage or lined sanitation infrastructure. The city is characterised by a variety of vegetation types including brachystegia, julbernardia and acacia among other species.

Gweru has developed infrastructure such as roads, health facilities, water systems among others. However, currently there are challenges in maintaining and expanding these systems to meet the growing demands of the population especially in emerging high-density suburbs. Access to clean water and adequate sanitation as well as healthcare still needs improvement.

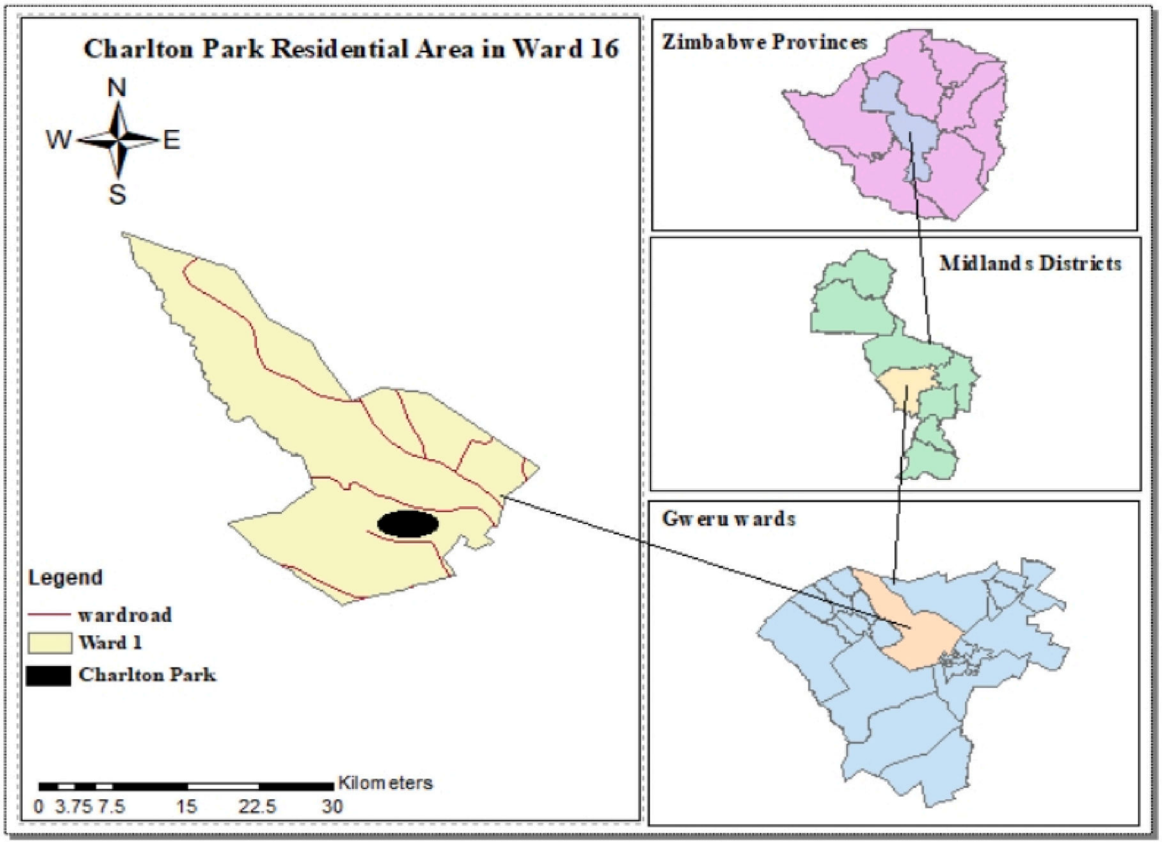


**Fig. 1.** The location of Charlton Park residential area in Gweru District, Zimbabwe.

## 3. Methodology

The study investigates the multifaceted socio-environmental subtleties of groundwater contamination in Charlton Park. To achieve this, a mixed-methods convergent parallel design (Creswell & Plano Clark, 2023) was employed. Using this design enabled the collection of quantitative data (water quality parameters, closed-ended survey responses) and qualitative data (open-ended responses, interviews, focus group discussions, observational notes) simultaneously. In this research quantitative data collection and analysis methods were used to determine the water quality in Charlton Park as well as determine the health risk factor emanating from groundwater contamination. In this regard water quality tests as well as closed ended questionnaires were used. Qualitative information and descriptive responses from participants were then used to support statistical analysis of water quality and quantitative responses from participants. Open-ended questions of the questionnaire, observations and interviews were utilized to obtain qualitative data. This study was greatly enhanced by the complementary effects of quantitative and qualitative data collection methods and other information obtained through various instruments in the field. The two datasets were analysed independently and then integrated during the interpretation phase to provide a holistic understanding of contamination sources, pathways, and health implications.

### 3.1. Target population and sampling

The study was conducted in Charlton Park, an emerging high-density residential suburb of Gweru, Zimbabwe (Fig. 1). The research targeted 196 Charlton Park households, Gweru City Council, Environmental Management Agency and the Mtapa Clinic near the study area. Charlton Park households were targeted as the main focus of the research because they are the ones who are directly impacted by the issue of groundwater contamination. This makes them an ideal target population to provide data on health effects of groundwater contamination and evidence of contamination. The Gweru City Council and Environmental Management Agency was found as the relevant source of information for this research due to its role in monitoring public health and safety issues and implementing measures to reduce groundwater contamination and its associated health impacts as experts in the environment. In addition to households and institutional stakeholders, the Mtapa Clinic was targeted for data collection. Mtapa Clinic was selected as the primary health data source because it is the closest public health facility serving Charlton Park residents and functions as the first point of care for waterborne and gastrointestinal illnesses within the community. According to clinic administration, the majority of Charlton Park residents seek treatment at Mtapa Clinic due to geographic proximity, affordability, and referral protocols, making it the most representative facility for assessing community-level disease burden.

#### 3.1.1. Sampling strategy

The research employs a hybrid sampling strategy which incorporates both probability and non-probability sampling techniques to ensure representativeness and depth of information. The sampling techniques for the household survey, the key informant interviews and the focus group discussions (FDGs) are reported below.

#### 3.1.2. Sampling procedure for the household survey

For the household survey, a single-stage random sampling technique was employed to select the respondents. To determine this, the standard sample size formula for a finite population (Equation (1)) proposed by Krejcie and Morgan (1970) was used.

$$n = \frac{N \times X}{X + (N - 1)} \quad (1)$$

where:

- $N$ = Population size (196 households)
- $X = Z^2 \times p \times (1 - p)/e^2$
- $Z$ = Z-score (1.96 for 95% confidence level)
- $p$ = Proportion of the population (set at 0.5 for maximum variability)
- $e$ = Margin of error (0.15, acceptable for exploratory studies in resource-limited settings)

Using this formula yielded a required sample of approximately 40 households. To select participating households for the survey, the researchers acquired a numbered list of all households from the ward councillor which were then entered into Microsoft Excel. Using the RANDBETWEEN function, 40 unique numbers were generated. the generated numbers represented the selected participants for the household survey. Systematic random sampling was not considered a viable option in this research, as the houses in the Charlton Park area are not arranged in uniform manner.

#### *3.1.3. Sampling procedure for key informant interviews*

To select participants for the key informant interviews, the researchers employed purposive sampling. Selection of the key informants was based on their expertise and institutional role: the GCC Senior Public Health Officer, the GCC Solid Waste Management Officer, the EMA Environmental Officer for Gweru, and the Mtapa Clinic Nurse-in-Charge.

#### *3.1.4. Selection of participants for the FGDs*

in addition to the household survey and the key informant interviews, we also conducted FGDs. In this regard, two FGDs were conducted. Eash focus group consisted of eight participants. Participants for the FGDs were purposively selected to include a mix of genders, ages, and household locations (proximal vs. distal to observed waste dumps). This was done to capture diverse community perspectives.

#### *3.1.5. Water quality sampling*

For the collection of water samples, a census approach was adopted for water sources in Charlton Park. The researchers identified seven (7) wells (both shallow and deep) and a single functional borehole. Given the small number of point sources, census sampling was adopted resulting in $n = 8$ water sources. This was done to establish a complete preliminary baseline for the area.

### *3.2. Data collection instruments and procedures*

#### *3.2.1. Household questionnaire*

A structured questionnaire with closed and open-ended questions was administered face-to-face. Aspects covered in the questionnaire were: i) household demographics and water sources, ii) observed water quality indicators, iii) perceived health issues and their frequency, and iv) knowledge of contamination sources and mitigation practices. Pretesting was done with 5 households in a similar adjacent suburb (not included in the study). This questionnaire was then self-administered to the randomly selected 40 households in Charlton Park residential area. The questionnaires were distributed in a space of 7 days to allow respondents ample time to respond to the questions.

#### *3.2.2. Key informant interviews (KIIs) and FGDs*

To collect data for the KIIs and the FDGs, semi-structured interview and discussion guides were used, respectively. KIIs explored institutional perspectives on contamination causes, regulatory challenges, and mitigation efforts. Before the interviews took place, the researchers contacted the key informants to make the necessary arrangements, such as the time and place of the interviews. On the other hand, FGDs explored community perceptions, experiences, and locally proposed solutions. All sessions were audio-recorded with consent and supplemented with field notes.

#### *3.2.3. Direct observation*

A standardised observational checklist was used to document physical evidence from the study area. The researchers were on the lookout for the condition of wells, proximity to sanitation facilities (measured using a handheld GPS Garmin eTrex 10, ±3 m accuracy), presence of waste dumps, and general sanitary conditions. Photographs were taken as evidence (with identifiers removed).

#### *3.2.4. Water quality sampling and analysis*

*3.2.4.1. Sampling protocol.* Water samples were collected during the dry season (August 2024). This was done to minimise the dilution effects from runoff. To ensure sampling of standing groundwater, all the wells were purged by extracting three well volumes of water using a sterilising bucket before collecting water samples. Following the purge, samples were collected in pre-sterilised 750 ml polyethene bottles containing sodium thiosulfate to neutralise any residual chlorine (though none was expected). Bottles were labelled, stored in a cool, dark container at 4 °C, and transported to the laboratory within 6 h. The researchers labelled all containers according to the names given to each of these wells (W1–W7, W indicating well and numbers being codes assigned to each well) and B1 for borehole using stickers and permanent markers for easy identification during laboratory tests.

*3.2.4.2. Laboratory analysis.* The primary parameter analysed was faecal coliform bacteria, a key indicator of contamination from human and animal waste. This parameter was selected because it considered a good indicator of groundwater contamination in settlements that use onsite sanitation for disposing human waste, decomposing crop residuals, availability of human waste among other reasons (Maruta et al., 2023).

The membrane filtration technique, as per Standard Methods 9222B (Bridgewater, 2017), was employed to quantify faecal coliforms, a standard indicator of recent faecal contamination. Briefly, 100 ml of each serially diluted sample was filtered through a 0.45 μm cellulose membrane. The filter was placed on Membrane Lauryl Sulphate Broth (MLSB) and incubated at 44.5 °C ± 0.5 °C for 24 ± 2 h. Faecal coliform colonies (yellow) were counted and expressed as Colony Forming Units per 100 ml (CFU/100 ml). The World Health Organization (WHO, 2017) guideline of **0 CFU/100 ml** for drinking water was used as the safety benchmark.

### *3.3. Data analysis*

#### *3.3.1. Quantitative data analysis*

Quantitative data was analysed using descriptive and inferential statistics. Quantitative data collected from the survey and the water quality tests were coded and analysed using Microsoft Excel 365 and IBM SPSS Statistics v.29. Frequencies, percentages, means, and standard deviations were calculated to describe household characteristics, water source use, and observed health symptoms.

The normality distribution of water quality data was determined using the Shapiro-Wilk test, and it indicated that the coliform count data were not normally distributed. As such, the non-parametric Mann-Whitney *U* Test was employed to compare contamination levels between shallow wells and deep wells, which were considered to be two independent groups. The authors also used the Kruskal-Wallis H Test for comparisons across more than two groups. Correlation analysis using the Spearman's Rank-Order Correlation (ρ) was used to assess the strength and direction of the relationship between two continuous/ordinal variables. In particular, the researchers assessed the relationship between the distance from a well to the nearest latrine and its faecal coliform count.

To examine the relationship between reported health outcomes and age group based on clinic data, the researchers initially planned on using a Chi-square test of independence. The prerequisite for this test is a contingency table of counts of individuals (cases vs. non-cases) categorized by age group (child/adult). However, this individual-level data was not available from the clinic aggregates and as a result the Chi-square test was not performed. Seeing this gap, the researchers calculated risk metrics from the aggregated clinic data (see Section 3.5.3).

Additionally, spatial analysis was also conducted to visualise the location of water sources vis-a-vis sanitation features. In this regard, GPS coordinates of water sources and sanitation features were plotted using QGIS 3.34 to visually analyse this proximity.

#### 3.3.2. Qualitative data

Audio recordings from KIIs and FGDs were transcribed verbatim. Transcripts, open-ended survey responses, and observational notes underwent **thematic analysis** (Braun & Clarke, 2006) using the following steps: 1) familiarisation with the data, 2) generating initial codes, 3) searching for themes, 4) reviewing themes, 5) defining and naming themes, and 6) producing the report. This analysis identified key themes regarding contamination sources, community coping strategies, and institutional challenges.

#### 3.3.3. Data integration and risk estimation

To ensure the robustness of study findings, the researchers used data triangulation. In this regard, findings from quantitative (water quality, survey) and qualitative (interviews, FGDs, observations) strands were compared and contrasted to validate and explain results.

Risk estimation was a critical part of this study as it gave a picture of the population that was more at risk from the exposure to contaminated water. Using the Mtapa Clinic aggregate data presented in Table 2, the researchers calculated the proportion of cases (Equation (2)) and relative risk (RR) (Equation (3)). This was used to compare disease burden between children and adults as follows:

$$\text{Proportion of Diarrhoea cases in Children} = \frac{12}{(4+12)} = 75\% \tag{2}$$

$$\text{RR (Diarrhoea)} = \frac{\text{Risk in Children}}{\text{Risk in Adults}} = \frac{12/(\text{Total Child Population})}{4/(\text{Total Adult Population})} \tag{3}$$

In this particular case, the exact child/adult population-at-risk was unknown. As such a simplified odds-like ratio was presented using case totals. This limitation has been clearly stated in the limitations of the study section.

#### 3.3.4. Ethical considerations

Ethical approval was obtained from the Midlands State University Faculty of Social Science ethics review board. Written informed consent was obtained from all survey, FGD, and interview participants. For illiterate participants, the information sheet and consent form were read aloud, and a thumbprint was obtained in the presence of a literate witness. Anonymity and confidentiality were assured. Data is stored on a password-protected computer and will be destroyed five years after publication.

**Table 1**
Bacteriological test results and source characterisation.

| Sample ID | Source Type | Depth (approx.) | Distance to Nearest Latrine (m) | Faecal Coliform (CFU/100 ml) |
|---|---|---|---|---|
| W1 | Deep well | >10 m | 15 | 5 |
| W2 | Deep well | >10 m | 10 | 8 |
| W3 | Deep well | >10 m | 25 | 0 |
| W4 | Deep well | >10 m | 20 | 0 |
| W5 | Shallow well | <5 m | 5 | 41 |
| W6 | Shallow well | <5 m | 15 | 10 |
| W7 | Deep well | >10 m | 8 | 34 |
| B1 | Borehole | >30 m | >30 | 0 |

Source: Field data

**Table 2**
Mtapa Clinic waterborne diseases reported from 2023 to 2024.

| Health issues reported at Mtapa Clinic | Number of adult cases | Number of children cases | Total |
|---|---|---|---|
| Stomach problems | 12 | 28 | 40 |
| Diarrhoea | 4 | 12 | 16 |
| Vomiting | 8 | 2 | 10 |
| Suspected cholera | 5 | 6 | 11 |
| Typhoid fever | 1 | 2 | 3 |
| | 30 | 50 | 80 |

Data source: Clinical records from Mtapa Clinic

## 4. Results and discussion

### 4.1. Characterisation of groundwater sources used in Charlton Park residential area

#### 4.1.1. Types, spatial distribution and reliability of groundwater sources

The findings indicated that residents in Charlton Park utilise various groundwater sources, including deep wells (10 m and above), borehole and shallow wells. The majority (60%) (Fig. 2) of respondents indicated that they rely on deep wells as their main water source. Twenty-five percent (25%) of respondents noted that they utilise a single borehole water source available within their community, due to the absence of access to deep wells at their households. They indicated that, a generous benefactor donated a borehole in response to water shortages in Charlton Park, alleviating the reported waterborne health issues for residents documented at Mtapa clinic. The provision of the borehole through philanthropy and not by the local authority is an illustration of the governance vacuum in Charlton Park which leads residents to manage their own water security. It was observed that a minority of residents (15%) rely on shallow wells, which are highly susceptible to contamination as their primary water source (Fig. 2).

During an interview, the Senior Public Health Officer, highlighted that the residential area has been impacted by the 2023 delimitation process, leading to jurisdiction contestations between Vungu Rural District Council and Gweru District Council. As a result neither of the local authorities provided services to the residents. This administrative contestation explains the infrastructure deficit documented in this study. Jurisdictional ambiguity affects capital investment, and shifts maintenance responsibilities. This burden is soon transferred to residents who are left to self-provide water, sometimes with detrimental health consequences. The delimitation dispute in Charlton Park represents an acute localised expression of this broader institutional pattern.

Literature supports that in developing countries like Zimbabwe and Zambia, emerging residential areas often experience delays in progress from responsible authorities regarding standard municipal water supply and sanitation facilities (Maruta et al., 2023; Mumba, 2020). This lack of infrastructure exposes residents to groundwater contamination health related issues. The reliance on groundwater sources observed in Charlton Park mirrors patterns reported in other emerging and peri-urban settlements globally. In Ogbomoso, Nigeria, Igboama et al. (2022) reported that over 70% of households depended on shallow wells located within 15 m of sanitation facilities, conditions strongly associated with faecal contamination. Similarly, Masindi and Foteinis (2021) documented widespread microbial contamination of boreholes and hand-dug wells in peri-urban South Africa, attributing this to poorly lined pit latrines and septic tanks.

The reliance on groundwater points, particularly deep wells,

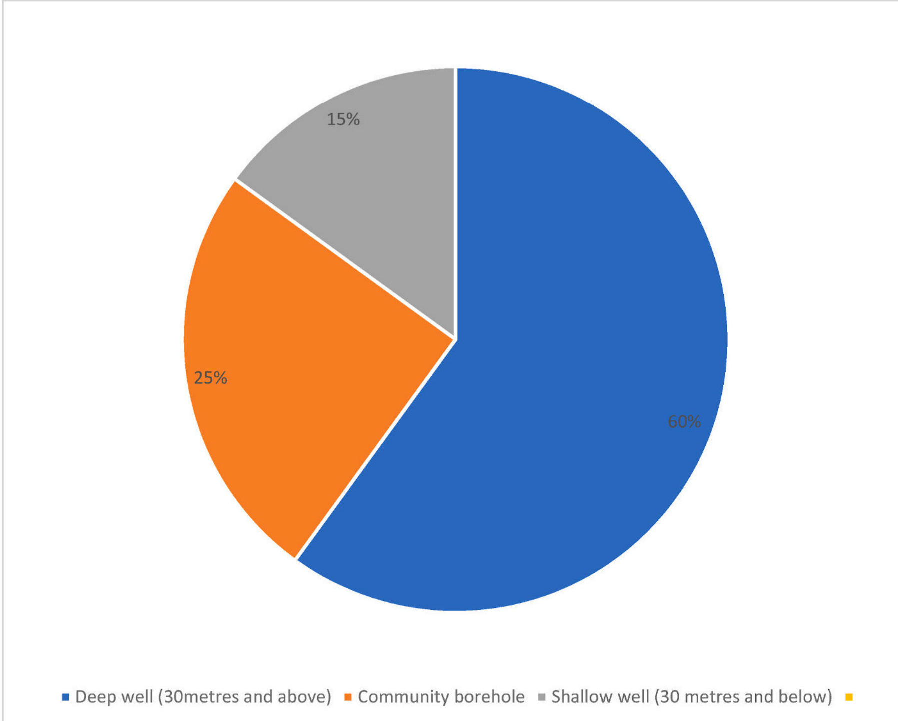


**Fig. 2.** Water sources used by residents in Charlton Park residential area.

highlights a critical infrastructure deficit in Charlton Park and a fragile form of water reliability. Self-supplied wells are the predominant source of water relied on by 60% of respondents over the single communal borehole (25%) showing household-level response to municipal service failure. This pattern is common in urban settlements across the Global South, where formal water networks is behind spatial expansion. In Charlton Park the choice of water sources is driven by availability and immediate necessity rather than safety. Similar findings have been reported in peri-urban settlements in South Africa, Nigeria, Ghana and Kenya where groundwater sources are often considered "reliable" due to year-round availability, despite known risks posed by contamination spikes and declining water tables during dry periods (Masindi and Foteinis, 2021; Igboama et al., 2022; Stoler et al., 2020; Okoto et al., 2015). Paradoxically, these sources are consistently available but consistently unsafe, masking a chronic public health risk with a coating of resourcefulness. This paradox is emphasized during drier months, when reduced recharge leads to concentration of existing contaminants in groundwater as demand increases and alternative sources disappear.

The observed dependency on shallow wells by a minority (15%) represents the most vulnerable demographic, often those unable to afford deeper excavation or living far away from the single community borehole. Given their proximity to the surface, shallow wells are directly exposed to faecal runoff, organic leachate and septic seepage. Consequently, the population group utilising this source carries the highest contamination risk within an already compromised water system. The continued dependence on shallow wells for domestic use by some respondents represents a point of failure in the settlement's water system and service delivery by the local authority. These findings are a mirror of socio-economic gradients in water access documented in informal settlements across Sub-Saharan Africa and South Asia, where access to water is determined by the depth of one's pockets (Rahim et al., 2025). In the same vein, access to reliable groundwater in Charlton Park is shaped more by governance gaps, infrastructural neglect, absence of redundancy within the water supply system and socio-economic status and not by hydrogeological sufficiency.

#### 4.1.2. *Distance between water sources and sanitation infrastructure*

According to international and national guidelines, a minimum horizontal distance of 30 m between a water source and a sanitation facility is recommended to mitigate contamination risk (WHO, 2017). Results from Charlton Park showed start contrast and non compliance with this guideline. The average measured separation distance between sanitation facility and water sources was between 11 and 20 m. Thirty-five per cent (35%) of household respondents hand water sources situated less than 10 m from a sanitation facility. Only 20% of the water sources were at least 30 m from a sanitation facility (Fig. 3). This widespread non-compliance with WHO-sanctioned safe distancing (WHO, 2017) is a common challenge in densely populated, informal settlements. The non-compliance rate of 80% observed in Charlton Park is consistent with findings from peri-urban Ghana, where studies of hand-dug wells in Aflao found that 37.3% of wells were sited within 10 m of latrines and all sampled wells exceeded WHO microbial guidelines (Amoako et al., 2025). It also aligns with findings from Nigerian informal settlements where space constraints and plot fragmentation undermine safe sanitation siting (Ayeni et al., 2025).

The observed proximity of sanitation facilities to groundwater sources in Charlton Park creates a critical contamination pathway for groundwater resources. This spatial relationship is consistent with studies across sub-Saharan Africa, which demonstrate the increased occurrence of wells located within 10–20 m of pit latrines in emerging towns (Murei et al., 2023; Masocha et al., 2019). In Charlton Park, the prevalence of distances below the WHO-recommended 30 m threshold indicates poor settlement design which increases the likelihood of groundwater contamination.

The situation in Charlton Park is arguably more dangerous due to the effects of sloping topography, high-permeability soils, and unregulated sanitation siting. Together, these risk factors increasingly facilitate lateral and vertical movement of faecal matter into groundwater systems (Alao et al., 2024). Emerging settlements such as Charlton Park expose how land baron developments in the Zimbabwe have significantly shaped the face of water and sanitation. The rampant non-compliance is not only a factor of negligence among residents but a culmination of poorly

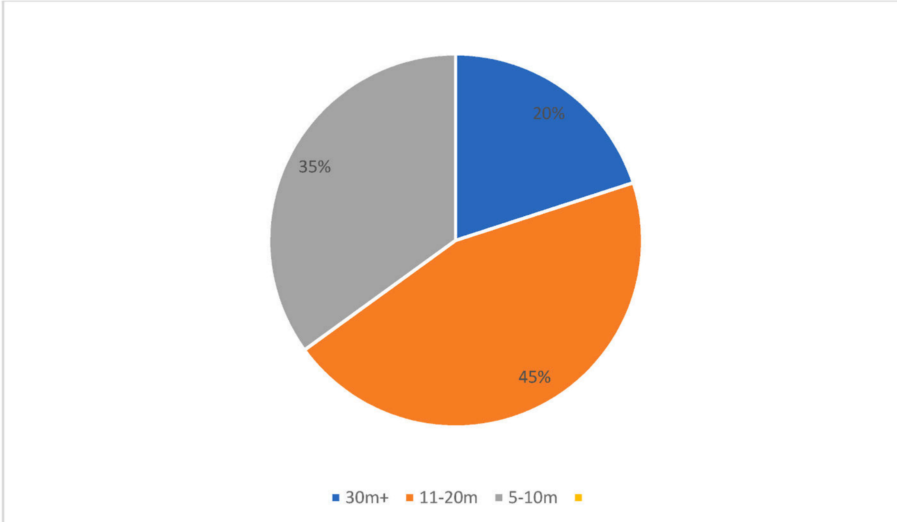


**Fig. 3.** Distance between sanitation facilities and water sources.

planned settlement growth and small plot sizes. Faced with a water crisis on their small sized land plots, most residents have no choice but to site their water and sanitation facilities within the confines of whatever space they have. Similar patterns have also been documented in informal settlements in Harare and Nairobi (Matsa et al., 2019). The findings therefore reinforce that groundwater contamination in emerging urban settlements is not merely a function of poor household practices, but a spatial indicator of regulatory failure and infrastructural absence.

### *4.2. Quality of groundwater sources in Charlton Park*

#### *4.2.1. Self-reported indicators of groundwater contamination*

Findings showed that residents Charlton Park are observing some physical signs of water contamination.

Forty percent (40%) of respondents revealed that their water had unusual tastes that might be a result of high (alkaline) or low pH value (acid). Literature indicates that decayed organic matter can release compounds that change the taste of water (Igboama et al., 2022) which indicates the contribution of dumpsite waste observed to water pollution. Half of the respondents (50%) noted that they encounter water discoloration in their wells, typically occurring during the mid-months of the year and coinciding with well dry-ups, (Fig. 4). When water tables drop during dry periods, the concentration of dissolved solids, organic matter, and contaminants in groundwater increases, producing visible discolouration and heightened turbidity. This concentration effect is well documented in shallow aquifer systems across semi-arid urban environments, where reduced recharge during dry seasons intensifies existing contamination rather than introducing new pollutants (Lapworth et al., 2017a,b). The seasonal discolouration in Charlton Park suggests vulnerability in the community's groundwater supply. Similar cases have also been reported in the Amsterdam Park residential area, where residents noted water discolouration, odour, and an unusual taste as evidence of well contamination, likely from human waste and nearby unlined septic tanks developed by residents (Maruta et al., 2023). This indicates that groundwater contamination issues extend beyond the confines of the Charlton Park residential area, but are increasingly common in emerging towns in Zimbabwe. The evidence from Charlton

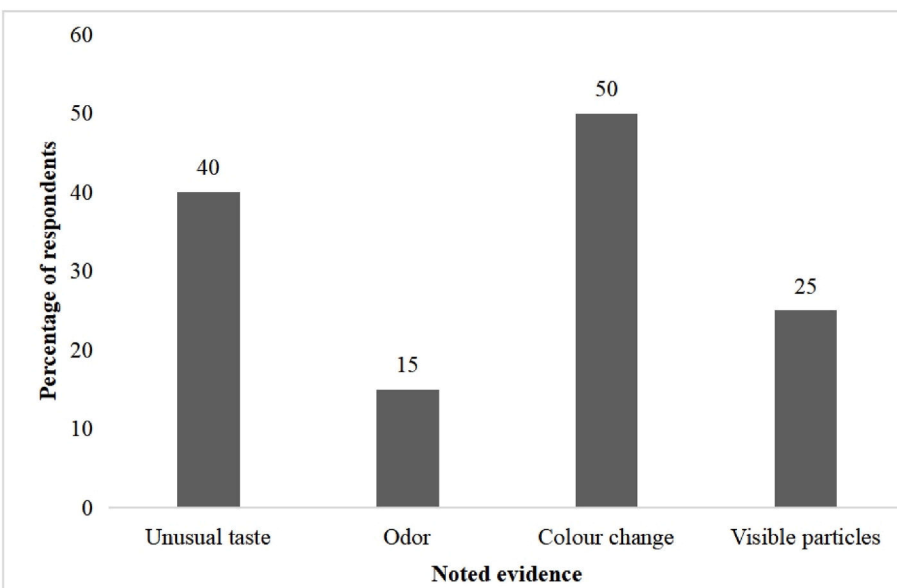


**Fig. 4.** Evidence of water quality deterioration observed by residents.

Park thus carries implications beyond the emerging settlement, pointing to a wider groundwater governance challenge across Zimbabwe's peri-urban zones.

#### 4.2.2. *Faecal coliform contamination patterns and compliance*

The results from the lab analysis showed a faecal coliform population ranging from 0 to 41 CFU/100 ml across the eight sampled sources (Table 1). Of critical concern, 87.5% (7 out of 8) of the water sources exceeded the WHO guideline of 0 CFU/100 ml for drinking water. Of the eight sampling points, two shallow wells (W5, W6) displayed the highest median contamination levels. However, wells 3, 4 and the borehole sample showed an absence of faecal coliform, indicating that the water is free from contaminants and safe for human consumption.

To evaluate the differences between water source types, the non-parametric Kruskal-Wallis test was performed. This test was selected given the non-normal distribution of coliform data collected from the study. The test revealed a statistically significant difference in faecal coliform counts across the three source types (Borehole, Deep Well, Shallow Well), *$H(2) = 7.89$, $p = 0.019$*. Additionally, post-hoc pairwise comparisons using the Mann-Whitney *U* Test indicated that shallow wells had significantly higher contamination than the borehole (*$U = 0$, $p = 0.036$*) and showed a strong, though not statistically significant at the 0.05 level, trend towards higher contamination than deep wells (*$U = 1$, $p = 0.057$*). This confirms the field observation that shallow wells are the most vulnerable to contamination.

The prevalence of faecal coliform contamination across groundwater sources in Charlton Park is a sign of widespread microbial vulnerability within the settlement's water supply system. The significantly higher contamination observed in shallow wells, compared to deep wells and the borehole, reflects the increased susceptibility of shallow aquifers to pathogen transport from nearby sanitation facilities due to limited vertical separation and natural filtration. This pattern aligns with evidence from peri-urban settlements in sub-Saharan Africa, where shallow wells exhibited consistently higher faecal contamination linked to poor sanitation siting and high settlement density than deeper or protected sources (Twinomucunguzi et al., 2021; Cronin et al., 2017). However, the presence of contamination in some deep wells located close to latrines suggests that abstraction depth alone does not guarantee safety where sanitation setbacks are inadequate, a finding also reported in urban India where deep wells near high sanitation density showed elevated microbial loads (Mukherjee and Singh, 2020).

#### 4.2.3. *Relationship between sanitation facility proximity and faecal contamination of groundwater sources*

The researchers also calculated Spearman's Rank Correlation to assess and better understand the relationship between the distance of each water source from the nearest sanitation facility (Fig. 3) and its faecal coliform count. In this regard, the researchers found a statistically significant, negative correlation ($\rho = -0.81$, $p = 0.015$). This result is a testament to the fact that as the distance between a water source and a latrine decreases, the level of faecal coliform contamination increases. The significant negative correlation provides strong empirical evidence of an association between sanitation siting and groundwater contamination, consistent with established subsurface transport mechanisms reported in similar settings. As latrines are located closer to water sources, the likelihood and intensity of faecal contamination increase, reflecting direct subsurface transport of pathogens in a shallow, poorly protected aquifer system. This high rate of faecal contamination is consistent with studies in other low-resource urban settings. For instance, research in Dhaka, Bangladesh, found 80% of shallow tubewells contaminated with *E. coli* (Ferguson et al., 2011), while in Accra, Ghana, similar prevalence was linked to informal settlement conditions (Fianko et al., 2009). A study conducted by Murei et al. (2023) in South Africa, indicated that 85% of the collected samples had coliform bacteria detected and were considered unsafe for human consumption. This was largely attributed to the prevalence of poorly constructed septic tanks and inadequate pit latrines in peri-urban areas. The correlation between contamination and latrine proximity ($\rho = -0.81$) found in this study aligns strongly with the mechanistic understanding established in these and other global studies, confirming the dominant pathway of onsite sanitation seepage. As such, there is an urgent need for enforceable spatial planning and engineered containment measures.

### 4.3. *Water quality-related health issues in Charlton Park residential area*

#### 4.3.1. *Self-reported health data*

The research findings indicated various health issues associated to contaminated water sources in Charlton Park. The most frequently self-reported symptom was stomach problems (55%), followed by vomiting (15%) and fever (15%) (Fig. 5). Stomach problems are the most recognised indicator of waterborne pathogen ingestion. The in other peri-urban settlements across sub-Saharan Africa, where unsafe water consumption has been identified as a determinant of gastrointestinal disease burden (He et al., 2023; Mutono et al., 2021). The results further indicated that the majority of surveyed residents had experienced stomach problems at least on a monthly basis, with 10% having such experiences on a weekly basis (Fig. 5). The recurrence of illness points to ongoing and chronic exposure, which has implications on community wellbeing.

Only a few residents (15%) indicated experiencing vomiting every month and have agreed that the consumption of unclean water might be the cause, while 10% of participants have reported encountering constipation once per month (Fig. 5). Five percent of respondents confirmed their suffering from dehydration due to consuming contaminated water on a frequency of more than once per month, while other 15% noted the frequency as once per month. Fifteen per cent (15%) and 5% of participants reported that they experienced fever on a frequency of more than once a month and once per month, respectively, as a result of consuming unsuitable water for drinking. Furthermore, 10% of the respondents have reported experiencing a loss of appetite on a weekly basis, while 25% respondents reported it happening once per month. However, some respondents confirmed that they had never experienced any signs and symptoms of these health issues, hence indicating not at all. These varied experiences among residents of Charlton Park may likely be a result of household water treatment practices, differences in consumption volumes, or individual physiological variation. During focus group discussions, some residents indicated that they are using various water treatment methods, such as boiling and home treatment kits. While these practices show risk awareness within the community, they require consistency in their use. Sobsey et al. (2008) established that whilst household water treatment interventions such as boiling, can reduce diarrhoeal disease incidence by up to 44%, their efficiency is reduced by irregular application. The variation in self reported health outcomes by Charlton Park residents suggests that treatment practices safeguard some households while others remain fully exposed to contamination risk.

#### 4.3.2. *Clinic-reported waterborne disease patterns*

Interviews with the nurse in charge at Mtapa Clinic confirmed the occurrence of multiple waterborne disease cases recorded between January 2023 and April 2024, all associated with Charlton Park residents (Table 2). Records showed that 80 cases were documented, namely stomach problems, diarrhoea, vomiting, suspected cholera, and typhoid fever. These records provide clinical proof for the water quality deficiencies identified in the household survey, establishing them as registered and not perceived.

Records showed that stomach problems represented largest disease burden, accounting for 50% of all recorded cases ($n = 40$), with children representing 70% ($n = 28$) of reported cases. Diarrhoeal disease showed a similar pattern, with 12 reported cases for children against 4 among adults. This disproportionate child disease burden is not coincidental. Children have immature and weak gastrointestinal and immune systems which makes them distinctly susceptible to enteric pathogens commonly

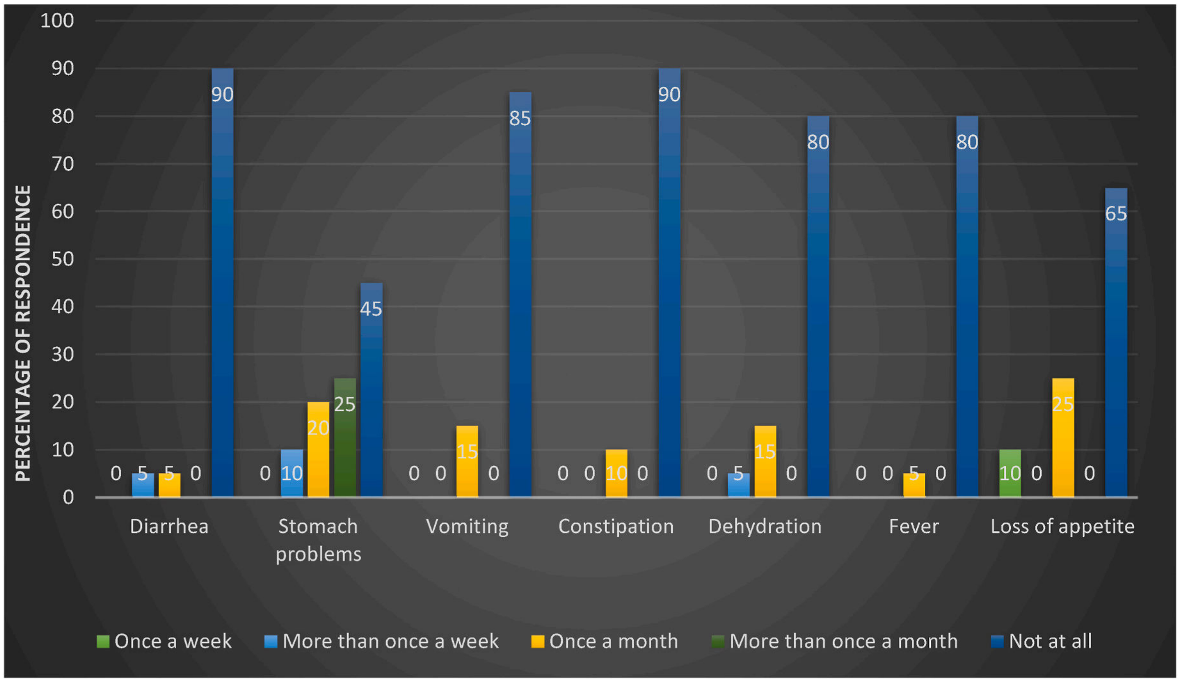


**Fig. 5.** Frequency experience of health issues.

transmitted through faecally contaminated water (Prüss-Ustün et al., 2019). A study conducted in Epworth, Harare, found a diarrhoea prevalence of 25.1% among children under five, with untreated water consumption identified as an independent risk factor, findings similar those in Charlton Park (Chari et al., 2023). This points to a systemic failure in water infrastructure delivery to emerging residential areas.

Over the same period, eleven suspected cholera cases and three typhoid fever cases were recorded. The nurse in charge indicated that all suspected cholera and typhoid cases were referred to an isolation facility and no fatalities were recorded. However, the co-occurrence of these diseases in Charlton Park over the study period is a cause for concern as both *Vibrio cholerae* and Salmonella typhi are pathogens whose transmission is exclusively linked to contaminated water (World Health Organization, 2022). Moyo et al. (2022) documented a similar pattern at Mzilikazi Clinic in Bulawayo, where borehole water consumption was identified as an independent risk factor for diarrhoeal disease outbreaks, . This confirms that clinic-level disease clustering around unsafe water sources is an increasingly common phenomenon across Zimbabwean urban settlements.

Whilst other diseases were more prevalent amongst children, vomiting cases presented a different pattern. Eight adults reported vomiting compared to only two children, with clinic records attributing these episodes to water with an unusual taste and odour. Whilst diarrhoea usually occurs as a result of repeated microbial exposure, vomiting is triggered by organoleptic changes, suggesting acute contamination events. According to Howard and Bartram (2003) adults are more susceptible to vomiting episodes because they consume greater volumes of water per day compared to children, whose intake is comparatively lower. This distinct finding shows that vulnerability in Charlton Park is also shaped by the nature of the contaminant and the behavioural patterns of residents.

### 4.4. *Analysis of health clinic data and relative risk*

Given the limitations of self-reported health data (Fig. 5), aggregated clinic records from Mtapa Clinic (Table 2) provided a more objective measure of community health burden. As individual-level patient data was not available for a formal Chi-square test, the distribution of cases was analysed using proportions and simplified comparative metrics.

As indicated in Table 2, the clinic recorded 80 waterborne disease cases from Charlton Park between January 2023 and April 2024. Of these 80 reported cases, children (defined as $\leq 15$ years) accounted for 62.5% ($n = 50$) of all cases, demonstrating a disproportionately higher reported disease burden among the young. This disparity was most pronounced for specific illnesses: children constituted 12 of 16 (75%) of diarrhoea cases and 6 out of 11 (55%) of suspected cholera cases.

To quantify this disparity in the absence of population denominators, a case distribution ratio (CDR) was calculated as a descriptive metric, comparing the ratio of child to adult cases for the community as shown below:

$$CDR = \frac{\text{Total Child Cases}}{\text{Total Adult Cases}} = \frac{50}{30} = 1.67$$

This result shows that for every adult case recorded at the clinic, approximately 1.67 child cases were recorded. For diarrhoea specifically, the CDR was 3.0 (12 child cases/4 adult cases).

While the CDR is not equivalent to a formal relative risk measure, it is a robust tool for characterising differences in disease burden. The findings reported in Charlton Park align with established regional evidence. A study across 36 sub-Saharan African countries recorded a diarrhoea prevalence of 18.44% among children under five, with unsafe water consumption identified as an independent risk factor and poorer households consistently producing higher child disease burdens (He et al., 2023). The CDRs recorded in Charlton Park are similar to the vulnerability gradients these studies document. This asserts that the age-differentiated burden observed at Mtapa Clinic is not unique but a common phenomenon within the region. This pattern common across the region is a result of rapid urbanisation which often trumps infrastructure expansion (Mutono et al., 2021). Charlton Park, as an emerging settlement where population growth has outrun water service delivery, fits precisely into this pattern. The situation in Charlton is thus not isolated but is a measurable public health consequence of inadequate water infrastructure in a growing residential settlement.

### *4.5. A socio-hydrological framework for mitigating groundwater contamination in unplanned urban settlements*

The faecal contamination observed in Charlton Park where 87.5% of sampled groundwater sources exceeded World Health Organization (WHO) drinking water guideline and its strong association with sanitation proximity ($\rho = -0.81$) are not isolated outcomes. These findings reflect a socio-hydrological failure common in rapidly urbanising settlements, where residential development precedes sanitation, waste management, and groundwater protection (Lapworth et al., 2017a,b; Twinomucunguzi et al., 2021). Similar contamination patterns have been reported in informal settlements across sub-Saharan Africa, including Kampala, Kisumu, and Makululu (Zambia), where over 90% of shallow groundwater sources were found to be microbiologically unsafe due to poor sanitation siting and high settlement density (Cronin et al., 2017; Sorensen et al., 2015).

This study demonstrates that traditional policy approaches that treat water supply, sanitation, solid waste management, and public health as separate administrative sectors are ineffective in such contexts. Twinomucunguzi et al. (2021) reinforce that groundwater contamination is not only a result of isolated technical failures but has its roots governance fragmentation, poor enforcement of planning regulations, and the spatial clustering of on-site sanitation in hydrogeologically vulnerable zones In the case of Charlton Park groundwater contamination is best understood as a socio-hydrological issue, where physical contamination pathways are created and worsened by social, institutional, and land-use choices rather than natural processes alone.

In response, this study proposes a Socio-Hydrological Intervention Framework (SHIF) that translates the empirical findings into a phased, evidence-based pathway for mitigating groundwater contamination and associated health risks in emerging urban settlements (Fig. 6). The SHIF is theoretically grounded in socio-hydrology and urban political ecology, which view environmental risks as the result of interactions between physical systems and social power relations rather than purely natural processes (Swyngedouw, 2009; Lapworth et al., 2017a,b). Unlike The DRASTIC model (Aller et al., 1987), and WHO WASH frameworks(WHO, 2022), the SHIF integrates physical contamination evidence with institutional dysfunction, jurisdictional uncertainty, and differential exposure risk into a single operational framework. Whilst Cronin et al. (2017) correctly identify governance fragmentation as a root cause of groundwater contamination in sub-Saharan African cities, they do not prescribe a structured, site-calibrated intervention pathway. The SHIF was developed with this in mind for the conditions that actually exist in emerging urban settlements rather than those that planning policy assumes should exist.

To make the framework robust, technical expertise was also sought from experts in the fields of water, sanitation and hygiene. The consulted stakeholders were posed with the following questions.

- How best can water contamination emerging from organic pollutants be minimised in Charton Park?
- What are the gaps in water contamination prevention in Charlton Park?
- Which stakeholders play a central role in minimising pollution?

Responses from these questions were then analysed using thematic analysis, combined with evidence from theory and practice and presented in the form of an illustrative framework (Fig. 6) which can be adopted as a collaborative effort to reduce groundwater contamination in Charlton Park. The proposed framework is also grounded in empirical findings from Charlton Park and structured to address contamination pathways identified through microbiological testing, spatial sanitation analysis, and health surveillance data.

The framework progresses from immediate public health protection, through engineered containment of contamination pathways, to long-term systemic reform aimed at preventing recurrence, as discussed in

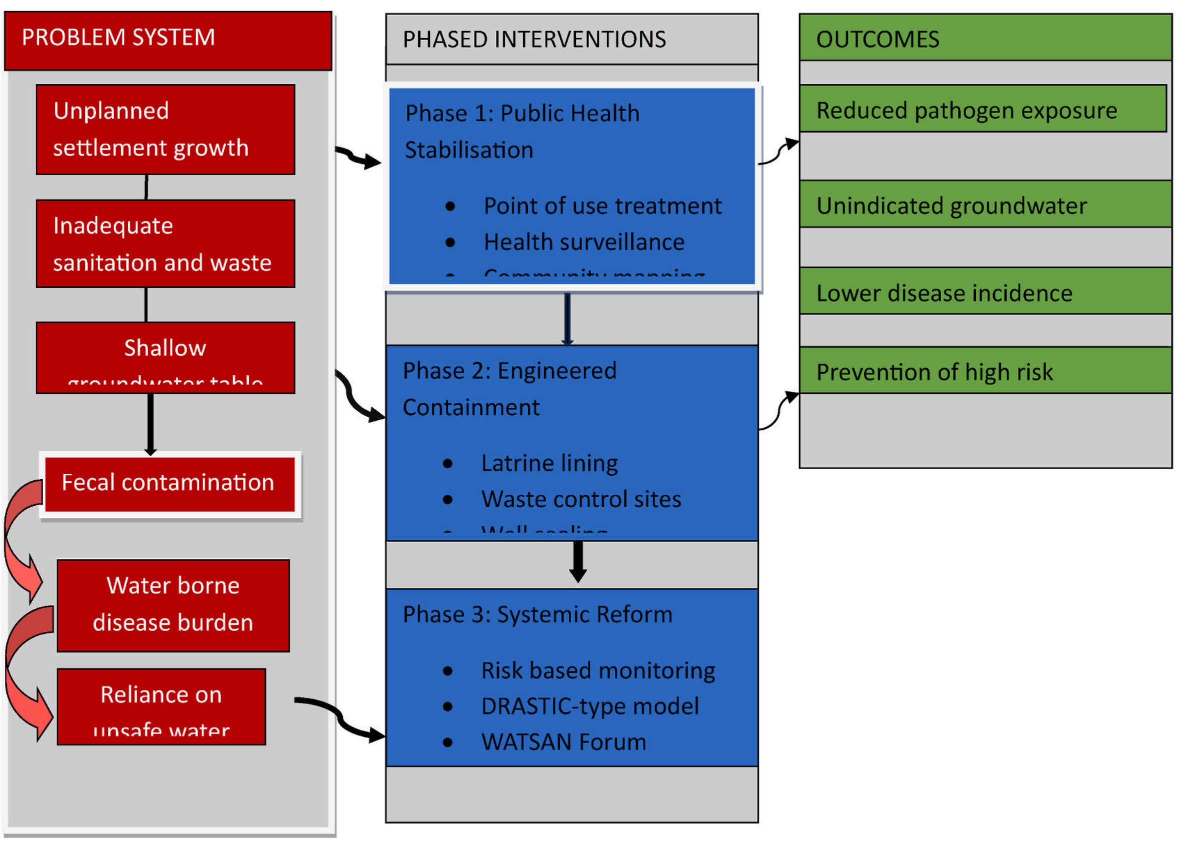


**Fig. 6.** Socio-Hydrological Intervention Framework (SHIF) for groundwater contamination risk reduction in unplanned urban settlements.

the following sections.

### 4.6. Phase 1: Emergency public health stabilisation (0–12 months)

The first phase of the framework addresses the acute public health risks identified in Charlton Park. The disproportionate burden of water-related illness among children, reflected in a case distribution ratio of 1.67, is consistent with findings from informal settlements in Kenya and Zambia, where children experience significantly higher exposure to faecally contaminated domestic water (Sorensen et al., 2015; Cronin et al., 2017). At this stage, the primary objective is to interrupt exposure rather than to undertake infrastructural transformation rapidly.

The main intervention involves distribution and promotion of point-of-use water treatment technologies, particularly chlorine-based disinfectants. This should be supported by community wide demonstrations as studies from peri-urban settlements in Bangladesh and sub-Saharan Africa show that information alone is not enough to change water treatment behaviour (Ahmed et al., 2013; Lapworth et al., 2017a,b). To ensure sustained reduction in microbial exposure, treatment products need to be subsidised, locally available, and accompanied by community-based demonstrations. In Charlton Park, this intervention directly addresses the continued reliance on microbiologically unsafe wells in the absence of viable alternatives.

This must be complemented by enhanced disease surveillance at Mtapa Clinic. Evidence from informal urban settings indicates that strengthening clinic-level reporting of diarrhoeal and waterborne diseases can significantly improve outbreak detection and response when linked to environmental risk data (WHO, 2022). In this framework, Mtapa Clinic functions not only as a treatment centre but as an early-warning node within the local water–health system.

During this phase, a community-led participatory mapping exercise should be implemented to spatially document water sources, sanitation facilities, and waste disposal sites. Systematically documenting the spatial relationship between wells, latrines, and waste disposal sites generates relevant risk information while building community capacity to recognise and articulate contamination pathways. Similar participatory mapping approaches in Kampala and Dar es Salaam have proven effective in generating actionable spatial data while building community ownership and risk awareness (Twinomucunguzi et al., 2021; Foster et al., 2018). This process provides the empirical foundation for targeted interventions under Phase 2 of the SHIF.

### 4.7. Phase 2: Engineered containment and intermediate infrastructure (1–3 years)

Phase 2 targets the physical contamination pathways identified by this study, particularly pathogen transport from pit latrines and unmanaged waste into shallow groundwater systems. The strong inverse relationship between latrine distance and microbial water quality indicates that pathogen transport from on-site sanitation systems is a primary contamination mechanism in Charlton Park's shallow aquifer environment. Sanitation interventions in Charlton Park and indeed other emerging residential areas must therefore prioritise containment. The authors propose a programme focused on lining existing pit latrines, as lined pits have been shown to significantly reduce pathogen migration in high water-table environments (Graham and Polizzotto, 2013). This can be enabled by a cost sharing program between residents and the local authority.

Solid waste management is equally critical. Open dumping, observed throughout Charlton Park, represents a continuous source of organic leachate and microbial loading. To address solid waste management, the local authority, regulators and relevant stakeholders should establish designated, managed waste collection points and promote decentralised composting for organic waste. These measures reduce leachate generation and limit diffuse contamination from open dumping. Studies from peri-urban Ghana and Indonesia show that the establishment of lined communal waste collection points, combined with decentralised organic composting, can significantly reduce groundwater contamination risk while improving local environmental conditions (Foster et al., 2018). Additionally, during this phase, severely contaminated shallow wells (e.g. W5 and W6) should be decommissioned and physically sealed, in line with public health protection measures applied in similar settings (Cronin et al., 2017).

Importantly, Phase 2 is not considered as a one-time technical fix. Infrastructure improvements feed back into health outcomes by reducing disease incidence. This in turn decreases households' dependence on unsafe nearby water sources, weakening the contamination–exposure feedback loop identified in the problem system (Fig. 6).

### 4.8. Phase 3: Systemic reform and integrated urban planning (3+ years)

Whilst the first two phase of the SHIF confront the immediate risks and contamination pathways, they do not address the structural conditions that resulted in groundwater contamination. Phase 3 addresses these structural drivers of groundwater degradation in Charlton Park and other emerging residential areas i.e. the development of urban space without integrated water and sanitation planning. Evidence from Zimbabwe and across sub-Saharan Africa shows that settlements are often established without hydrological suitability assessments and adequate water and sanitation, resulting in persistent public health risks (Lapworth et al., 2017a,b; Makurira et al., 2021). As such a vital intervention in this phase is the development and application of a local-scale groundwater vulnerability model, adapted from DRASTIC-type frameworks but calibrated to local hydrogeological and settlement conditions. Applications of DRASTIC-based models in rapidly urbanising cities such as Dar es Salaam have demonstrated their effectiveness in identifying high-risk zones and informing land-use planning decisions (Foster et al., 2018). Integrating such a model into development approval processes would shift planning from a reactive administrative exercise to a science-informed public health intervention.

To ensure that this plan works, the framework proposes the establishment of a permanent multi-stakeholder Water and Sanitation (WATSAN) Forum for emerging settlements. By formally linking municipal authorities, environmental regulators, health services, and community representatives, the forum addresses the governance fragmentation that underpins groundwater contamination in Charlton Park. Further, the WATSAN Forum is envisaged to provide a mechanism for oversight, accountability, and continuous learning. Similar multi-stakeholder platforms have been shown to improve coordination, accountability, and regulatory enforcement in complex urban water systems (WHO, 2022).

This phased structure reflects both the urgency of the current disease burden and the structural drivers underlying groundwater degradation. By embedding a dynamic vulnerability model within urban planning, the framework shifts policy from reactive remediation to anticipatory prevention. Although developed using Charlton Park as a case study, the SHIF is transferable to other rapidly urbanising contexts where groundwater remains a primary domestic water source. In this sense, it offers a scientifically grounded and operational pathway for advancing Sustainable Development Goals 6 and 11 within the constraints faced by cities in Zimbabwe and across the Global South.

## 5. Implications for policy and water, sanitation and health

The past few decades have seen the development of new residential areas in Zimbabwe. More often than not, service delivery relating to water sanitation and health in these emerging residential areas is often lacking. This results in increased groundwater contamination and health risks in the communities.

This study is of particular importance as it could nudge city planners and decision makers towards improving groundwater management in emerging residential areas. It develops a framework that can be operationalised and guide the management of groundwater in emerging residential areas. This is particularly important in Zimbabwean context as the country gears towards the achievement of the sustainable development goals (SDGs) and the localised national development strategy 1 (NDS 1). With regards to SDGs, this study is important to the achievement of SDG 11(reducing the impact of cities on the environment through sustainable management of municipal and other forms of waste) and target 6.3 of SDG 6 (improving water quality by reducing the volumes of untreated wastewater and through recycling and resource recovery from wastewater).

Given the findings of this study, Gweu Urban Council and the government of Zimbabwe need to take into account the following:

- Investment in research and infrastructure that is aimed improving groundwater monitoring
- Partnerships with research institutions and entrepreneurs involved in water sanitation and health to find long lasting solutions to groundwater contamination.
- Gweru Urban Council should ensure that land and property developers apply with local and national by-laws.
- Gweru Urban Council and the Zimbabwean government in general should develop a groundwater monitoring and regulatory system in residential areas and invest in awareness campaigns that will highlight the importance of abiding with city by-laws regarding citing of groundwater sources and septic tanks.
- Gweru Urban Council and ZINWA should increase investment in groundwater quality remediation. Investments, partnerships and exchange programs with other experts from other regions and countries will ensure skills development and transfer of the latest technology in groundwater remediation.

These modifications, if taken into consideration, will address groundwater contamination in emerging residential areas.

## 6. Limitations of the study

This study has limitations. The results and findings are based on representative water samples collected from specific wells and boreholes in Charlton Park, and do not encompass all water sources in the area. Therefore, further comprehensive studies are needed to assess groundwater quality across Charlton Park and other residential suburbs in Gweru. Additionally, the study relies on secondary health data from local clinics, which introduces self-reporting bias from these institutions. The research identifies associations but cannot definitively determine causality between water contamination and health outcomes. The health data, obtained through self-reporting for surveys and institutional records for clinics, are susceptible to recall and reporting biases; clinic data may underestimate the true burden of waterborne illnesses due to self-treatment and informal care, though the convergence with household-reported symptoms enhances the validity of observed health patterns. While census sampling of accessible water sources was used, the small sample size of $n = 8$ limits the statistical power of the inferential tests conducted. Consequently, findings should be interpreted with caution. Future research should increase the number of sampled sources across multiple rounds and seasons to better establish observed associations. Moreover, water quality analysis was limited to faecal indicator bacteria; future studies should also examine chemical contaminants such as nitrates and phosphates for a more comprehensive understanding of organic waste contamination. Lastly, sampling took place during the dry season; contamination levels and health outcomes may vary during the rainy season, restricting the generalisability of the findings throughout the year. Despite these limitations, the study remains relevant as it contributes valuable insights to the decision-making process toward achieving clean water and sanitation in emerging residential areas.

## 7. Conclusion

The findings demonstrate that the rapid urbanisation, population growth and inadequate infrastructure development on sanitation facilities and water sources have led to significant groundwater contamination which had repercussions on public health. It was noted that the majority residents in Charlton Park utilise wells as their primary source of water which is a vulnerable water source given, improper waste management in this developing residential area. Results confirmed the presence of bacteria coliform, in most of the water sources used by residents in Charlton Park, indicating widespread contamination by faecal or organic waste from open dumpsites. Statistical analysis confirmed shallow wells as significantly more contaminated than deeper sources, directly linked to their proximity to sanitation facilities. A comprehensive framework aimed at improving water quality and reducing groundwater -related health issues in the rapidly developing Charlton Park residential area and other similar residential areas was developed. This framework encourages stakeholder cooperation to help people in emerging residential areas. Findings suggest that the health of residents in emerging residential areas is under threat as they depend on water from contaminated sources. This study concludes that, residential settlement in Zimbabwe's urban peripheries precedes water and sanitation infrastructure, and communities bear the predictable but preventable health consequences of this. The SHIF proposed it is an operational response to a documented emergency, designed for immediate deployment by the stakeholders who caused the conditions it seeks to remediate.

## CRediT authorship contribution statement

**Oshneck Mupepi:** Writing – review & editing, Supervision, Conceptualization. **Tererai Kundishora:** Writing – original draft, Investigation, Formal analysis. **Roberta Mavugara:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis.

## Consent to participate

All authors participated and agreed to participate up to final revision of the manuscript.

## Ethics approval

Approval was granted by Midlands State University to carry out the research as well as to publish under its name. All sources were properly cited to avoid plagiarism.

## Consent for publication

Authors agreed to let the paper published when considered for publication.

## Funding

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## References


Ahmed, S., Hasan, K., Khan, M.S., Islam, M.S., 2013. Effectiveness of point-of-use water treatment on reducing diarrhoeal disease in low-income urban settlements: a quasi-experimental study. Trop. Med. Int. Health 18 (4), 454–462. https://doi.org/10.1111/tmi.12078.

Alao, J.O., Bello, A.Y., Lawal, H.A., Abdullahi, D., 2024. Assessment of groundwater challenge and the sustainable management strategies. Results in Earth Sciences 2, 100049.

Aller, L., Bennett, T., Lehr, J.H., Petty, R.J., Hackett, G., 1987. DRASTIC: a Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings. United States Environmental Protection Agency, Washington, D.C: USEPA. EPA/600/2-87-035.

Amoako, E.E., Antwi-Agyei, P., Owusu-Ansah, E.D.J., 2025. Risk assessment of hand-dug well water: a case study of Aflao in Ghana. J. Water, Sanit. Hyg. Dev. 15 (6), 507–521. https://doi.org/10.2166/washdev.2025.108484.

Ayeni, O.I., Ugwu, N.F., Anibueze, A.U., Oyegbami, G.A., 2025. Behavioural adherence to sanitation and water safety of households in Ado-Ekiti, Ekiti State, Nigeria. Unizik Journal of Educational Laws and Leadership Studies 2 (1).

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qualitative Research in Psychology 3 (2), 77–101.

Bridgewater, L.L., 2017. *Standard methods for the examination of water and wastewater*. American Public Health Association.

Carriço, N., Ferreira, B., Barreira, R., Antunes, A., Grueau, C., Mendes, A., Covas, D., Monteiro, L., Santos, J., Brito, I., 2020. Data integration for infrastructure asset management in small-medium size water utilities. Water Sci. Technol. 82 (10), 2166, review article on impact of groundwater contamination due to dumpsites using geophysical and physiochemical methods.

Chaminuka, N., Dube, E., Kabonga, I., Mhembwe, S., 2021. Enhancing urban farming for sustainable development through sustainable development goals. Food Secur. Energy Clim. Act. Biodiv. 2, 63–77.

Chari, S., Mbonane, T.P., Van Wyk, R.H., 2023. Social and environmental determinants of diarrheal diseases among children under five years in Epworth Township, Harare. Children 10 (7), 1173. https://doi.org/10.3390/children10071173.

Creswell, J.W., Plano Clark, V.L., 2023. Revisiting mixed methods research designs twenty years later. Handbook of Mixed Methods Research Designs 1 (1), 21–36.

Cronin, A.A., et al., 2017. Urban groundwater contamination in Sub-Saharan Africa: a review of mechanisms, sources, risks and governance. Water Int. 42 (8), 873–906. https://doi.org/10.1080/02508060.2017.1370585.

Ferguson, A.S., Mailloux, B.J., Ahmed, K.M., van Geen, A., McKay, L.D., Culligan, P.J., 2011. Hand-pumps as reservoirs for microbial contamination of well water. J. Water Health 9 (4), 708–717. https://doi.org/10.2166/wh.2011.106.

Fianko, J.R., Osae, S., Adomako, D., Achel, D.G., 2009. Relationship between land use and groundwater quality in six districts in the eastern region of Ghana. Environ. Monit. Assess. 153 (1–4), 139–146. https://doi.org/10.1007/s10661-008-0344-0.

Foster, S., MacDonald, A., Gemmell, A., 2018. Groundwater vulnerability mapping in urban Africa: methods and policy relevance in Dar es Salaam. Hydrogeol. J. 26 (6), 1757–1771. https://doi.org/10.1007/s10040-018-1761-7.

Gleick, P.H., Cooley, H., 2021. Freshwater scarcity. Annu. Rev. Environ. Resour. 46, 319–348. https://doi.org/10.1146/annurev-environ-012220-101319.

Graham, J.P., Polizzotto, M.L., 2013. Pit latrines and groundwater contamination: state of the science. Environ. Health Perspect. 121 (5), 521–530. https://doi.org/10.1289/ehp.1206426.

Gyimah, R., Lebu, S., Owusu-Frimpong, I., Semiyaga, S., Salzberg, A., Manga, M., 2024. Effluents from septic systems and impact on groundwater contamination: a systematic review. Environ. Sci. Pollut. Res. 31 (54), 62655–62675.

He, Z., Ghose, B., Cheng, Z., 2023. Diarrhea as a disease of poverty among under-five children in Sub-Saharan Africa: a cross-sectional study. Inquiry: J. Health Care Org. Provis. Financ. 60. https://doi.org/10.1177/00469580231202988.

Howard, G., Bartram, J., 2003. Domestic Water Quantity, Service Level and Health. World Health Organization, Geneva. Available at: https://www.who.int/publications/i/item/WHO-SDE-WSH-03.02.

Igboama, W.N., Hammed, O., Fatoba, J., Aroyehun, M., 2022. Impact of groundwater contamination due to dumpsites using geophysical and physiochemical methods. Appl. Water Sci. 12 (6). https://doi.org/10.1007/s13201-022-01653-z.

Igboama, W.N., Hammed, O.S., Fatoba, J.O., Aroyehun, M.T., Ehiabhili, J.C., 2022. An assessment of the availability of water sources and hygiene practices in response to the Cholera outbreak in Harare City, Zimbabwe. Received: 2 July 2020 / Accepted. (Accessed 14 March 2022).

Kazama, S., Takizawa, S., 2021. Evaluation of microbial contamination of groundwater under different topographic conditions and household water treatment systems in special region of Yogyakarta province. Water 13 (12), 1673.

Kirschke, S., Avellán, T., Bärlund, I., Bogardi, J., Carvalho, L., Chapman, D., Dickens, C., Irvine, K., Lee, S., Mehner, T., Warner, S., 2020. Capacity challenges in water quality monitoring: understanding the role of human development. Environ. Monit. Assess. 192 (10), 1007.

Krejcie, R.V., Morgan, D.W., 1970. Sample size determination table. Educational and psychological Measurement 30 (3), 607–610.

Kusena, W., Nicolau, M., Nojiyeza, I.S., 2022. Implications of the urban water and food systems governance nexus for household food security in the City of Gweru, Zimbabwe. Urban Forum 33 (3), 329–348.

Lapworth, D.J., Baran, N., Stuart, M.E., Ward, R.S., 2017a. Emerging contaminants in groundwater: a review of sources, fate, and occurrence. Hydrogeol. J. 25 (1), 1–26. https://doi.org/10.1007/s10040-016-1516-6.

Lapworth, D.J., Baran, N., Stuart, M.E., Ward, R.S., 2017b. Emerging contaminants in groundwater: a review of sources, fate and occurrence. Environ. Sci. Technol. 51 (10), 5129–5150. https://doi.org/10.1021/acs.est.7b00164.

Makaya, E., Maphosa, M.T., 2023. Spatial analysis of groundwater quality in Bulawayo, Zimbabwe: geogenic and anthropogenic contributions. Phys. Chem. Earth.

Makurira, H., Tumbare, M., Love, D., Chagutah, T., 2021. Urban groundwater quality in Zimbabwe: impacts of informal development and sanitation practices. Sci. Total Environ. 752, 142103. https://doi.org/10.1016/j.scitotenv.2020.142103.

Maruta, E., Matsa, M., Mupepi, O., Dzawanda, B., 2023. Water safety and associated public health impacts in upcoming and informal urban settlements in Zimbabwe: case of Amsterdam Park in Harare. Sustain. Water Resour. Manag. 9 (5), 138.

Masindi, V., Foteinis, S., 2021. Groundwater contamination in Sub-Saharan Africa: implications for groundwater protection in developing countries. Clean. Eng. Technol. 2, 100038.

Masocha, M., Dube, T., Dube, T., 2019. Integrating microbiological and physico-chemical parameters for enhanced spatial prediction of groundwater quality in Harare. Phys. Chem. Earth Part a/b/c 112, 125–133.

Matsa, M., Chokuda, F., Mupepi, O., Dzawanda, B., 2021a. An assessment of groundwater quality in Zimbabwe's urban areas: case of Mkoba 19 suburb, Gweru. In: Journal of Environment Monitoring and Assessment. Midlands State University, Gweru, 193(7).

Matsa, M., Mupepi, O., Musasa, T., 2021b. Spatio-temporal analysis of urban area expansion in Zimbabwe between 1990 and 2020: the case of Gweru city. In: Environmental Challenges, 4. Midlands State University, Gweru, 100141.

Matsa, M., Mavugara, R., Dzawanda, B., 2019. Urban domestic water supply crisis in the City of Gweru, Zimbabwe. In: Geo-Journal Spatially Integrated Social Sciences and Humanities. Springer. https://doi.org/10.1007/s10708-019-10118-x, 86 Pages1-20ISSN 0343-2521no.3.

Ministry of Health and Child Care, 2024. Zimbabwe's Health Ministry Update on Cholera Outbreak, January 19, the Herald.

Moyo, T.M., Juru, T.P., Sibanda, E., Marape, G., Gombe, N.T., Govha, E., Tshimanga, M., 2022. Risk factors for contracting watery diarrhoea in Mzilikazi, Bulawayo City, Zimbabwe, 2020: a case control study. Pan African Med. J. 41, 145. https://doi.org/10.11604/pamj.2022.41.145.30551.

Mukherjee, A., Singh, R.K., 2020. Groundwater contamination and sanitation linkages in urban India: spatial analysis and risk mapping. Water, Air, Soil Pollut. 231 (4), 166. https://doi.org/10.1007/s11270-020-04551-1.

Murei, A., Kamika, I., Samie, A., Momba, M.N.B., 2023. Assessment of the water sources for potential channels of faecal contamination within Vhembe District Municipality using sanitary inspections and hydrogen sulphide test. Sci. Rep. 13 (1), 6250.

Mutono, N., Thuo, N., Wright, J., Mutua, M., Wanyonyi, L., Thumbi, S.M., 2021. The nexus between improved water supply and water-borne diseases in urban areas in Africa: a scoping review. AAS Open Res. 4, 3. https://doi.org/10.12688/aasopenres.13137.2.

Ng'andwe, S., Ogendi, G.M., Muoria, E., Ngoma, J., 2025. Seasonal variations of microbial water quality from shallow wells and prevalence of water-related diseases. J. Geosci. Environ. Protect. 13 (5), 1–19.

Odewade, L.O., Imam, A.A., Adesakin, T.A., Odewade, J.O., 2025. Assessment of human faecal contamination on groundwater quality and reporting consequent waterborne diseases in Funtua Metropolis, Katsina State, Nigeria. Front. Water 7, 1561777.

Olatunji, E.O., Elakhame, L.A., Osimen, E.C., Edegbene, A.O., 2023. Assessing the effect of environmental stressors on the community structure of macroinvertebrates and water quality of River Ugbalo, Nigeria. Pollution 9 (4), 1317–1332.

Onipe, T., Edokpayi, J., Odiyo, J.O., 2020. A review on the potential sources and health implications of fluoride in groundwater of Sub-Saharan Africa. J. Environ. Sci. Health Part A 55 (9), 1078–1093.

Pradhan, B., Chand, S., Rout, P.R., Naik, S.K., 2023. Emerging groundwater contaminants: a comprehensive review on their health hazards and remediation technologies. Groundwater Sustain Dev. 20, 100868.

Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M.C., Gordon, B., Hunter, P.R., Medlicott, K., Johnston, R., 2019. Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low- and middle-income countries. Int. J. Hyg Environ. Health 222 (5), 765–777. https://doi.org/10.1016/j.ijheh.2019.05.004.

Rahim, F.B., Swarnokar, S.C., Roy, S., Rahman, M.M., Das, T.K., 2025. The quality of groundwater in shallow aquifers impacted by inadequately managed sanitation facilities in coastal Bangladesh. Cleaner Water 100154.

Sekgobela, J.M., Murei, A., Khabo-Mmekoa, C.M., Momba, M.N.B., 2023. Identification of fecal contamination sources of groundwater in rural areas of Vhembe District Municipality, Limpopo Province, South Africa. Water Environ. Res. 95 (12), e10965.

Sobsey, M.D., Stauber, C.E., Casanova, L.M., Brown, J.M., Elliott, M.A., 2008. Point of use household drinking water filtration: a practical, effective solution for providing sustained access to safe drinking water in the developing world. Environ. Sci. Technol. 42 (12), 4261–4267. https://doi.org/10.1021/es702746n.

Sorensen, J.P.R., et al., 2015. Water quality in peri-urban areas: sanitation, groundwater contamination and health implications. Sci. Total Environ. 536, 316–326. https://doi.org/10.1016/j.scitotenv.2015.07.010.

Stoler, J., Jepson, W.E., Wutich, A., 2020. Beyond handwashing: Water insecurity undermines COVID-19 response in developing areas. J. Global Health 10 (1), 010355.

Sunny, A.R., Mithun, M.H., Prodhan, S.H., Ashrafuzzaman, M., Rahman, S.M.A., Billah, M.M., Hossain, M.M., 2021. Fisheries in the context of attaining Sustainable Development Goals (SDGs) in Bangladesh: COVID-19 impacts and future prospects. Sustainability 13 (17), 9912.

Swyngedouw, E., 2009. The political economy and political ecology of the hydro-social cycle. J. Contemp. Water Res. Educat. 142 (1), 56–60. https://doi.org/10.1111/j.1936-704X.2009.00054.x.

Twinomucunguzi, F.R.B., Nahabwe, H., Kayaga, S., 2021. Socio-institutional drivers of groundwater contamination hazards: the case of on-site sanitation in the Bwaise informal settlement, Kampala, Uganda. Water 13 (16), 2153. https://doi.org/10.3390/w13162153.

World Health Organization, 2022. Guidelines for Drinking-Water Quality, fourth ed. WHO Press, Geneva. Available at: https://www.who.int/publications/i/item/9789240045064. (Accessed 7 February 2026).

World Health Organization. (2017). Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines.

ZIMSTAT (Zimbabwe National Statistical Agency), 2022. Census 2022: Preliminary Report. Zimbabwe National Statistics Agency, Harare, Zimbabwe.