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Research Article

ASSESSMENT OF GROUNDWATER QUALITY AND SPATIAL ACCESSIBILITY USING INTEGRATED GIS AND LABORATORY ANALYSIS IN RURAL BINGA, ZIMBABWE

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Abstract

Access to safe drinking water, adequate sanitation, and hygiene (WASH) remains a significant public health challenge in rural regions of developing countries. In these developing countries, particularly in rural communities like Binga, Zimbabwe, water scarcity and inadequate WASH infrastructure continue to undermine public health and livelihoods in rural Binga District, Zimbabwe. This study presents an integrated approach combining Geographic Information Systems (GIS) and laboratory water quality analysis to evaluate groundwater safety and spatial accessibility in randomly selected seven wards of Binga District. Sixteen boreholes and deep wells were geolocated and sampled for key physicochemical and microbiological parameters, while GIS techniques, particularly buffer analysis and Inverse Distance Weighting (IDW) interpolation assessed household proximity to water sources and spatial distribution patterns. Results indicate that while most water quality parameters meet World Health Organization (WHO) guidelines, fluoride concentrations consistently exceed safe limits, posing a geogenic public health risk. Critically, fewer than 5% of 467 mapped households fall within the recommended 1 km access radius, reflecting severe inequities in borehole distribution and water accessibility. The identified mismatch between groundwater quality and availability highlights infrastructural barriers as the primary driver of water insecurity. The integrated GIS-laboratory framework provides a replicable methodology for diagnosing water access challenges and informs strategic planning for targeted water resource management in similarly vulnerable rural settings.

Keywords: WASH, Inverse Distance Weighting; Interpolation; Buffering; Water quality parameters.

INTRODUCTION

Access to safe drinking water, sanitation, and hygiene (WASH) is a cornerstone of public health, socioeconomic development, and resilience in rural communities globally. The provision of safe water is not only essential for preventing waterborne diseases such as cholera and diarrhoeal illnesses frequently resulting from the consumption of contaminated water and inadequate sanitation, but also foundational to food security, educational attainment, livelihoods, and dignity in vulnerable populations (Mweembe, 2022). In Zimbabwe, the Binga district of Matabeleland North province epitomizes the multifaceted WASH challenges endemic to arid and semi-arid environments in sub-Saharan Africa. Binga's climate, defined by low annual rainfall (approximately 98 mm), high temperatures (mean yearly temperature 25.2°C), and persistent droughts, has led to severe water stress, food insecurity, and recurrent humanitarian crises even in years of favourable national precipitation (Kachere, 2023). Water scarcity in the region significantly amplifies public health risks, with chronic malnutrition, recurrent cholera outbreaks, and high child morbidity underscoring the urgent need for strengthened WASH infrastructure and targeted interventions. Agricultural activity, already constrained by erratic and insufficient rainfall, faces further setbacks as staple crops such as maize routinely fail, and food shortages become acute during drought periods.

These vulnerabilities are worsened by persistent infrastructural deficits including inadequate boreholes, failing dams, and limited sanitation coverage are widespread. Borehole failures and drying water sources in villages like Siansundu and Wards such as Sikalenge have led to severe hardship, closure of essential services, and continued threats to the fundamental rights of health, education, and life. Historical displacement resulting from the construction of the Kariba Dam has further marginalized Binga's populations, increasing their exposure to water insecurity and climate shocks. In this context, Geographic Information Systems (GIS) have emerged as powerful tools for evaluating WASH challenges, enabling the integrated analysis and mapping of water distribution networks, source reliability, and resource allocation (Rawat & Singh, 2018; Singh *et al.,* 2013; Srivastava *et al.,* 2013). Recent studies demonstrate that GIS-supported approaches enhance the planning, implementation, and monitoring of water interventions, and facilitate evidence-based responses to dynamic environmental threats (Kahsay *et al.,* 2019; Chakraborty *et al.,* 2021).This study leverages GIS technology and laboratory water quality analysis to assess spatial and temporal patterns of water distribution and water quality in Binga district. Through this integrated approach, the research aims to inform sustainable water management strategies and targeted WASH interventions necessary to address the acute and chronic water challenges confronting Binga's communities.

METHODS AND MATERIALS

Binga District was selected as the primary study area to investigate water quality and distribution challenges in a semi-arid region of Zimbabwe due to its persistent water shortages, vulnerability to drought, and critical WASH issues affecting rural communities. Seven wards; Lubanda, Dobola, Chinonge, Kabuba, Tinde, Lubimbi, and Sinamagondewere purposively chosen as representative sites, with 16 boreholesand deep wells (Figure 1) randomly selected for groundwater sampling. GIS was used to map each sampling location by recording GPS

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coordinates (WGS 84 system), enabling spatial analysis and visualization of borehole distribution and groundwater accessibility.GIS analysis involved spatial interpolation (IDW) to estimate unsampled conditions and vulnerability analysis, with a 500m buffer around boreholes estimating household coverage and highlighting water quality hotspots and rehabilitation needs. Water samples were collected at these points analysed at the Zimbabwe School of Mines Metallurgical and Assay Laboratory for a comprehensive suite of physical, chemical, and biological parameters, including pH, turbidity, dissolved solids, metals, and microbial contaminants, with strict adherence to standardized testing and quality control protocols.

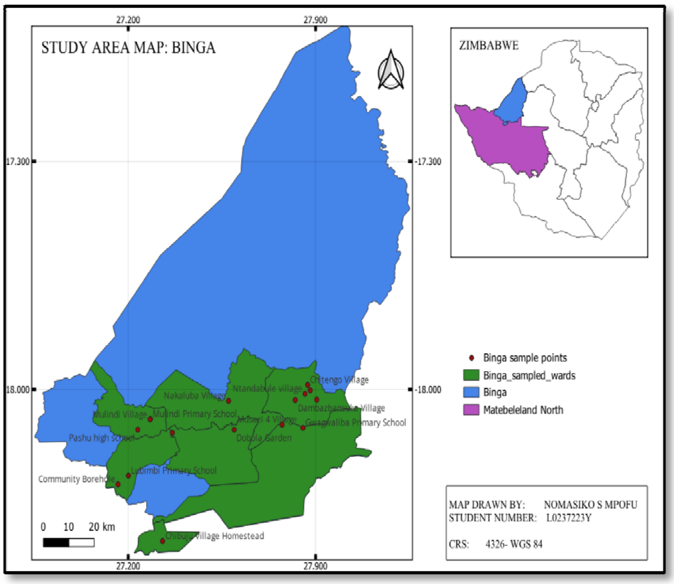

Figure 1. Binga District Map showing borehole sampling points

Field observations, and participatory community mapping were conducted alongside laboratory analysis to ensure meaningful inclusion of local stakeholders and enhance the relevance of results. Quantitative survey and water test data were statistically analysed for patterns and correlations, while qualitative data underwent thematic analysis.Ethical standards were maintained throughout, including informed consent and confidentiality for all participants.

RESULTS

GIS Mapping and Water Distribution Assessment

GIS analysis of the 16 sampled boreholes in Binga District highlighted notable patterns in water accessibility. In Lubanda, Chinonge, and Dobola wards (Figure 2), the spatial mapping of 467 homesteads relative to borehole locations showed that fewer than 5% of households were situated within the WHO-recommended 1 km radius of a water source. Most households were located 3–5 km from the nearest borehole. Buffer and spatial interpolation analyses revealed clusters of homesteads with limited proximity to boreholes, indicating uneven distribution of water points across the study area. The maps also illustrated areas where multiple boreholes were closely spaced, contrasting with regions where boreholes were sparse or absent, visually depicting the spatial disparities in groundwater accessibility.

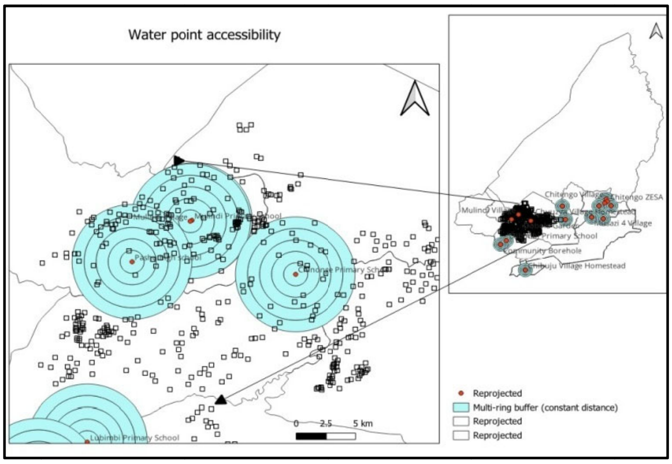

Figure 2. Map showing accessibility of water points with 1-meter buffers

1. Physicochemical Characteristics of Groundwater

Sixteen groundwater samples were analysed to evaluate drinking-water quality across Binga District. Key physicochemical results are summarised in Table 1, which compares measured concentrations against WHO (2019) guideline limits.

Table 1. Physiochemical results for water samples (ND means Not Detected)

Sample ID	As	Hg	F^-	Mg	DO	Cl^-	NO_3^-	Ecoli	CN (%)	pH	Ec (µS)	Tds	Salinity
WHO Guidelines	0.01	0.02	1.5	1.30	None Given	250	10	Un-acceptable	0.07	6.5 – 8.5	1000	500	600
Mulindi Primary School B/H	ND	ND	3.02	0.025	7.02	114.41	0.13	ND	NIL	7.90	103	51	0.05
Pashu High School B/H	ND	ND	3.18	0.09	6.71	59.90	0.14	ND	NIL	7.03	142	42	0.09
Mulindi Village Coomunity B/H	ND	ND	3.01	0.034	6.82	74.34	0.12	ND	NIL	7.05	112	45	0.04
Chinonge Primary B/H	ND	ND	3.17	0.065	7.01	110.25	0.13	ND	NIL	7.45	105	47	0.06
Lubimbi Primary B/H	ND	ND	3.15	0.013	6.94	62.70	0.15	ND	NIL	7.87	134	50	0.07
Tinde Ward Community Borehole	ND	ND	2.98	0.076	6.93	111.34	0.11	ND	NIL	7.62	124	43	0.03
Chibuju village homestead D/W	ND	ND	3.12	0.012	7.01	75.03	0.15	ND	NIL	7.51	135	48	0.05
Nakuluba Village D/W	ND	ND	3.01	0.034	7.03	87.65	0.11	ND	NIL	7.36	33	156	0.06
Dobola garden B/H	ND	ND	2.94	0.027	6.95	68.32	0.45	ND	NIL	7.49	37	208	0.02

The dataset illustrates consistent chemical signatures across boreholes and deep wells, with notable exceedances for selected parameters.

The stacked bar chart (Figure 3) shows the multi-parameter variations across sampling sites. The results depicted in the stacked bar chart demonstrate significant spatial variability in key water quality parameters across different sampling sites, with notable variations observed at Dodola Garden, Nakaluba Village, Chitengwa Village, Gwevavhila Primary School, and Lubuli Primary School. These locations exhibit elevated levels of parameters such as total dissolved solids, chloride, nitrate, and salinity, indicating pronounced water quality fluctuations potentially due to site-specific influences like local geology, land use, or pollution sources. In contrast, parameters like pH and dissolved oxygen remain relativelyconsistent across sites.

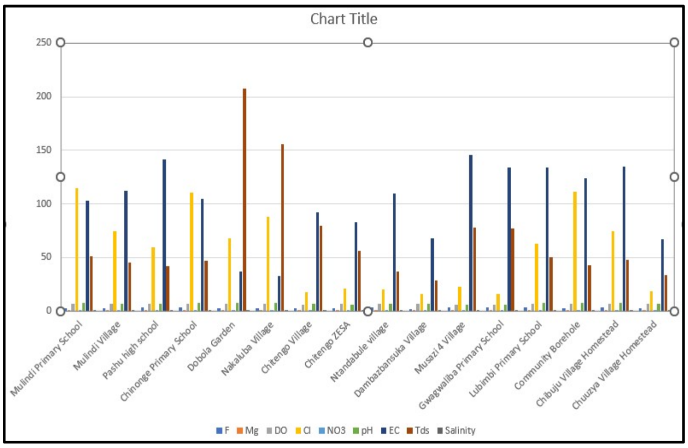

Figure 3. Concentrations of different physiochemical parameters

In addition, no detectable concentrations of arsenic (As), mercury (Hg), or cyanide (CN) were observed in any sample. Similarly, Ecoli was absent across all sites. The absence of both toxic trace elements and faecal contamination indicates minimal influence from mining activities or sanitation-related pollution within the sampled areas.

3. *FlourideMagnesium and Dissolved Oxygen*

Fluoride exhibited the most significant deviation from WHO standards. All samples exceeded the 1.5 mg/L guideline, with concentrations ranging from 2.03 mg/L to 3.18 mg/L. Fluoride was highest at Pashu High School borehole and lowest at Dambazbansuka Community borehole.

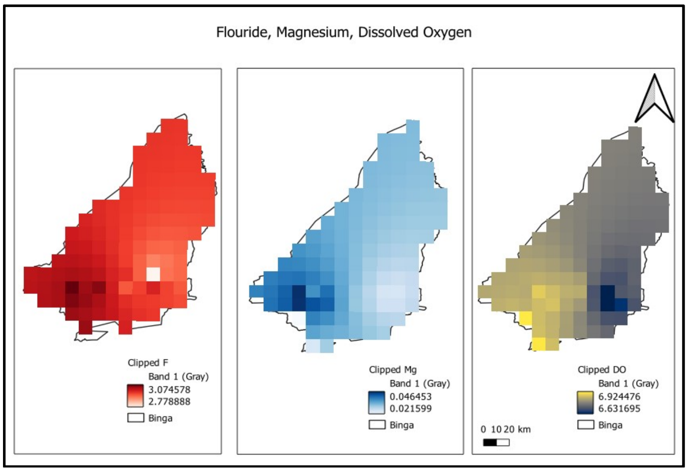

Figure 4. Interpolated Flouride Magnesium and Dissolved Oxygen values

IDW interpolation (Figure 4) demonstrates a spatially coherent pattern of elevated fluoride across the sampled wards, indicating a district-wide geogenic source. This pattern aligns with the geology of the Binga–Hwange region, which is dominated by Karoo sediments associated with high-fluoride lithologies. Magnesium concentrations were uniformly low, ranging from 0.012 to 0.09 mg/L, well below the WHO limit of 1.30 mg/L. Dissolved oxygen (DO) ranged from 6.21 to 7.12 mg/L, with no exceedances or anomalies observed. Spatial modelling of DO (Figure 4) indicates generally consistent groundwater oxygenation across the district.

2. *Chloride, Nitrate, and pH*

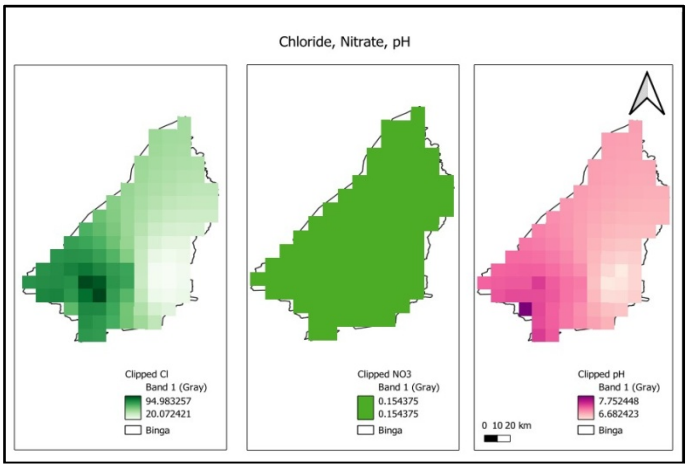

Figure 5. Interpolated chloride, nitrate and pH values

Chloride levels were moderate (16.32–114.41 mg/L) and within WHO limits. Nitrate concentrations were low (0.11–0.45 mg/L) across all sites; the highest values occurred at Dobola Garden borehole, likely reflecting agricultural inputs.pH values ranged from 6.21 to 7.90. Three sites; Chitengo ZESA, Musazi 4, and Gwagwaliba Primaryexhibited slightly acidic conditions (pH < 6.5), potentially reflecting natural interactions with sulphide-bearing Karoo sediments. IDW-derived surfaces for chloride, nitrate, and pH are shown in Figure 5.

3. *Electrical Conductivity, Total Dissolved Solids, and Salinity*

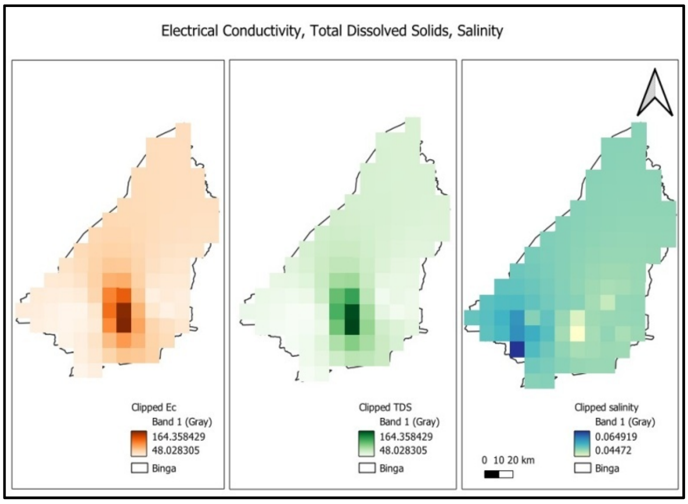

Figure 6. Interpolation of Electrical conductivity, Total dissolved solids and salinity values

Electrical conductivity (EC) values (33–146 µS/cm) were far below the WHO limit of 1,000 µS/cm. Total dissolved solids (TDS) ranged from 42 to 208 mg/L, also below the 500 mg/L threshold. Salinity values were low across all samples (0.02–0.09 mg/L). Spatial interpolation of these parameters (Figure6) shows minimal variability and no zones of elevated salinity or conductivity, indicating overall low mineralisation of groundwater.

DISCUSSION

The integration of laboratory analyses with GIS-based spatial modelling provided a comprehensive understanding of water security challenges in rural Binga. While laboratory results confirmed that most sampled boreholes met acceptable physico-chemical and microbiological standards, the GIS findings reveal that the benefits of this water quality rarely translate into real household access. The combined results indicate that water scarcity in Binga is driven less by groundwater contamination and more by spatial inequities in borehole distribution, exacerbated by drought-induced reductions in surface water availability. Chemical and microbiological tests showed that the majority of boreholes fell within WHO and Zimbabwean drinking-water guidelines, suggesting that groundwater from protected boreholes is generally safe for consumption. The absence of E. coli and toxic elements like arsenic and mercury is highly positive. It suggests that the groundwater is effectively isolated from widespread faecal contamination and that anthropogenic pollution from mining or industrial sources is not a current pressing issue. Similarly, the low levels of nitrate, TDS, and salinity indicate generally good mineralization and limited influence from agricultural runoff, which aligns with the region's low-intensity farming. However, the universal exceedance of fluoride beyond the WHO guideline of 1.5 mg/L is a serious public health concern. The consistency of elevated fluoride levels (2.03–3.18 mg/L) across all sampled wards, as further confirmed by the spatially coherent IDW interpolation surface, strongly indicates a geogenic origin. This finding is consistent with the known geology of the Binga-Hwange area, which is dominated by the Karoo Supergroup sediments. These formations are known to contain fluoride-bearing minerals such as fluorite and apatite, which can release fluoride ions into groundwater through water-rock interaction processes over long residence times. Chronic consumption of water with fluoride concentrations above 1.5 mg/L is a well-established cause of dental fluorosis in children and can lead to debilitating skeletal fluorosis in adults after prolonged exposure. The elevated fluoride, therefore, transforms the perceived "safe" groundwater into a source of a slow-onset, insidious public health threat. The fact that this contamination is geogenic means it is not easily mitigated at the source, shifting the intervention focus to point-of-use treatment. However, the most striking finding is the profound spatial disparity in water access. The GIS model demonstrated that fewer than 5% of the 467 mapped households in Lubanda, Chinonge, and Dobola wards reside within the WHO-recommended 1 km walking distance. Most households instead travel 3–5 km, and in some cases farther, to reach the nearest functioning borehole. Multi-ring buffer analysis and IDW interpolation clearly outlined large swaths of settlement areas lying outside the effective service zones of existing water points, creating pockets of extreme vulnerability. This spatial inequity, visually articulated through the GIS maps, underscores that the water scarcity crisis in Binga is not merely hydrological but also infrastructural. The clustering of boreholes in some areas and their absence in others, as identified through IDW interpolation, points to historical planning deficiencies and highlights an urgent need for strategic, evidence-based placement of new water points to achieve equitable distribution.

This mismatch between water quality and water accessibility has critical implications. The distance barrier forces many households to rely on unsafe open sources rivers, ponds, and seasonal pools especially during peak drought periods when borehole queues lengthen and shallow wells dry up. This explains the continued prevalence of diarrhoeal diseases in the district despite the availability of safe groundwater. The GIS-derived vulnerability patterns also highlight that areas with clustered boreholes do not necessarily coincide with areas of greatest population density, revealing inefficiencies in historical borehole placement. Furthermore, interpolation surfaces depicting groundwater quality gradients suggest that isolated contamination “hotspots” are linked to localized overuse, poor maintenance, or vulnerability to surface infiltration. However, these risks remain secondary compared with the systemic challenge of inadequate borehole coverage. Thus, the public health risk in Binga is not principally a water-quality issue but an accessibility and distribution problem, driven by infrastructural gaps, drought conditions, and heavy reliance on distant water points.

Conclusion

The study demonstrates the value of integrating laboratory-based water quality assessments with GIS-driven spatial modelling to provide a holistic evaluation of water security in rural Binga, Zimbabwe. While laboratory results show that most boreholes meet WHO and national drinking-water guidelines, the GIS analysis reveals that the spatial distribution of these water points severely limits their practical utility to surrounding communities. The findings indicate that safe groundwater exists, but its benefits are constrained by the geographic inaccessibility of boreholes, with fewer than 5% of mapped households situated within the recommended 1 km walking distance. Multi-ring buffer outputs, IDW interpolation, and settlement overlay maps consistently highlight large areas where populations remain outside effective service zones, underscoring persistent inequalities in water access. Thus, the contrast between satisfactory water quality and poor spatial accessibility underscores a fundamental mismatch in the water supply system. Furthermore, although groundwater quality surfaces indicate isolated contamination hotspots, these are localized anomalies rather than systemic threats. The wider challenge is structural: historical borehole placement does not align with current settlement patterns, resulting in service inefficiencies that perpetuate pockets of severe vulnerability. Hence, the integrated GIS–laboratory approach applied in this study proves effective for diagnosing the underlying drivers of water insecurity in data-scarce rural environments. By capturing both the chemical integrity of groundwater and its spatial accessibility to households, the model provides an evidence-based platform for optimizing future water point placement, prioritizing underserved areas, and strengthening resilience to climate-induced water stress. The methodology and insights generated here offer a replicable framework for rural water resource planning in Zimbabwe and similar drought-prone regions across sub-Saharan Africa.

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Credit author statement: Nomasiko Shantelle Mpofu: Conceptualization, data collection and analysis, writing – review and editing; Ashley Ruvimbo Sabao: Writing - original draft preparation, dataanalysis; Paul Matshona: Conceptualization, writing – review and editing; Fyrence Ndebele: Funding acquisition, data analysis; Ernesty Gotosa: Data collection, writing – review and editing. The authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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