water

MDPI

Article

Assessment of Groundwater Quality and Vulnerability in the Nakivale Sub-Catchment of the Transboundary Lake Victoria Basin, Uganda

Emmanuel Nabala Hyeroba [1,2,*] and Robert M. Kalin [1,*]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK
[2] Directorate of Water Resources Management, Ministry of Water and Environment, Kampala 20026, Uganda
* Correspondence: nabala.emmanuel91@gmail.com or nabala.emmanuel@mwe.go.ug (E.N.H.); robert.kalin@strath.ac.uk (R.M.K.); Tel.: +256-783553292 (E.N.H.); +44-7772025478 (R.M.K.)

Abstract: This study evaluates the quality and vulnerability of groundwater within the Nakivale Sub-catchment of the transboundary Lake Victoria Basin in Southwestern Uganda. Groundwater quality assessment focuses on its suitability for both drinking and agricultural uses. Hydrochemical analysis of 19 groundwater samples revealed that 90% comply with World Health Organization drinking water standards, although localized contamination was noted, particularly in terms of total iron, nitrate, potassium, magnesium, and sulfates. The drinking groundwater quality index shows that over 90% of the samples fall within the good-to-excellent quality categories. Elevated nitrate levels and chloride–bromide ratios indicate human impacts, likely due to agricultural runoff and wastewater disposal. For irrigation, Sodium Adsorption Ratio analysis revealed medium-to-high salinity hazards in the region, while Sodium Percentage and other parameters indicated low-to-moderate risks of soil degradation. DRASTIC vulnerability assessments identified low contamination risks due to impermeable geological layers, steep terrain, slow groundwater recharge, deep aquifer depth, and clayey soil cover. These findings emphasize the need for conjunctive water resource management, including improved groundwater quality monitoring, public education on sustainable practices, and protective measures for recharge zones and areas highly susceptible to contamination. By addressing these issues, this study aims to preserve groundwater resources for domestic and agricultural use, ensuring long-term sustainability in the region.

Keywords: groundwater quality; groundwater vulnerability; Nakivale; Victoria basin

check for updates

Citation: Hyeroba, E.N.; Kalin, R.M. Assessment of Groundwater Quality and Vulnerability in the Nakivale Sub-Catchment of the Transboundary Lake Victoria Basin, Uganda. *Water* **2024**, *16*, 3386. https://doi.org/10.3390/w16233386

Academic Editors: Guanxing Huang and Liangping Li

Received: 21 October 2024
Revised: 18 November 2024
Accepted: 20 November 2024
Published: 25 November 2024

1. Introduction

Access to clean and safe water is vital for human survival, economic growth, and sustainable development [1]. In many developing regions in Africa, water scarcity and poor water quality pose significant challenges, hindering development and trapping communities in cycles of poverty [2]. Recognizing the importance of clean water, international frameworks such as the United Nations Sustainable Development Goal (SDG) 6, which strives to ensure the availability and sustainable management of water and sanitation for all, have placed water security at the forefront of global and local agendas [3,4]. SDG 6 emphasizes equitable access to clean water, improved water management, and the protection of water-related ecosystems [1].

One region where clean water supply is critically a challenge is the Nakivale Sub-catchment in Southwestern Uganda [5,6]. This area is located within the Isingiro District and lies within Uganda's cattle corridor [5]. The cattle corridor is known for its water stress, particularly during dry spells, which are marked by declining groundwater levels from boreholes and the drying up of seasonal water bodies [7,8].

This situation greatly affects the socio-economic welfare of the 616,700 people in the area, a third of whom are refugees living in Nakivale refugee camp, one of the oldest in Uganda, hosting refugees from Burundi, the Democratic Republic of Congo, Rwanda, Somalia, Sudan, and South Sudan [9]. With an annual population growth rate projected at 3.6% [10], the challenge of accessing clean water is becoming increasingly urgent [9].

For the riparian communities in Nakivale, access to clean water is not only essential for survival but also a crucial factor in breaking the cycle of poverty [11]. Water is a key resource that supports livelihoods in agriculture, livestock farming, and small-scale industries within the project area [7,9,12]. However, scaled groundwater quality and its vulnerability to contamination are not well understood [13]. Evaluating the quality and susceptibility of groundwater is vital to ensure its sustainable use and to safeguard it for future generations [14].

Previous studies by [15,16] focused on the hydrogeochemical evolution of groundwater resources within the region, offering valuable insights into the factors controlling groundwater hydrochemistry. The latter also provided key information on groundwater recharge, flow, and occurrence within the study area. The authors of one study [6] conducted a national groundwater resources availability and demand assessment, which involved an evaluation of groundwater quality in various catchments, including the Rwizi catchment, where the project area is located. This study highlighted emerging groundwater quality issues, such as nitrate contamination in urban areas of Mbarara district, situated upstream of the project area. The authors of [5,17] identified growing water quality concerns in the region, driven by a rapidly increasing population and urbanization. Other studies [5,18,19] also provided important insights into contamination challenges within regional hydrological systems, with a major focus on surface water.

Despite the valuable contributions from these studies, none have specifically focused on scaled assessment of groundwater quality and vulnerability within the Nakivale catchment. Localized assessments are crucial due to the inherent heterogeneity of the underlying hydrological systems [20,21]. Groundwater chemistry can vary significantly over small spatial scales, influenced by local geological, biological, and chemical factors [22]. These assessments account for these intrinsic variations, which are essential for accurately understanding groundwater dynamics that broader assessments might overlook [23]. The groundwater quality and vulnerability assessment is of paramount importance in determining the current status of groundwater resources and the risks they face [24].

Groundwater quality, particularly in regions with limited alternative water sources, is often assessed for its intended purpose, such as drinking and irrigation suitability [25–29]. This study employed a comprehensive approach using the Groundwater Quality Index (GWQI), which consolidates various chemical and physical water parameters into a single value to facilitate a clear assessment of water quality suitability for human consumption [25–33]. The GWQI method was selected due to its ability to integrate multiple water quality parameters [29,30,34,35] and enable targeted comparisons across regions [26,30]. For irrigation, hydrochemical indices such as Sodium Adsorption Ratio (SAR), Kelly's Ratio (KR), Sodium Percentage (SP), Magnesium Adsorption Ratio, Residual Sodium Carbonate (RSC), among others, provided insight into possible impacts on soil health, crop yield, and the risk of soil degradation [28,31,33,36], all of which affect agricultural productivity over time [28].

Complementing quality assessments, groundwater vulnerability assessments determine how susceptible aquifers are to contamination from surface sources [37]. This is especially relevant in Nakivale, where agricultural runoff and land use practices may threaten groundwater resources [7]. For this purpose, the DRASTIC model was chosen for its established capability to assess aquifer vulnerability by incorporating essential hydrogeological parameters that directly influence contaminant percolation, including depth to water, net recharge, aquifer media, soil media, topography, impact of the vadose zone, and hydraulic conductivity [23,34,38,39]. By analyzing these specific factors, the DRASTIC model effectively estimates the likelihood of contaminant migration through soils and aquifers [38,39], providing a robust measure of groundwater susceptibility to surface-based contamination sources [14,24,34,35,37–42].

This study serves as an initial investigation, aiming to establish a baseline understanding of groundwater quality, potential contamination threats, and vulnerability of this vital resource within the Nakivale Sub-catchment. The findings are intended to guide policymakers, local authorities, and stakeholders in implementing targeted interventions for the sustainable management of groundwater resources in both the study area and the broader Victoria basin. Additionally, this research provides a foundational reference for future studies focused on assessing groundwater quality and vulnerability across the region.

The specific objectives of this study are to assess the current groundwater quality for both drinking and agricultural usage in the Nakivale Sub-catchment by analyzing key physio-chemical parameters such as major ions, trace elements, minor ions, nutrients concentrations, and hydrochemical field parameters; to identify key sources of groundwater contamination; to evaluate the vulnerability of groundwater resources to contaminants emerging from the surface; and to provide recommendations for the sustainable management of groundwater resources, with a focus on enhancing groundwater resilience to climate variability and population growth in the Nakivale riparian communities.

2. Materials and Methods

2.1. Study Area

The study area is located between latitudes (9,900,000 N; 9,930,000 N) and longitudes (230,000 E; 280,000 E) within the Isingiro District in Southwestern Uganda (Figure 1). It spans 760 km^2 and is part of the Rwizi catchment, which falls within the greater Victoria Basin [5,6,13]. The landscape is predominantly composed of remnants of lowland surfaces, which account for over 60% of the sub-catchment. These lowland surfaces are significant for groundwater discharge within the region [16].

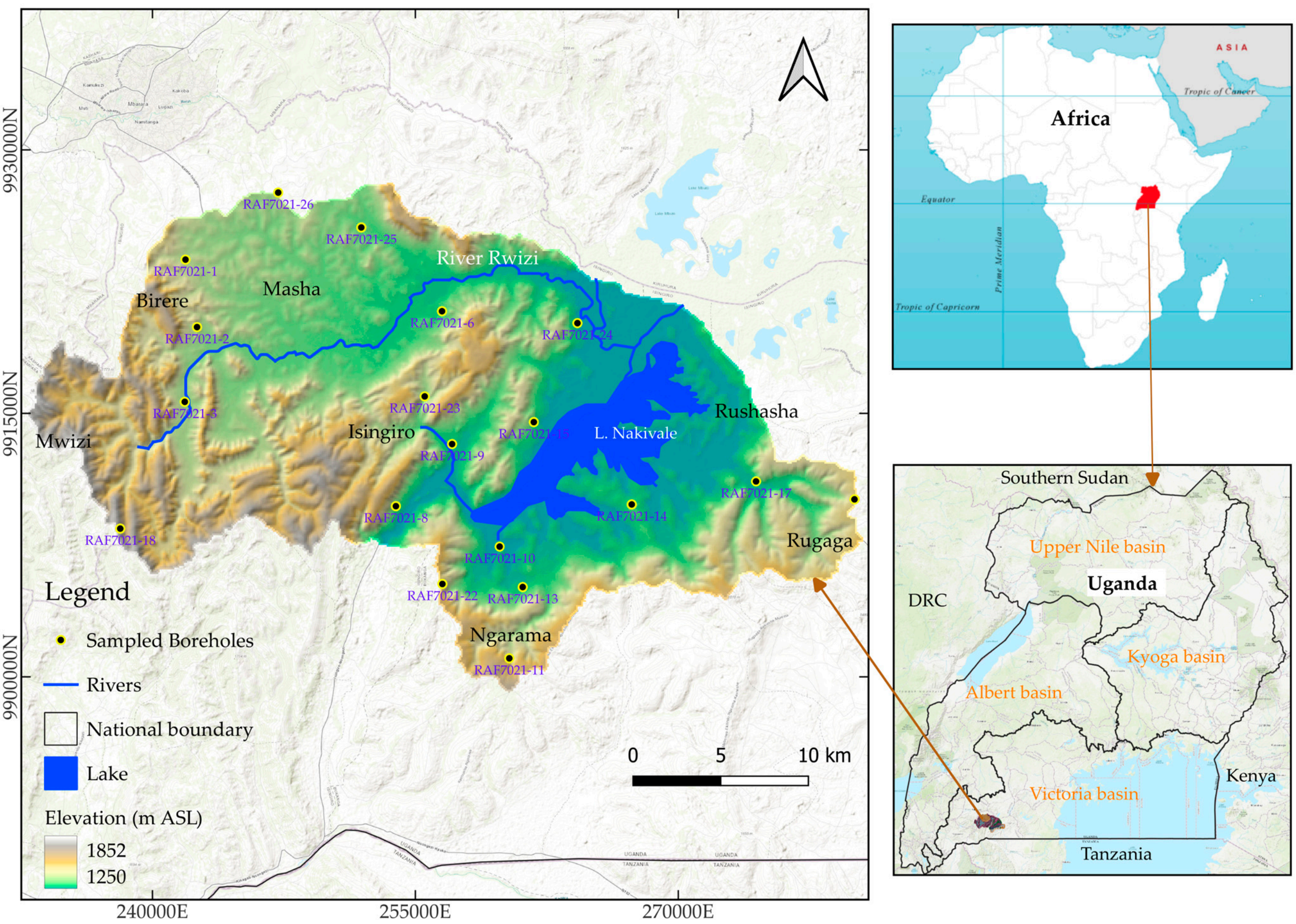

Figure 1. Location map of Nakivale Sub-catchment within Southwestern Uganda.

Infill areas are found in the western and eastern parts of the sub-catchment and are characterized by poorly sorted outwash fans that impact groundwater infiltration and quality due to the heterogeneity of the sediments. High-relief areas are located along the extreme margins of the catchment and are covered by remnants of upland surfaces, which are prone to erosion. According to [16], these elevated areas are zones of groundwater recharge and are associated with high hydraulic head gradients relative to the lowlands.

The riparian communities primarily engage in livestock farming and banana plantations [11]. These social-economic activities are heavily reliant on groundwater resources [5,13]. The local communities tend to settle on the lower flanks of the area in nucleated settlement patterns [7]. The lower lands are rich in thick, loamy soils, which support agricultural productivity [7]. Given the area's reliance on groundwater for both agriculture and domestic purposes [11], understanding its vulnerability to degradation from both geogenic and anthropogenic effects is of paramount importance [24,37].

This understanding is critical for ensuring the protection and sustainable use of groundwater resources in the Nakivale Sub-catchment. Groundwater of good quality is not only essential for human survival [5], but it is also a cornerstone of economic development within the study area [26]. Safeguarding these water resources is, therefore, crucial for maintaining agricultural productivity, supporting livestock, and ensuring the well-being of the communities that depend on them [11,17,24].

2.2. Geological and Hydrogeological Setting

The study area is overlain by the Proterozoic Karagwe-Ankolean system of metasedimentary rocks that exhibit varying degrees of metamorphism (Figure 2). These rocks include shales, slates, and phyllites. These host rocks were intruded by younger granitic rocks of variable mineral compositions [43]. The area's hydrogeology is heavily influenced by these geological formations, which play a crucial role in determining groundwater recharge, flow, storage, and quality [5,6,13]. The predominant aquifer in the region is the weathered and fractured aquifer [5,6], typically found at depths greater than 60 m above sea level [44]. Additionally, other aquifer types include paleo-channels and sedimentary alluvial aquifers [5,6], both of which also contribute to the local groundwater system [44,45]. According to [6], the hydraulic conductivity (K) and specific storage (Ss) values for the fracture domain are 1.7×10^{-2} m/day and 3.76×10^{-2} m^{-1}, respectively, while for the matrix domain, these values are 1.4×10^{-7} m/day and 4.37×10^{-4} m^{-1}. The same study reports that annual recharge in the area ranges between 50 and 100 mm.

Over 80% of the area is covered by fine-grained clayey soils formed from the weathering of in situ argillaceous rocks [16]. These soils are associated with poor hydraulic properties [46], which significantly hinder groundwater flow and storage processes [47]. Active groundwater recharge in the Nakivale Sub-catchment area predominantly occurs in elevated areas that are characterized by a network of lineaments [16], which enhance water infiltration. In contrast, groundwater discharge zones are primarily located in the lowlands, particularly in areas occupied by Lake Nakivale and the Rwizi River (Figure 2). This distribution of recharge and discharge areas underscores the importance of the region's geological features in shaping the flow and storage processes of the underlying local aquifer systems.

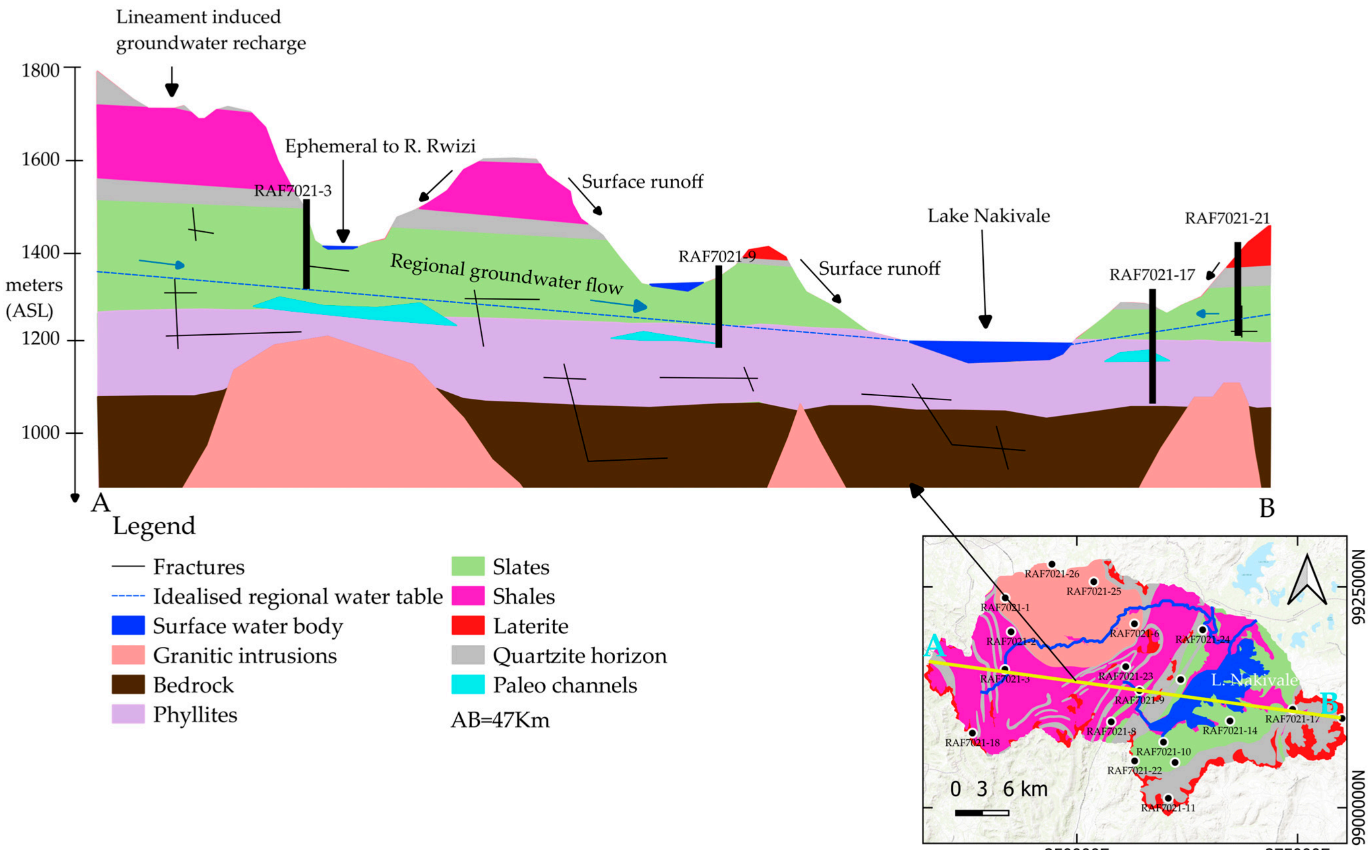

Figure 2. Hydrogeological cross-section between points A and B for Nakivale Sub-catchment, Southwestern Uganda.

2.3. Climate

This area experiences a tropical climate with two distinct rainy seasons: March–April–May and September–October–November, with annual rainfall ranging from 966 mm to 1380 mm [5,13]. These seasonal rainfall patterns are primarily influenced by the movement of the inter-tropical convergence zone (ITCZ), a low-pressure belt [6,16]. The position of the ITCZ in relation to the study area has a significant effect on local seasonal variations [48]. The region also experiences a mean monthly temperature of 27 °C and a mean monthly dew point of 19 °C [5]. These meteorological conditions play a pivotal role in shaping the local hydrological system, as they influence the amount of hydrological input [49], which directly affects both surface and groundwater quantifiable attributes [13]. Rainfall largely determines water availability, while temperatures and dew points affect evapotranspiration rates [50], influencing how much water is lost to the atmosphere [51]. These factors together shape the overall water balance in the area, directly impacting the quantity of water stored in surface reservoirs and subsurface aquifers [52].

2.4. Groundwater Sample Collection and Analysis

This study is based on a total of 19 groundwater samples collected from strategically selected borehole locations to capture variations in geology, land use, geomorphology, and hydrology, ensuring that they represent the intrinsic heterogeneity of the area, as emphasized by [16]. According to the same study, sampling occurred during the dry season, from 15 February to 20 February 2024. The geographic coordinates of each borehole were recorded, and groundwater levels were measured using a dip meter to accurately assess the water table. To guarantee representative samples, each borehole was purged for five minutes prior to sample collection. Water samples were collected in sterile containers to maintain their chemical integrity. Field measurements of key parameters, including dissolved oxygen, pH, temperature, and electrical conductivity, were carried out using a calibrated HANNATM multi-parameter meter (HI 9829_S/N 07100011101) (Hanna Instruments, Woonsocket, RI, USA). Total alkalinity was determined through acid-base titration using 0.02 M hydrochloric acid.

For laboratory analysis, samples for cation and anion measurements were collected in tightly sealed 500 mL HDPE bottles. The cation samples were filtered using GF/C filter papers and acidified with concentrated nitric acid (analytical grade) to reduce the pH to less than 2, ensuring their stability for transport. These samples were then shipped to the Centre National de l'Energie des Sciences et des Techniques Nucléaires (CNESTEN) chemical laboratory in Morocco under the IAEA RAF7021 project for hydrochemical analysis.

The major ions in the water samples were analyzed in mg/L using the ion chromatography method. These ions included Sodium (Na^+), Potassium (K^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Chloride (Cl^-), Nitrate ($NO_3{}^-$), and Sulfate ($SO_4{}^{2-}$). The bicarbonate concentration was determined through titration against a standardized acid, with the endpoint of the reaction identified using a pH indicator. Additionally, the minor ions, Aluminium (Al), Iron (Fe), Silicon (Si), and Boron (B), were analyzed in their elemental forms using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). This method allows for highly sensitive and precise measurements of elements at very low concentrations [53].

A robust quality control (QC) and quality assurance (QA) system was implemented to ensure the integrity and reliability of hydrochemical analyses. Both the sampling and laboratory hydrochemical analysis process strictly followed the IAEA Groundwater Sampling Procedures, ensuring that each sample was properly collected, labeled, and stored to prevent any contamination or alteration of its hydrochemical composition. Charge balance errors (CBE) were calculated for each sample as a critical QC measure. This was performed using (Equation (1)), with cations and anions expressed in meq/L. This process ensured that the ionic concentrations were correctly measured and balanced within acceptable limits, typically less than ±5%, considered acceptable or 5–15%, and treated with caution [54].

$$\text{CBE} = \left(\frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} \right) \times 100 \tag{1}$$

2.5. Groundwater Quality Assessment

The assessment employed a twofold methodological approach, integrating spatial analysis using Quantum Geographic Information System (QGIS) Version 3.36.3 with an index-based assessment of groundwater quality.

2.5.1. Spatial Analysis

The spatial analysis involved generating groundwater quality maps for both major and minor ions. Additionally, it included spatial mapping of hydrochemical parameters, groundwater quality indices, and the chloride–bromide ratio. The maps were created using the Inverse Distance Weighting (IDW) interpolation method, a deterministic technique that assigns greater influence to nearby points based on distance, making it particularly effective for estimating values in areas with irregularly spaced data [55]. IDW is well-suited for groundwater quality mapping of sparse data as it does not rely on spatial autocorrelation, which requires evenly distributed data [29,56,57]. However, due to the complex and unpredictable nature of many underlying groundwater systems, it is essential to interpret the results cautiously, recognizing the basic principles inherent to the IDW method.

2.5.2. Drinking Groundwater Quality Index Assessment

Drinking groundwater quality was assessed through the computation of the groundwater quality index for each groundwater sample. This method has been utilized by various researchers to assess groundwater quality based on its hydrochemical composition [25,26,30]. The approach involved assigning weights w_i on a scale from 1 to 5 to each analyzed chemical species deemed significant for groundwater potability needs. After assigning weights (w_i), the relative weight (W_i) for each parameter was computed using the formula below (Equation (2)).

$$W_i = \frac{w_i}{\sum_i^n w_i} \quad (2)$$

The rating scale for each parameter, denoted by (q_i), was subsequently calculated by dividing the concentration (C_i) in mg/L of each parameter by the World Health (WHO) standard value (S_i) in mg/L for portable water (Equation (3)).

$$q_i = \frac{C_i}{S_i} \times 100 \quad (3)$$

The relative weights (W_i) assigned to each parameter, along with their corresponding rating scales (q_i), were then multiplied to derive the sub-index (SI_i) for each parameter.

$$SI_i = W_i \times q_i \quad (4)$$

Finally, the groundwater quality index (GWQI) for each sample was calculated by summing the sub-indices of each parameter for a given water sample, as indicated by Equation (5).

$$GWQI = \sum_i^n SI_i \quad (5)$$

The Table 1 shows the water quality index range and the corresponding water quality classification for each sample.

Table 1. Groundwater quality index range and class [25,30,58].

Groundwater Quality Index Range	Groundwater Quality Class
<50	Excellent Groundwater
50–100	Good Groundwater
100–200	Poor Groundwater
200–300	Very Poor Groundwater
>300	Unsuitable Groundwater

2.5.3. Irrigation Groundwater Quality Assessment

This assessment centered on analyzing key hydrochemical indices that determine the suitability of water for agricultural use. The parameters evaluated included Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), Kelly's Ratio (KR), Magnesium Adsorption Ratio (MAR), Sodium Percentage (SP), and Residual Sodium Carbonate (RSC). These indices were examined to assess risks related to soil permeability reduction, nutrient imbalance, and the potential buildup of salinity and alkalinity. Each parameter was classified according to established thresholds (Table 2), facilitating a comprehensive evaluation of groundwater quality for irrigation while highlighting both the individual and combined effects of the indices on soil health and crop productivity. This irrigation water quality indexing assessment approach has been widely recognized and utilized globally to assess the suitability of water resources for irrigation [28,31,33,36,58–61]. The following mathematical models were used to calculate the respective groundwater quality indices for irrigation, with each hydrochemical species expressed in meq/L:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (6)$$

$$MAR = \frac{Mg^{2+}}{Ca^{2+} Mg^{2+}} \times 100 \quad (7)$$

$$KR = \frac{Na^{+}}{Ca^{2+} + Mg^{2+}} \tag{8}$$

$$SP = \frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \times 100 \tag{9}$$

$$RSC = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+}Mg^{2+}) \tag{10}$$

Table 2. Classification ranges for the assessed irrigation groundwater quality indices.

Index	Classification Range	Class
KR	<1	Safe
	>1	Unsuitable
MAR (%)	<50	Suitable
	>50	Unsuitable
SAR	<10	Excellent
	10–18	Good
	18–26	Marginal
	>26	Poor
SP (%)	<20	Excellent
	20–40	Good
	40–60	Permissible
	60–80	Doubtful
	>80	Unsuitable
RSC (meq/L)	<0	Low
	0–1	Medium
	1–2.5	High
	>2.5	Very high

2.6. Groundwater Vulnerability Assessment

This study employed the DRASTIC assessment approach to evaluate the vulnerability of groundwater resources to contaminants from surface sources. The DRASTIC model is based on seven critical hydrogeological parameters that influence the movement of contaminants into aquifer systems [23]. These parameters include Depth to groundwater (D), Net recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the vadose zone (I), and Hydraulic conductivity (C). The decision to use DRASTIC over other groundwater vulnerability models, such as GOD and GALDIT, stems from its capability to assess the intrinsic vulnerability of groundwater at each specific location [34,38,39]. While the GOD model is simple, it tends to overgeneralize and is unable to capture localized variations [41,62], and the GALDIT model is designed primarily for coastal aquifers [35,40].

In the DRASTIC model, weights (w) of 5, 4, 3, 2, 1, 5, and 3 were assigned to the respective parameters. Ratings were then applied on a scale of 1 to 10 based on the range of each parameter at each groundwater well, following the guidelines set by [23] for confined aquifers. This approach involved careful yet subjective judgment informed by field experience and available data to ensure that the ratings accurately reflect the specific conditions of each site. The DRASTIC index was subsequently calculated using Equation (11) in Microsoft Excel, where subscripted parameters represent the ratings corresponding to each DRASTIC model input parameter.

$$\text{DRASTIC Index} = (D_r \times 5) + (R_r \times 4) + (A_r \times 3) + (S_r \times 2) + (T_r \times 1) + (I_r \times 5) + (C_r \times 3) \tag{11}$$

3. Results and Discussion

3.1. Hydrochemical Parameter Analysis

All 19 analyzed groundwater samples passed the charge balance error (CBE) test (Table S4). A total of 84% of the samples had a CBE of less than 5%, while 16% of the samples had a CBE between 5 and 10%. The results from the latter were treated with caution. The table below presents a descriptive summary of the hydrochemical test results for major parameters. See Table 3.

Table 3. Summary of descriptive statistical analysis of major water quality parameters (adapted from [16], with additional parameters).

Parameter	Mean	Standard Deviation (SD)	Max.	Min.	WHO Guideline Value (GV)	% of Samples > WHO GV
pH	6.7	1.0	9.3	4.5	6.5–8.5	31
HCO_3^- (mg/L)	141.5	134.0	439.3	10.0	-	-
Cl^- (mg/L)	48.6	25.6	96.1	16.0	250.0	-
NO_3^- (mg/L)	16.4	14.1	46.1	0.0	50.0	-
SO_4^{2-} (mg/L)	204.7	148.9	515.6	29.9	500.0	5
Na^+ (mg/L)	59.9	27.4	134.6	8.7	200.0	-
K^+ (mg/L)	6.6	3.8	15.1	2.8	12.0	5
Mg^{2+} (mg/L)	23.5	15.6	51.5	0.0	50.0	10
Ca^{2+} (mg/L)	59.0	42.3	144.0	0.7	300.0	-
Total Fe (mg/L)	0.8	1.5	5.1	0.02	0.3	47
Alkalinity (mg/L $CaCO_3$)	145.2	136.1	445.3	11.4	-	-
EC (µS/cm)	746.8	366.3	1538.0	297.0	1857	5

3.1.1. Analysis of Major Cations

Sodium and calcium concentrations from all 19 analyzed samples fall within acceptable WHO guideline ranges. Potassium (K^+) concentrations vary from 2.8 to 15.1 mg/L, with a mean of 6.6 mg/L and a standard deviation (SD) of 3.8. The WHO guideline value for potassium is 12 mg/L, with only 5% of the samples exceeding this limit. This suggests minor potassium contamination, which may lead to taste issues in drinking water but generally poses low health risks at these levels [63].

Magnesium (Mg^{2+}) concentrations range from 0.0 to 51.6 mg/L, with an average of 23.5 mg/L and a standard deviation of 15.6. Only 10% of the samples exceed the WHO guideline of 50 mg/L, indicating potential localized magnesium issues. Elevated Mg^{2+} levels can contribute to water hardness, affecting taste and usability for domestic purposes. Additionally, high magnesium concentrations have been linked to an increased risk of ischemic heart disease [64].

Total iron (Fe) levels range from 0.01 to 5.1 mg/L, with a mean of 0.8 mg/L and a standard deviation of 1.5. The WHO guideline value for iron is 0.3 mg/L, and 47% of the samples slightly exceed this limit. Elevated iron levels can cause several issues, including staining of laundry and plumbing fixtures, a metallic taste in drinking water, and potential health effects, such as gastrointestinal irritation [65].

3.1.2. Analysis of Major Anions

Chloride (Cl^-), bicarbonate (HCO_3^-), and nitrate (NO_3^-) concentrations fall within acceptable WHO guideline values, with the exception of sulfate (SO_4^{2-}). Sulfate levels range from 29.9 to 515.6 mg/L, with a mean of 204.7 mg/L and a standard deviation (SD) of 148.9. The WHO guideline for sulfate is 500 mg/L, with 5% of the samples exceeding this threshold. Elevated sulfate levels may lead to a bitter taste in water, laxative effects, and potential corrosion of plumbing systems [66].

The hydrochemical maps indicate both localized point contamination sources and diffuse sources (Figure 3), attributed to a combination of anthropogenic and geogenic factors. According to [15,16], groundwater chemistry in the region is primarily governed by water–rock interaction processes. Groundwater composition is significantly influenced by the mineralization of the underlying geological formations, predominantly composed of mafic and felsic feldspars (such as muscovite, orthoclase, anorthite, and biotite) [16] and sulfide minerals like pyrite and chalcopyrite, particularly evident in the Igayaza area of

Isingiro District [67]. High localized iron concentrations are linked to the potential rusting of galvanized iron commonly used in the installation of handpumps in the Nakivale area.

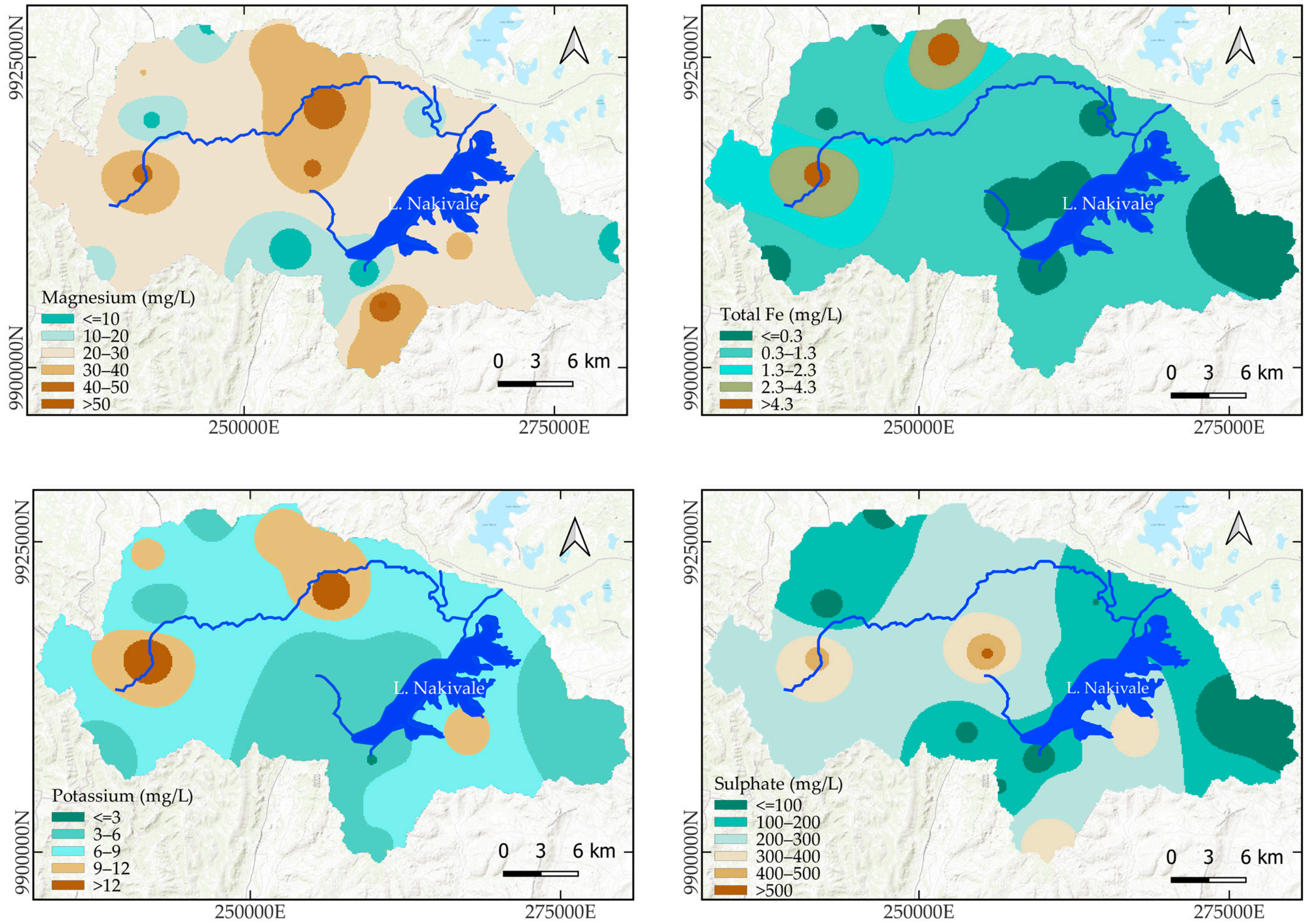

Figure 3. Groundwater quality maps showing spatial distribution of major ions exceeding WHO guideline values for drinking water.

Figure 3 highlights major contamination issues, with levels exceeding WHO guideline values for magnesium (50 mg/L), total iron (0.3 mg/L), potassium (12 mg/L), and sulfate (500 mg/L) in the northwestern and southwestern parts of the study area. Additionally, a central portion exhibits elevated concentrations of magnesium and sulfates, surpassing the WHO guidelines.

3.1.3. Analysis of Other Chemical Parameters

Electrical conductivity (EC) varies from 314 to 1726 μS/cm, with elevated values concentrated in low-lying areas (Figure 4). These high EC levels in the discharge zones suggest chemically enriched, metamorphosed water resulting from rock–water mineralization along groundwater flowlines, as noted by [16]. Additional potential sources of elevated EC include agricultural activities involving fertilizers and pesticides, as well as industrial waste in the region [5].

This analysis also reveals a range of Eh values across the study area, indicating different redox conditions. Lower Eh values (−500 to 0 mV) in the Lake Nakivale region indicate reducing conditions, typically found in older or deeper groundwater with limited oxygen exchange [68]. In contrast, higher Eh values (31 to 178 mV) in elevated areas suggest oxidizing conditions commonly associated with recently recharged or shallow groundwater. A comparable trend is also evident in dissolved oxygen levels. These results align with the findings of [16], which identified groundwater likely older than 20 years characterized by low tritium levels in the lower flanks of the study area.

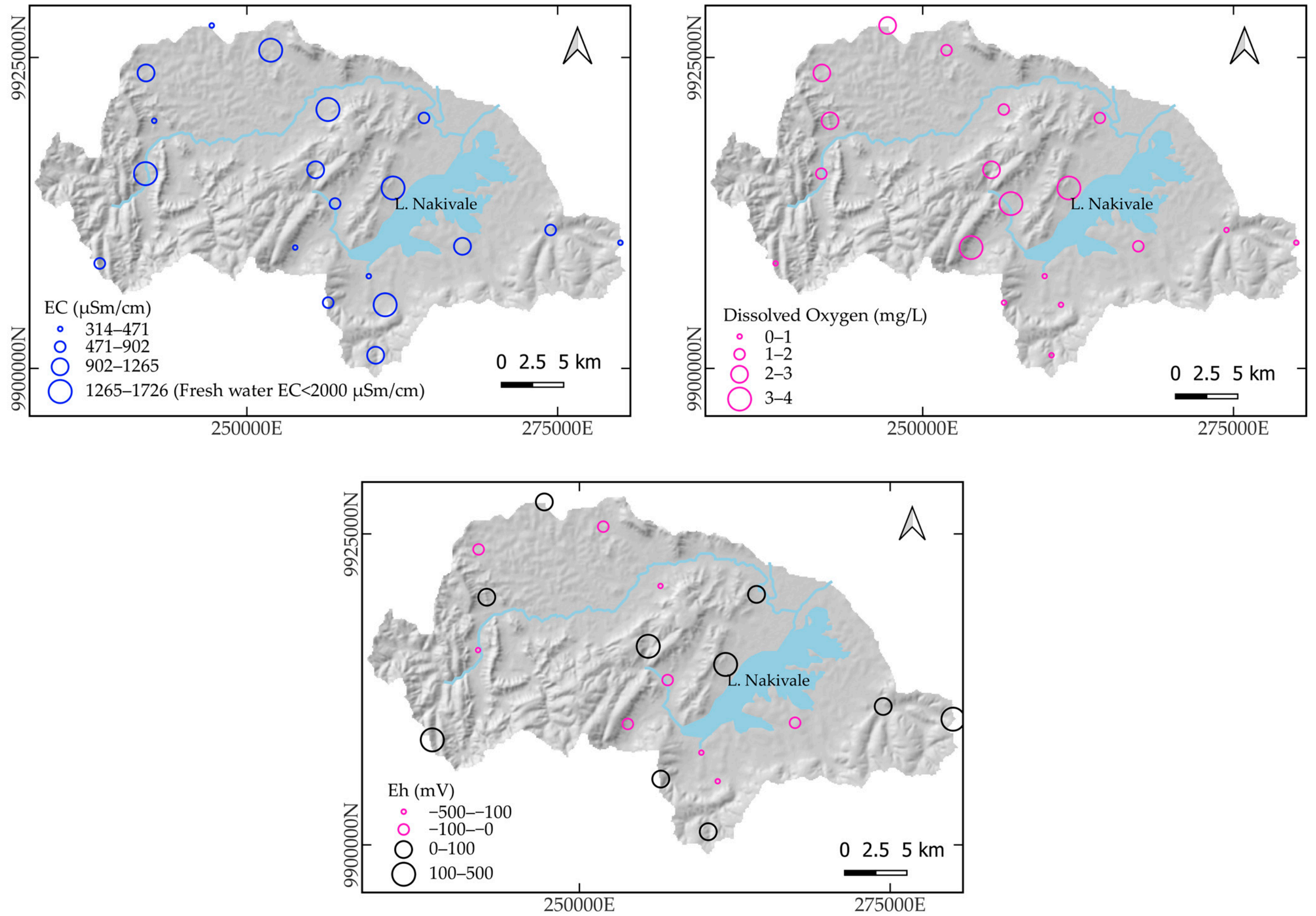

Figure 4. Groundwater quality maps showing Electrical Conductivity, Dissolved Oxygen, and Redox Potential spatial distribution within the project area.

3.2. Drinking Groundwater Quality Index Assessment

The majority of the groundwater samples (90%) have a groundwater quality index of less than 100. Ten groundwater samples (53%) have indices below 50, while seven samples (37%) have indices ranging from 50 to 100 (Figure 5 and Table 4). However, two samples, RAF7021-3 and RAF7021-25, obtained from Masha and Nyamuyanja, respectively, exhibit exceedingly high groundwater quality indices above 200, primarily due to high concentrations of total iron (Figure 5). The elevated concentration of total iron can be attributed to localized anthropogenic sources from the use of galvanized iron pipes commonly installed for handpump boreholes in the study area. However, this assumption needs to be confirmed through fieldwork. Additionally, the high GWQI of these two boreholes is also influenced by relatively elevated levels of magnesium, potassium, and sulfate, which slightly exceed WHO guideline values. According to [15,16], the concentration of these major ions in groundwater within the study area is mainly controlled by rock–water interaction processes. Overall, the study area is underlain by good-to-excellent quality groundwater for drinking, as over 90% of the sampled groundwater points have a groundwater quality index below 100. A total of 90% of all analyzed parameters for all groundwater samples also fall within plausible values stipulated by the WHO for drinking water.

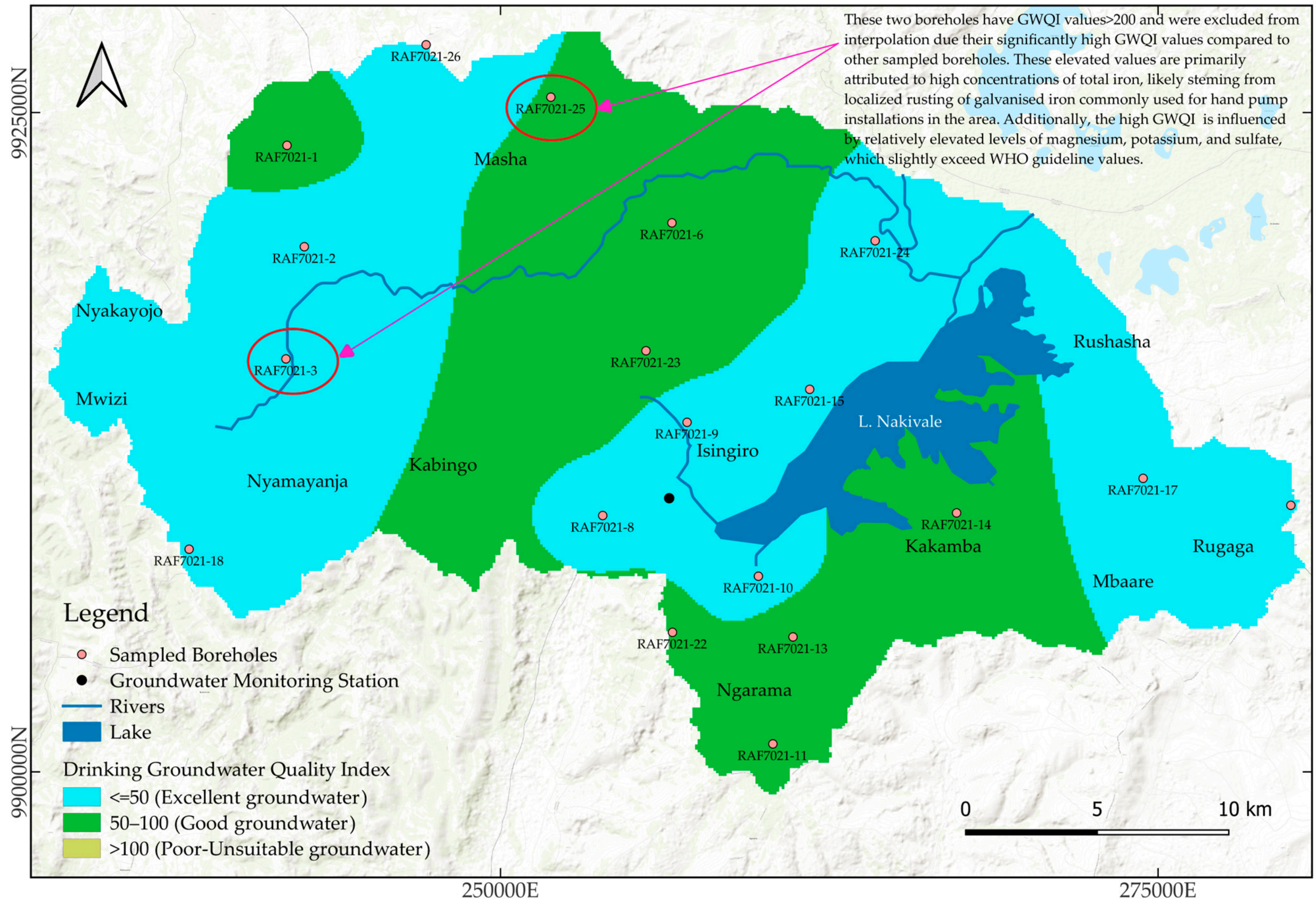

Figure 5. Drinking groundwater quality index map for Nakivale Sub-catchment (excluding samples from RAF7021-3 and RAF7021-25 due to potential localized contamination within these boreholes rather than reflecting the overall groundwater quality of the underlying aquifer system).

Table 4. Groundwater quality index (GWQI)-based classification for groundwater samples collected from 19 hand pump boreholes in Nakivale Sub-catchment, Southwestern Uganda.

Sample Number	GWQI	Groundwater Quality Type	Sample Number	GWQI	Groundwater Quality Type
RAF7021-1	64.2	Good	RAF7021-15	38.2	Excellent
RAF7021-2	25.0	Excellent	RAF7021-17	30.0	Excellent
RAF7021-3	276.0	Poor	RAF7021-18	45.8	Excellent
RAF7021-6	87.9	Good	RAF7021-21	25.2	Excellent
RAF7021-8	47.8	Excellent	RAF7021-22	53.0	Good
RAF7021-9	38.0	Excellent	RAF7021-23	67.5	Good
RAF7021-10	22.1	Excellent	RAF7021-24	42.3	Excellent
RAF7021-11	98.3	Good	RAF7021-25	262.6	Poor
RAF7021-13	76.8	Good	RAF7021-26	34.7	Excellent
RAF7021-14	80.1	Good			

3.3. Analysis of the Chloride–Bromide Ratio

The chloride–bromide (Cl/Br) ratio is a valuable tool for tracing factors that influence groundwater quality due to its conservative nature [61,69,70]. However, its interpretation requires careful consideration of potential overlaps between geogenic and anthropogenic sources [61]. Geogenic processes, such as the dissolution of halite, generally result in high Cl/Br ratios because chloride is more prevalent in these natural sources compared to bromide [69]. Anthropogenic activities, such as industrial waste disposal, agricultural pollution, and landfill leachate, can also introduce significant amounts of chloride with minimal bromide, thereby elevating the Cl/Br ratio [71]. See Figure 6.

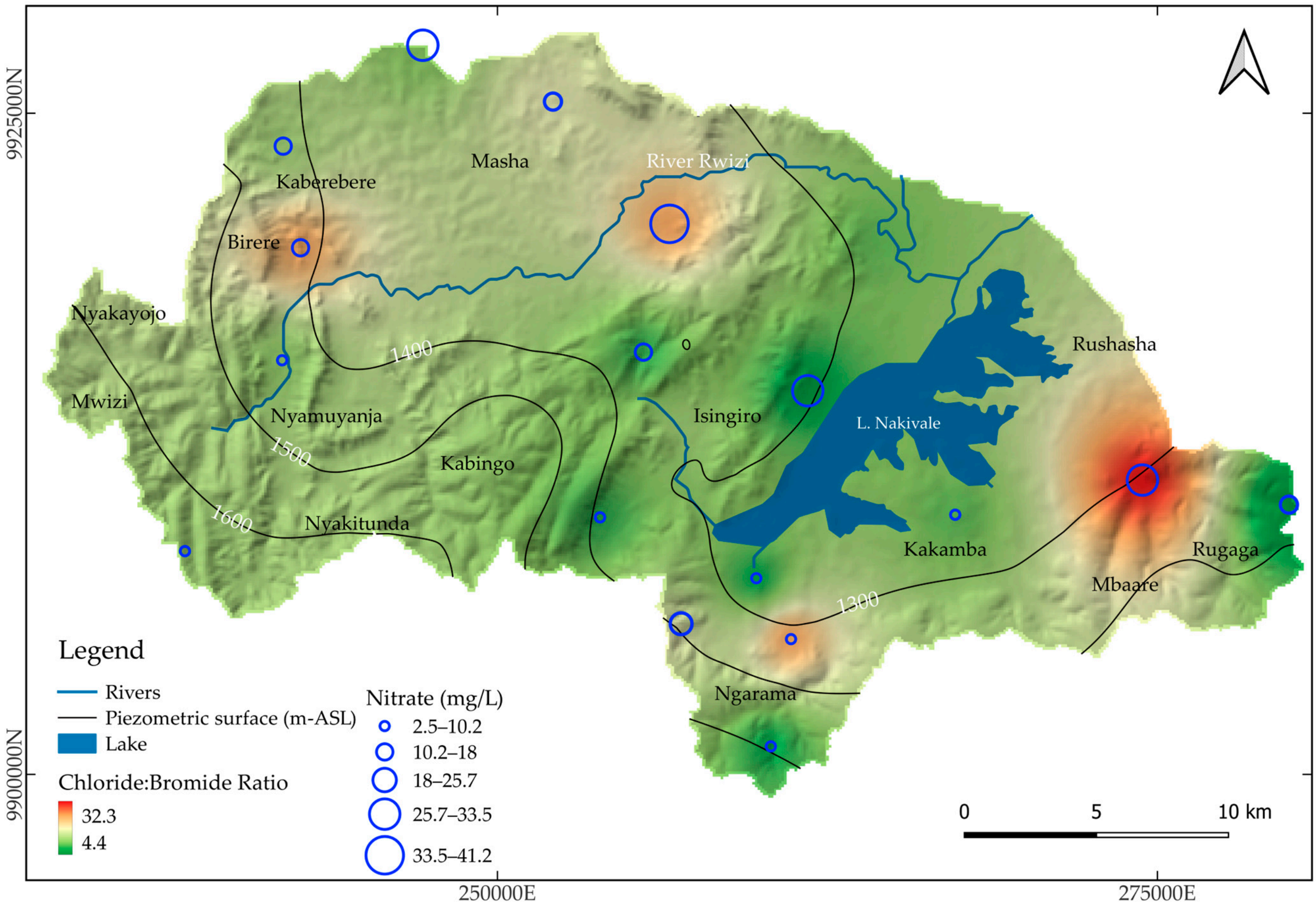

Figure 6. Chloride–bromide ratio map for tracing sources of groundwater contamination.

To accurately differentiate between geogenic and anthropogenic influences, the Cl/Br ratio was analyzed alongside nitrate levels. This combined approach provides a more nuanced understanding of whether high Cl/Br ratios are due to natural processes or human activities [70]. Areas with high nitrate levels and elevated Cl/Br ratios likely indicate anthropogenic impacts on groundwater quality, possibly from nitrate-rich and chloride-rich wastes, respectively [70,72]. Nitrate concentrations vary from 2.5 to 41.2 mg/L, with higher levels linked to existing and emerging anthropogenic effects such as agricultural pollution, septic effluent, and industrial waste discharge [5]. This relationship is also evident in (Figure 7), where elevated nitrate levels correlate with built and farmland land use and land cover (LULC) classes. Furthermore, an increase in the Cl/Br ratio along groundwater flowlines suggests a systematic alteration in groundwater chemistry, potentially due to the preferential adsorption of bromide, which is larger than chloride ions [61].

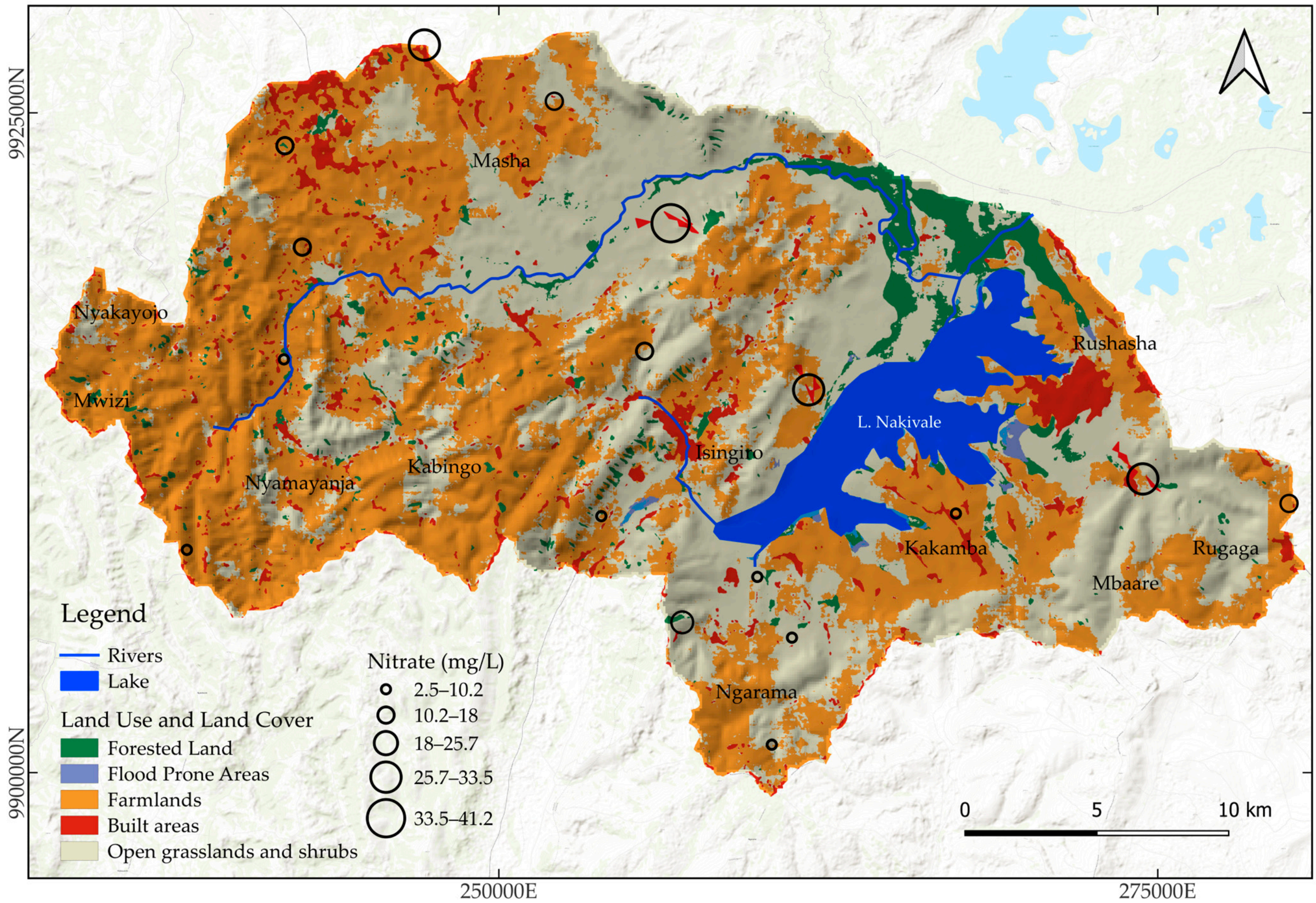

Figure 7. Land Use and Land Cover (LULC) map for Nakivale Sub-catchment (Data Source: FAO, 2024).

3.4. Irrigation Groundwater Quality Assessment

The analysis of the Sodium Adsorption Ratio (SAR) reveals that 94% of the samples fall within the C2-S1 (47%) and C3-S1 (47%) SAR-Electrical Conductivity regions (Figure 8). C2 and C3 indicate medium-to-high salinity hazards, respectively, while S1 reflects a low sodium (alkali) hazard. Despite the low sodium hazard, the results suggest that the region could face emerging issues with reduced crop productivity, driven by potential changes in the osmotic potential of crops if salinity levels increase, which could impede their growth [32,33,73]. One sample falls in the C2-S2 region, indicating medium sodium and salinity hazards, which also highlights the risk of lower crop productivity if sodium and salinity levels rise in the future [19,28].

According to the Sodium Percentage (SP), which measures sodium concentration relative to other cations [73], 74% of samples are within the Good range (20–40% SP); 16% are Permissible (40–60% SP), and 10% are Doubtful (60–80% SP) (Figure 9). While most samples fall in the Good range, indicating safe sodium levels, those in the Doubtful range may require managed irrigation to avoid long-term sodium accumulation in soils [73].

Kelly's Ratio (KR) assesses sodium risk relative to calcium and magnesium [28], with values less than 1 indicating Safe water (79% of samples) (Table S1) and those over 1 classified as Unsuitable (21% of samples) [31,73]. High KR values suggest an elevated sodium content, which could affect soil structure [28], leading to reduced permeability and increased runoff, impacting crop root zones [73].

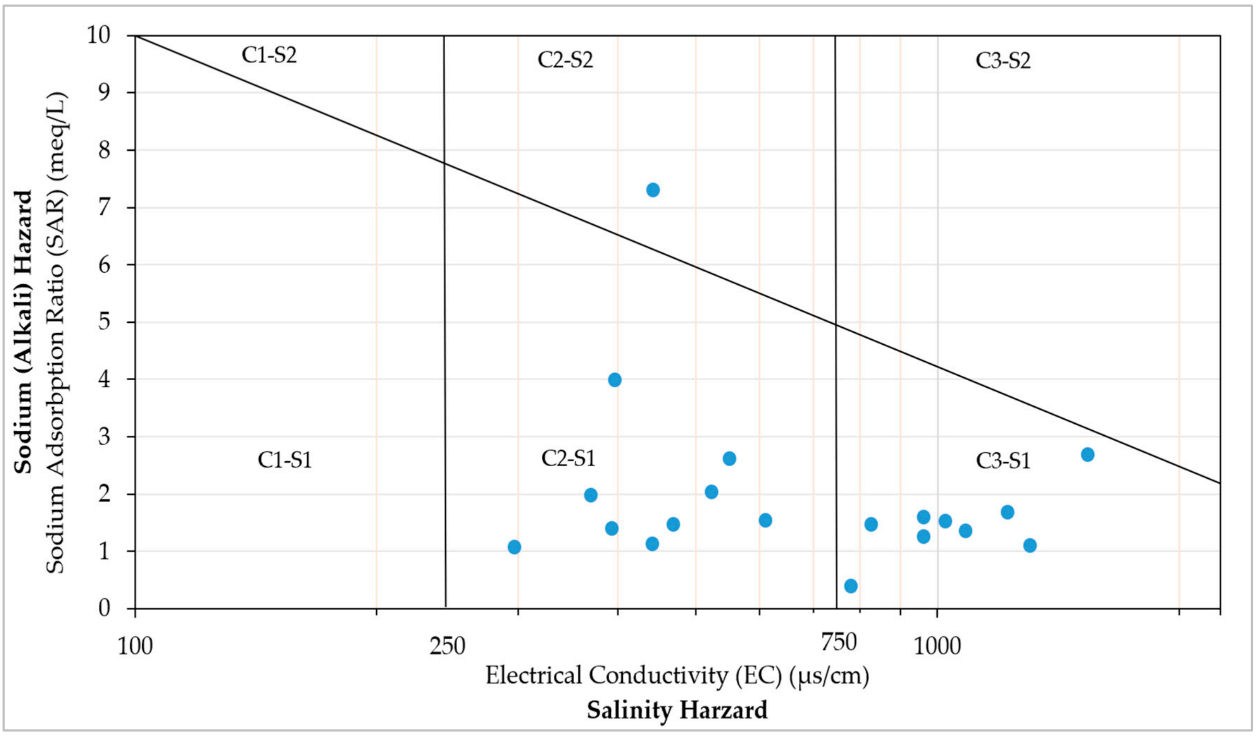

Figure 8. Sodium Adsorption Ratio (SAR) vs. Electrical Conductivity (EC) diagram for Classification of Irrigation water.

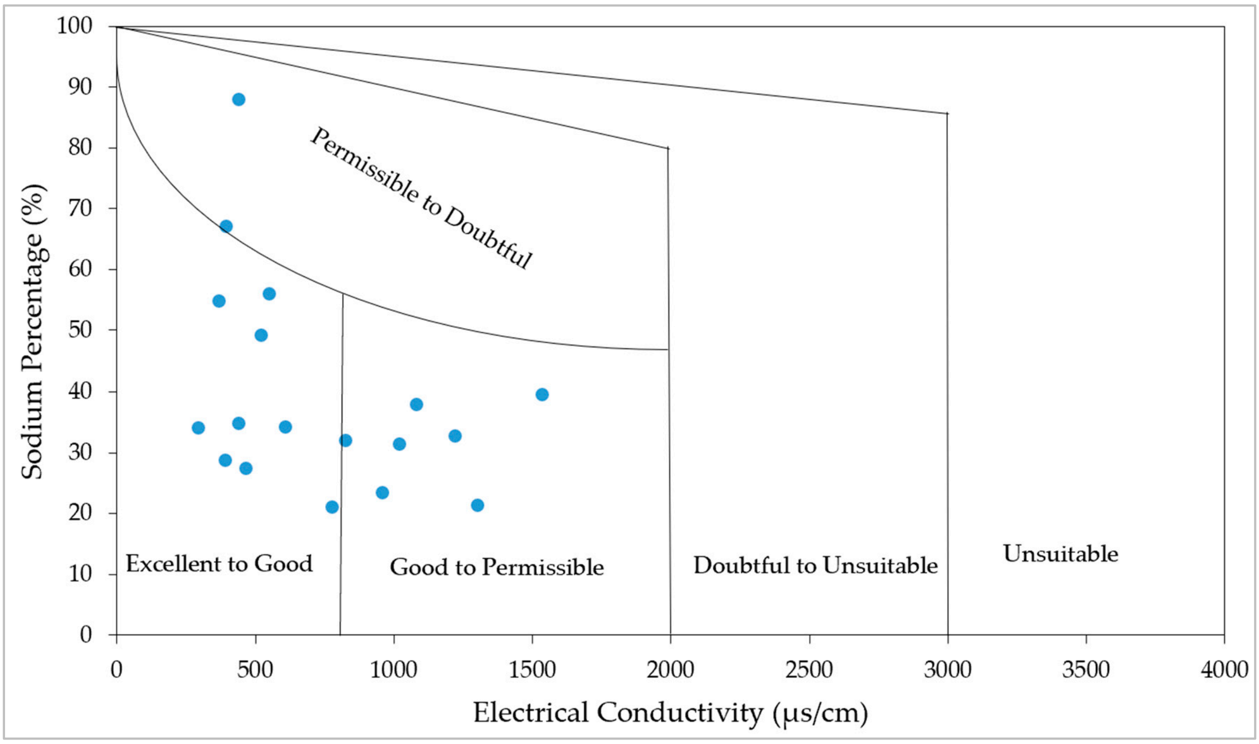

Figure 9. Sodium Percentage (SP) vs. Electrical Conductivity plot for classification of suitability of water for irrigation.

The Magnesium Adsorption Ratio (MAR) evaluates the dominance of magnesium, with values under 50% considered Suitable (89% of samples) (Table S1) and those above deemed Unsuitable (11% of samples) [25,28,73]. Excessive magnesium concentrations in Unsuitable samples may exacerbate soil alkalinity, potentially affecting nutrient availability to crops and, thereby, influencing plant health [28,31,73].

Residual Sodium Carbonate (RSC) measures the relative abundance of carbonate and bicarbonate over calcium and magnesium [28,31], with values of less than zero being Low (89% of samples), 0–1 being Medium (0%), 1–2.5 being High (11%), and above 2.5 being Very High (0%) (Table S1). The 11% of samples with High RSC levels suggest a potential risk for soil alkalinity issues, as excess carbonate may reduce soil permeability and lead to reduced crop productivity [31].

The overall groundwater quality for irrigation in the region shows low-to-moderate risks, with primary concerns centered around potential salinity hazards and isolated cases of high sodium and carbonate levels. This analysis supports the importance of consistent monitoring and management to address salinity and sodium hazards, as well as careful management and control of anthropogenic Na-rich chemical inputs, which may contribute to rising salinity and sodium levels in the region.

3.5. Groundwater Vulnerability Assessment

The seven DRASTIC model parameters influencing groundwater vulnerability, as suggested by [23], were evaluated to assess the susceptibility of groundwater resources within the Nakivale Sub-catchment to contamination from surface sources.

Depth-to-water table (D) varies spatially across the sub-catchment, ranging from 5 to 60 m [6]. Generally, shallower depths to aquifers are situated with lower elevation areas, increasing the potential for contamination. Given the low-to-moderately high depth to the aquifer window and the natural confining conditions, ratings were assigned between 3 and 6, with lower scores assigned to areas where the depth was greater, as deeper water tables offered greater protection from surface contamination [23].

Net recharge (R) within the sub-catchment is low, ranging between 50 and 100 mm/year [6]. This low recharge is attributed to the presence of low-permeability geological formations such as shales, slates, and phyllites, which restrict water infiltration except at structural weaknesses like joints and faults. A rating of 4 was assigned to areas with low recharge, while a slightly higher rating was given to areas near lineament features, where recharge and contamination potential were moderately elevated.

The aquifer media (A) primarily consists of fine-grained formations, such as shales, slates, and phyllites, which limit contaminant transport due to their low permeability (Figure 2). These formations were assigned a rating of 2. However, areas with surface lineament features, fractured and fluvial aquifer types, as identified in historical borehole drill reports, received a higher rating due to their enhanced permeability and vulnerability.

The area is primarily composed of clayey to silty soils, with smaller sandy sections near rivers and wetlands (Figure S2). The clay and silt offer some protection against contamination due to their fine texture, while sandy soils allow for quicker contaminant transport [47]. Consequently, ratings were set between 3 and 6, with higher ratings applied to sandy soils (Table 5).

Slopes range from 0 to 18% across the study area, with flat terrains (0–2%) receiving higher ratings (9–10) due to their increased susceptibility to infiltration (Figure S1). Conversely, steeper slopes were assigned lower ratings, as the risk of groundwater contamination decreased with increased runoff [23].

The vadose zone in Nakivale is primarily composed of impermeable formations like slates and phyllites (Figure 2). These rocks significantly reduce contaminant transport unless fractured. Areas with fractured zones or lineament features received a higher rating of 3 due to their increased permeability and associated vulnerability.

Table 5. The DRASTIC parameters, their corresponding weights, index score intervals, and ratings used in the vulnerability assessment (adapted from [23]).

DRASTIC Factor	Weight	DRASTIC Factor Interval	Rate
1. Depth-to-water table (D)	5	<1.50 m	10
		1.50–4.50 m	9
		4.51–9.00 m	7
		9.01–15.00 m	5
		15.01–22.50 m	4
		22.51–30.00 m	3
		30.01–50.00 m	2
		>50.00 m	1
2. Net Recharge (R)	4	<30.00 mm/year	1
		30.01–50.00 mm/year	2
		50.01–70.00 mm/year	4
		70.01–90.00 mm/year	5
		>90.00 mm/year	6
3. Aquifer Media (A)	3	Shales, slates, phyllites	2
		Fractured bedrock (crystalline rocks)	4
4. Soil Media (S)	2	Clay	3
		Silt	4
		Loam	5
		Sand	6
5. Topography (Slope) (T)	1	<2.00%	10
		2.01–6.00%	9
		6.01–12.00%	5
		12.01–18.00%	3
		>18.00%	1
6. Impact of Vadose Zone (I)	5	Sedimentary and metasedimentary (Shales, slates, phyllites)	3
7. Hydraulic Conductivity (C)	3	<0.050 m/day	1
		0.051–0.100 m/day	2
		0.101–0.500 m/day	3
		0.501–1.000 m/day	4
		1.001–10.000 m/day	7
		>10.000 m/day	8

The hydraulic conductivity varies spatially across the project area and inherent hydrogeological domains. According to [6], the fracture domain possesses a hydraulic conductivity of 1.7×10^{-2} m/day, and the matrix domain possesses a much lower value of 1.4×10^{-7} m/day. Due to this variability, areas within the fracture domain were given higher scores (2), reflecting a higher potential for contaminant transport, while a lower score (1) was assigned to matrix-dominated areas.

This assessment reveals low DRASTIC indices for the Nakivale Sub-catchment (<110) (Table S3). These low values generally indicate a reduced risk of groundwater contamination from surface sources [23,37–39]. This is primarily due to the area's varied steep slopes, moderately thick vadose zone, clayey soils, and the presence of impervious shales, slates, and phyllites, which cover over 90% of the region, consequently impacting groundwater recharge (Figure 1).

Groundwater vulnerability varies across the sub-catchment, with different areas exhibiting distinct levels of susceptibility (Figure 10). Birere, Nyamuyanja, Mwizi, and Kakamba have very low vulnerability, attributed to protective geological and soil characteristics. In contrast, Masha and Rugaga demonstrate moderate vulnerability, driven by factors such as slightly more permeable soils, a thin vadose zone, a relatively flat landscape, and shallow groundwater depths, all of which facilitate contaminant infiltration into underlying aquifers [23]. Kabingo, Ngarama, and parts of Kaberebere exhibit moderately low vulnerability, balancing protective and risk-enhancing characteristics.

The DRASTIC model results were validated by overlaying nitrate concentration data onto the groundwater vulnerability map (Figure 10). This overlay revealed that areas with high nitrate concentrations tended to correspond with regions of greater groundwater susceptibility compared to those with lower contamination risks. It is important to note that while there is a correlation between groundwater vulnerability and nitrate levels, nitrate concentrations remain below the WHO guideline value (50 mg/L) overall, which highlights the limited vulnerability of groundwater resources to surface contaminants. This resilience is due to protective hydrogeological conditions within the area. However, it is also prudent to note that the DRASTIC model may not directly identify areas with groundwater contamination issues but, instead, provides insights into the spatial vulnerability of groundwater resources across the study area based on inherent hydrogeological conditions [23,24,37,38,42].

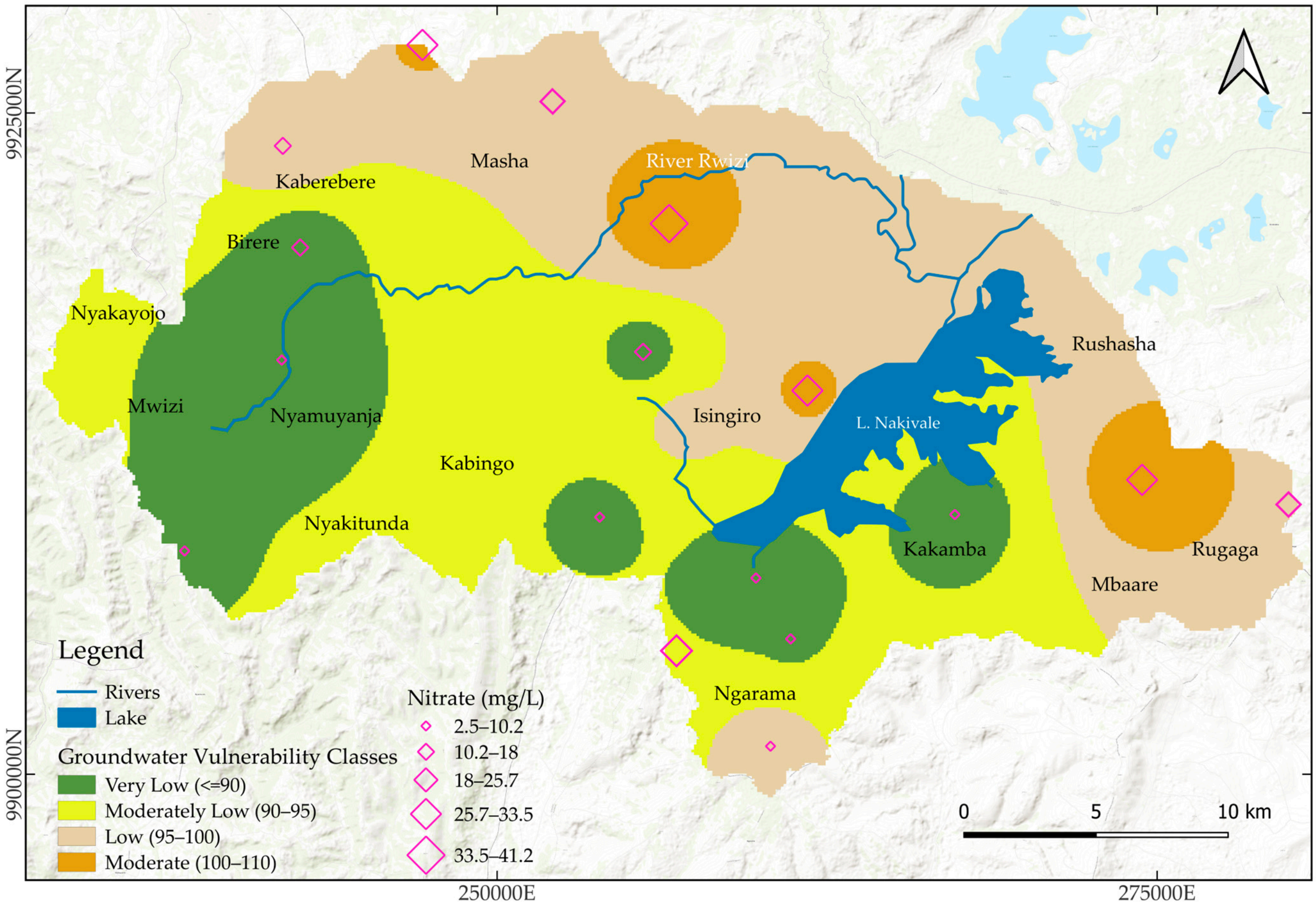

Figure 10. Groundwater Vulnerability DRASTIC Index map for Nakivale Sub-catchment.

4. Conclusions and Recommendations

4.1. Conclusions

This study assessed the groundwater quality and vulnerability in the Nakivale Sub-catchment, Southwestern Uganda, using a combination of hydrochemical analysis, groundwater quality indices, irrigation suitability parameters, and the DRASTIC groundwater vulnerability model. The results indicate that the majority of groundwater samples exhibit good-to-excellent water quality, with more than 90% of the samples falling below the groundwater quality index (GWQI) threshold of 100, suggesting generally safe drinking water. However, two samples showed high GWQI values (above 200), primarily due to elevated concentrations of total iron and other ions (Mg^{2+}, K^+, and $SO_4{}^{2-}$). These elevated iron levels are potentially linked to localized anthropogenic contamination, particularly from the use of galvanized iron pipes in handpump boreholes.

The hydrochemical analysis revealed some localized contamination concerns, particularly elevated concentrations of iron, magnesium, potassium, and sulfate in certain areas, which may impact water aesthetics and usability. In addition, the chloride–bromide (Cl/Br) ratio analysis revealed potential anthropogenic influences, especially in regions with agricultural or industrial activities. Nitrate concentrations, while within WHO limits, showed correlations with land use activities, further suggesting anthropogenic contributions to groundwater quality in specific zones.

From an irrigation perspective, the groundwater in the region generally falls within safe ranges for sodium and salinity hazards, though emerging salinity risks and localized sodium issues were identified in a few samples. The Sodium Adsorption Ratio (SAR) and related irrigation quality parameters, including Sodium Percentage (SP) and Kelly's Ratio (KR), suggest that while most of the groundwater is suitable for irrigation, certain areas may require careful management to avoid long-term soil degradation. Additionally, elevated carbonate concentrations in some areas point to the potential for increased soil alkalinity, which could affect agricultural productivity.

The DRASTIC model, used to assess groundwater vulnerability, revealed low vulnerability indices for the Nakivale Sub-catchment, reflecting the protective geological and hydrogeological conditions, such as clayey soils and impermeable formations (shales, slates, and phyllites). However, areas with shallower groundwater tables and more permeable soils, such as Masha and Rugaga, were identified as having moderate vulnerability. The validation of the DRASTIC model with nitrate concentration data highlighted that regions with higher nitrate levels correspond to areas with greater groundwater vulnerability, although nitrate concentrations remained below the WHO guideline value, indicating limited contamination from surface sources.

Overall, the groundwater resources in the Nakivale Sub-catchment provide safe drinking water for the majority of the population, with localized concerns related to specific contaminants, primarily iron and magnesium. While the area demonstrates resilience to surface contamination, there is a need for ongoing monitoring to address potential emerging issues, particularly with respect to salinity, sodium, and carbonate levels. This study underscores the importance of sustainable groundwater management, particularly in areas with anthropogenic influences, to ensure long-term water quality and safeguard agricultural productivity in the region.

4.2. Policy Recommendations

The findings of this research highlight the need for conjunctive management of groundwater resources in the Nakivale Sub-catchment area. Below are policy recommendations to ensure the sustainable management of groundwater resources within the study area:

- The elevated concentrations of total iron in localized areas of the Nakivale Sub-catchment highlight the importance of regulating anthropogenic contaminants, particularly from infrastructure such as galvanized iron pipes commonly used in handpump boreholes. Policies should be introduced to mandate the use of corrosion-resistant and non-reactive materials for water infrastructure. This will reduce the release of metals like iron into groundwater, enhancing drinking water quality. Additionally, there should be a focused effort to assess and minimize the impact of industrial waste, particularly from agricultural and industrial practices, which contribute to the contamination of groundwater;
- To ensure the ongoing safety and sustainability of groundwater resources, a robust monitoring and surveillance system should be established. Regular testing of water quality parameters, such as heavy metals (including iron), major ions, and microbial contaminants, is critical. The data gathered would not only inform public health interventions but also guide future management practices. Areas identified with higher concentrations of contaminants should be prioritized for more frequent testing, and local authorities should be trained to interpret and act on water quality data promptly;

- The findings underscore the role of agricultural activities in groundwater contamination, particularly through nitrate pollution. Policies should focus on encouraging sustainable farming practices, such as the adoption of organic fertilizers, efficient irrigation techniques, and integrated pest management strategies. Additionally, farmers should be educated on the importance of reducing the use of chemical fertilizers and pesticides to prevent nutrient leaching into groundwater. Financial incentives or subsidies for environmentally friendly practices could also support the transition to sustainable agriculture;
- Given the identified risks related to salinity, especially in areas falling within the C2-S1 and C3-S1 regions, it is important to implement comprehensive irrigation management plans. These should include guidelines for optimizing water use and minimizing salinity buildup. Policies can promote the use of salt-tolerant crop varieties, the application of soil conditioners, and techniques like drip irrigation to reduce water wastage and prevent salinization of soil. Training and extension services for farmers in these areas are crucial for ensuring that these practices are adopted effectively;
- Based on the vulnerability assessment using the DRASTIC model, regions with shallow water tables, low permeability, and high recharge rates should be designated as groundwater protection zones. Within these zones, stricter land-use regulations should be enforced to limit activities that could introduce contaminants into the groundwater system, such as industrial waste disposal, large-scale agricultural runoff, and urban expansion. These zones should be monitored closely to ensure compliance with environmental protection standards and prevent any activities that could compromise groundwater quality;
- Lastly, there should be an integrated approach to water quality management that combines local, regional, and national policies. Public awareness campaigns are essential to educating communities about the importance of protecting groundwater resources and the risks posed by poor land-use practices, over-extraction, and contamination. Local stakeholders, including community leaders, farmers, and water managers, should be involved in decision-making processes to ensure policies are context-specific and effectively address local needs.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/w16233386/s1, Figure S1: Spatial variation in topographical slope within Nakivale Sub-catchment; Figure S2: Soil texture within Nakivale Sub-catchment, Southwestern Uganda; Table S1: Calculated Irrigation groundwater quality indices each groundwater sample; Table S2: Computed groundwater quality sub-index for each hydrochemical parameter and overall groundwater quality index (GWQI) for each sample; Table S3: Assigned weights and ratings for each respective parameter within the applied DRASTIC aquifer vulnerability assessment model; Table S4: Estimated Change Balance Error (CBE) for each sample.

Author Contributions: Conceptualization, E.N.H. and R.M.K.; methodology, E.N.H. and R.M.K.; software, E.N.H.; validation, E.N.H. and R.M.K.; formal analysis, E.N.H. and R.M.K.; investigation, E.N.H.; resources, E.N.H. and R.M.K.; data curation, E.N.H. and R.M.K.; writing—original draft preparation, E.N.H.; writing—review and editing, E.N.H. and R.M.K.; visualization, E.N.H.; supervision, R.M.K.; project administration, E.N.H.; funding acquisition, E.N.H. and R.M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the International Atomic Energy Agency (IAEA) through the RAF7021 project in collaboration with Uganda's Ministry of Water and Environment. This study was carried out during a fellowship (Code: EVT2304936-0001-UGA) at the University of Strathclyde in the United Kingdom, spanning from 9 October 2023 to 8 November 2024.

Data Availability Statement: The data utilized in this research are available upon request from the corresponding authors.

Acknowledgments: The authors gratefully acknowledge IAEA TC Project RAF7021 for the invaluable financial support extended throughout all stages of the project's implementation. The authors are also thankful for the financial support of the Scottish Government under the Climate Justice Fund Water Futures Program (research grant HN-CJF-03), awarded to the University of Strathclyde (R.M. Kalin PI).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. United Nations Environment Programme. Goal 6: Clean Water and Sanitation [Internet]. 2024. Available online: https://www.unep.org/explore-topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-6 (accessed on 2 September 2024).
2. African Union. *The African Union Commission Agenda 2063 Framework Document*; African Union: Addis Ababa, Ethiopia, 2015; pp. 1–172.
3. de Lázaro Torres, M.L.; Borderias Uribeondo, P.; Morales Yago, F.J. Citizen and educational initiatives to support Sustainable Development Goal 6: Clean water and sanitation for all. *Sustainability* **2020**, *12*, 2073. [CrossRef]
4. Cai, J.; Zhao, D.; Varis, O. Match words with deeds: Curbing water risk with the Sustainable Development Goal 6 index. *J. Clean. Prod.* **2021**, *318*, 128509. [CrossRef]
5. Ministry of Water and Environment. *Rwizi Catchment Management Plan*; Ministry of Water and Environment: Kampala, Uganda, 2020.
6. Ministry of Water and Environment. *Baseline Groundwater Resources Assessment Report: National Groundwater Study*; Ministry of Water and Environment: Kampala, Uganda, 2022.
7. Adonia, K.; Kakurungu, B. Assessment of the effects of changing land use from pastoralism to crop farming on Lake Nakivale wetland system in Isingiro District, Uganda. *J. Afr. Stud.* **2014**, *6*, 56–66. [CrossRef]
8. Nanfuka, S.; Mfitumukiza, D.; Egeru, A. Characterisation of ecosystem-based adaptations to drought in the central cattle corridor of Uganda. *Afr. J. Range Forage Sci.* **2020**, *37*, 257–267. [CrossRef]
9. Ronald, M.A. An assessment of economic and environmental impacts of refugees in Nakivale, Uganda. *Migr. Dev.* **2022**, *11*, 433–449. [CrossRef]
10. Uganda Bureau of Statistics. Census Population Counts (2002 and 2014) by Region, District, and Mid-Year Population Projections (2015–2021) [Internet]. 2023. Available online: https://www.ubos.org/explore-statistics/20/ (accessed on 7 September 2024).
11. Aturihaihi, C.; Tumwesigye, W.; Opio, F.; Beyihayo, G.A. Knowledge, Attitude and the Practice of Climate-Smart Agriculture among Smallholder Farmers in Isingiro District, South Western Uganda. *East Afr. J. Agric. Biotechnol.* **2023**, *6*, 82–97. [CrossRef]
12. Bjørkhaug, I. Revisiting the refugee–host relationship in Nakivale Refugee Settlement: A dialogue with the Oxford Refugee Studies Centre. *J. Migr. Hum. Secur.* **2020**, *8*, 266–281. [CrossRef]
13. Ministry of Water and Environment. *National Water Resources Assessment Report*; Ministry of Water and Environment: Kampala, Uganda, 2013.
14. Chenini, I.; Zghibi, A.; Kouzana, L. Hydrogeological investigations and groundwater vulnerability assessment and mapping for groundwater resource protection and management: State of the art and a case study. *J. Afr. Earth Sci.* **2015**, *109*, 11–26. [CrossRef]
15. Owor, M.; Muwanga, A.; Tindimugaya, C.; Taylor, R.G. Hydrogeochemical processes in groundwater in Uganda: A national-scale analysis. *J. Afr. Earth Sci.* **2021**, *175*, 104113. [CrossRef]
16. Nabala, E.H. Hydrochemical and Isotopic Characterisation of Groundwater Resources in Nakivale Sub-Catchment in Isingiro District, Southwestern Uganda. Master's Thesis, University of Strathclyde, Glasgow, UK, 2024.
17. Songa, P.; Rumohr, J.; Musota, R. A shared water risk assessment for a vulnerable river basin: River Rwizi in Uganda. *WIT Trans. Ecol. Environ.* **2015**, *197*, 213–224.
18. Nimusiima, D.; Byamugisha, D.; Omara, T.; Ntambi, E. Physicochemical and microbial quality of water from the Ugandan stretch of the Kagera Transboundary River. *Limnol. Rev.* **2023**, *23*, 157–176. [CrossRef]
19. Walter, O.; Wasswa, J.; Nakiguli, C.K.; Ntambi, E. *Spatial Variation in Physicochemical Surface Water Quality in River Rwizi, Western Uganda*; Mbarara University of Science & Technology: Kampala, Uganda, 2019.
20. Chatterjee, R.; Ray, R.K. A proposed new approach for groundwater resources assessment in India. *J. Geol. Soc. India* **2016**, *88*, 357–365. [CrossRef]
21. Rojas, R.; Commander, P.; McFarlane, D.; Ali, R.; Dawes, W.; Barron, O.; Hodgson, G.; Charles, S. Groundwater resource assessment and conceptualization in the Pilbara Region, Western Australia. *Earth Syst. Environ.* **2018**, *2*, 345–365. [CrossRef]
22. Lions, J.; Devau, N.; Elster, D.; Voutchkova, D.D.; Hansen, B.; Schullehner, J.; Petrović Pantić, T.; Samolov, K.A.; Camps, V.; Arnó, G.; et al. A broad-scale method for estimating natural background levels of dissolved components in groundwater based on lithology and anthropogenic pressure. *Water* **2021**, *13*, 1531. [CrossRef]
23. Aller, L. *Thornhill JDRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*; Robert, S., Ed.; Kerr Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency: Ada, OK, USA, 1987.
24. Tufano, R.; Allocca, V.; Coda, S.; Cusano, D.; Fusco, F.; Nicodemo, F.; Pizzolante, A.; De Vita, P. Groundwater vulnerability of principal aquifers of the Campania region (southern Italy). *J. Maps* **2020**, *16*, 565–576. [CrossRef]

25. Ibrahim, M.N. Assessing groundwater quality for drinking purpose in Jordan: Application of water quality index. *J. Ecol. Eng.* **2019**, *20*, 101–111. [CrossRef]
26. Balan, I.; Shivakumar, M.; Kumar, P.M. An assessment of groundwater quality using water quality index in Chennai, Tamil Nadu, India. *Chron. Young Sci.* **2012**, *3*, 146. [CrossRef]
27. Alqarawy, A.; El Osta, M.; Masoud, M.; Elsayed, S.; Gad, M. Use of hyperspectral reflectance and water quality indices to assess groundwater quality for drinking in arid regions, Saudi Arabia. *Water* **2022**, *14*, 2311. [CrossRef]
28. Vranešević, M.; Zemunac, R.; Grabić, J.; Salvai, A. Hydrochemical Characteristics and Suitability Assessment of Groundwater Quality for Irrigation. *Appl. Sci.* **2024**, *14*, 615. [CrossRef]
29. Ketata, M.; Gueddari, M.; Bouhlila, R. Use of geographical information system and water quality index to assess groundwater quality in El Khairat deep aquifer (Enfidha, Central East Tunisia). *Arab. J. Geosci.* **2012**, *5*, 1379–1390. [CrossRef]
30. Shuaibu, A.; Kalin, R.M.; Phoenix, V.; Banda, L.C.; Lawal, I.M. Hydrogeochemistry and water quality index for groundwater sustainability in the Komadugu-Yobe Basin, Sahel Region. *Water* **2024**, *16*, 601. [CrossRef]
31. El Osta, M.; Masoud, M.; Alqarawy, A.; Elsayed, S.; Gad, M. Groundwater suitability for drinking and irrigation using water quality indices and multivariate modeling in makkah Al-Mukarramah province, Saudi Arabia. *Water* **2022**, *14*, 483. [CrossRef]
32. Worwornyo, S.K. *Assessment of Groundwater Quality and Its Suitability for Domestic and Agricultural Purposes in the North-Western Part of the Central Region, Ghana*; University of Ghana: Accra, Ghana, 2014.
33. Alogayell, H.M.; EL-Bana, E.M.M.; Abdelfattah, M. Groundwater Quality and Suitability Assessment for Irrigation Using Hydrogeochemical Characteristics and Pollution Indices: A Case Study of North Al-Quwayiyah Governorate, Central Saudi Arabia. *Water* **2023**, *15*, 3321. [CrossRef]
34. Gonçalves, V.; Albuquerque, A.; Carvalho, P.; Almeida, P.; Cavaleiro, V. Groundwater Vulnerability Assessment to Cemeteries Pollution through GIS-Based DRASTIC Index. *Water* **2023**, *2023*, 812. [CrossRef]
35. Recinos, N.; Kallioras, A.; Pliakas, F.; Schuth, C. Application of GALDIT index to assess the intrinsic vulnerability to seawater intrusion of coastal granular aquifers. *Environ. Earth Sci.* **2015**, *73*, 1017–1032. [CrossRef]
36. Markus, U.I.; Ilori, O.P.; Wada, I.M.; Musa, S.T.; Peter, J.E. Hydrogeochemical evaluation and geospatial distribution modeling of the major ion chemistry of groundwater and their suitability for drinking and irrigation in Lagelu, Southwestern Nigeria. *Appl. Water Sci.* **2022**, *12*, 160. [CrossRef]
37. Abu-Bakr, H.A.E.A. Groundwater vulnerability assessment in different types of aquifers. *Agric. Water Manag.* **2020**, *240*, 106275. [CrossRef]
38. Barbulescu, A. Assessing groundwater vulnerability: DRASTIC and DRASTIC-like methods: A review. *Water* **2020**, *12*, 1356. [CrossRef]
39. Malakootian, M.; Nozari, M. GIS-based DRASTIC and composite DRASTIC indices for assessing groundwater vulnerability in the Baghin aquifer, Kerman, Iran. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 2351–2363. [CrossRef]
40. Pisciotta, A.; Suozzi, E.; Tiwari, A.K. A modified GALDIT-NUTS index to assess Favignana Island aquifer vulnerability. *Geocarto Int.* **2022**, *37*, 11706–11731. [CrossRef]
41. Kaddour, K.; El Hacen, B.; Hlima, D.; Yasmina, D. Groundwater vulnerability assessment using GOD method in Boulimat coastal District of Bejaia area North east Algeria. *J. Biodivers. Environ. Sci.* **2018**, *13*, 109–116.
42. El Osta, M.; Niyazi, B.; Masoud, M. Groundwater evolution and vulnerability in semi-arid regions using modeling and GIS tools for sustainable development: Case study of Wadi Fatimah, Saudi Arabia. *Environ. Earth Sci.* **2022**, *81*, 248. [CrossRef]
43. Stheeman, H.A.; Stheeman, H.A. Various Phases of Folding-Nature of Contact-Manner of Intrusion. In *The Geology of Southwestern Uganda: With Special Reference to the Stanniferous Deposits*; Springer: Berlin/Heidelberg, Germany, 1932; pp. 53–64.
44. Tindimugaya, C. *Groundwater Flow and Storage in Weathered Crystalline Rock Acquifer Systems of Uganda: Evidence from Environmental Tracers and Acquifer Responses to Hydraulic Stress*; UCL (University College London): London, UK, 2008.
45. Taylor, R.G.; Howard, K.W.F. Post-Palaeozoic evolution of weathered landsurfaces in Uganda by tectonically controlled deep weathering and stripping. *Geomorphology* **1998**, *25*, 173–192. [CrossRef]
46. Kohno, M. Effects of hydraulic gradient and clay type on permeability of clay mineral materials. *Minerals* **2020**, *10*, 1064. [CrossRef]
47. Boynton, S.S.; Daniel, D.E. Hydraulic conductivity tests on compacted clay. *J. Geotech. Eng.* **1985**, *111*, 465–478. [CrossRef]
48. Toma, V.E.; Webster, P.J. Oscillations of the intertropical convergence zone and the genesis of easterly waves. Part I: Diagnostics and theory. *Clim. Dyn.* **2010**, *34*, 587–604. [CrossRef]
49. Riedel, T.; Weber, T.K. The influence of global change on Europe's water cycle and groundwater recharge. *Hydrogeol. J.* **2020**, *28*, 1939–1959. [CrossRef]
50. Bui, A.; Johnson, F.; Wasko, C. The relationship of atmospheric air temperature and dew point temperature to extreme rainfall. *Environ. Res. Lett.* **2019**, *14*, 74025. [CrossRef]
51. Vicente-Serrano, S.M.; McVicar, T.R.; Miralles, D.G.; Yang, Y.; Tomas-Burguera, M. Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change. *Wiley Interdiscip. Rev. Clim. Change* **2020**, *11*, e632. [CrossRef]
52. Conicelli, B.; Hirata, R.; Galvão, P.; Bernardino, M.; Simonato, M.; Abreu, M.C.; Aranda, N.; Terada, R. Determining groundwater availability and aquifer recharge using GIS in a highly urbanized watershed. *J. S. Am. Earth Sci.* **2021**, *106*, 103093. [CrossRef]
53. Montaser, A.; Golightly, D.W. (Eds.) *Inductively Coupled Plasmas in Analytical Atomic Spectrometry*; John Wiley & Sons: Hoboken, NJ, USA, 1996.

54. Fritz, S.J. A survey of charge-balance errors on published analyses of potable ground and surface waters. *Groundwater* **1994**, *32*, 539–546. [CrossRef]
55. Lu, G.Y.; Wong, D.W. An adaptive inverse-distance weighting spatial interpolation technique. *Comput. Geosci.* **2008**, *34*, 1044–1055. [CrossRef]
56. Mahalingam, B.R.M.D.B.; Bhauso, R.; Deepali, M.; Jayashree, P. Assessment of groundwater quality using GIS techniques: A case study of Mysore City. *Int. J. Eng. Innov. Technol.* **2014**, *3*, 117–122.
57. Gorantla, S.S.; Pradeep Kumar, G.N. Spatial distribution of groundwater quality indices using decision support system in Cheyyeru Watershed, YSR District, India. *Spat. Inf. Res.* **2021**, *29*, 297–307. [CrossRef]
58. Maurya, P.K.; Ali, S.A.; Zaidi, S.K.; Wasi, S.; Tabrez, S.; Malav, L.C.; Ditthakit, P.; Son, C.T.; Cabral-Pinto, M.M.; Yadav, K.K. Assessment of groundwater geochemistry for drinking and irrigation suitability in Jaunpur district of Uttar Pradesh using GIS-based statistical inference. *Environ. Sci. Pollut. Res.* **2023**, *30*, 29407–29431. [CrossRef] [PubMed]
59. Hasan, M.; Shang, Y.; Akhter, G.; Jin, W. Evaluation of groundwater suitability for drinking and irrigation purposes in Toba Tek Singh District, Pakistan. *Irrig. Drain. Syst. Eng.* **2017**, *6*, 185.
60. Taherian, P.; Joodavi, A. Hydrogeochemical characteristics and source identification of salinity in groundwater resources in an arid plain, northeast of Iran: Implication for drinking and irrigation purposes. *Acque Sotter. Ital. J. Groundw.* **2021**, *10*, 21–31. [CrossRef]
61. Goldowitz, J. *The Chloride to Bromide Ratio as an Environmental Groundwater Tracer, with a Field Study at the Wellton-Mohawk Irrigation and Drainage District*; The University of Arizona: Tucson, AZ, USA, 1989.
62. Huang, C.C.; Yeh, H.F.; Lin, H.I.; Lee, S.T.; Hsu, K.C.; Lee, C.H. Groundwater recharge and exploitative potential zone mapping using GIS and GOD techniques. *Environ. Earth Sci.* **2013**, *68*, 267–280. [CrossRef]
63. Aizman, R.I.; Gerasev, A.D.; Aizman, O.; Krasheninina, G.I.; Trofimovich, E.M. Physiological and hygienic basis of potassium norm in drinking water: Theoretical and practical implications. *Novosib. State Pedagog. Univ. Bull.* **2018**, *8*, 266–284. [CrossRef]
64. Marx, A.; Neutra, R.R. Magnesium in drinking water and ischemic heart disease. *Epidemiol. Rev.* **1997**, *19*, 258–272. [CrossRef]
65. Liap, Z. *Environmental Chemistry of Trace Elements and Their Biological Effect*; Chinese Environmental Science Press: Beijing, China, 1992; p. 320.
66. Burlingame, G.A.; Dietrich, A.M.; Whelton, A.J. Understanding the basics of tap water taste. *J. Am. Water Work. Assoc.* **2007**, *99*, 100–111. [CrossRef]
67. Nagudi, B. *Status of Geological Resources in Uganda*; For the Embassy of the Republic of Korea in Uganda: Kampala, Uganda, 2011.
68. Glynn, P.D.; Plummer, L.N. Geochemistry and the understanding of ground-water systems. *Hydrogeol. J.* **2005**, *13*, 263–287. [CrossRef]
69. Andreasen, D.C.; Fleck, W.B. Use of bromide: Chloride ratios to differentiate potential sources of chloride in a shallow, unconfined aquifer affected by brackish-water intrusion. *Hydrogeol. J.* **1997**, *5*, 17–26. [CrossRef]
70. Ratri, D.; Putra, D.P.E.; Wilopo, W. Nitrate source detection using nitrate/chloride ratios and chloride/bromide ratios in shallow groundwater, Bantul. In *AIP Conference Proceedings*; AIP Publishing: Yogyakarta, Indonesia, 2023; Volume 2598.
71. Katz, B.G.; Eberts, S.M.; Kauffman, L.J. Using Cl/Br ratios and other indicators to assess potential impacts on groundwater quality from septic systems: A review and examples from principal aquifers in the United States. *J. Hydrol.* **2011**, *397*, 151–166. [CrossRef]
72. Hudak, P.F. Chloride/bromide ratios in leachate derived from farm-animal waste. *Environ. Pollut.* **2003**, *121*, 23–25. [CrossRef]
73. Amwele, H.R.; Kgabi, N.A.; Kandjibi, L.I. Sustainability of groundwater for irrigation purposes in semi-arid parts of Namibia. *Front. Water* **2021**, *3*, 767496. [CrossRef]