Asia Pacific
Academy of Science Pte. Ltd.

Sustainable Social Development 2024, 2(1), 2344.
https://doi.org/10.54517/ssd.v2i1.2344

Article

Geological and hydro-chemical characterisations of groundwater resources in the Wa municipal district

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CITATION

Bukari FIM, Ziblim SD, Aabeyir R. Geological and hydro-chemical characterisations of groundwater resources in the Wa municipal district. Sustainable Social Development. 2024; 2(1): 2344. https://doi.org/10.54517/ssd.v2i1.2344

ARTICLE INFO

Received: 20 October 2023
Accepted: 17 November 2023
Available online: 30 January 2024

Abstract: Few studies go beyond one or two parameters of groundwater characterisation at a time. This paper uses a multifaceted approach to describe the nature of groundwater beyond water quality, including the physical, environmental, and practical aspects of groundwater prospecting, the health effects, and how these conform to expected standards in global and national contexts. This was achieved by exploring the geological and hydrochemical characterisations of groundwater in the Wa municipality of Ghana. The main objective was to describe the spatial, hydro-geological, and hydro-chemical characteristics of groundwater in the rural areas of the Wa municipality. Using a sequential exploratory mixed research design and a digital elevation model, this study found that groundwater constitutes the main source of safe drinking water for rural and peri-urban communities, geologically dominated by granite and sandstone aquifers. The average transmissivity was 8.88 m^2/day, the average hydraulic conductivity was 0.18 m/day, the average aquifer thickness was 56.8 mbgl, and the average borehole water yield was 14.54 L/min. However, there were technological constraints on the ability to prospect water from confined aquifers at sites in the higher parts of the digital elevation model. Also, a lack of water quality tests for some boreholes results in the exposure of users to the effects of fluoride, causing dental fluorosis. The use of ultra-deep hand pump technologies, water quality testing of all boreholes, and artificial groundwater recharge methods for sustainable borehole water yield were recommended.

Keywords: characterisation; geology; groundwater; hydrology; Wa municipal; water quality

1. Background of the study

Groundwater is a resource hidden in the rocks of the earth's crust [1]. It is formed by natural and artificial means [2]. Naturally, rainwater infiltrates into the soil and surface water bodies such as rivers and lakes, and part of it is absorbed into underground water-bearing rocks, known as aquifers. In areas with inadequate surface water, the natural groundwater recharge cannot be balanced [3], so artificial recharge is used by spreading excess water on the surface of the earth or using recharge wells to increase infiltration to replenish an aquifer [4].

Groundwater is exploited from springs and wells, provides 30% to 50% of global water needs, and is consumed directly as safe drinking water [5]. In developing countries, groundwater accounts for 95% to 100% of potable water supplies [6]. Other important aspects of groundwater include provisioning services, by which groundwater is used for various human needs such as agriculture, industry, and domestic uses; regulatory services, involving the ability of aquifers to regulate the quantity and quality of groundwater systems; supporting services, through which the needs of groundwater-dependent aquatic and terrestrial ecosystems are met; and cultural services, associated with the leisure, traditional, and spiritual properties of groundwater [7]. In areas where human activities pollute surface water to lose its quality for most domestic uses, the demand for groundwater is a necessity [8]. These are the reasons why characterisation of groundwater is imperative for the purpose of planning its effective use.

Several studies have been conducted on the characterisation of groundwater. For example, Gorai and Kumar [9] conducted a study on the characterisation of groundwater at Ranchi in India. However, they focused only on spatial distribution analysis of the groundwater quality index. Bodrud-Doza et al. [10] also conducted a study on groundwater in Bangladesh, but their study was narrowed to the characterisation of groundwater quality using various evaluation indices. In Ghana, Okofo et al. [11] and Manu et al. [12] concerned themselves with the hydrogeochemical characterisation of groundwater in the 'Tamnean' plutonic suite aquifers in the Garu-Tempane District of the Upper East Region and the Pra Basin, respectively. However, these studies were based on the rigorous geodesy of rocks and their chemical and water-holding properties.

From the above, apart from the spatial gap of non-coverage of the Wa municipality in the literature on groundwater, most studies on the characterisation of groundwater focus on the geology and water quality characteristics. But ordinarily, characterisation is about the description of the distinctive features of something [13]. Accordingly, this paper describes the nature of groundwater beyond water quality by incorporating the physical, environmental, and practical aspects of groundwater prospecting and how these conform to expected standards in global and national contexts.

Spatially, the focus is on features of the study phenomenon related to the geographic location or study area [14], that is, the Wa municipality. This study therefore investigated the groundwater situation in terms of its distinctive attributes in the study area. Geologically, groundwater is found in aquifers and sediments, and the more porous the rocks of an aquifer, the higher the capacity to store groundwater [15]. The nature of the bedrock and soil types and the relationship between these and groundwater were of interest in this study. For instance, in a study of the Qaidam Basin of Northwest China, Zhang et al. [16] found that areas with high groundwater holding capacities had sandstone, slates, coarse sand, and sandy clayey soils, with the water emanating from the fissures of their bedrocks. Kesse [17], cited in Asante-Annor and Ewusi [8], also found that in the Adansi mining area of Ghana, the Birimian and Tarkwaian bedrocks are common and have high water storage capacity, which may flow through the rock fractures and bedding patterns. However, these studies did not go beyond geological and hydrochemical characterisations to include issues of drilling success rates and operation outcomes associated with groundwater infrastructure.

Research findings on the characterisation of subsurface geological layers and their influence on groundwater supply are essential in planning for the promotion of water security [18]. In general, whereas mainstream literature is replete with information on the spatial, geological, and physicochemical aspects of groundwater, such findings are usually focused on some specific distinctive feature, such as geology or water quality. This leaves a research niche for multifaceted analysis of groundwater prospecting and use, for a detailed understanding of the groundwater situation in a study area.

2. Objectives of the study

This paper describes:

- The study area: relevant characteristics of rural areas of the Wa municipality as the spatial unit of analysis;
- The hydro-geological and hydro-chemical characterisation of groundwater.

The paper is structured to achieve these objectives with a background statement, description of the hydrological cycle and groundwater formation, conceptual framework, research methods, discussion of results, and conclusions.

3. Hydrological cycle and groundwater formation

Groundwater formation is part of the hydrologic cycle, which explains the continuous movement of water above and below the surface of the earth [19]. **Figure 1** shows that radiation from the sun causes evapotranspiration from surface water bodies such as the sea, rivers, and lakes, as well as plants and animals. These rise into the atmosphere to cool, condense, and return to the land and surface water bodies as precipitation [2].

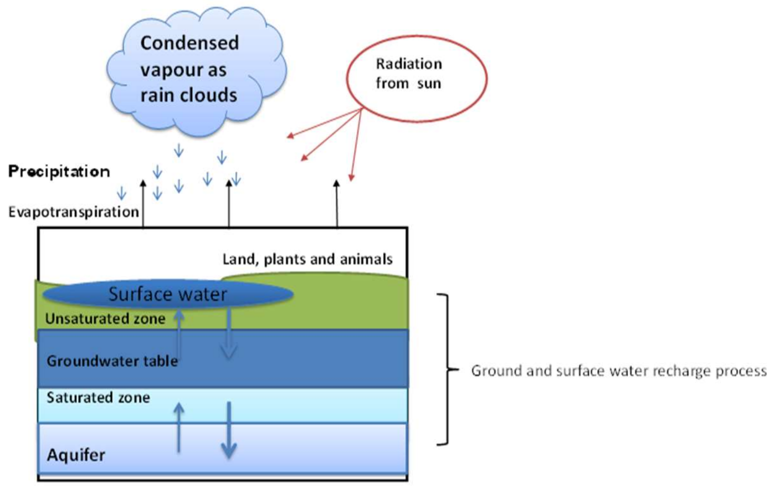

Figure 1. Hydrological cycle and groundwater formation process.
Source: Author's own construct.

Part of the water from precipitation permeates downward through soil pores and rock fractures to form aquifers underground [19]. Also, part of the surface runoff from precipitation and groundwater moves into the sea, rivers, and lakes to recharge them [20]. The water below the surface of the earth exists in layers. Beneath the topsoil is the unsaturated zone, containing water and air in the soil and rock pores [21]. This is followed by the groundwater table and the saturated zone, respectively. The saturated zone contains an excess amount of water and lies above the aquifer [2]. Both surface and groundwater sources recharge each other. Aquifers gain water through precipitation, surface runoff, and water bodies. Surface water bodies also gain water from aquifers through capillary force, which pulls groundwater upward against gravity [22].

The above relationship has practical implications for how to address water insecurity issues in semi-arid and arid areas [4]. For example, the drying up of surface water bodies does not spell absolute water shortage, since part of it would have been stored in aquifers to be prospected as groundwater. Thus, while lamenting that Ghana's One-Village-One-Dam programme was a failure because the dams dried up, constructing boreholes at the spots where the dams were constructed could provide safe water from the aquifers near the dams. The dams in this regard, then serve as artificial methods of groundwater recharge [3].

4. Conceptual framework

Figure 2 illustrates the relationship between the spatial unit, hydro-geological and hydro-chemical characterisations of groundwater, each of which has been explained below.

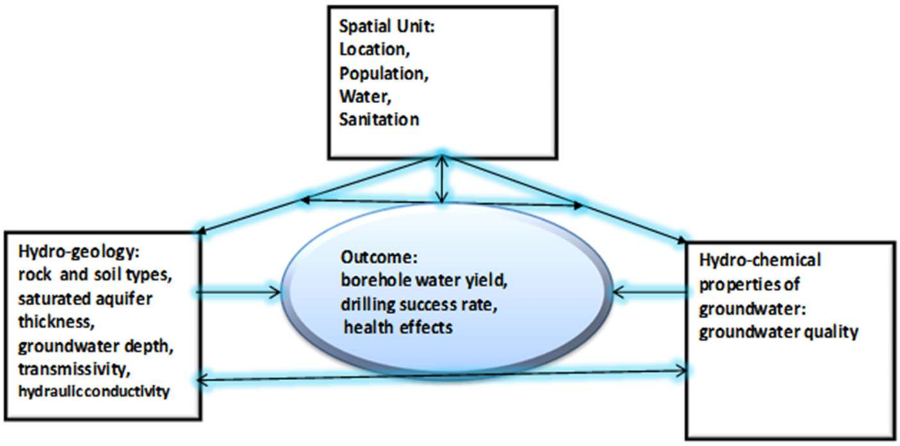

Figure 2. Conceptual framework of hydrogeological characterisation of groundwater.

4.1. Spatial unit

Spatial aspects in research relate to features of the study phenomena in the study area [14]. **Figure 2** shows the location, population, water, and sanitation as basic variables of interest in this study. The location in terms of region, district, community, and climatic belt has bearings on stratification by settlement types and hydrological significance, including surface and groundwater [23]. The Upper West Region in which the Wa municipal district is located is found in the tropical continental climatic belt of Ghana, which has a single maximum rainfall regime. This has implications for the amount of precipitation that recharges surface and groundwater [19,20]. Accordingly, changes in the rainy and dry seasons in the study communities linked to groundwater availability and use were ascertained.

Population as a spatial factor is measured as a variable in order to match groundwater infrastructure against population by planning standards, to see where gaps exist in terms of adequacy or not. Water and sanitation, as well as all aspects of the spatial unit, have been looked at in the broader context of hydro-geo-chemical characterisations.

4.2. Hydrogeology

Hydrogeology, also referred to as geohydrology, deals with how groundwater interacts with the surrounding soils and rocks through the processes of recharge, as it flows from the surface and enters aquifers underground [24]. This study assessed the rock and soil types and their water-holding characteristics in terms of aquifer thickness, aquifer depth, and transmissivity.

The common soils of northern Ghana, in which the study area is located, are clay and sandy soils, with 80% of the soil being sandy clay [25]. Clay and sandy soils are weathered from mudstone and sandstone rocks, respectively [26]. Coarse-textured sandy soils have large pore spaces for easy infiltration of water to reach the water table [27]. However, clay soils are less porous, slowing down the permeability of water to the water table [28]. The types of rocks, soils, and their relationships with other groundwater characteristics as presented in **Table 1** have been examined in the specific contexts of the study communities.

Table 1. Types of aquifer rocks and their relationships with groundwater.

Aquifer rock type	Major form	Water holding characteristics	Hydraulic conductivity	Chemical properties and water quality concerns
Sedimentary rocks	Consolidated or unconsolidated	High primary porosity and the primary water-bearing and producing rock	Very high hydraulic conductivities	Arsenic (causes cancer, skin lesions, cardiovascular disease, diabetes); Chromium (causes lung, nasal, and sinus cancer)
Igneous and metamorphic rocks	Crystalline-rock and volcanic-rock	Igneous and metamorphic rocks are permeable only where they are fractured, and they generally yield only small amounts of water to wells. But when they extend over large areas they yield large volumes of groundwater	Wide range of hydraulic properties due to variations in rock type	Arsenic (causes cancer, skin lesions, cardiovascular disease, diabetes); Calcium (improves the nervous system, blood circulation, and muscle movement); Aluminum (causes kidney disease); Magnesium (essential cofactor of several enzymes, improves neuromuscular conduction); Iron (needed for body growth and development)
Limestone	The upper units of limestone aquifers may be crushed or weathered materials, whereas the lower units are generally unaltered or fractured hard materials	Fractured limestone aquifer is considered a highly productive aquifer	Very low hydraulic conductivity	Calcium carbonate (causes constipation, flatulence, and bloating); Magnesium carbonate (acts as an antacid by neutralizing the excess acid in the stomach), Calcium hydroxide (it neutralizes acidic pickling juices, which reduces their antibacterial properties); Magnesium hydroxide (causes gastrointestinal irritation, and watery diarrhea)
Sandstone	Consolidated rocks	When extended over a large area, sandstone aquifers can be highly productive and provide large volumes of water	The hydraulic conductivity of sandstone aquifers is low to moderate	Silicon dioxide (no evidence to suggest that silicon dioxide is dangerous to human health); Calcium carbonate (causes constipation, flatulence, and bloating)
Granite	Plutonic and crystalline	They have a medium to low permeability, and so contain aquifers with modest water resources	Coarse-grained granite aquifers have greater length and higher hydraulic conductivity	Potassium (lowers urinary calcium excretion and plays an important role in the management of and kidney stones); Feldspar (causes nausea, weakness, chest pain); Mica (abdominal pain, diarrhea, and vomiting)

Source: Akanbi [42]; El-Rawy and Smedt [43]; Sudheer et al. [41].

An aquifer is a body of porous or permeable unconsolidated sediments or fissured rocks containing groundwater, hydraulically continuous according to its size and from which groundwater could be exploitable in useable quantities [23]. Of interest in this study was saturated aquifer thickness. Saturated aquifer thickness is the vertical thickness of the pore spaces of the rock forming the aquifer and filling it with water [29]. It was necessary to investigate aquifer thickness, especially for unconfined aquifers in this study because it influences aquifer storativity, which measures the volume of water dischargeable from an aquifer per unit area and per unit reduction in hydraulic head, independent of aquifer dimensions [30]. Unconfined aquifers were of interest because only boreholes related to them were studied. They are aquifers with groundwater in direct contact with the atmosphere through the open pore spaces of the overlying soil or rock, and atmospheric pressure could increase or decrease the groundwater in such aquifers [31].

Aquifer size is synonymous with a description of the size of a 'container' that stores groundwater. In other words, it is the volumetric storage capacity of an aquifer and is measured by the bulk volume of the aquifer rock times its mean specific yield [32]. However, the geology of some areas dominated by sandstone aquifers impedes the ability to assess the aquifer size homogenously. Although these extend over large areas and provide large amounts of water [33], the sandstone aquifers in the study area, or the Upper West Region of Ghana in general, are largely discontinuous, making it easier to estimate their thicknesses rather than sizes [34]. Hence, there was a need to investigate the average aquifer thickness and its implications on borehole water yield.

Aquifer depth as a geohydrological factor refers to the mean depth below the surface of the earth at which groundwater can be found for the purposes for which it is required [35]. Aquifer depth varies spatially and seasonally, with several studies reporting various results. For instance, Green et al. [36] found minimum and maximum aquifer depths of 15 mbgl to 90 mbgl at the Gwydir River catchment area in Australia. In the case of Ghana, Kyere et al. [37], in their study of groundwater prospecting in the Bawku West District, found aquifer depths ranging between 10 mbgl and 40 mbgl, and an average depth of 21.4 mbgl. According to Rural Water Supply Network [38], the standard aquifer depth for a borehole fitted with a hand pump is 50 mbgl or less. This study therefore ascertained the aquifer depths of boreholes fitted with hand pumps in the study area to determine their conformity to acceptable standards, which could inform water resource use planning.

Transmissivity describes the ability of the aquifer to transmit groundwater throughout its entire saturated thickness and is measured as the rate at which groundwater can flow through an aquifer section of unit width under a unit hydraulic gradient [39]. In simple terms, it is the ease with which groundwater flows below the surface of the ground in an aquifer. The commonest aquifer rocks in northern Ghana are granite and sandstone [40]. The transmissivity of granitic aquifers varies from 10.28 to 90.06 m^2/day with a mean of 33.6 m^2/day [41], and a water yield of 56.8–91.1 m^3/day [42]. Sandstone (basic aquifer rock) has a transmissivity average of about 400 m^2/day [43], and a water yield of between 138 and 1683 m^3/day [44]. Transmissivity was determined in this study for comparison to the expected standard. Related to this is hydraulic conductivity, a parameter that measures the ease of water flow through a permeable aquifer under the influence of other characteristics of the aquifer and the nature of groundwater, including density and viscosity [45]. This was also ascertained for the explanation of groundwater movement behaviour.

4.3. Hydro-chemical properties of rocks

Table 1 presents details of the hydro-chemical properties of some common aquifers by listing sedimentary rocks, igneous and metamorphic rocks, sandstone, limestone, and granite as examples. It also shows the forms in which the aquifer rocks occur, as well as their water holding and chemical properties, including the health effects of each chemical property, based on the findings of Akanbi [42], El-Rawy and Smedt [43], and Sudheer et al. [41].

4.4. Outcomes

Figure 2 presents 'outcomes' as the dependent variable. The independent variables (spatial unit, hydrogeology, and hydro-chemical properties) and their subcomponents together contribute to the outcomes. Key indicators of the outcomes include the effects of the independent variables on the performance of groundwater-related point source facilities, specifically boreholes with hand pumps. The outcomes component of the framework shows borehole water yield, drilling success rate, and health effects.

Borehole water yield is the volume of water that can be abstracted from a borehole. It is the rate at which water is abstracted from the borehole in terms of quantity per unit of time and can be expressed as L/s, m^3/hr, and m^3/d among others [46]. Knowledge of borehole water yield is important because it avoids over-pumping of the borehole in order not to induce saline intrusion and excess lowering of the water table and cause borehole failure [46]. Borehole drilling success rate refers to the chance of drilling a borehole to discover water [47]. This study measured the drilling success rate by assessing the number of boreholes drilled and the successful outcomes.

The health effects of groundwater use were also considered as an outcome because they emanate from the hydro-chemical and bacteriological properties of groundwater-bearing rocks, which also relate to the geohydrological (aquifer properties) and spatial units (human impacts, e.g., waste disposal practices) of the conceptual framework. For instance, calcium carbonate in sandstone aquifers causes constipation, mica in granite aquifers causes nausea and vomiting, while indiscriminate waste disposal and open defecation in a settlement as a spatial unit causes E. coli contamination, resulting in abdominal complications [41–43]. The outcomes guided the assessment of the effects of spatial, hydrogeological, and hydro-properties of groundwater on the performance of boreholes in terms of water yield and the health effects on the water users. Although the literature reveals the availability of information on aspects of the study in other spatial settings, the uniqueness of the results of this study lies in the integrated and multi-factorial nature of the exploration of groundwater characterisation.

5. Materials and methods

This section describes the methodological procedures used to achieve the research objectives.

5.1. Research design

The sequential exploratory mixed research design, comprising the sequential use of quantitative and qualitative methods and approaches, was used [48]. Quantitative methods were used first, followed by qualitative. The quantitative approach involved the collection of both secondary and primary data expressed in quantitative forms, using numbers, percentages, tables, and graphs. This was followed by the qualitative approach, involving the collection of both secondary and primary data, expressed in words in the forms of quotations, narrations, descriptions, tables, maps, and pictures. Secondary data collection included desk reviews as presented in **Table 2**, involving sourcing data from relevant institutional reports, as well as published articles and other website information.

Table 2. Desk review strategy.

Area of review	Sources of information	Inclusivity criteria	Relevant institutions
Background of the study to diagnose the research problem	Articles, books, past project reports by other institutions, policy documents	Reviewed documents should not be much older than a decade; and relevant to the spatial, geological, and social contexts of the study	WaterAid Ghana, UN, Ghana Statistical Service, Center for Indigenous Knowledge and Organisatioonal Development
The study area (spatial unit): location, population, water sanitation	Municipal/District profile, population census reports, journal articles	Reviewed documents should not be much older than a decade; and relevant to the spatial contexts of the study	Wa Municipal Assembly, Ghana Statistical Service, WaterAid Ghana, UN,
Geology: rock and soil types, water-holding characteristics, hydraulic conductivity, transmissivity & water yield, physicochemical properties	Articles, books, past project reports by other institutions, policy documents, CWSA reports	Reviewed documents should not be much older than a decade; and relevant to the geological contexts of the study	Ministry of Sanitation and Water Resources, Environmental Protection Agency- Ghana, Community Water and Sanitation Agency, Water Resources Commission at Wa, CWSA, borehole engineers
Social domain: policy contexts, institutional framework and roles (management), infrastructure, accessibility, availability, affordability, human impacts, challenges and prospects	Ghana Water Policy, MGDs & SDGs, Africa Water Vision for 2025, Articles, books	Reviewed documents should be within the current policy duration period. Books and articles should not be older than a decade	Ministry of Sanitation and Water Resources, Environmental Protection Agency-Ghana, Community Water and Sanitation Agency (CWSA)

Structured household interview checklists, key informant interview guides, questionnaires, focus group discussion guides, and observation checklists were used for primary data collection. The data from such instruments was both quantitative and qualitative. In the first phase of the sequential method, any use of such instruments is aimed at quantitative data, followed by qualitative data in the second phase.

5.2. Sampling

A 2-phase multistage sampling technique was applied. Multistage sampling is used when the elements of the population are spread over a wide geographical region and it is not possible to obtain a representative sample with only one technique [49]. Groundwater studies have a number of characteristics that make it difficult to obtain a representative sample based on one sampling method. In phase one, purposive sampling was used to select five communities of the Wa municipal district, out of the 20 largest communities as listed by the Ghana Statistical Service [GSS] [50]. The study communities were overlaid on a Digital Elevation Model (DEM) with the elevation classes (or heights) represented by the colours defined in the legend in **Figure 3**.

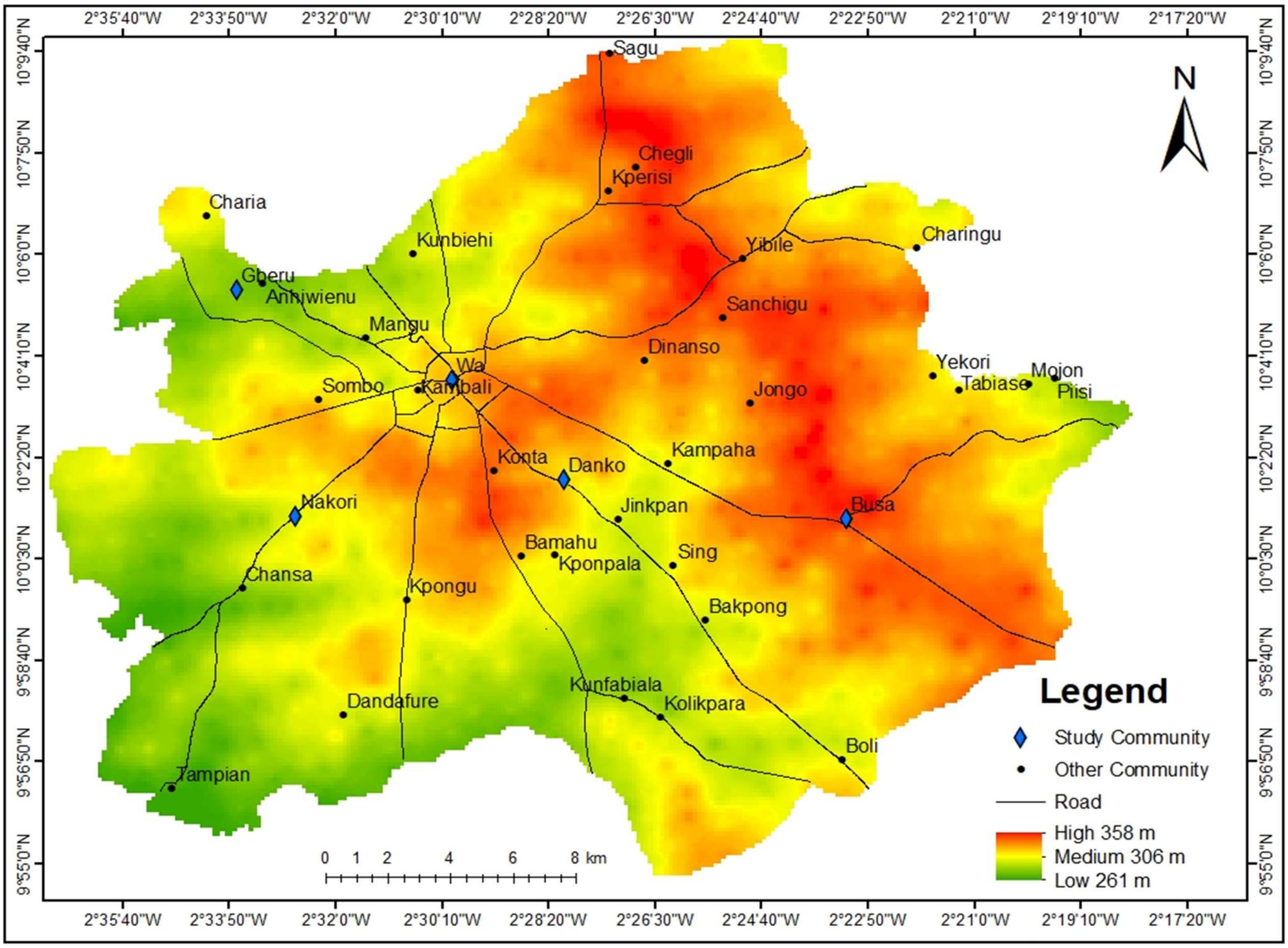

Figure 3. Sample communities within the context of a digital elevation model of the study area.

In phase two, five communities were purposively selected: two rural, one urban, and two peri-urban in Wa municipality. The purpose of the selection by stratification of settlement type is to facilitate a comparison of groundwater resource accessibility among them. Each of the five communities was selected in a different DEM class. The classification by DEM was to ascertain how differences in the slope of the land affect borehole construction success or water yield in the various seasons (rainy and dry). **Table 3** specifies the communities and their settlement status in each district, while **Table 4** summarises the sampling process and data collection methods.

Table 3. Selected study communities.

SN	Wa municipal	Settlement status
1	Wa (Konta)	Urban
2	Nakori	Peri-urban
3	Busa	Rural
4	Danko	Peri-urban
5	Gberu	Rural

Table 4. Target population, information sought, and methods of data collection.

Objective	Target	Specification	Number	Information required	Technique/tool of data collection and sampling method
Describe the relevant characteristics of the spatial unit (communities of the Wa municipal) of analysis	Communities	Any 18-year-old or older household member (other members of the same household could then participate) Community Water and Sanitation Management Board (CWSMB) members	400	Details of respondents, main sources of water, sanitation, seasonal variations in borehole water flow, observable aspects of water quality	Face-to-face interview/structure household interview checklist. Sampled by fishbowl and accidental methods
	Ghana Statistical Service	NA	NA	Location details, population, percentage access to water and sanitation infrastructure, climate, geology	District Analytical Profiles were obtained from the GSS website
	Wa Municipal Assembly	Community Development Officers	1		Self-administered questionnaires; observation checklist
		Works Department Officers	1		
Ascertain the hydro-geological and physicochemical characterisation of groundwater	CWSA	Hydrologist	1	Groundwater quality in terms of bacteriological and physicochemical properties of groundwater, number of boreholes constructed, groundwater management/governance, borehole water yield, aquifer thickness, transmissivity, borehole drilling success rate	Self-administered questionnaires
	Borehole construction companies	Borehole Engineer	1		Self-administered questionnaires
	Ghana Health Service	Municipal Health Officer	1	Impact of poor sanitation on groundwater and the health implications	Self-administered questionnaires

The actual locations of the communities in the district context are illustrated in **Figure 4**, which are compared to relative positions in **Figure 3** to identify the DEM.

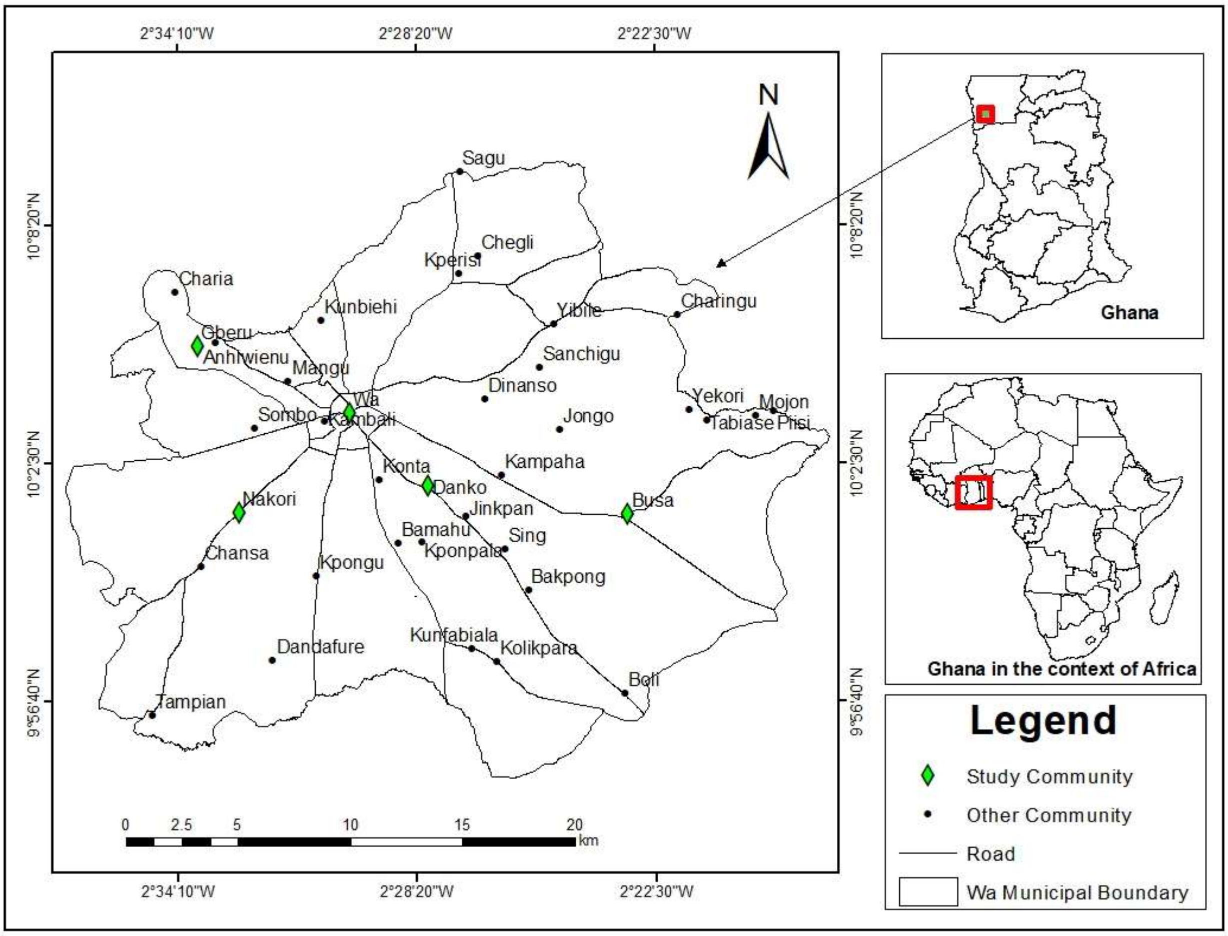

Figure 4. Study communities in the Wa municipal district context.

5.2.1. Sampling of respondents

5.2.1.1. Target population and sampling methods

The selection of houses was by the fish bowl or lottery method. Houses in each cross-section were enumerated, coded, and randomly selected using the lottery or fish-bowl method for the proportion of respondents calculated for each community from the sample size. Once in a house, the first household member to meet, who was 18 years and above was selected accidentally for interview based on informed consent, using a structured interview checklist with largely close-ended questions by face-to-face technique. This was preferred to questionnaires because the abilities of rural household respondents to read survey questions and write responses were uncertain.

Purposive sampling was used for focal groups and officials of government departments and private sector agencies listed in **Table 4**. It was preferred to use questionnaires for formal sector officials because they are literate. Questionnaires were issued in advance, to enable respondents to access and provide the right information, with a deadline of not more than three days. Designations and contact numbers of respondents were taken, to facilitate follow-up interviews and data cleaning if it became necessary. Community-level focal groups were engaged through discussions, using the focus group discussion guide, with a time frame of 30 min to 1 h per group.

5.2.1.2. Sample frame and sample size

The sample frame included the actual lists of sampled houses with households that are users of groundwater facilities. Members of the Community Water and Sanitation Management Boards were also targeted at the community level.

Sample size: The Wa municipality has numerous sub-sections without known population sizes because they sum up together to give the population of their capital city. As a result, we estimated a sample size for the study population in the five communities using Equation (1):

$$\text{Samplesize (n)} = \frac{t^2 \times p(1-p)}{m^2} \tag{1}$$

where n = required sample size, t = Confidence level at 95% (standard value of 1.96), p = Estimated prevalence of people depending on groundwater for drinking (these are unknown, so the best decision is 50% or 0.5), m = Margin of error at 5% (standard value of 0.05). Therefore, $n = \frac{1.96^2 \times 0.5(1-0.5)}{0.05^2}$ = 384.

The sample size of 384 was rounded off to 400, divided equally among the five study communities, giving 80 household respondents for each study community indicated in **Table 5**.

Table 5. Sample size of study communities per district.

SN	Wa municipal	Settlement status	Number of respondents
1	Wa (Konta)	Urban	80
2	Nakori	Peri-urban	80
3	Busa	Rural	80
4	Danko	Peri-urban	80
5	Gberu	Rural	80
		Total	400

5.3. Measurement procedures

(a). Measuring unconfined aquifer water yield

Equation (2), adopted from Michigan Technological University [51], is used for measuring the flow rate or borehole water yield of unconfined aquifers.

$$Q = \frac{\pi k(h_2^2 - h_1^2)}{\ln \frac{r^2}{r^1}} \tag{2}$$

where Q = flow rate of water from the borehole (cfs), k = coefficient of permeability of soil (fps), h_1 = height of water surface above the bottom of the aquifer at the perimeter of the well (ft), h_2 = height of water surface above the bottom of the aquifer at distance r^2 of a borehole well centreline (ft), r^1 = radius of a borehole well (ft), r^2 = radius of water surface whose height is h_2 above the bottom of the aquifer (ft), ln = natural logarithm

An unconfined aquifer is an aquifer with its water in direct contact with the atmosphere through the open pore spaces of the overlying soil or rock, and the groundwater could be increased or decreased by atmospheric pressure. On the other hand, confined aquifers are groundwater-bearing rocks overlain by relatively impermeable rock or clay that limits groundwater movement into or out of the aquifer [31].

Alternatively, a specific yield (S_y) could be measured. “Specific yield is the percent ratio of the volume of water that an unconfined aquifer will yield by gravity to the unit volume of the unconfined aquifer” [52]. Given that confined aquifers were not of interest in this study, the S_y for unconfined aquifer is calculated by Equation (3):

$$S_y = \frac{\text{volume of water an unconfined aquifer will yield by gravity}}{\text{unit volume of the unconfined aquifer}} \tag{3}$$

This study involved only boreholes constructed on unconfined aquifers because all construction attempts on confined aquifers were unsuccessful in the study area due to technological constraints. This is why the focus on measurement is on unconfined aquifers. Measuring borehole water yield provides information for the regulation of the use of the borehole by preventing overpumping and borehole failure during seasonal variations in groundwater level.

(b). Measuring borehole water depth

A borehole/protected well depth gauge was used for the monitoring of groundwater depth/aquifer depth. The gauge is attached to a tape measure and inserted from the top through the tube of the borehole. The tape is uncoiled as the gauge goes down the borehole.

Upon getting into contact with water, the pedestal sends a sound, and the graduated tape measures the water level. Monitoring the level of groundwater was found to be of water security significance with livelihood implications because:

- It helps to know the level of groundwater with seasonal variations, such as in the rainy and dry seasons.
- The level of groundwater helps in the determination of rules of allocation of water from various sources in order to ensure that safe water for drinking and other domestic uses is judiciously used to avoid shortages in the dry season.
- The rules of allocation partly deal with which source of water is used for what livelihood activity based on the results of groundwater levels.

In most cases, Community Water and Sanitation Management Boards at the community level measure the aquifer depth, and wherever such information was available, the researchers took advantage of that.

(c). Measuring saturated aquifer thickness

The meaning of saturated aquifer thickness has already been provided in earlier sections of this paper. According to the Louisiana Department of Environmental Quality [52], data on saturated aquifer thickness should be available to the well/borehole drilling agency. The determination of saturated aquifer thickness of an existing borehole could therefore be done by obtaining the data from the published reference boring/well logs of the borehole/well driller or field data. The saturated aquifer thickness has the dimensions of length for unconfined aquifers, the saturated thickness of confined aquifers corresponds to the thickness of the aquifer (ibid.). This study therefore ascertained data on saturated aquifer thickness through interviews with CWSA officials, the Works Department of the Wa Municipal Assembly, and relevant borehole engineers.

(d). Measuring transmissivity

Transmissivity has also already been defined earlier in this paper (see Murray Water [39]). It is calculated by Equation (4), provided by the Louisiana Department of Environmental Quality [52]:

$$T = K \times b \tag{4}$$

where T = transmissivity (ft 2 /day), K = hydraulic conductivity (ft/day), b = saturated aquifer thickness (ft).

where different units of measurement were used, such as liters (L) and meters (m), they were specified. Transmissivity was determined in this study to assess the ease of groundwater prospection from boreholes and for the purpose of comparison to the expected standard.

5.4. Hydraulic conductivity

Hydraulic conductivity is a hydrogeological parameter that measures the ease of water flow through a permeable aquifer under the influence of other characteristics of the aquifer and the nature of groundwater, including density and viscosity [45]. It is expressed as Equation (5):

$$\mathrm{K} = \frac{\mathrm{T}}{\mathrm{b}} \tag{5}$$

where K = hydraulic conductivity, T = transmissivity, b = saturated aquifer thickness.

It was essential to determine K in order to ascertain the permeability of aquifers and how aquifer thickness and transmissivity affect groundwater movement to account for borehole water yield.

Groundwater quality test:

Groundwater quality tests help determine if specific contaminants (physical, chemical, and biological) have infected a body of water, and the test results help inform how contaminated water needs to be further treated. The tests could be classified into bacteria tests (e.g., for E. coli, due to fecal contamination), mineral tests (e.g., chlorine, chloride, nitrate and nitrite, lead, copper, iron, zinc, potassium, and sodium, which could emanate from the aquifer rock), pH test (which measures the concentration of hydrogen ions in the water), among others [53].

The first step in water quality testing is sampling the sources of water being tested, that is, boreholes in this regard. The selection process takes into consideration, sources that are most prone to contamination and the use of the water. Samples of borehole water are collected in sterile tubes following some guidelines to avoid contamination. Once the samples are collected they are transported to laboratories to be tested using specialized equipment for the various parameters identified in the types of tests discussed earlier (Perfect Pollucon Services, n.d.).

However, this study did not conduct a water quality test. It depended on available water quality test results on existing boreholes provided by the Hydrology Department of the CWSA in Wa, which is responsible for the management of rural and small-town water services. It was discovered, however, that most boreholes owned by private individuals and donor-funded did not go through water quality testing. The failure to conduct a water quality test under this study was recorded as a methodological challenge due to funding constraints.

5.5. Data sources and analysis

The sources of data were categorised into two: desk review of the literature and relevant institutional reports and policy documents (see **Table 2**) and primary sources, presented in **Table 4**, with target respondents, type of information sought, and data collection methods. Chronologically, the data collection process began in June 2019 and ended in August 2019. Data presentation and analysis also began in September 2019 and ended in November 2019. All data presented in this report, whether primary or secondary, are based on 2019 as the reference year. However, some sources of literature have been updated.

Both quantitative and qualitative approaches were used in data presentation and analysis. The quantitative methods were the presentation of data using descriptive statistics with the aid of Microsoft Office Excel, such as frequency tables and graphs, using absolute numbers (1, 2, 3, …), percentages (%), and relevant units of measurement, such as meters (m), kilometres (km), centimetres (cm), litres (L), seconds (s), hours (h), days (d) among others. The qualitative methods were narrations, direct quotations, pictures, and maps, among others. Quantitative and qualitative analyses of primary and secondary data were concurrently, supplemented by reviewed literature. The mixed methods used facilitated cross-triangulation and comparison to lay bear, the contribution of this study to new knowledge.

5.6. Challenges of the research

The challenges were mainly related to scheduling, methodological creep, and accessibility to data. In terms of methodological creep, the original research proposal sought to undertake water quality tests by using samples of water from boreholes in each of the study communities. It was also intended to involve geologists in a study of the rock compositions of the study districts with an emphasis on the detection of chemical contaminants, such as arsenic and fluoride, and water-holding properties. However, these aspects were constrained by budget limitations. Accordingly, researchers had to rely on available secondary data on hydrogeological and physico-chemical properties of groundwater and groundwater quality, related to specific wells in particular communities in the study districts.

Also, some formal sector institutional respondents could not be reached for their responses to questionnaires. However, through triangulation of questions and the availability of secondary data on their roles, the failure did not affect the findings significantly.

6. Results and discussion

6.1. The spatial unit

This section discusses the relevant features of the spatial unit or study area, pertaining to the first research objective. In line with the conceptual framework in **Figure 2**, the location, population, water, and sanitation issues have been discussed. **Figure 4** presented in the methods sections shows a map of the study area.

The Wa municipality is one of the districts of the Upper West Region (UWR) of Ghana and is located within longitudes 9º55′ W and 10º5′ W and latitudes 2º15′ N and

2º40′ N. It is bounded to the north and east by the Nadowli and Wa East Districts, respectively, and to the west and south by the Wa-West District. Wa, is the capital town of the UWR and central city of the Wa Municipality. It has a land area of approximately 579.86 km^2, a population of the municipality is 107,214 with a density of 185 persons/km^2 and forms 15.3% of the region's total population. About 35% of the population is under 15 years old. Over 34% (36,453) reside in rural areas [50]. The large population has implications for the demand for water by households. It is also located in the tropical continental climatic belt of Ghana, which has one rainy season between May and October, followed by a dry for another half of the year. The mean annual rainfall is between 1000 mm and 1150 mm, compared to the other climatic zones in Ghana, which all have double maxima rainfall regimes and mean annual rainfalls exceeding 1150 mm. The municipality therefore has semi-arid conditions. Programmes and policies on water, targeting the cheapest sources that rural people depend on, such as groundwater, therefore require prioritization.

Figure 5 presents details of the household respondents. It shows the age and sex distributions, as well as the settlement types respondents belonged to. The data reveal that the respondent population is youthful and female-dominated, as the age group 18–33 and females had the highest frequencies in both study districts. This is consistent with the analytical reports of GSS [50], that the Wa municipality has a higher female population of 50.6%, and that youthful age groups dominate in the municipality.

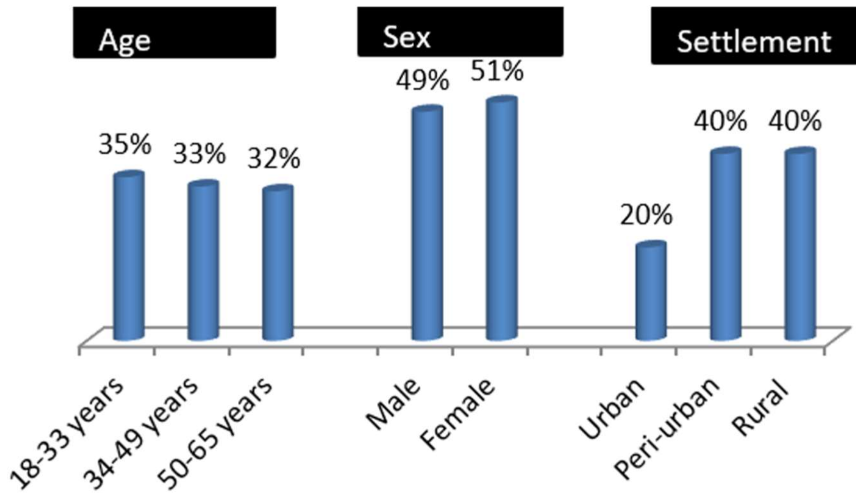

Figure 5. Age, sex, and settlement types of respondents.

The data shows that only 20% of respondents in the Wa municipality are urban. The largely rural nature of settlements is the reason why studies in groundwater characterisation and prospecting are essential since it constitutes the main source of safe water for rural communities in Ghana [47]. **Figure 6** shows that groundwater constitutes the major source of water for rural and peri-urban household respondents through the use of boreholes and wells.

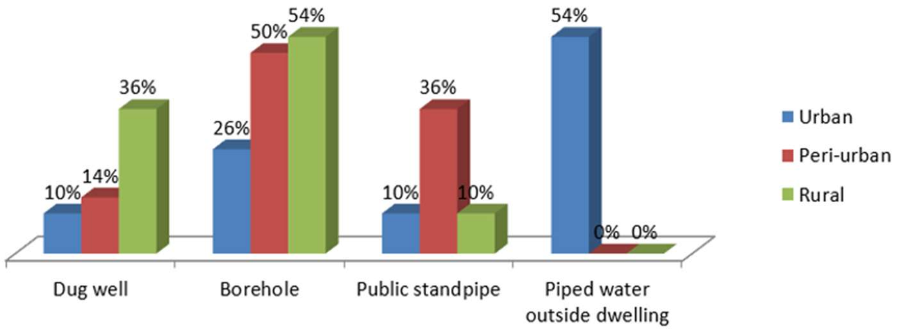

Figure 6. Evidence of dominance of groundwater infrastructure.

In terms of waste disposal, **Figure 7** shows that open dump sites and indiscriminate disposal methods are widely used by rural and peri-urban respondents. This increases the risk of contamination of surface water bodies as surface runoff and wind carry the waste into the water bodies to pollute them.

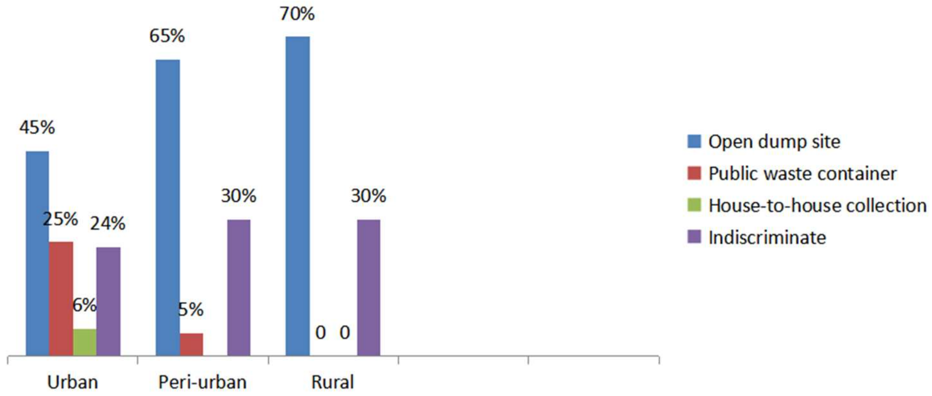

Figure 7. Means of waste disposal.

However, since surface water bodies also recharge groundwater aquifers, contaminated surface water also poses a threat to groundwater quality [3]. This calls for an examination of the hydro-chemical and bacteriological characterisation of groundwater to assess its quality and how it impacts health, as part of the outcome as a dependent variable in the conceptual framework of this study.

6.2. Hydro-geological and hydro-chemical characterisation of groundwater

This section addressed the second objective of this study, which aimed to ascertain the hydro-geological and hydro-chemical characterisation of groundwater. It explored the rock and soil types constituting the aquifers, transmissivity, aquifer thickness, water yield, and hydro-chemical and bacteriological properties of groundwater, as dictated by the conceptual framework. **Table 6** presents the data on the relationship between geology, soil, and groundwater as provided by the CWSA.

Table 6. Relationship between geology, soil, and groundwater

Aquifer rock type	Major form	Relationship between rock type and groundwater	Major soil type	Relationship between soil type and groundwater
Sandstone	Consolidated rocks	High transmissivity in the rainy season, but low transmissivity in the dry, may have silicon dioxide and calcium carbonate. When extended over a large area, sandstone aquifers can be highly productive and provide large volumes of water	Sandy soil, sandy clay, lateritic soil, lateritic soil	Highly porous and promotes quick groundwater recharge
Granite	Plutonic and crystalline	Groundwater assumes the chemical composition of granitic rocks, especially potassium, feldspar, and mica. Transmissivity values for groundwater in granitic terrains are minimal. They have a medium to low permeability, and so contain aquifers with modest water resources.	Clayey	Low percolation of surface runoff to recharge groundwater

Source: Hydrology Department of the CWSA, September 2019.

Responding to a question on the relationship between rock type and groundwater, an official of the CWSA at Wa, stated:

"The aquifers in the Wa municipality are mainly granite and sandstone. Granitic rocks and clayey soils have the attributes of causing minimal transmissivity and slow recharge rates of groundwater, while sandstone, associated with sandy soils, is more porous, promotes groundwater recharge quickly, and has high transmissivity. The average transmissivity in the municipality is 7.4 m^2/day, the average aquifer depth is 62 mbgl, and the average borehole water yield is 44.22 L/min."

It should be noted that in 62 mbgl, 'mbgl' means 'metres below ground level', hence mbgl is the same as meters (m). So mbgl is only used to distinguish values in metres associated with groundwater. Comparing the findings from the interview results above to the relationships between geology and groundwater in the mainstream literature, Sudheer et al. [41] report that the transmissivity of granitic aquifers varies from 10.28 to 90.06 m^2/day with a mean of 33.6 m^2/day, and a water yield of 56.8–91.1 m^3/day [42]. El-Rawy and Smedt [43] also assert that sandstone aquifer rock has a transmissivity average of about 400 m^2/day, while Al-Sudani [44] found water yield of between 138 and 1683 m^3/day to be associated with sandstone aquifers. **Table 7** presents data on the hydrological characteristics of selected boreholes and the corresponding digital elevations, derived from the DEM in **Figure 3** of this paper.

Table 7. Hydrological characteristics of selected boreholes.

SN	Wa municipal	Aquifer depth (mbgl)	Saturated aquifer thickness (mbgl)	Transmissivity (m^2/day)	Borehole water yield (L/min.)	Hydraulic conductivity (m/day)	DEM (m)
1	Wa (Konta)	67	42	8.49	14	0.20	358
2	Nakori	57	80	9.48	15	0.12	306
3	Busa	71	37	8.40	13.90	0.23	358
4	Danko	62	40	8.44	14.30	0.22	345
5	Gberu	54	85	9.61	15.49	0.11	212
6	Average	62.2	56.8	8.88	14.54	0.18	315.8
7	Expected	25-85	60	12.4	6.0- 18		

Source: This study, 2019.

The findings in **Table 7** show that the averages of aquifer depth and aquifer thickness are comparable to the average values of the Wa municipality as reported by the CWSA and the Wa Municipal Assembly's Works Department, as well as the expected standard values of 6 mbgl–120 mbgl for aquifer thickness in Ghana by the Food and Agricultural Organisation [FAO] [54]; water yield of 6–18 L/min for hand pump boreholes reported by Rural Water Supply Network [55], and an aquifer depth of 60 mbgl by Cobbing [47]. A groundwater depth of 50 mbgl or less is ideal for standard boreholes fitted with hand pumps. But transmissivity falls short of the 12.4 m^2/day requirement for both domestic and agricultural purposes [56], while the average water yield in **Table 7** (14.54 L/min) is below the reported value of 44.42 L/min by the CWSA, and the average transmissivity of 8.88 m^2/day is also higher than the reported 7.4 m^2/day. The data reported by the CWSA and Municipal Assembly were available before this 2019 study. Hence, changes in precipitation could cause changes in groundwater parameters [19].

The gap in the literature is, however, the inability to account for how other factors, such as digital elevation, affect geohydrological groundwater parameters. **Table 7** shows that boreholes located on the lower DEM have higher aquifer thickness, lower aquifer depths, and lower hydraulic conductivity. For instance, hydraulic conductivity, which measures the ease of water flow in an aquifer, is influenced by the nature of groundwater, including density or aquifer thickness [45]. Thus, given Equation (6) hydraulic conductivity (K) is expressed as:

$$K = \frac{T}{b} \tag{6}$$

With a larger aquifer thickness (b) of 85 m and a transmissivity (T) of 9.61 for the Gberu community borehole, hydraulic conductivity is:

$$K = \frac{9.61\text{msq/day}}{85\text{m}} = 0.11 \text{ m/day}$$

This means the hydraulic conductivity is lower, compared to Busa, which is K = 0.23 with an aquifer thickness of 37 m and transmissivity of 8.40 m^2/day. Impliedly, as the density or aquifer thickness increases, groundwater flows slower in an aquifer. On the other hand, transmissivity, which describes the ability of the aquifer to transmit groundwater throughout its entire saturated aquifer thickness [39], is a product of hydraulic conductivity and aquifer thickness. So, an increase in any of the factors (K or b) or both increases T, because $T = K \times b$.

For instance, at Danko, where the hydraulic conductivity (K) is 0.22 m/day and aquifer thickness (b) is 40 m, T = 0.22 m/day × 40 m = 8.22 m^2/day.

Both transmissivity and conductivity are impacted by the porosity or permeability of the aquifer itself. Impermeable aquifers have lower K and b values. Linking transmissivity and conductivity as independent variables in the conceptual framework of this study (**Figure 2**), to the dependent variable of outcomes, especially water yield, Akinwumiju and Olorunfemi [57] assert that transmissivity is one of the factors affecting borehole water yield. This was confirmed by this study in **Table 7**, as communities with higher transmissivity values, equally have higher borehole water yields. For example, the transmissivity value of Gberu is 10 m^2/day the highest in **Table 7**, with a correspondingly highest water yield of 15.49 L/min at the lowest DEM of 212 m. But according to Scherrer et al. [58], boreholes are often drilled where the needs are highest and not where hydrogeological conditions are most favourable.

In terms of aquifer thickness, this study found an average of 56.8 mbgl, which is higher than the range of 15–22 mbgl reported for the coastal regions of Lagos in Nigeria, where groundwater is also extensively used [59]. This information is therefore relevant for policy consideration for large-scale groundwater prospecting for purposes beyond domestic uses in the Wa municipal communities.

Also related to the outcomes is another dependent variable, namely borehole drilling success rate. According to Cobbing [47], the success of drilling a borehole to obtain water is dependent on how well-fractured the aquifers are, the aquifer depth, and whether it is confined or unconfined. **Table 8** presents evidence of actual boreholes drilled in the study districts between 2015 and 2017, obtained from the officials of the CWSA and the Works Department of the Wa Municipal Assembly.

Table 8. Drilling success rate.

Year	Districts	Total number of borehole drilling attempts	Number of successful drills	Number of unsuccessful drills
2015	Wa municipal	4	4 (100%)	0 (0%)
2016	Wa municipal	13	11 (85%)	2 (15%)
2017	Wa municipal	7	6 (86%)	1 (14%)

Source: CWSA and Wa Municipal Assembly, September 2019.

Borehole drilling could be described as shallow or unconfined well drilling when it does not go beyond the top layer of the saturated aquifer. From the data provided for 2015 and 2017, the chances of drilling a borehole to have an economically feasible amount of water were between 85% and 100%. The results confirm the report by Cobbing [47] that communities in the Upper West Region have a high borehole drilling success rate due to the well-fractured rocks.

However, there have been instances of unsuccessful well drills. In line with this, this research also investigated evidence of the relationship between digital elevation and the possible challenges of constructing boreholes to find groundwater in the study communities. **Table 9** presents the causes of failure in borehole drilling attempts and associated digital elevations (refer to **Figure 3**). The data show that four out of the seven cases shown in **Table 9** were in the high DEM, two in the medium, and one in the low DEM. This implies that most of the attempted borehole sites were either along hills or slopes with deep aquifers, for which reason surface runoff does not easily convey and permeate into the aquifers. This is supported by the findings of Janyani et al. [60] that the ideal location of boreholes is valleys or lowland areas, which also have nearby streams or springs.

Table 9. Challenges of borehole construction.

Wa municipal communities	Aspect of physical scarcity threat	Digital elevation (DEM)/ranking
Wa (New Market area and Konta areas)	Failed attempt to drill due to underground rock	368 m (high)
Busa	Failed attempt to drill due to underground rock (70)	358 m (high)
Danko	Failed attempt to drill due to underground rock (70 m)	345 m (high)
Gberu	Failed attempt to drill due to underground rock at the attempted site (60 m); at least, one borehole has a dry well	212 m (low)
Bamahu	Deep aquifer (more than 80 m), no groundwater at attempted site	360 m (High)
Charingu	Failed attempt to drill due to underground rock, inadequate groundwater at the attempted site (deep aquifer: more than 70 m)	306 m (high)
Nakori	Deep aquifer (more than 80 m), inadequate groundwater at attempted site	306 m (high)

Source: Field survey, 2019.

Rural Water Supply Network [38] aver that under circumstances such as those expressed in **Table 9**, ultra-deep hand pump technologies should be used, because standard hand pumps are unreliable for regularity of borehole water yield in such areas. Specifically, the PolDaw Ultra Deep Well is a PolDaw Designs (UK) Technology. This was a response to the need for pumping from aquifers with depths of 200 to 300 feet (60 to 90 m), in various countries. WaterAid runs pilot programmes using the PolDaw Ultra Deep Well technology in some water-scarce localities of African countries. WaterAid could therefore be resourceful for details of the technology and cost implications of its adoption if the Wa municipality expresses interest in the promotion of adequate groundwater access in the area.

Apart from the hydro-geological characteristics discussed above, during focus group discussions with the local Community Water and Sanitation Management Boards, respondents in the study communities expressed their indigenous knowledge of the detection of groundwater availability. At Busa in the Wa municipality, a participant in the FGD said that:

"The signs of groundwater availability are classified as physical and biological. The physical signs include the presence of sandy-clay soil, closeness to the foot of hills, heat, and ease of flooding. The biological signs include the presence of termite and ant hills, some identified tree species, areas with thick vegetation cover, tall trees with green leaves and tall grasses."

Figure 8 shows some successfully constructed boreholes and their proximities to biological indicators of groundwater availability based on the indigenous knowledge of community-level FGD participants. Ant hills can be spotted around a mechanised borehole in Busa, for small-town water supply, constructed by the CWSA.

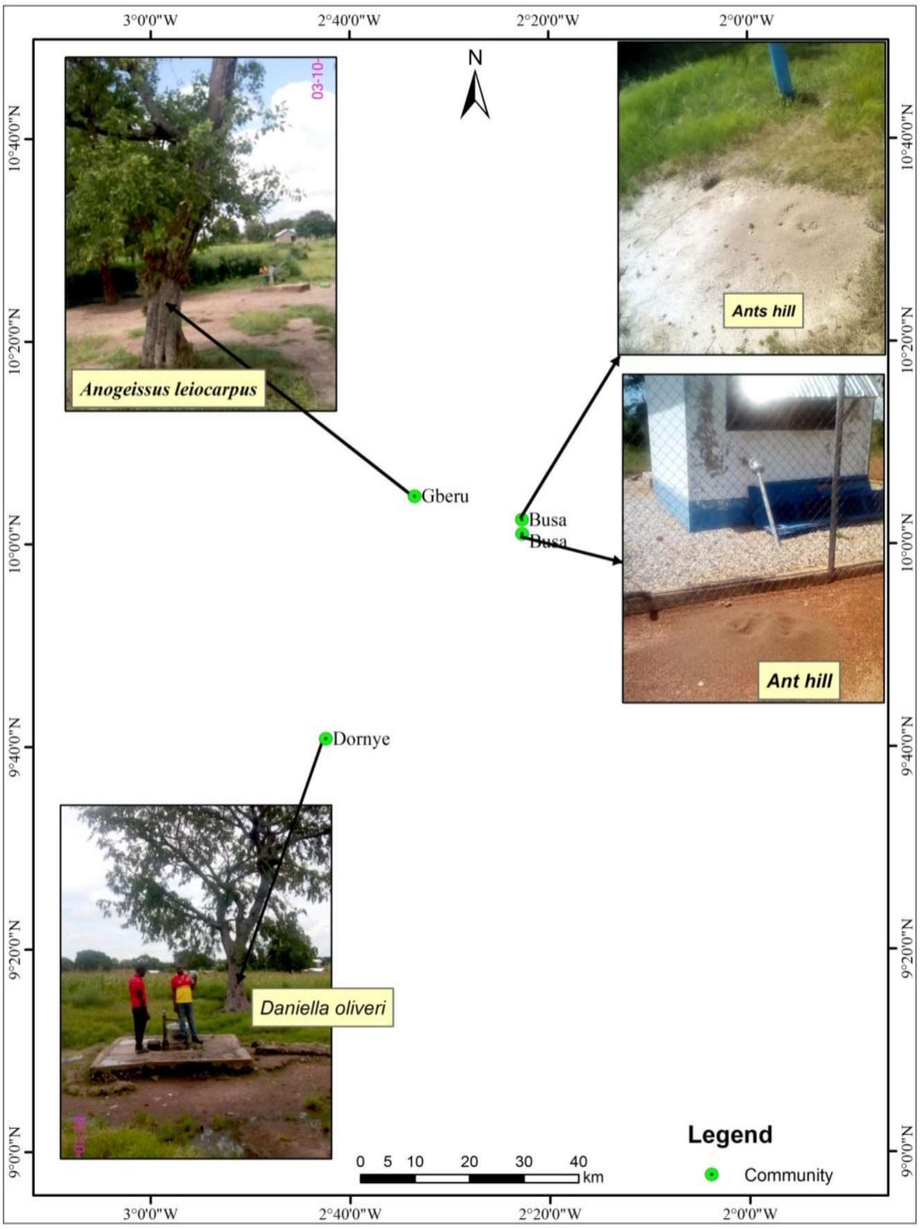

Figure 8. Signs of groundwater availability.

Source: Filed survey, September 2019.

Figure 8 further shows Dornye and Gberu communities with successfully constructed boreholes closer to the Anogiessusleiocarpus and Daniella Oliveri trees, respectively. The findings are consistent with those of Condon and Maxwell [61], that the availability of groundwater is influenced by the vegetation, soil, and rock types, the topography of the land, and the climate of the area.

6.3. Borehole water yield

Borehole water yield is a measure of the volume of water that can be abstracted by pumping a borehole per unit of time [62]. Reports on values of borehole water yield in the Wa municipality by the Hydrology Department of the CWSA-Wa and the Borehole Drilling Unit of the Works Department of the Wa Municipal Assembly revealed an average of 44.22 L/min, while this study found an average of 14.54 L/min. Hand pump boreholes should have a sufficient yield of around 0.1–0.3 L/sec (6.0–18

L/min.), but for a small-town water supply, the normal yield should be 2–10 L/sec or 120–600 L/min [55]. Thus, Wa municipality has good water yield records on average, for hand pump boreholes.

6.4. Seasonal variations in water yield

Table 10 also provides data from household respondents on user experiences of borehole water yield in the rainy and dry seasons, by using reduced water flow necessitating the need to pause for borehole water recharge as an indicator. The results reveal that it is only in the dry season that 34% of the respondents experienced reduced water yield in their boreholes, as most respondents in the high DEM communities reported cases of pausing for borehole recharge in the dry season. Gberu, the only study community on a lowland of 212 m reported no cases of pausing for borehole water recharge. This finding suggests that the use of DEM in groundwater projects is important for construction success, which is lacking in most groundwater-related research findings. In the rainy season, **Table 10** shows that all respondents in both study districts chose the 'No need to pause' option. This also substantiates the role of precipitation in groundwater recharge [19].

Table 10. Pausing for borehole recharge in the dry and rainy seasons.

District		Dry season			Rainy season		
	Community	No need to pause	Need to pause	Total	No need to pause	Total	DEM
Wa West	Busa	2.5% (10)	17.5% (70)	20% (80)	20% (80)	20% (80)	358 m (high)
	Danko	12.5% (50)	7.5% (30)	20% (80)	20% (80)	20% (80)	345 m (high)
Wa municipal	Gberu	20% (80)	0% (0)	20% (80)	20% (80)	20% (80)	312 m (low)
	Nakori	20% (80)	3.5% (14)	20% (80)	20% (80)	20% (80)	306 m (high)
	Wa	14.5% (51)	5.5% (29)	20% (80)	20% (80)	20% (80)	358 m (low)
	Total	66% (257)	34% (143)	100% (400)	100% (400)	100% (400)	

Source: Field survey, September 2019.

The fluctuation of borehole water yields breeds the need to explore alternative means of aquifer recharge in areas faced with dry wells in the dry season. Following the assertion of Wang et al. [22] that surface and groundwater systems recharge each other, deliberately increasing dugouts to serve as surface water buffer stocks in the rainy season for the regulation of aquifer recharge throughout the year is a gap in the practice of groundwater resource management in Ghana.

6.5. Hydro-chemical and bacteriological parameters of groundwater quality

The safety of groundwater depends on how free the source is of harmful hydro-chemical properties of the aquifer, bacteriological, and other anthropogenic sources of pollutants, as presented in **Table 11**.

Table 11. Results of water quality analysis.

Sample source-boreholes	**Districts: Wa Municipal Borehole: Danko**	**Districts: Wa West district Borehole: Dorimon**	**Date of analysis**	**Time sample was taken: Wa Municipal: 12:30 PM Wa West: 12:00 PM**
Sample source: Boreholes (Mark Sams Limited)				
Tested parameters	**Date of sampling: 14/06/2017**	**Date of sampling: 19/04/2017**	**Ghana standards**	**Remarks**
Ph	6.84	6.7	6.5–8.5	Satisfactory
Conductivity (us/cm)	272	106.9	1000	Satisfactory
Total dissolved solids (mg/L)	136	53.5	≤500	Satisfactory
App/true colour (HU)	<5	5	≤5	Satisfactory
Turbidity (NTU)	2.42	4.62	0–5	Satisfactory
Total alkalinity (as $CaCO_3$) – mg/L	54	49	200	Satisfactory
Total hardness (as $CaCO_3$) – mg/L	164	141	500	Satisfactory
Calcium hardness (as $CaCO_3$) – mg/L	83	74	N/A	Satisfactory
Magnesium hardness (as $CaCO_3$) – mg/L	81	65	N/A	Satisfactory
Calcium (mg/L)	33.2	29.6	100	Satisfactory
Magnesium (mg/L)	19.7	15.8	50	Satisfactory
Chloride (mg/L)	28.4	22.7	≤250	Satisfactory
Nitrate-Nitrogen (NO_3) (HR)	4.6	0.740	≤50.0	Satisfactory
Nitrite-Nitrogen (NO_2) HR	0.05	0.001	≤3.0	Satisfactory
Total iron (as Fe) – mg/L	0.21	0.023	≤0.3	Satisfactory
Fluoride (as F^-) – mg/L	0.49	0.28	≤1.5	Satisfactory
Sulphate (as SO_4^{-2}) mg/L	12.45	3.1	≤400	Satisfactory
Ammonia (NH^-_3-N) – mg/L	0.61	0.04	≤1.5	Satisfactory
Arsenic (as As) –mg/L	0.0	0.0	≤0.01	Satisfactory
Aluminium (Al) – mg/L	0.0	0.01	≤ 0.2	Satisfactory
Total coliform (CFU/100 mL)	0	0	0	Satisfactory
Faecal coliform (CFU/100 mL)	0	0	0	Satisfactory
E. coli (CFU/100 mL)	0	0	0	Satisfactory

Source: Provided by CWSA, Wa- September 2019.

The World Health Organisation [WHO] [63] lists improved sources of water in order of priority, namely household piped water connections and public standpipes as treated surface water sources; groundwater sources such as boreholes, protected dug wells, and protected springs; and finally harvested rainwater. Other sources, such as unprotected wells and springs, vendors, and water tankers providing services, as well as bottled water are labeled as unimproved sources of water. Available borehole water quality test results in **Table 11**, for some communities in the Wa Municipal and Wa West District of the Upper West Region, show conformity to acceptable water quality standards and are safe for human consumption. **Table 11** shows that the groundwater was free of hydro-chemical and bacteriological contaminants and so safe for direct consumption. However, the limitation is that the tests were performed on specific boreholes without adequate sampling of boreholes to ascertain their water quality conditions for most boreholes constructed in the communities. Responding to the question of the performance of water quality tests for groundwater supply facilities, the hydrologist of the CWSA reported that:

Most households and schools use water from local hand-dug wells, privately constructed boreholes, or philanthropist or donor-funded boreholes. Some of these are constructed without following the due processes of seeking abstraction rights from the Water Resources Commission or impact assessment and permits from the EPA, especially the local wells. However, due to a lack of adequate funding from the District Assemblies, it is usually difficult to ban the use of such facilities without providing alternative sources of safe drinking water for the communities. Ensuring compliance with the bans is a challenge for us.

6.6. Health effects

During a focus group discussion with Community Water and Sanitation Board members at Gberu in the Wa municipality, responding to the question on the quality of the borehole water, a participant said:

"The borehole is the main source of our drinking water, so whether it is good or not, we have no choice. The water is clear in the rainy season, but in the dry season between January and March, the water turns brownish and is not clear enough to see through very well. But it still tastes good, and we drink it."

Asked whether they conduct water quality tests for their borehole, another participant said that:

"We are not aware of any water quality tests. But some children grow up in this community with brown teeth, and when we take them to the hospital, the doctors say it is from the water they drink."

Figure 9 shows the suspected case of dental fluorosis.

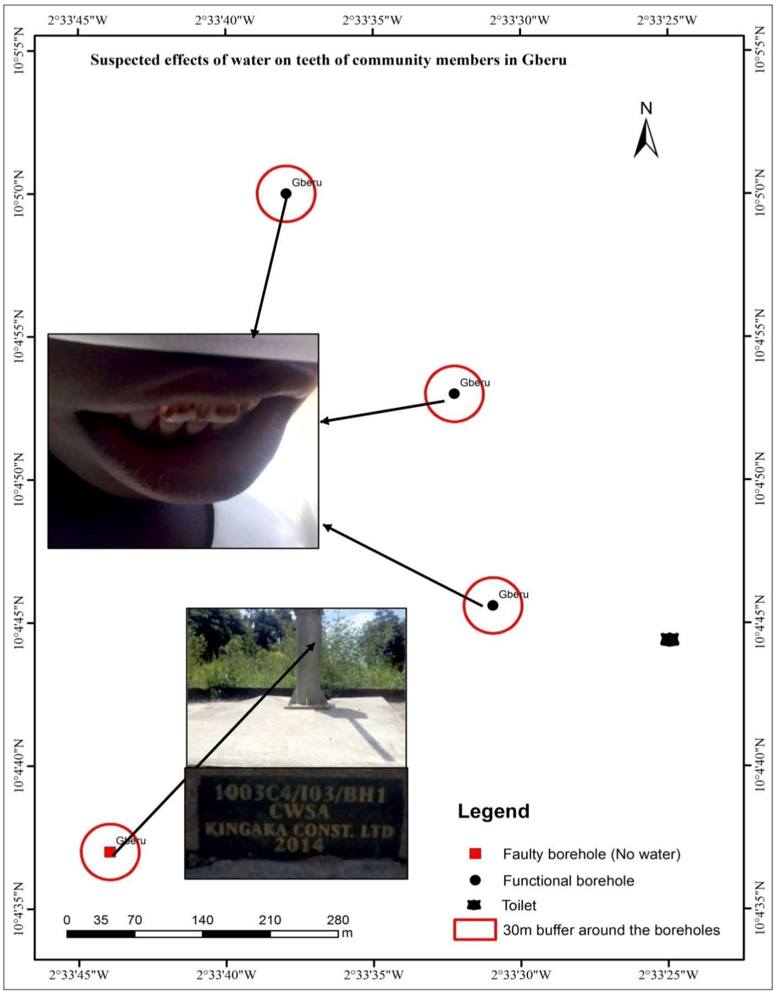

Figure 9. Suspected case of dental fluorosis at Gberu.

Source: Field survey, September 2019.

Responding to a questionnaire on the health effects of bad water quality, an official of the GHS in Wa stated that:

"Most rural people drink water from boreholes, wells, and streams that have not been tested for water quality analysis. So, most cases of dental fluorosis, I mean brown teeth caused by the presence of too much fluoride in water and other unsafe water-related diseases are reported by patients from the villages."

This is consistent with an assertion by Cobbing [47], that hydro-geological health scientists use signs such as the prevalence of dental and cancerous health problems to detect the consumption of unsafe water by patients. The extreme left of **Figure 9** shows a basic school student in the Gberu community of the Wa municipality with a suspected case of dental fluorosis.

In line with the report above, Taonameso et al. [64] investigated the potential health risks of borehole water in rural South Africa. They found that inadequate distribution of improved sources of water causes uneven access by rural households, which exposes disadvantaged ones to water-related health risks due to the consumption of water contaminated by pathogens. Their study found E. *coli* and fecal coliforms in samples of borehole water. These cause gastrointestinal disturbances and diarrhoea. The authors also blamed the gaps in rural water supply on the inefficiencies of municipalities.

7. Conclusions

By the spatial unit, it was found that the Wa municipality is located in the tropical continental climatic belt of Ghana, which has semi-arid weather conditions. It has a single maximum rainfall regime, with a mean annual average between 1000 mm and 1150 mm, compared to the other climatic zones in Ghana, which all exceed 1150 mm. This impacts negatively on both surface and groundwater resources, as some boreholes experience dry well conditions during the dry season (from November to April) and lack of adequate surface water to recharge groundwater. With a rural population of 36,453, which represents 34% of the population of the municipality, 54% depend on boreholes fitted with hand pumps, and another 36% depend on dug wells, summing up to 90% of the rural households depending on groundwater resources as drinking water, based on the respondent population of 400 as a sample. In terms of sanitation, 45%, 65%, and 70% of urban, peri-urban, and rural households, respectively, make use of open dump sites for waste disposal, which is a threat to both surface and groundwater quality through pollution.

Hydrogeologically, granite and sandstone constitute the major aquifer rocks of the Wa municipality. Granite weathers into clayey soils, both of which are associated with lower transmissivity values and slow infiltration of surface runoff into groundwater. Sandstone, on the other hand, weathers into sandy soils and has high porosity and transmissivity values. This study found that the average transmissivity of borehole aquifers in the municipality was 8.88 mbgl, with an average aquifer thickness of 56.8 mbgl.

Residents use biophysical indicators of aquifers, such as valleys and sandy-clay soils, as well as tall trees, termites, and anthills. Generally, places on the lower DEM had more favourable conditions of groundwater for borehole construction than those on higher elevations. The average groundwater depth was 62.2 mbgl, compared to the standard groundwater depth of 60 mbgl and the global standard of 50 mbgl for boreholes fitted with hand pumps. The groundwater situation was observed to be ideal for meeting domestic water needs and has the potential to be exploited for agricultural purposes as well. The major challenge was confined aquifers, which impeded borehole construction.

Hydrochemically, available groundwater quality test results showed conformity to acceptable safe drinking water requirements. However, most boreholes and wells are not tested for water quality, making dental fluorosis common in some communities due to the excess of fluoride in the water.

By revisiting the conceptual framework of this study, the spatial unit characterised by population characteristics, dominated by rural households, and the location in terms of climatic belt and accessibility to water and sanitation demonstrated features of rural communities. These make groundwater a basic necessity in the area. Findings further demonstrated the linkages between the spatial unit from which hydro-geological and hydro-chemical parameters emanate. It was also revealed that the hydro-chemical properties of groundwater were directly related to the geology, or the soil and rocks constituting the aquifers. The outcomes manifested in the form of borehole water, water yield with an average of 14.54 L/min., and drilling success rates ranging from 85% to 100%. Lack of water quality tests results in the use of borehole water contaminated with fluoride, which causes the adverse health effects of dental fluorosis.

A number of recommendations are advanced to address the major problems identified. In the spatial context, it is recommended that the CWSA extend its role in sensitizing communities to the effects of poor waste disposal practices on water resources in the study communities. Providing training on cheap and sustainable methods of waste disposal, such as composting, waste reuse, and recycling methods, and linking communities to business units engaged in waste collection for recycling could be prioritised.

Hydrogeologically, the Wa Municipal Assembly, in collaboration with the CWSA and other groundwater resource development partners, should engage the services of geological surveyors. It was found that granite and clay soils, as well as sandstone and sandy soils, dominate in the study communities. Since aquifers with granite rocks and clay soils are less porous and have low transmissivity levels, geological surveys could detect aquifers with sandstone and sandy soils spreading over wider lowland areas for borehole construction to ensure high transmissivity, greater aquifer thickness, and water yield throughout the year.

For areas with dry well experiences in the dry season, the artificial groundwater recharge method is recommended. By doing so, dugouts could be constructed to store water in the rainy season, which could serve as artificial water recharge for boreholes in the dry season, providing safe drinking water on a sustainable basis. In other words, since Ghana is already running the One Village, One Dam program, the Wa Municipal Assembly, in collaboration with the CWSA, should list communities with groundwater scarcity challenges and recommend the same for inclusion in the village dam program. Surface dugouts or small dams could then be constructed at preferred locations in the communities where both surface and groundwater sources are needed.

This should go along with the construction of boreholes with hand pumps. In the rainy season, both boreholes and dugouts would be recharged by rainwater. In the dry season, both borehole aquifers and surface dugouts are expected to gradually dry up. But part of the groundwater would infiltrate into groundwater aquifers for aquifer recharge. Although the dams would dry out, the adjacent boreholes would continue to yield safe drinking water for a longer time than if they depended on the groundwater table.

For the cost implications of using surface dugouts to boost aquifer recharge, there is already an ongoing program for villages in Ghana, and so the costs of the projects should be contingent on the overall program budget. The social feasibility of the surface dugout-borehole combined project for water supply is that it would contribute to the achievement of SDG 6, which is about clean water and sanitation for all. In terms of economic feasibility, the aquifer thickness, transmissivity, conductivity, and water yield of boreholes could be enhanced to go beyond domestic and livestock uses and include dry-season irrigated farming. The environmental cost of the project, in terms of possible mosquito breeding by the dams and possible increases in malaria incidences, should not be taken for granted. Malaria prevention education and the provision of preventive and curative healthcare services should also be enhanced.

For areas with confined aquifers and deep groundwater depths that impede borehole construction, the Wa Municipal Assembly, in collaboration with the CWSA and WaterAid Ghana, should work towards the adoption of the PolDaw Ultra Deep Well technology, described in the analysis section of the paper. WaterAid Ghana would be resourceful in such a project if this recommendation were to be implemented.

To address the hydro-chemical problems related to groundwater quality, the CWSA, in collaboration with the Municipal Assembly, the Water Resources Commission, and the EPA, should organize training workshops for Community Water and Sanitation Management Boards (CWSMB) in rural and small-town communities. The aim should be to sensitize them about the dangers of indiscriminate borehole and well construction, which could lead to the consumption of water contaminated with dangerous substances such as fluoride, arsenic, and fecal coliform, which cause diseases such as dental fluorosis, cancer, and diarrhea. The CWSMBs could then be used as a task force to prevent indiscriminate boreholes and well construction and to educate community members about the right procedures to follow when constructing groundwater point source facilities. The Wa Municipal Assembly should also vote for part of the common funds for water quality testing of all existing boreholes and wells in rural and small-town communities in the municipality. All the boreholes and wells that fail the tests should be locked down or refilled.

Author contributions: Conceptualization, FIMB, SDZ and RA; methodology, FIMB; software, RA; validation, FIMB, SZ and RA; formal analysis, FIMB; investigation, FIMB, RA and SDZ; resources, FIMB; data curation, SDZ; writing—original draft preparation, FIMB and SDZ; writing—review and editing, FIMB, SDZ and RA; visualization, SDZ; supervision, FIMB; project administration, FIMB; funding acquisition, FIMB and RA. All 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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