



Research



Delineation of aquifer promising zones and protective capacity for regional groundwater development and sustainability

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Abstract

Water security is the central mission of the sustainable development goals. The demand for potable and clean water has skyrocketed due to frequent borehole failures and population expansion, which requires adequate groundwater resource management strategies. Identifying groundwater potential zone, overburden protective index capacity and installations of alternative/artificial storage support mechanisms for water security and sustainability under the growing water challenge and demand is critical. This study identifies; (i) aquifer promising zones (ii) aquifer protective capacity through geophysical investigation and suggests (iii) improving aquifer recovery management strategy as the top three targets for groundwater development. An electric resistivity technique was applied to acquire a total of sixty (60) vertical electrical sounding points with Schlumberger arrays. The study indicates the resistivity layer of the aquifer unit ranges from 21 to 294 Ω m, while the aquifer layer thickness values spread from 8 to 59 m and the overburden thickness overlays the aquifer unit extends from 3 to 20 m. The deeper aquifer zones were encountered between 30 and 59 m, which could be suitable for groundwater development, and the shallow aquifer occurs between 8 and 14 m, which is not encouraging for groundwater development and may be susceptible to surface contaminations. However, for water security and sustainability, multiple boreholes should be sited at the delineated aquifer promising zone where the aquifer is fractured and occurs within a depth of 30 m and above. The weathered/fractured units constitute the regional aquifer units, which are largely responsible for the groundwater potential. The hydraulic conductivity of the regional aquifer was estimated to vary between 0.337 and 10.62 m/day, which invariably enhances the aquifer recovery processing. Groundwater quality and the risk of surface contamination were examined through overburden protective index capacity.

Article Highlights

- Aquifer storage support mechanism (ASSM) proposed in response to water resource management.
- Groundwater promising zone with a very high aquifer protective index capacity was examined
- ASSM for harvesting the untapped excess rainwater for water security and sustainability

Keywords Groundwater potential · Management strategies · Sustainability · Vulnerability · Water security

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1 Introduction

Humankind often paid much attention and unnecessary commitment to non-life sustainable things but paid less or no attention to the main requisite for a living. The security of groundwater is unnegotiable as it remains a valuable hidden natural resource [1]. This is because irrespective of human social condition, educational background, political development, economic status and technological advancement, are entitled to have access to drinking water in good quality and quantities [2]. Groundwater remains an integral natural resource for human development because more than 1.5 billion of the world's population heavily relies on it [3]. However, continuous efforts toward providing adequate water, while reducing water pollution using all means of resources have not yet yielded significant results. Therefore, providing adequate storage capacity under the current growing water demand and unstable climate conditions remains one of the major global concerns for water management in the last few decades [4]. Though accurate approximation does not exist, from now till a few decades, the demands on groundwater resources will be more critical and additional multiple storage mechanisms plus the present storage capacity will be required to provide adequate water [4], especially during dry periods.

However, some considerable literature works have identified rainwater harvesting as a storage reservoir option for water security [5, 6], because the bulk of rainwater remains untapped as much still runs off to sea, while only a few (about 800,000) dams across the world store less than one-fifth of all rainwater [5]. Therefore, an adequate ASSM can serve as alternative water storage and a measure to curb the challenge of groundwater, especially under the current global climate variations [7]. ASSM is an artificial aquifer storage option for water preservation, security and sustainability. In other words, ASSM is a water security innovation and enhancement to encourage and harmonize water resources management for sustainability in both developing and advanced nations. A broad survey of groundwater potential and the essential requirement for water quantity and quality management strategies is a key factor for health and environmental protection [1, 2].

This study delineates a groundwater promising zone and its protective capacity to evaluate groundwater vulnerability to surface contamination alongside ASSM to enhance water security and associated problems. With the groundwater depletion in many urban cities and the heavy reliance on groundwater (over-exploitation), especially in some parts of arid and semi-arid

regions for both municipal use and irrigation activities [8]. The groundwater development and water distribution mechanisms should be designed to ensure quality groundwater exploration for sustainability [9]. Groundwater protection is a good approach and a key factor for water security and sustainability because the challenge of water scarcity does not always mean a lack of abundance of water but it could sometimes mean the quality of water available [1, 10]. Groundwater vulnerability has been defined as the state where an aquifer (water-bearing unit) becomes susceptible to contaminants from an external source, which in turn becomes unfit for consumption. Therefore, the quality of groundwater can be improved by identifying a suitable zone with high aquifer protective capacity or less vulnerability to surface contamination. Groundwater pollution has been attributed to several anthropogenic activities such as oil spillage, domestic waste, fertilizers, pesticides etc. However, dumpsite leachate plumes appear to be the major source of groundwater pollution [1, 11]. Therefore, indiscriminate disposal of solid wastes and other pollution sources should discourage religiously. This is because many pollution sources like solid waste leachate plumes, sewages and fuel storage tank linkages are more likely to discharge beyond the ground surface down to the aquifer units [1], thereby breaking aquifer protective cover usually provided by the soil layers [11, 12]. A study noted that the aquifers in the Precambrian Basement Complex usually occur at shallow depths [13]. That is, an adequate subsurface layer thickness with low hydraulic conductivity can provide an effective soil layer protective capacity for groundwater reservoirs. Therefore, mapping aquifer protective capacity and aquifer vulnerability to avoid water pollution is becoming more critical to address the degree of groundwater susceptibility to surface contamination [2, 10, 12, 14].

However, groundwater contamination, frequent borehole failures, aquifer vulnerability, and climate variability phenomena have been attributed to the major challenge of water supply and sustainability in many parts of the world [13, 15–18]. To mitigate against these challenges, three clear priorities are identified, starting with the most critical one, (i) the public health challenges resulting from aquifer vulnerability to surface contamination, (ii) water scarcity resulting from frequent borehole failures, (iii) preservation and sustainability through adequate storage support mechanism to ensure all citizens have free access to water in quantity and quality. All three priorities are very important for achieving both local and global water security and water management (sustainability). This research focuses on three major aspects of water resource management strategies, starting from (i) identifying the aquifer promising zone and (ii) the aquifer overburdened

protective capacity layer overlaying the groundwater reservoirs through geophysical investigation, and (iii) the aquifer storage support mechanism as well to improve the existing storage facilities. The study also engages on what is needed to be done to effectively manage water systems for local, national and international current circumstances. Finally, the way forward in resolving the current challenge and tackling the priorities may vary from one nation to another depending on the concerned nation's current circumstances and the nature of groundwater resources available.

2 Background study

2.1 Borehole failures in Nigeria

Studies on groundwater development in Nigeria and the neighbouring African countries have a long history as reported by several studies. Continuous efforts to ensure the country's water quality and quantity have not yet yielded the required results and expectations. Borehole failure is a common phenomenon across the world, especially in developing nations like Nigeria where boreholes are located according to the owners' choice of location [2]. A study reported the performance of 69 boreholes drilled in the Basement complex rocks of Kaduna, Nigeria [19]. The result shows that out of 69 boreholes investigated, about 30% were not productive, while (70%) indicate successes with low yields. The study noted that the high failure rate was because most of the boreholes drilled were located without good hydrogeological/geophysical investigation of the site. However, to identify aquifer promising zone, adequate knowledge of regional hydrogeology is required, and geophysical techniques provide better aquifer information in different geological contexts [1, 20]. A separate report on 256 boreholes drilled in different parts of the crystalline rocks of Southwestern Nigeria, shows that the boreholes sited in different parts of crystalline rocks have a record of low yields and failures [15]. The report shows that 105 boreholes constructed by one driller indicated 100% success. 111 boreholes drilled by three drillers show that about 35 boreholes were unproductive, representing a 32% failure rate, while the so-called successes were not encouraging due to low yield [15], identified seasonal variation in the level of groundwater, poor geophysical investigation, shallow penetration in the water-bearing unit, and machinery failure are major causes of borehole failure.

Another 40 boreholes drilled by other companies reported 24 failures representing a 60% failure rate, while the rest 16 boreholes indicate success performance is low. This high failure rate was attributed to the seasonal variations in water level and lack of geophysical investigation

of the site concerned. A study investigates the causes of borehole failures in recent times in Kaduna Nigeria [21]. The result shows that 79% of boreholes are functional, while 20% are not functional. It further noted that 80% of the drilling companies undergo post-drilling evaluation of the performance of drilled wells before the actual drilling. The study attributed the high borehole failure rate to the depletion of the aquifer, equipment failure, poorly well design and construction. [17], applied VES to investigate the causes of massive borehole failure in Kaura, Kaduna, Nigeria, using state resistivity tomography techniques. The report shows that out of 50 boreholes drilled within the study area, 31 boreholes are not functioning, while only 19 boreholes are functioning. The investigation identified poor design and construction, poor groundwater potential, hydrogeological investigation, and maintenance as possible factors of borehole failures in the region. It was noted that a poorly designed and constructed borehole could lead to sand/clay pumping, which in turn affects the hand pump's rubber seals [17].

2.2 Water security and sustainability

Atlit-Yam village in northern Israel maintains the oldest hand-dug well installed about 8000 years ago [22]. However, mankind has undoubtedly enjoyed groundwater until rapid population expansion and urbanization, which has increased pressure on groundwater resources and consequently upsurge in groundwater depletion and pollution. Therefore, the concept of water security and sustainability became an issue of concern for both local and international communities [23]. Several studies have attributed groundwater depletion to harsh climatic conditions in most developing nations, especially in the sub-Saharan Africa region [16, 24]. This horrible climate has led to drought in several African countries, which has negatively impacted aquifers' potential and vulnerability. However, it has been noted that aquifer vulnerability is low when the infiltration rate is high and vice versa [12]. Several UN organizations made a collaborative effort in 2000 to evaluate groundwater vulnerability in many African nations [25], whose central mission is to address the quality of groundwater for sustainability.

2.3 Site description

The study area has vast farmland located at Kujama, Kaduna, Nigeria. It is characterized by gentle slopes and penepains (Fig. 1). It is located on the geographical coordinates of latitude and longitude 10° 26' 36" N and 07° 32' 36" E. The study area covers a total landmass of 17,600 square meters with an average height of 662 m above sea level within Kujama farmland. The case study consists of

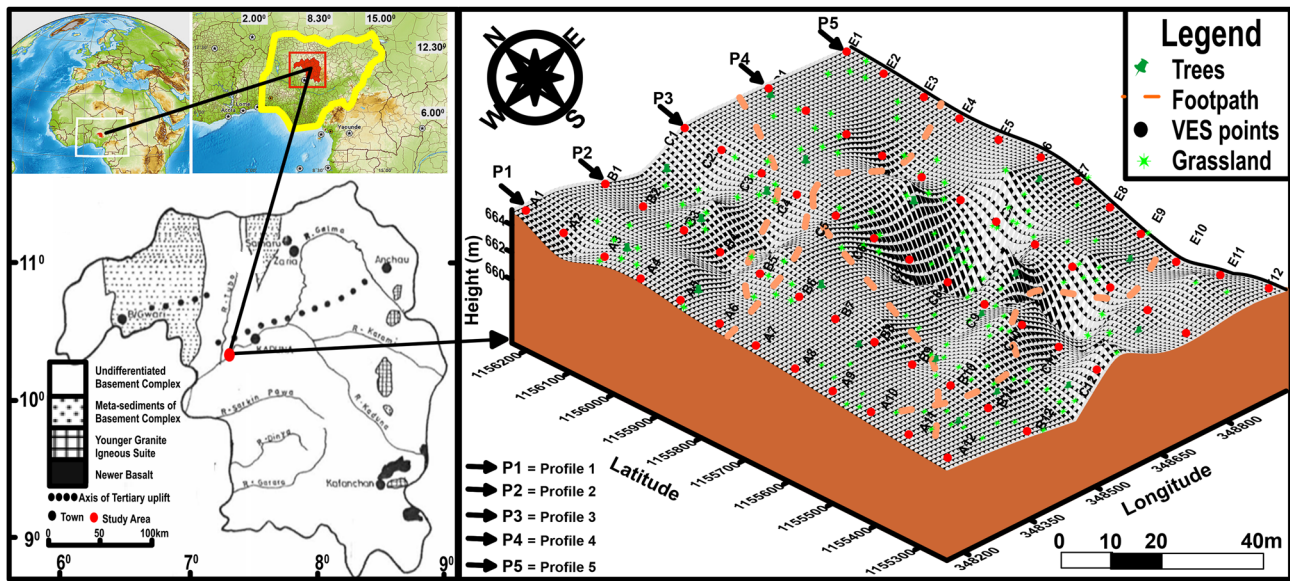


Fig. 1 Map of study area showing the VES points, the profiles and their elevation

a crystalline basement complex with metamorphic rocks. The main aquifer components of the basement complex occur within the silty/clay/ weathered and fractured basement [26, 27]. The rocks in the area are usually capped by laterites and sandstones. The laterite is highly consolidated, especially at the surface and weathered into lateritic nodules mixed with silty and sandy clays [28]. The study area consists of regional gneisses, granites and soil layers of lateritic soil, clay, silty, clayey and weathered/ fractured bedrock [26]. However, some rock outcrops of hard-resistant granite in the area are usually exposed to erosion and affected by weathering activities [28]. The current crops grown in the study area include both cash and food crops (such as guinea corn, maize, groundnuts, millet, tomatoes, beans, ginger, and other variety of vegetables. Irrigation canals are rarely practised in the area of study. According to [2], the study area is usually drained by both infiltration and runoff, and it exhibits swampy conditions during rainy seasons, while the upper parts of the terrane drain freely, the streams in the area fluctuate seasonally.

3 Materials and methods

Figure 2 illustrates a geophysical approach and important steps in identifying groundwater promising zone for water security and sustainability.

3.1 Electrical resistivity survey

Electrical resistivity was generated using the Schlumberger array. A grid layout of 5 by 12 VES points was established

in the NW–SE direction of the study area. The subsurface property (resistivity) is measured from the response of subsurface materials to the current flow [29], and it can be expressed by Eq. (1):

$$\Rightarrow \rho_a = RK \tag{1}$$

where R is resistivity ($i.e.R = \Delta V/I$), and K is the geometrical factor, which depends on the arrangement of the four electrodes [29]. The K-factor can be defined in Fig. 3 as:

$$K = 2\pi \left[\left(\frac{1}{AC} - \frac{1}{CB} \right) - \left(\frac{1}{AD} - \frac{1}{BD} \right) \right]^{-1} \tag{2}$$

Considering Fig. 3, we can say;

$$\begin{cases} AC = BD = \left(\frac{L-a}{2} \right) \\ CB = AD = \left(\frac{L+a}{2} \right) \end{cases} \tag{3}$$

Substituting Eq. (4) into Eq. (3), the geometry factor for the Conventional Schlumberger array becomes:

$$K = \frac{\pi}{4} \left[\frac{L^2 - a^2}{a} \right] \tag{4}$$

3.2 The Dar Zarrouk parameters

Dar Zarrouk (D-Z) parameters can be applied to compute the aquifer protective capacity [30]. D-Z is a vital tool for groundwater exploration because D-Z parameters provide a useful and bold solution in delineating aquifer potential.

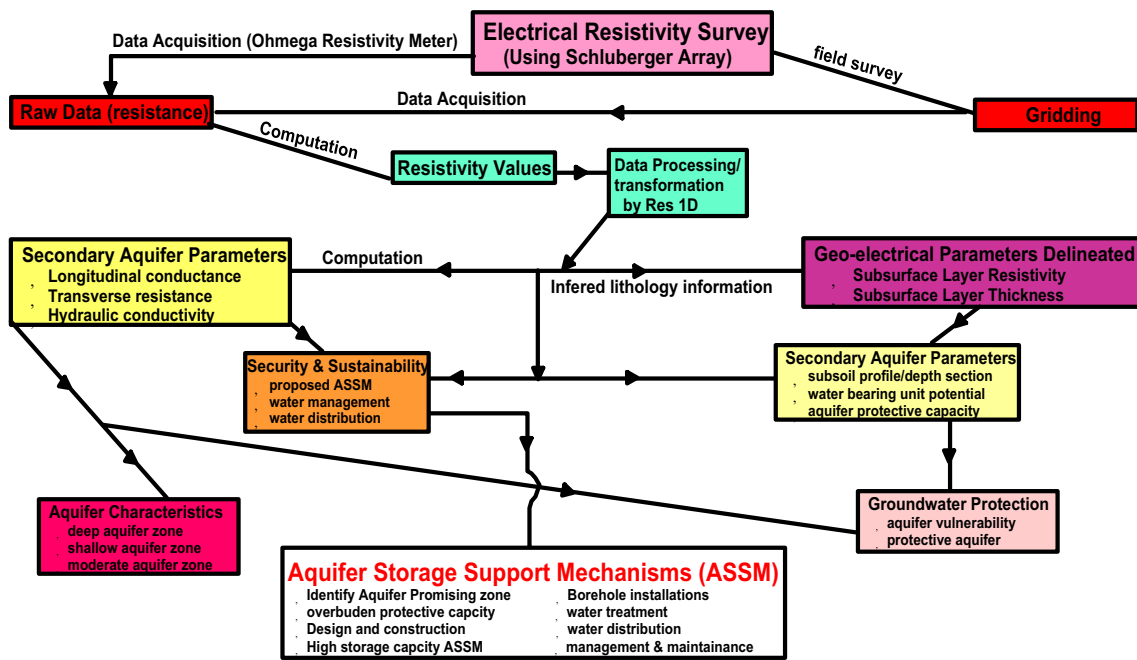


Fig. 2 Flowchart illustrating the processes and results

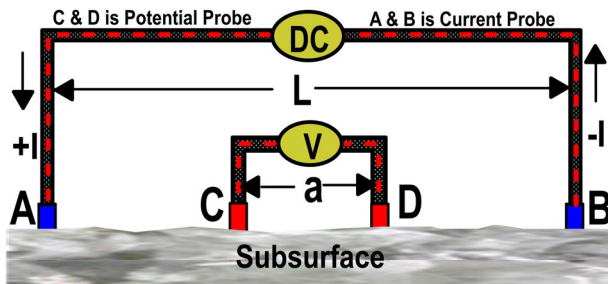


Fig. 3 Schlumberger configuration

Geoelectric layer thickness (h_a) and apparent resistivity (ρ_a) are the basic parameters adopted by DZ to define the longitudinal conductance, (S_L) and transverse resistance, (R_T) expressed in Eqs. (5) and (6) respectively [30, 31]:

$$S_L = \sum_{i=1}^n \frac{h_a}{\rho_a} \tag{5}$$

$$R_T = h_a \cdot \rho_a \tag{6}$$

where: ρ_a is the resistivity of the overburden layer and h_a is the thickness of the overburden layer. High values of transverse resistance and longitudinal conductance reflect a relative sequence of thick stratiform, which should be accorded the highest priority in terms of groundwater promising zones [2].

Table 1 Protective capacity rating [32]

Protective capacity (mhos)	Rating
< 0.1	Poor
0.1–0.19	Weak
0.2–0.69	Moderate
0.7–4.9	Good
5–10	Very good
> 10	Excellent

3.3 Aquifer protective capacity

Aquifer protective capacity is a measurement of the resistive nature and the thickness of subsurface layers of soil overlying the aquifer. For an effective soil layer protective capacity for groundwater reservoirs, the water-bearing unit should be overlying by adequate subsurface layer thickness with low hydraulic conductivity. This is because recent studies identified the earth's subsurface as a natural filter to the infiltrating fluid and its ability to resist fluid is a measure of its protective capacity [2, 12, 32, 33]. Therefore, aquifer protective capacity (P_c) can be expressed by Eq. (7) (Table 1):

$$P_c = \sum \frac{h_a}{\rho_a} \left(\sum S_L \right) \tag{7}$$

3.4 Hydraulic conductivity

Hydraulic conductivity has been identified as one of the most vital parameters for estimating the rate at which contaminants travel [34]. However, computation of effective hydraulic conductivity is not usually obtained directly from aquifer geo-electrical parameters but through aquifer pumping tests, which has been considered one of the most reliable means [31]. When aquifers' yield is low, a slug test is required, but where these data are not available, hydraulic conductivity could be estimated [12]. Consequently, Eq. (8) establishes an expression between the hydraulic conductivity and the layer resistance [31, 35]. Where K is the hydraulic conductivity.

$$K = \frac{1}{9750000} \rho_a^{1.195} \text{ (m/sec)} \tag{8}$$

3.5 Geological section from borehole data

Figure 4 is borehole data acquired by the National water resources institute (NWRI) around the study area [36], which provides subsurface vertical information in a six-inch diameter cylindrical borehole. The data provides a good geological insight for this research for critical analysis. The down-hole data presents four (4) distinctive subsurface layers as shown in Fig. 4 [36]. While the topsoil is made up of soft lateritic soil/lateritic clay layer, the second layer consists of gravel, brownish fine sand and quartz interpreted to be a weathered layer with an average thickness of 18 m. The third layer with an average thickness of 10 m indicates a gap and is interpreted to be a fractured zone (Fig. 4). The layer consists of granite rocks with an infinite depth encountered at 40 m depth and is interpreted to be the fresh basement within the region [36].

4 Data processing

To investigate the subsurface structural trends and soil profile sequence of the subsurface formation, the acquired data were qualitatively interpreted with the use of computer Iteration software (*Res ID version 1.00.07 Beta*). Res1D is automatic computer software that processes the subsurface data aquifer to determine the ground layers, resistivity values and layer thickness. The soil depth section or profile was prepared from the resistivity model parameters obtained from RED 1D for critical analysis of groundwater potential. Consequently, Eqs. (5), (6) and (8) were used to compute aquifer parameters such as transverse resistance, longitudinal conductivity and hydraulic conductivity presented in Table 2.

5 Results and discussion

Table 2 shows the summary results of the aquifer parameters obtained from the study area across the sixty (60) VES stations. The primary geo-electrical parameters delineated were transformed and used to prepare the geo-electric section (depth profile) (Fig. 5). This is to reveal the extent of the geo-electric aquifer geometry and subsurface layers in the investigated region, which reflects both vertical and lateral lithological variations.

The resistivity values and the aquifer thickness, which is the top priority to identify groundwater potential where aquifers occur at a deep subsurface and fractured zone. Figure 6a, b display the variation in aquifer thickness and the depths to the aquifer unit respectively. The overburden thickness overlaying the aquifer unit portrayed in Figs. 5 and 6a could serve as aquifer protective index capacity due to the presence of sand/lateritic clay soil, which can filter contaminants from the seeping ground. However, this

Fig. 4 Geological well-logs (borehole) data around the study area modelled after [36]

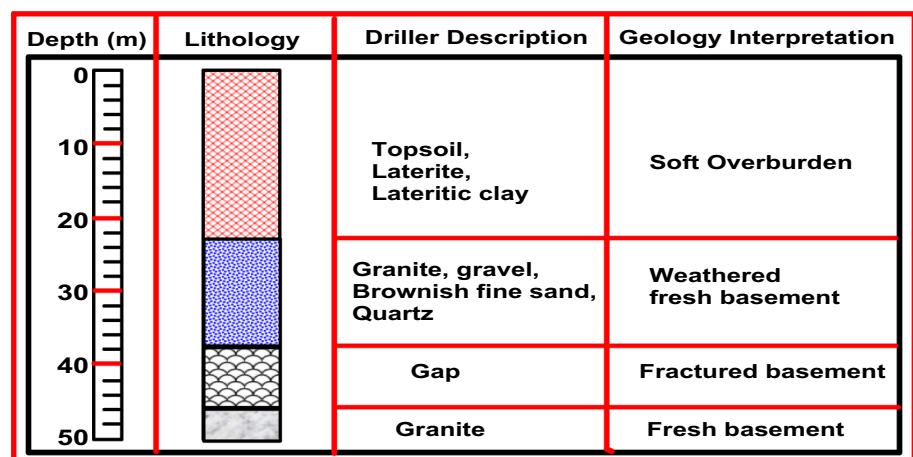


Table 2 The Summary of the aquifer parameters estimated from the geoelectric parameters across the sixty (60) VES stations of the case study

SN	VES Pts	Overburden thickness overlay the aquifer x(m)	Aquifer resistivity ρ (Ω m)	Aquifer thickness h (m)	Transverse resistance R_T (Ωm^2)	Longitudinal conductivity S (Ω^{-1})	Hydraulic conductivity K (m/day)
1	A1	7	85	9	765	0.1059	1.7913
2	A2	13	290	10	2900	0.0345	7.7638
3	A3	8	240	9	2160	0.0375	6.1924
4	A4	9	289	16	4624	0.0554	7.7318
5	A5	19	328	26	8528	0.0792	8.9945
6	A6	9	231	27	6237	0.1169	5.9159
7	A7	9	160	30	4800	0.1875	3.8145
8	A8	15	290	13	3770	0.0448	7.7638
9	A9	9	194	33	6402	0.1701	4.8021
10	A10	8	89	21	1869	0.2360	1.8925
11	A11	6	75	24	1800	0.3200	1.5424
12	A12	8	21	9	189	0.4286	0.3369
13	B1	13	216	32	6912	0.1481	5.4599
14	B2	19	285	16	4560	0.0561	7.6041
15	B3	8	54	22	1188	0.4074	1.0416
16	B4	3	101	9	909	0.0891	2.2013
17	B5	9	182	27	4914	0.1484	4.4493
18	B6	9	162	8	1296	0.0494	3.8715
19	B7	5	37	14	518	0.3784	0.6630
20	B8	6	307	45	13,815	0.1466	8.3107
21	B9	4	246	36	8856	0.1463	6.3779
22	B10	5	107	32	3424	0.2991	2.3584
23	B11	5	93	32	2976	0.3441	1.9946
24	B12	10	210	43	9030	0.2048	5.2791
25	C1	10	87	35	3045	0.4023	1.8418
26	C2	6	67	8	536	0.1194	1.3479
27	C3	18	87	33	2871	0.3793	1.8418
28	C4	12	293	38	11,134	0.1297	7.8598
29	C5	8	263	32	8416	0.1217	6.9081
30	C6	10	24	10	240	0.4167	0.3952
31	C7	12	104	52	5408	0.5000	2.2796
32	C8	6	77	33	2541	0.4286	1.5917
33	C9	8	268	8	2144	0.0299	7.0653
34	C10	10	138	37	5106	0.2682	3.1964
35	C11	15	261	44	11,484	0.1686	6.8453
36	C12	19	206	16	3296	0.0777	5.1592
37	D1	7	290	33	9570	0.1138	7.7638
38	D2	13	793	59	46,787	0.0744	25.831
39	D3	8	150	8	1200	0.0533	3.5313
40	D4	8	294	17	4998	0.0578	7.8919
41	D5	19	39	22	858	0.5641	0.7060
42	D6	8	57	11	627	0.1930	1.1111
43	D7	9	225	8	1800	0.0356	5.7328
44	D8	3	173	9	1557	0.0520	4.1877
45	D9	9	63	14	882	0.2222	1.2523
46	D10	8	277	20	5540	0.0722	7.3497
47	D11	5	218	29	6322	0.1330	5.5203

Table 2 (continued)

SN	VES Pts	Overburden thickness overlay the aquifer x(m)	Aquifer resistivity ρ (Ω m)	Aquifer thickness h (m)	Transverse resistance R_T (Ω m ²)	Longitudinal conductivity S (Ω^{-1})	Hydraulic conductivity K (m/day)
48	D12	8	248	19	4712	0.0766	6.4399
49	E1	3	160	8	1280	0.0500	3.8145
50	E2	8	76	38	2888	0.5000	1.5670
51	E3	5	210	40	8400	0.1905	5.2791
52	E4	4	49	16	784	0.3265	0.9275
53	E5	9	45	18	810	0.4000	0.8377
54	E6	10	137	20	2740	0.1460	3.1688
55	E7	7	69	27	1863	0.3913	1.3962
56	E8	3	156	30	4680	0.1923	3.7008
57	E9	4	264	40	10,560	0.1515	6.9395
58	E10	6	333	23	7659	0.0691	9.1586
59	E11	5	377	13	4901	0.0345	10.623
60	E12	6	211	34	7174	0.1611	5.3092
Average		8.6	185	24	4954	0.1922	4.7420

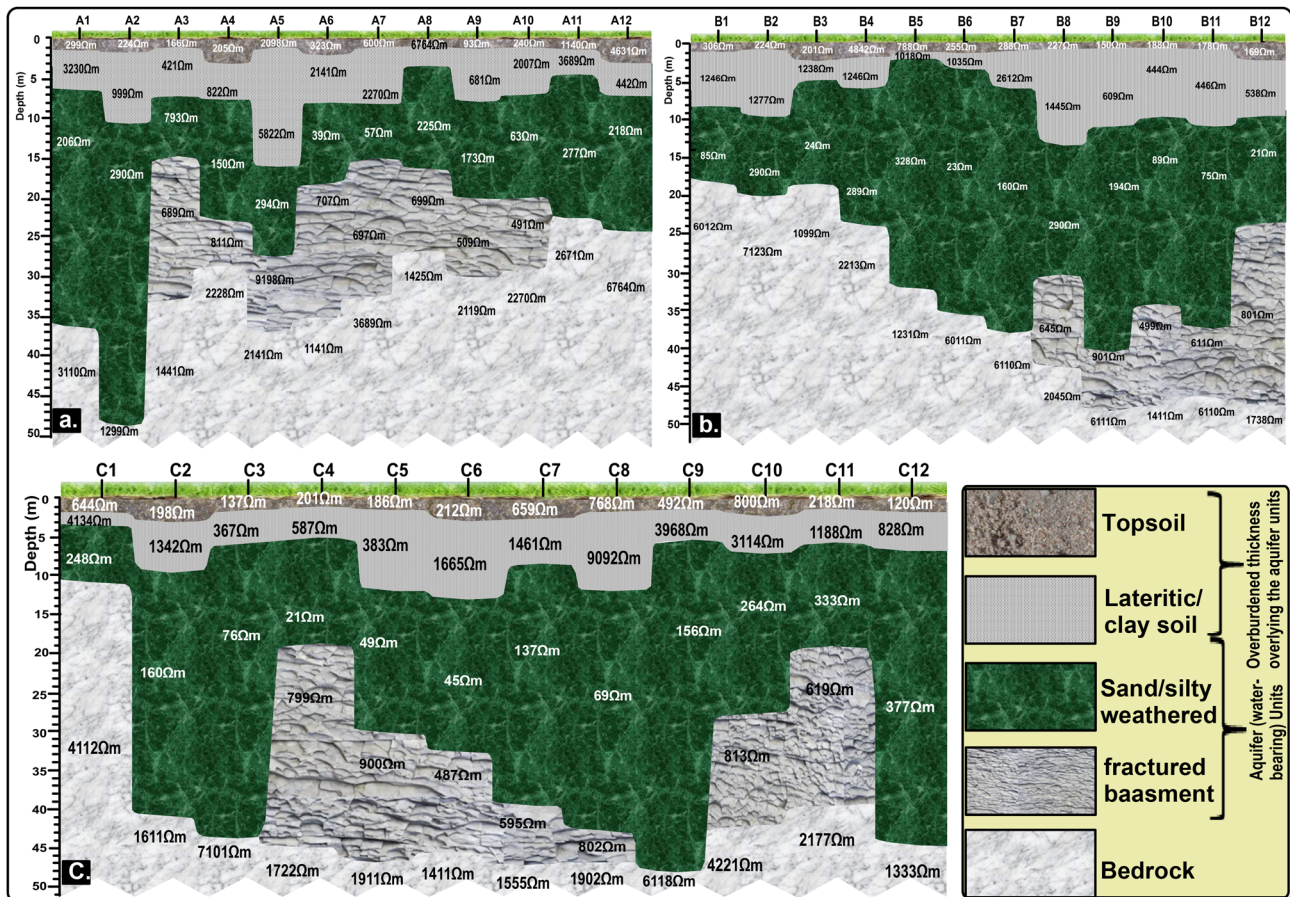


Fig. 5 Goelectric/geologic section concerning five sounding points of the first to third profile (a–c) of the study area showing the resistivity values and the layer thickness

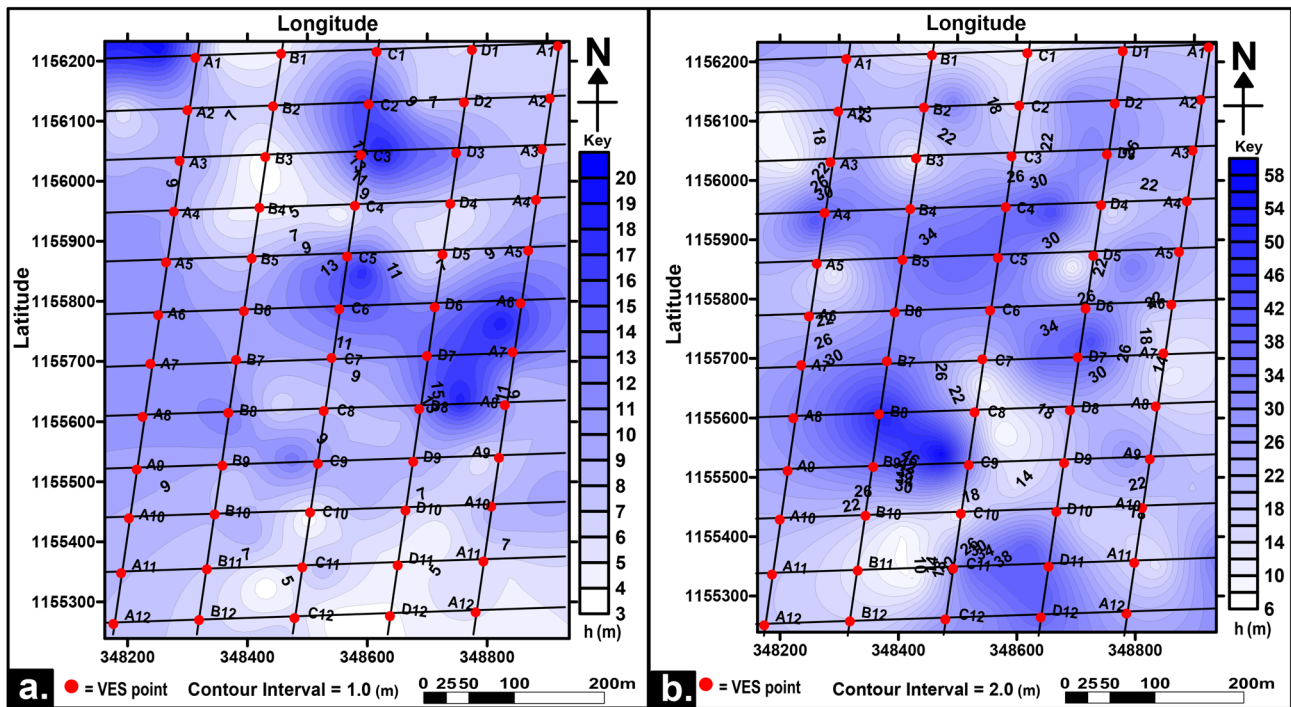


Fig. 6 Aquifer potential parameters showing **a** the overburden thickness overlain the water-bearing unit and **b** the thickness of the regional aquifer (water-bearing) unit

is limited, especially when there is a geological vent paving way for pollutants. [2], noted that aquifers occurring within the depths of 1–11 m are considered shallowed, while 12–29 m are considered moderate, and beyond 29 m is a deeper aquifer, which is the most favourable zones for ground development. Since the regional aquifer layer resistivity values vary between 21 and 294 Ω m, while the aquifer layer thickness values vary between 8 and 59 m and the overburden thickness overlay the aquifer unit varies between 3 and 20 m. The deeper aquifer zones vary between 30 and 59 m (Table 2), which could be suitable for groundwater development. The shallow aquifer occurs between 8 and 14 m, these regions of the aquifer are not suitable for groundwater development and are susceptible to surface contaminations. The intermediate or moderate region of the aquifer occurs between the depths of 12–29 m (Table 2). This section of the aquifer could be suitable for groundwater development considering the borehole data in Fig. 4. However, for water security and sustainability, multiple boreholes should be sited at the delineated aquifer potential promising zone where the aquifer is fractured and occurs within a depth of 30 m and below. The weathered/fractured basement constitutes the delineated aquifer potential zone. However, fine sand/weathered/fractured encountered in most parts of the study area constitute the regional aquifer units, which are largely responsible for the groundwater

potential. Identification of high aquifer potential zones is a fantastic approach for groundwater development, which will resolve the challenge of borehole failures. The hydraulic conductivity of both aquifer regions and the overburdened thickness overlying the aquifer was estimated from the layered resistivity values. The results show that the estimated hydraulic conductivity of the aquifer zone varies between 0.337 and 10.62 m/day on an average of 4.36 m/day (Table 2), which is highly variable. However, the overburdened soil layers overlying the aquifer demonstrated poor hydraulic conductivity values varying between 0.0721 and 0.639 m/day. A high hydraulic conductivity index indicates high groundwater movement and this could enhance the aquifer recovery and yield processing.

Figure 7a is aquifer transverse resistance illustrating an aquifer promising region with high productive index capacity in the study area. Groundwater quality is a function of many geological and environmental factors such as rock geochemistry, waste materials, sewage water, oil spillage etc. Groundwater depletion may not always mean a drop in groundwater level but could also be attributed to the quality of water available for consumption [18]. Groundwater reservoir protection (GRP) was evaluated from aquifer longitudinal conductance. The longitudinal conductance was computed from aquifer layer resistivity and its thickness and contoured to produce an aquifer protective capacity map (Fig. 7b). The overburden protective

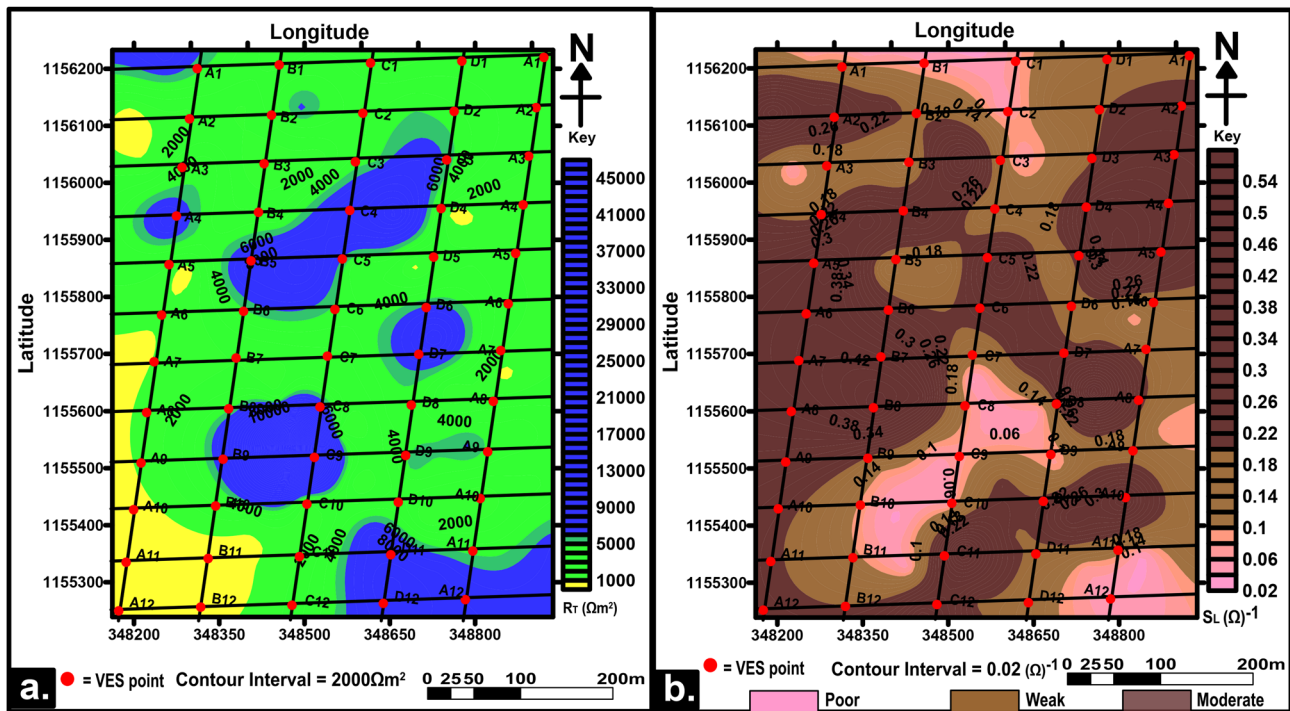


Fig. 7 Aquifer potential and protective Index parameters showing **a** the transverse resistance and **b** the longitudinal conductance

capacity was categorized into poor, moderate and good protective capacity. The moderate and good protective capacity zone is the favourite zone for groundwater development. Studies show that the higher the longitudinal conductance, the higher the aquifer protective capacity [2, 12]. Though, several nations, especially developed nations have since adopted sanitary landfills that can prevent leachate plumes from seeping the ground down to the water table [18, 37]. Identification of an area of high aquifer potential zone with a very high aquifer protective capacity is a better approach for groundwater protection and sustainability. The aquifer protective capacity accounts for groundwater vulnerability to surface contaminants emanation from anthropogenic activities such as dumpsite leachates, oil spillage, agrochemical activities etc. These contaminants can seep down the ground to pollute the groundwater if the subsurface protective layers overlying the groundwater are porous. Groundwater pollution is a consequence of a weakly overburdened protective capacity, which shortchanges water security as a central mission of sustainable development goals (SDGs). However, the poor hydraulic conductivity nature of overburden layers overlying the aquifer units indicated a high aquifer protective capacity index against subsurface contaminations. Considering Fig. 5, fractured zones were encountered in VES points A3–A10 (Fig. 5a), B8–B12 (Fig. 5b) and C4–C8, C10–C11 (Fig. 5c). In addition, these fractured regions also occur at deeper zone, which

invariably makes them safe from near-surface contaminants. However, A1, A2, B5–B7, C2, C3C9, and C12 show strength in groundwater potential due to their thickness (occurring within 30–40 m).

6 Alternative storage support mechanisms (ASSM)

Identification of an aquifer-promising zone with a high protective capacity index is a good approach for groundwater development but may not be enough for water security and sustainability in the face of the growing scarcity of quality water, which has significantly increased pressure on urban groundwater across the world. This paper emphasized the use of additional ASSM in response to water security as the way forward for water resource management and sustainability, which has been suggested by several remarkable pieces of literature [4, 7]. The major target of ASSM is to enhance water security while improving the existing water storage facilities. With the recent and ever-upsurge of borehole failures across the globe as drought and unfavourable climate events unfold, there is a need for critical research to identify alternative measures to support natural ground aquifer storage. However, previous efforts mostly focused on the delineation of aquifer promising zone and aquifer protective capacity but continuous increases in groundwater depletion and frequent

borehole failures in urban regions have compelled the current effort towards water surety and sustainability. ASSM is an alternative or additional artificial water storage facility to harvest rainwater and groundwater, especially during the wet season. ASSM can be designed to function as a: (i) rainwater harvesting reservoir for tapping untapped excess rainwater, and (ii) groundwater storage reservoir for storing ground, especially during wet seasons, where two major sources of water (rainwater and groundwater) will be used (Fig. 8). Therefore, as pressure mounted on our nation's groundwater resources especially in the global metropolitan cities due to over-exploitation via agricultural irrigation, and domestic and industrial use. ASSM proves essential requirements to forestall water security, especially during dry periods. Effective ASSM can be achieved through the following steps;

- Identify aquifer promising zone: this will ensure constant water supply through all the seasons.
- Overburden protective capacity: this will ensure the regional groundwater is protected against surface contamination.
- Design and construction: should be done with anti-corrosive materials such as ceramic materials to avoid rusting.
- High storage ASSM: should be designed with high storage capacity index to ensure water reservoir and ade-

quately supplies water, while enhancing water security and sustainability, especially during dry periods.

- Installation of boreholes: the boreholes are proposed to be installed in an aquifer promising zones where the basement rocks are fractured and occurred at deeper.
- Water treatment and distribution: should be designed to accommodate water treatment mechanisms to ensure quality water supplies.
- Management and maintenance: all the decision-makers and the stakeholder in water resource management should be involved in adequate maintenance of facilities.

7 Conclusion

The central mission of the study is to identify aquifer promising zones and aquifer protective capacity index where the basement rocks are fractured occurring at a deep depth to promote regional groundwater development and sustainability in response to water security and sustainability via geophysical investigation. However, continuous efforts made by previous studies, governmental, and non-governmental agencies towards the pursuit of abundant and quality water have not yielded the required results to meet up with the ever-desire water security and sustainability under the growing water demand and

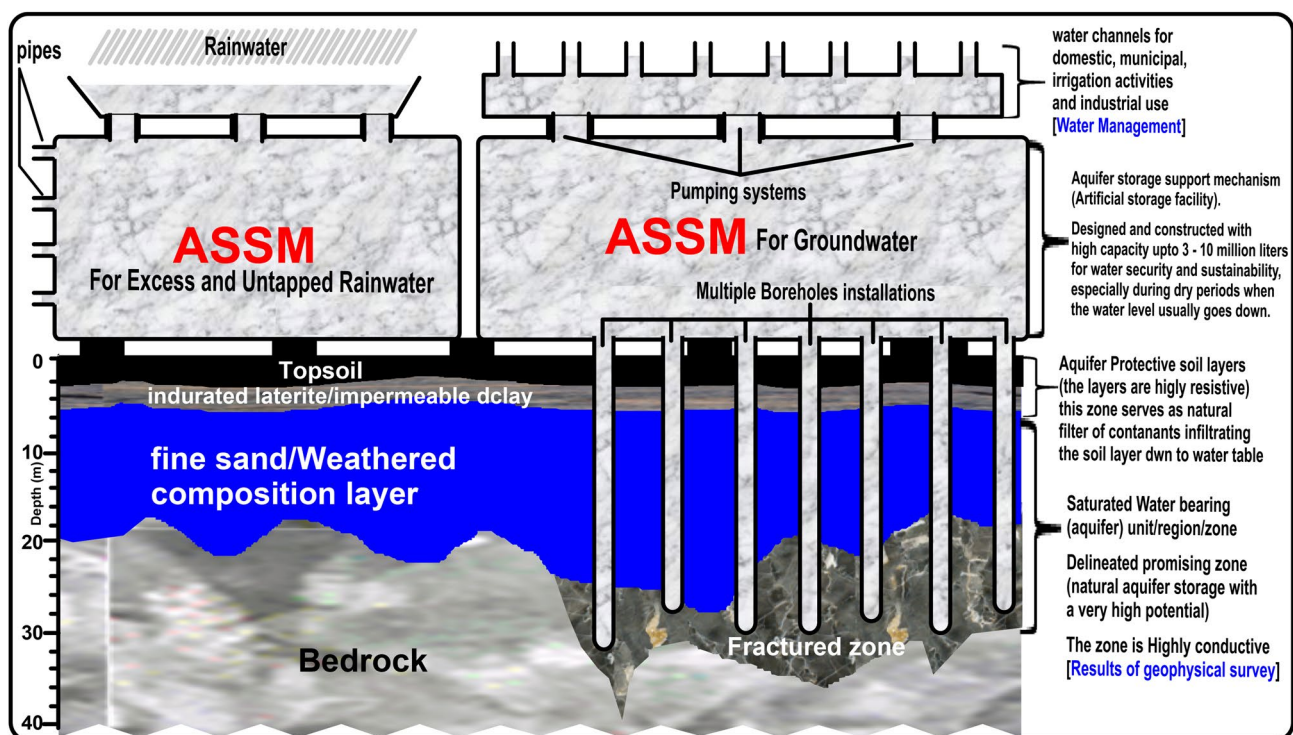


Fig. 8 Aquifer promising zones and alternative/artificial storage support mechanisms

challenge. The study provides a valuable and bold step in delineating an aquifer-promising zone with a very high overburden protective capacity and identifying ASSM to promote the central mission of SDGs (water security). With the horrible nature of the climate in most developing nations, especially in sub-Saharan Africa, a substantial artificial storage support mechanism is required to support the natural groundwater storage capacity for water security and sustainability. To achieve this, the study suggests that geophysical data should be used to identify the high aquifer potential zone with high aquifer protective capacity, thereafter, installation of multiple boreholes to supply well-designed and constructed artificial storage support mechanisms. With these three phenomena identified, the three clear priorities (public health, water scarcity, and preservation and sustainability) of the study were addressed. More also, to attain water security, aquifer zones encountered between the depths of 15–59 m could be used for groundwater development. The study, therefore, draws the following conclusion;

- a. Dc electrical resistivity investigation has been successfully used to delineate aquifer potential promising zone and overburden protective capacity overlying aquifer region, and it remains the best option for groundwater exploration and sustainability.
- b. The study provides a valuable and bold step in delineating aquifer promising zone to promote the central mission of SDGs (water security).
- c. The target of water security goes beyond the assurance of abundant water, but the safety and quality of available water is the top priority of the water security crusade.
- d. Groundwater supply mechanisms should be designed and constructed with sufficient storage support mechanisms to ensure the quality of groundwater extraction and sustainability
- e. Identification of an area of high aquifer potential with a very high aquifer protective capacity is a better approach for groundwater development, security and sustainability.
- f. High aquifer promising zone with a very high overburden protective capacity against surface contaminations alongside ASSM provides the answer to the current global groundwater problems, especially in developing nations and Saharan regions during dry periods.
- g. One significant consequence of the ASSM is groundwater booming and water security, especially in developing nations and Saharan regions.
- h. ASSM will harness the excess and unharvested rainwater for domestic, agricultural and municipal use to meet the growing water demand.

Finally, the geophysical investigation indicates a good tool for identifying the promising zone for groundwater development, while the determination of overburden protective capacity helps to identify a thick subsurface layer with a low hydraulic conductivity that can provide an effective soil layer protective capacity for groundwater reservoirs. The storage support mechanism provides a water storage facility that can support groundwater storage capacity, especially during dry periods. The rate of population expansion and climate variability in the world, especially in Nigeria, required additional storage facilities such as ASSM that will be 5 times the current storage capacity in the next few decades to come, which may even increase if necessary steps are not taken into account for future direction.

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Data availability The datasets generated during and/or analyzed during this study are available on request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial conflicts of interest to disclose.

Ethical approval I declare that this research is original work carryout by all the authors and that no part of this work has been previously published in any journal. All information provided in this work has been duly acknowledged in the text and the references provided.

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