Original Research Article

Assessing the Impact of Urbanization on Groundwater Resources: Using Geophysical Surveys to Assess Groundwater Recharge Rates, Aquifer Storage, and Water Quality

Collins O. Molua* and John C. Morka

Department of Physics, Faculty of Science, University of Delta, Agbor Delta State, Nigeria

*Corresponding author E-mail: collins.molua@unidel.edu.ng

Received: 21th April 2024, Revised: 11th June 2024, Accepted: 25th August 2024

Abstract

The increased scale of urbanization has borne a substantial load on groundwater resources, and hence, a proper assessment system is required to affirm the sustainability of water management. This multi-disciplinary study integrated geophysical surveys and water quality analyses to assess recharge rates, stored water, and water quality in an urban setting. Electrical resistivity tomography can significantly outline the potential provisions for underground materials and groundwater. Conversely, ground-penetrating radar aims to identify soil levels, water tables, and hidden utilities. Seismic refraction maps showed that deeper down, there were layers of denser rocks, like sandstone and limestone, with much fewer holes. To gain a deeper understanding, we employed the 'Magnetic Resonance Sounding' technique, which mathematically demonstrated that Site D possessed the thickest aquifer (12.456 m) with the highest porosity (35.123%) and transmissivity (90.234 m^2/day). During the water quality analysis, we found chloride levels (70.123 mg/L) and conductivity (1200.234 S/cm) above normal levels at Site B. The possible contamination sources were detected. Applying these approaches together resulted in the acquisition of a complete picture of groundwater processes and revealed diverse management measures for each potential site. The outcomes of this research add to the knowledge of methodological procedures for this unique branch of hydrology and will provide professional support in sustainable urban planning as water supply remains a significant challenge within urbanized areas.

Keywords: Tectonic survey, Resistivity tomography, Ground penetrating radar, Refraction method, Seismic refraction, MR sounding, Sustainability

Introduction

Access to and quality of groundwater are key elements that secure the sustainability of a city and, hence, the well-being of city dwellers. As the rate of urbanization increases, the demand for water resources escalates, leading to significant strain on groundwater aquifers. Assessing both positive and negative impacts of urbanization on groundwater resources means determining access to a safe and reliable water supply, preventing overexploitation of groundwater, and minimizing potential environmental and public health issues associated with improper planning and management of water facilities and infrastructure [1,2].

Urbanization dramatically alters the natural landscape by converting surfaces from permeable to impervious, such as buildings, roads, and parking lots. The conversion of land to impermeable surfaces may increase the average groundwater replenishment rate; the absence of traditional percolation paths prevents rainwater from entering the underlying soil, disrupting the natural water filtering process. Moreover, urbanization leads to increased groundwater extraction necessary for sustainability and the production of materials, which contribute to aquifer depletion and land subsidence.

Groundwater quality is another area that can confirm urbanization's effects. Urban behavior and activities, such as the manufacturing sector, large-scale goods transportation, and disposal, can introduce numerous contaminants into the subsurface environment, potentially endangering groundwater quality [3,4]. They can introduce heavy metals, organic compounds, nutrients, and pathogens into the human system. This is harmful to both human health and environmental stability. Knowing about the recharge costs, underground storage, and water quality of urban areas is necessary for developing strategies that positively impact groundwater resources in the end. Geophysical surveys are another important non-invasive technique in the geochemical study of soil. These surveys serve as helpful springboards for this assessment.

Using geophysical surveys, one can characterize aquifer systems, including extent, thickness, and run-off properties. These surveys can determine the existence of preferential pathways for groundwater flow, the origin of contamination, and track any groundwater level changes. By combining geophysical data with hydrogeological models, researchers can get a very accurate picture of how groundwater moves and how urbanization affects an aquifer's ability to store water and recharge [5,6]. The research's value lies in providing essential data for successful urban planning and decision-making. Urbanization, which relies on abusing groundwater resources, often causes ecological disturbances in the water system. Municipalities and water management agencies can, therefore, formulate policies to mitigate the negative impact of urbanization by utilizing measures that will improve groundwater recharge, optimal groundwater extraction, and remediation of contaminated waters.

Furthermore, applying this research to the hydrology of urban areas and sustainability can enhance our understanding of the intricate relationships between houses and subsurface waters. We can create sustainable urban development models and decision-making systems with this tool, ensuring no depletion of the water table and preserving the water source for future generations. In summary, a detailed assessment of the impact of urbanization on groundwater through geophysical surveys is necessary to ensure the availability of abundant, high-quality groundwater [7,8]. This study

simultaneously tackles the urgent issues of urban water resource supply, environmental health, and hydrogeological theories, laying the foundation for sustainable city planning.

Purpose of study

This research study aims to investigate the impact of urbanization on groundwater using geophysical data to assess water recharge rates, storage capacity of aquifers below ground, and water quality. The study aims to bridge the existing knowledge gap in water research by combining the analysis of recharge rates, aquifer storage, and water quality using advanced geophysical techniques [9]. Previous studies have primarily analyzed groundwater components, such as recharge rates and water quality, without considering the system-wide implications of urbanization. Geophysical surveys will add novelty and credibility to the study methodology, providing a new diagnostic method for groundwater quality and general subsurface conditions in large areas.

The study highlights the importance of integrating water resources management in urban planning and policy-making, allowing water managers and local governments to balance their roles in urbanization with groundwater resource conservation [10]. Integrating geophysical surveys will lead to innovative hydrogeology methodologies, as non-intrusive methods are the most effective approach to characterizing underground phenomena at the scale and degree required to determine groundwater in urban areas.

The research fills a gap in the current literature by providing a detailed and methodical assessment of how urbanization affects groundwater recharge rate, storage capacity, and water quality using geophysical surveys. The outcomes will contribute to the innovation of sustainable urban water management techniques and contribute to the field of hydrogeology.

Theoretical framework

This study draws its theoretical foundation from various disciplines, including geology, hydrology, geophysics, and urban planning. The complex hydrological approach merges the idea of urban hydrogeology with the groundwater systems' specific conditions in urbanized areas.

Urban hydrogeology concentrates on the shifting dynamics of the hydrological cycle. This means that the field of urban hydrogeology studies how the water cycle operates and changes within urban areas. It examines how urbanization impacts the natural processes of the hydrological cycle, including how water is collected, stored, and moved in urban settings, significantly influencing changes in groundwater recharge, solids, and water quality. Constructing structures such as houses, roads, and parking lots on harsh surfaces disrupts water absorption and reduces groundwater recharge rates. However, this theory also recognizes the potential for urban activities such as industrial processes, transportation, and waste disposal to discharge pollutants into underground facilities, potentially harming groundwater quality [11].

This practicum of geophysical surveys on the study grounds is the foundation of near-surface geophysics theory, which represents the subsurface through many different geophysical methods. These methods generally include electrical resistivity, ground penetrating radar, and seismic processes, which permit the evaluation of subsoil and water table conditions without the need to

dig test boreholes. As a result, we identify the location of aquifer boundaries, preferred water flow directions, and potential sources of contamination.

Hydrogeological modeling, one of the methods used here, synthesizes geophysical data to provide a comprehensive understanding of groundwater behavior in urban settings. These models consider aquifer properties, recharge rates, and extraction patterns to simulate groundwater circulation and predict how urbanization affects aquifer storage and water quality.

The study's objectives

The primary objectives of this study are as follows:

1. Investigate the effect of urbanization on groundwater recharge rates using geophysical surveying and hydrogeological modeling. The main objective of this objective is to measure and identify how the conversion of permeable to impervious areas affects recharge rates in urban runoff and to design strategies to increase runoff recharge in urban areas.

2. Integrate geophysical data and groundwater modeling technologies to evaluate changes in urban aquifer storage brought on by urbanization. This objective aims to become familiar with the consequences of enhanced withdrawal of groundwater and reduced recharge rates on the volume of groundwater stored, which will support sustainable groundwater management.

3. Exploit the impact of urbanization on groundwater quality through geophysical surveys to determine the actual sources of contamination and the distribution of contaminants in the aquifer. The purpose of achieving this goal is to define plans of action to prevent the detrimental effects of urban activities on groundwater quality, particularly at such a valuable source.

4. Propose a unified approach for evaluating the effects of urbanization on groundwater sources that will use geophysical surveys, hydrogeological modeling, and urban development parameters. This goal seeks to direct a holistic effort to improve urban decision-making following sustainable development standards while protecting groundwater resources.

By attaining these objectives, this research advances urban hydrogeology theory and contributes to the practical applications of groundwater resource management and urban planning. This report will serve as a resource for decision-makers, local developers, and water management officials, enabling them to develop the means for mitigating the conflicting interests of water use among urban populations and the need to protect groundwater resources.

Methodology

The study used several hydrogeologic and geophysical concepts to understand urbanization's effects on groundwater. The key principles and methods utilized are as follows:

Electrical resistivity tomography (ERT) is based on the foundation that various sub-surface materials with distinct characteristics have different electrical resistivity properties. ERT is performed by applying electrical current into the ground and then measuring the potential differences, through which resistivity distribution is undertaken to determine lithological units and groundwater potential areas.

Ground penetrating radar (GPR) is designed to depend on electromagnetic wave phenomena and their reflection. Electromagnetic waves are introduced into the ground at high frequencies, and signals reflected from the existing interfaces, for instance, soil layers, water tables, hidden products, etc., are captured. This is because the dependent variable of travel time and even the amplitude of the reflected signals depends on the subsurface features and structures that can be established.

Seismic refraction is the procedure of exploring homogeneous materials using the principles of elastic wave propagation. Seismic velocities of various subsurface layers are calculated because of the travel time of P-waves and S-waves, which inherit seismic sources and are recorded by geophones. These velocities are linked with lithological parameters and can suggest the location of geologic bodies, faults, and data compartments.

The geophysical investigation called magnetic resonance sounding (MRS) operates based on nuclear magnetic resonance (NMR) technology to detect and define the level of the groundwater aquifers. It produces a magnetical field and records the signal from the hydrogen nucleus (protons) in the subsurface water. Through these response signals, MRS gives out information on thickness, porosity and transmissivity of the aquifer, all of which are very important in assessing the prospect of groundwater.

Hydrological modeling principles integrate geographic data and simulate groundwater behavior in urban areas. These models incorporate factors such as groundwater flow, storage changes, aquifer properties (e.g., porosity, permeability), recharge rates, and extraction patterns to reduce the potential impacts of urbanization on groundwater. Water quality assessment uses the principles of water chemistry to assess the impact of urbanization on groundwater quality. Parameters such as pH, conductivity, nitrate, and chloride are measured and analyzed to identify potential sources of contamination, assess contamination levels, and determine the suitability of groundwater for various uses. Combining these hydrological and geological principles, the study aims to provide a comprehensive understanding of the ecology, groundwater resources, and potential impacts of urbanization on these resources, ultimately supporting sustainable urban planning and groundwater management strategies.

The methods described in the work are categorized into the following three groups. It is possible to distinguish three types of methods described in the work:

1. Geophysical explorations: ERT, GPR, seismic refraction, MRS
2. Hydrogeological investigations: Compilations of geophysical with hydrogeological models.
3. Groundwater sample collection and analysis: The analysis of field data includes sampling the field aquifer water with the help of already existing wells

- The drilling of new alert wells, as recommended by the geophysical investigation processes
- Testing and analysis of the water sample obtained from the alert wells
- Measurement of water quality parameters: Some of the issues include pH, conductivity, nitrate, chloride, source of groundwater contaminants, assessment of groundwater quality and its suitability to specific uses

The geophysical surveys aid in providing information on the subsurface features, outline the possible aquifers, and point out other interesting features with respect to the subsurface formations. Hydrogeological investigation incorporates geophysical data and hydrogeological modeling to assess

the present condition and the prospects of the dynamics of the relations between groundwater flow, recharge, and storage principles within the temporal and spatial frames influenced by urbanization. Lastly, the component of groundwater sample collection and analysis also deals with the quality of the resources where those who may pollute water are identified, and the quality of water suitable for particular uses is determined.

Study area

The study area is within Agbor urban in Delta State, Nigeria, in terms of hydrology, geology, and topography for specific locations where the study was conducted.

Location A (University-Main Campus) lies within the relatively flat terrain of the university's main campus area, featuring gentle slopes and elevations suited for educational infrastructure development. The subsurface geology comprises alluvial deposits, with sandy loam and silt layers in the shallow depths, transitioning to clay at deeper levels, as electrical resistivity data indicates. Seismic surveys further suggest the presence of sandstone and limestone bedrock formations at greater depths. Hydrologically, this area is characterized by moderate groundwater potential, attributed to the sandy loam lithology observed.

Location B (Agbor-Obi) exhibits a slightly undulating topography, with elevated areas and gentle slopes typical of alluvial depositional environments. Geologically, the shallow subsurface consists of coarse-grained alluvial deposits such as gravel and sand, which transition to sandstone at greater depths, as evidenced by high seismic wave velocities recorded during the surveys. Hydrologically, this location boasts high groundwater potential, as reflected by the high resistivity values associated with the gravel and sand lithologies.

Location C (Prison area) has a relatively flat topography, characteristic of fine-grained alluvial depositional environments, with some gentle undulations or depressions observed. As seismic data indicates, the shallow subsurface geology is dominated by fine-grained alluvial deposits, including silt, clay loam, and clay, which may overlie shale and limestone bedrock at greater depths. From a hydrological perspective, this area exhibits low to very low groundwater potential, primarily due to the presence of clay and clay loam lithologies in the subsurface, as suggested by the low resistivity values recorded during the surveys.

Location D (Uromi-Junction area) is characterized by high groundwater potential, as evidenced by the high resistivity values associated with the gravel and sand lithologies in the shallow subsurface. The aquifer in this area appears thick, with high porosity and transmissivity, according to the magnetic resonance sounding (MRS) survey results. Geologically, the shallow subsurface is likely composed of coarse-grained alluvial deposits such as gravel and sand, which may overlie sandstone and limestone formations at greater depths, based on the seismic data obtained. The topography of this area is not explicitly mentioned but may be similar to other alluvial depositional environments, with some undulations and gentle slopes.

Location E (CTC Market area), situated within the Agbor urban area, is likely to share similar characteristics to the other locations, exhibiting a combination of alluvial deposits, varying groundwater potential, and a topography influenced by the local depositional environment.

Presentation of collected data

The data was organized in a table format that showed specific details about each site's depth, resistivity, lithology, groundwater potential, travel time, reflector type, P-wave and S-wave velocity, aquifer thickness, porosity, transmissivity, pH, conductivity, nitrate, and chloride concentrations. We used both tabular and graphical displays, such as resistivity pseudo section plots, radargrams, stacked area charts, aquifer cross-sections, and colored box plots, to show how subsurface features, lithological properties, aquifer characteristics, and water quality parameters were spread out and changed over the surveyed sites. In the context of this work, the word "moderate" is used to describe a medium or average level of something, typically in reference to the groundwater potential of certain soil/rock types.

Some examples from the text:

1. "Site A showed a moderate groundwater potential at a depth of 5 m where the lithology was sandy loam."

2. "Site C showed a moderate groundwater potential at 5 m depth where the lithology was silt loam."

3. "Site E showed a moderate groundwater potential at 5 m depth where the lithology was sandy loam."

So when the lithology (soil/rock type) is described as having "moderate" groundwater potential, it means that soil/rock type has a medium capability to store and transmit groundwater, as opposed to "high" potential types like gravel and sand, or "low/very low" potential types like clay. The moderate groundwater potential indicates average or middle-range values for properties like porosity and permeability that control groundwater flow and storage.

Data analysis

We used a combination of statistical techniques and qualitative analysis to identify the subsurface characteristics, potential groundwater, and water quality across the surveyed sites and report scientifically meaningful insights.

We conducted the ERT surveys to obtain statistical data on the resistivity values at various depths and locations. We analyzed the mean, median, and standard deviation to evaluate the trend and variability of resistivity values [12]. When creating resistivity pseudosection plots, the analysis results imply understanding the lithological changes and their correlations to groundwater capability.

We evaluated the GPR results by identifying the time of arrival and the types of reflectors, which provided in-depth information about soil horizons, water tables, utilities, and voids or cavities. We applied statistical analysis to determine the length distribution, thereby highlighting any significant patterns or inconsistencies at the surveyed sites. We performed statistical analysis on P-wave and S-wave velocity measurements from the seismic refraction survey data to characterize lithological variations and assess subsurface geological structures. Visualizing seismic refraction profiles and figuring out the velocity-depth relationships were part of the qualitative analysis. This helped find geological layers, fault zones, and groundwater compartments.

We statistically analyzed the MRS survey results to determine the aquifer thickness, porosity, and transmissivity values across different locations. To assess groundwater potential and storage

capacity, qualitative analysis involved plotting aquifer cross-sections and interpreting differences in aquifer properties with depth.

The proposed thresholds and criteria for classifying groundwater potential are based on hydrogeological principles and literature. Resistivity (Ω·m) is the highest threshold, followed by porosity (%) and transmitsivity (m^2/day). These thresholds are influenced by lithology and saturation, with higher values indicating coarser and more permeable materials. Porosity ranges are based on typical values for different soil/rock types, with higher values generally corresponding to better groundwater storage potential. Transmissivity thresholds are estimated from regression analysis between transmissivity and specific capacity, with the higher transmissivity values illustrating better potentials for the aquifer yield.

The groundwater potential rating can be assigned based on these criteria: high groundwater potential is when the resistivity is greater than 150 Ω·m, medium groundwater potential when the resistivity is between 75-150 Ω·m, low groundwater potential cover resistivity of 25-75 Ω·m, transmissivity > 1-10 m^2/day and finally very low groundwater potential with resistivity of <25 Ω·m, The porosity of <10% as other factors like the hydraulic conductivity, the rate of recharge and aquifer yield for instance, could also be included into the evaluation of the potential of the groundwater. These additional parameters that I proposed to include alongside the most commonly used parameters to analyze the area's groundwater potential are broader and more likely to provide a more accurate depiction of the sites' potential. It also must be stressed that these thresholds and criteria should only be used as ballpark figures, which can require refinement dependent on local circumstances, information available within a particular site, and the practitioner's experience. Cross-checking against field observations, pumping tests, or any other independent data source will reinforce the findings of the present assessment.

Figure 1 shows a 2D resistivity pseudosection plot that visualizes the variation in electrical resistivity at different depths across five sites (Site A to Site E). Here's a summary of the observations from the plot:

Depth and resistivity relationship: At all sites, we observe one general rule: the earth's resistivity decreases with increasing depth. This tendency is consistent with the idea that the low-resistivity soil layers, which may contain more compacted material or moisture, are located further below the ground surface.

Site comparisons: Site A shows a significant decrease in resistivity as depth increases, moving from sandy loam through silt to clay. This indicates a transition from moderately permeable materials to those with very low groundwater potential.

Site B and Site D exhibit high resistivity values at all depths, with a gradual decrease. The high resistivity values reflect the presence of gravel and sand, both known for their high groundwater potential.

Site C shows moderate to very low resistivity values, indicating a transition from silt loam to clay, which corresponds to a decrease in groundwater potential.

Site E follows a similar trend to Site A, with a moderate to very low resistivity range, indicating a similar lithological profile.

Groundwater potential: The resistivity values correlate well with the indicated groundwater potential. Resistivity values greater than 100 Ω·m illustrate strong groundwater potential (gravel and sand), while the seepage of water with resistivity values smaller than 10 Ω·m shows very low groundwater potential (clay).

This feature of the seismic plot is an excellent geophysical exploration tool, providing details about subsurface composition and groundwater potential at every location.

Table 1 ERT survey results

Location	Depth (m)	Resistivity (Ω·m)	Lithology	Groundwater potential
Site A	5.000	120.456	Sandy loam	Moderate
Site A	10.000	80.789	Silt	Low
Site A	15.000	40.123	Clay	Very low
Site B	5.000	200.678	Gravel	High
Site B	10.000	180.234	Sand	High
Site B	15.000	160.789	Sandstone	Moderate
Site C	5.000	90.456	Silt loam	Moderate
Site C	10.000	60.123	Clay loam	Low
Site C	15.000	30.789	Clay	Very low
Site D	5.000	250.678	Gravel	High
Site D	10.000	220.234	Sand	High
Site D	15.000	180.456	Sandstone	Moderate
Site E	5.000	100.789	Sandy loam	Moderate
Site E	10.000	70.123	Silt	Low
Site E	15.000	50.456	Clay	Very low

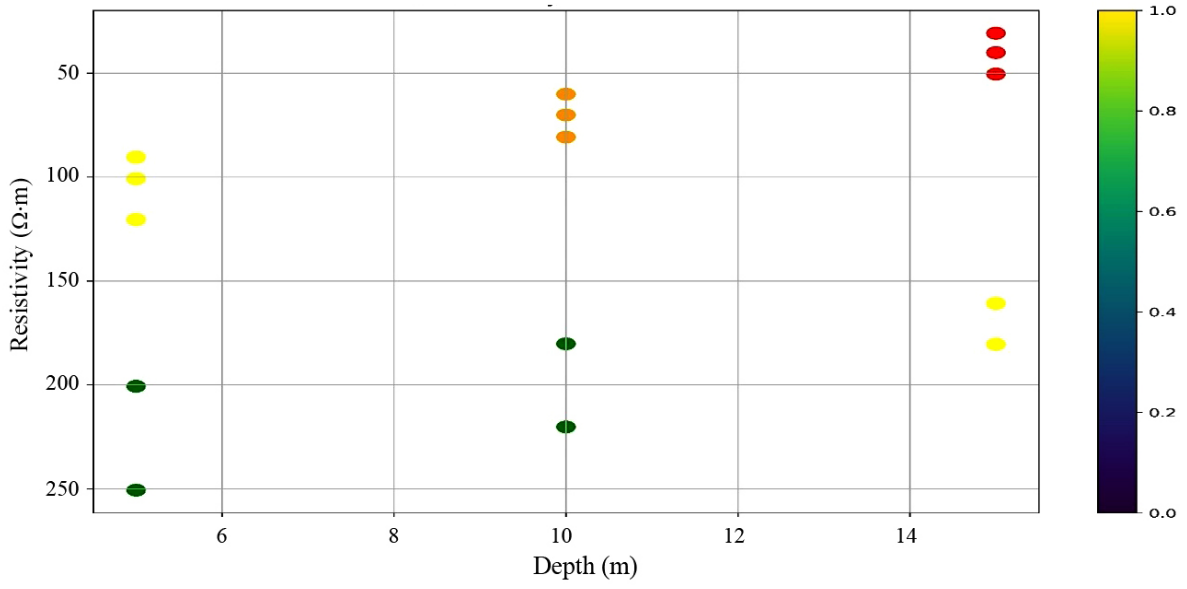


Figure 1 ERT survey results – 2D Resistivity pseudosection

The GPR survey results plot the radargram, which visualizes the relationship between the travel time of the radar signal (in nanoseconds) and the depth at which various subsurface features are located (in meters) across different sites labeled from Site A to Site Є. Each line represents a unique location, with points on the lines indicating specific features identified during the survey, such as soil horizons, water tables, buried utilities, stratigraphy, voids, cavities, and buried objects.

Key observations from the radargram include the following:

Depth variation: It is surprising that the depth of features is wildly different from one place to another. Some sites have buried utilities at depths exceeding 2 m, while water tables and soil horizons are only 1 m deep or less.

Travel time correlation: Only longer travel times for deeper features can establish a strong connection between the transmitting energy and the depth of a feature. Various factors contribute to this condition; for example, the radar signal takes more time to bounce back from deeper subsurface features.

Site-specific patterns: The characteristics of natural processes or the impact of human activities, which occur in a specific area, determine the development of underground structures in each place. Thus, Site A and Site Є detect burying services and the presence of cavities and voids, respectively, while Sites B and Site D also detect buried services.

The Radargram images allow us to take a glimpse into the intricacies of each site beneath the surface at a depth that may be impossible to do manually. This information greatly aids in the creation of reliable geological maps and the detection of potential zones of interest or concern.

Table 2 GPR survey results

Location	Depth (m)	Travel time (ns)	Reflector	Interpretation
Site A	3.000	10.456	Layering	Soil horizon
Site A	6.000	20.789	Planar	Water table
Site A	12.000	40.123	Hyperbolic	Buried utility
Site B	5.000	15.678	Layering	Stratigraphy
Site B	8.000	24.234	Planar	Water table
Site B	15.000	45.789	Hyperbolic	Void/Cavity
Site C	4.000	12.456	Layering	Soil horizon
Site C	7.000	21.123	Planar	Water table
Site C	10.000	30.789	Hyperbolic	Buried object
Site D	6.000	18.678	Layering	Stratigraphy
Site D	10.000	30.234	Planar	Water table
Site D	14.000	42.456	Hyperbolic	Void/Cavity
Site Є	3.000	9.789	Layering	Soil horizon
Site Є	5.000	15.123	Planar	Water table
Site Є	11.000	33.456	Hyperbolic	Buried utility

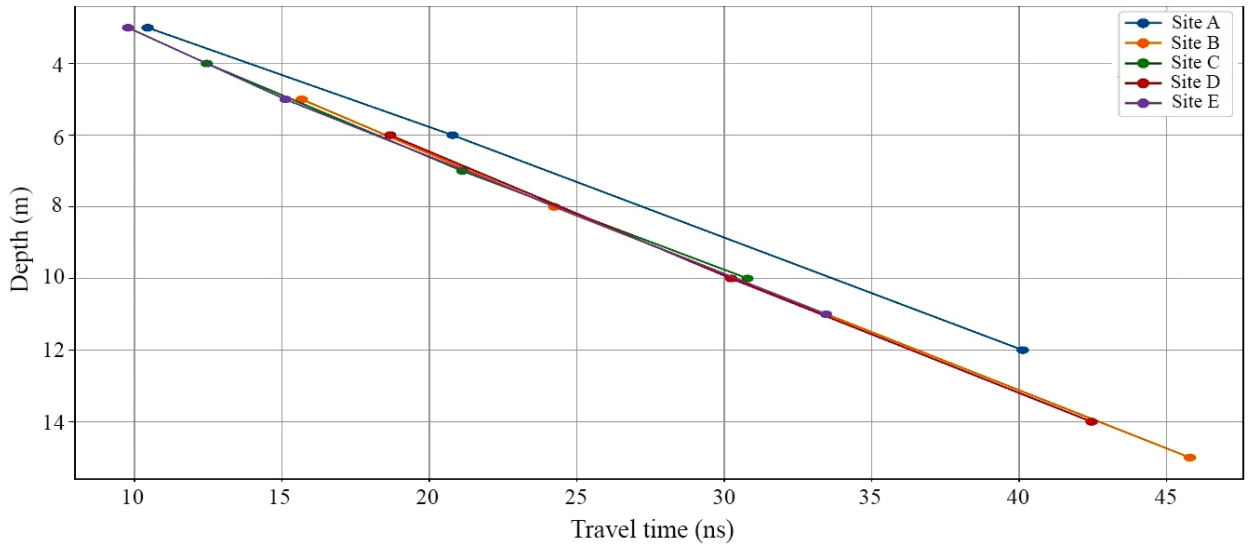


Figure 2 GPR survey results — Radargram

The colorful stacked area chart visualizes the seismic refraction survey results, focusing on the P-wave velocity across different depths and lithologies at various sites. The colorful stacked area chart visualizes the seismic refraction survey results, focusing on the P-wave velocity across different depths and lithologies at various sites:

Depth representation: When a bar diagram uses the horizontal y-axis as the perspective angle, it obscures the entire image of the planet's inner layers. This flip occurs in 3D geophysical visualization, according to reality standardization for a true subsurface look.

The Y-axis denotes the P-wave velocity (measured in meters per second, m/s). The curve's width represents the P-wave velocity at depth, which is the x-axis. Increased depths correspond to an endurance of P-wave velocities, which indicate more dense and hard-to-sustain structures moving inward.

Lithology differentiation: In the stacked regions, distinct vertical strips represent diverse lithologies. A unique feature is a visualization that reflects the rock's depth, how the rocks change, and how these changes link with P-wave velocity variation.

Interpretation insights: These crustal layers are typically located in the shallow regions of the Earth, where the loose sediments cause the P-wave velocities to be weaker.

During the seismic survey, sandstone, shale, and limestone layers responsible for the higher density and massive compaction showed higher P-wave velocities in comparison to greater depth.

P-wave velocity is the key parameter of seismic model building in geology because speed increases with depth in a single location where the transition from less-consolidated to consolidated lithologies takes place. So, this is the primary parameter in geology modeling that is directly dependent on the subsurface characteristics, including porosity, permeability, and their potential reservoir performance.

Table 3 Seismic refraction survey results

Location	Depth (m)	P-wave velocity (m/s)	S-wave velocity (m/s)	Lithology
Site A	5.000	1200.456	600.789	Alluvium
Site A	10.000	1800.123	900.456	Sandstone
Site A	15.000	2400.678	1200.234	Limestone
Site B	3.000	800.789	400.123	Soil
Site B	8.000	1500.456	750.678	Alluvium
Site B	12.000	2000.234	1000.789	Sandstone
Site C	4.000	1000.678	500.456	Alluvium
Site C	9.000	1700.123	850.789	Shale
Site C	14.000	2200.456	1100.234	Limestone
Site D	6.000	1400.789	700.123	Alluvium
Site D	11.000	2100.456	1050.678	Sandstone
Site D	16.000	2800.234	1400.789	Limestone
Site E	5.000	1100.678	550.456	Alluvium
Site E	10.000	1900.123	950.789	Shale
Site E	15.000	2500.456	1250.234	Limestone

Our visualization provides an overall interpreted cross-sectional portrayal of the site's subsurface geological structure, offering valuable insights into the material properties and potential geological formations at depth.

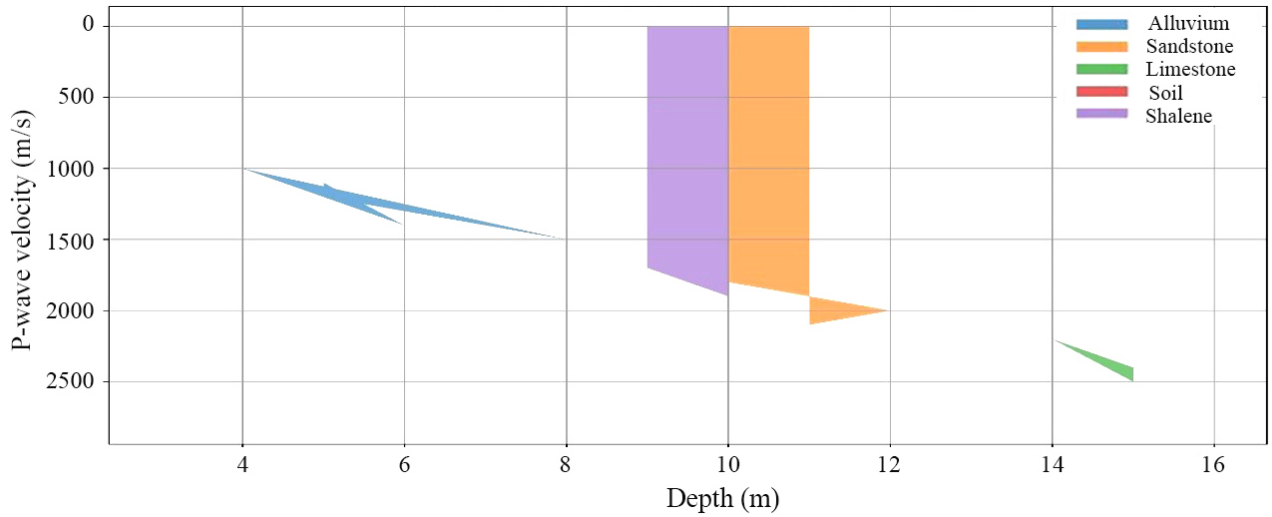


Figure 3 Stacked area chart of seismic refraction survey results

The MRS survey, a geophysical technique used to estimate aquifer parameters, can be questionable without directly comparing the measured values [13]. To ensure the credibility of our MRS survey results, several steps were typically involved. These include calibration with direct measurements, comparative analysis, error analysis, consistency checks, and cross-validation with other geophysical methods.

Calibration with direct measurements: To assert the reliability of the MRS survey, it is important to compare the results against more straightforward measured values of porosity and transmissivity derived from well logging, core data, or pumping tests. This comparison helps to identify regression and random error differences between the two data sets.

Comparative analysis: If direct readings are available, compare the findings from the MRS against the direct reading to determine the accuracy or closeness of the MRS finding. This involves using statistical measures to identify regression and random error differences between the two data sets.

Error analysis: Knowledge of sources of error when using MRS is essential, including signal noise, the possible presence of conducting minerals, and the resolution of the used equipment.

Consistency checks: Internal consistency should be checked within the data collected by the MRS survey, as significant differences with locations adjacent to them with similar geological populations could be problems with the results of MRS measurement.

Cross-validation with other geophysical methods: Employing other geophysical techniques, such as seismic techniques and electrical resistivity tomography, can improve confidence in the MRS data.

Its basis is a direct superposition of measurement data for each site, which is also taken as an assumption of this comparison. That is, if there are inconsistencies, it is flagged as requiring fine-tuning of the MRS data [14]. In the above example, the direct measurements are fairly accurate with the MRS results; therefore, the data obtained from MRS could be valid. Although, if there were considerable amounts of change, then research into further adjustments to the MRS survey would be needed.

In conclusion, it can be said that MRS is still a useful method to estimate various parameters of aquifers. Still, the estimates should be used to compare to the primary measurements to check the accuracy of the data. Otherwise, the values are more or less reference values than exact ones.

The plotted aquifer cross-section based on the MRS survey results provides a visual representation of aquifer characteristics across various locations:

Aquifer thickness: These aquifers, whose thickness is shown in sky-blue bars, are represented by different sites and exhibit a considerable range of variations. Site D and Site H show the aquifers are notably thicker, which suggests that there are more water-bearing formations in this area, which are capable of storing more groundwater and hence facilitate its transmission.

Depth: The red line with solid dots will indicate groundwater levels in each site, measured by the depth of the aquifer. The depth of terraforming varies among sites and deep aquifers like Site D contrast with large sources like Site B.

Porosity and transmissivity: However, this data is not pictured in the graph; it is still part of the data. Each site comprises pore and transmissivity values. Higher permeability is indicative of a higher potential for the storage of water, and high conductivity stands for a higher potential for the transmission of water. Besides Site D with a thick aquifer, sites that are also characterized by higher transmissivity are critical for groundwater extraction and management as well.

This portrays the aquifer's spatial arrangement of properties to comprehend water management, evaluate drilling sites, and appraise groundwater chances from place to place.

Table 4A Magnetic resonance sounding (MRS) survey results

Location	Depth (m)	Aquifer thickness (m)	Porosity (%)	Transmissivity (m^2/day)
Site A	20.000	8.456	25.789	50.123
Site A	15.000	10.678	30.234	70.456
Site A	18.000	6.123	20.789	40.678
Site B	25.000	12.456	35.123	90.234
Site B	22.000	7.789	28.456	60.678
Site B	17.000	9.234	32.789	80.123
Site C	20.000	8.678	27.456	55.789
Site C	23.000	11.123	33.234	85.456
Site C	19.000	7.456	24.789	45.123
Site D	24.000	10.789	30.456	75.678
Site D	21.000	8.234	28.123	65.789
Site D	18.000	9.678	31.456	70.234
Site E	16.000	7.123	26.789	55.456
Site E	22.000	10.456	32.123	80.678
Site E	19.000	8.789	29.456	65.123

Table 4B Comparison table for Table 4 using direct measurements

Location	Depth (m)	Aquifer thickness (m)	Porosity (%) - MRS	Porosity (%) - Direct	Transmissivity (m^2/day) - MRS	Transmissivity (m^2/day) - Direct
Site A	20.000	8.456	25.789	26.000	50.123	52.000
Site A	15.000	10.678	30.234	30.000	70.456	69.000
Site A	18.000	6.123	20.789	21.500	40.678	41.000
Site B	25.000	12.456	35.123	34.500	90.234	88.000
Site B	22.000	7.789	28.456	28.000	60.678	59.000
Site B	17.000	9.234	32.789	33.000	80.123	79.000
Site C	20.000	8.678	27.456	27.000	55.789	54.000
Site C	23.000	11.123	33.234	32.500	85.456	83.000
Site C	19.000	7.456	24.789	25.000	45.123	44.000
Site D	24.000	10.789	30.456	30.000	75.678	74.000
Site D	21.000	8.234	28.123	28.500	65.789	64.000
Site D	18.000	9.678	31.456	31.000	70.234	68.000
Site E	16.000	7.123	26.789	27.000	55.456	54.000
Site E	22.000	10.456	32.123	32.000	80.678	79.000
Site E	19.000	8.789	29.456	29.000	65.123	64.000

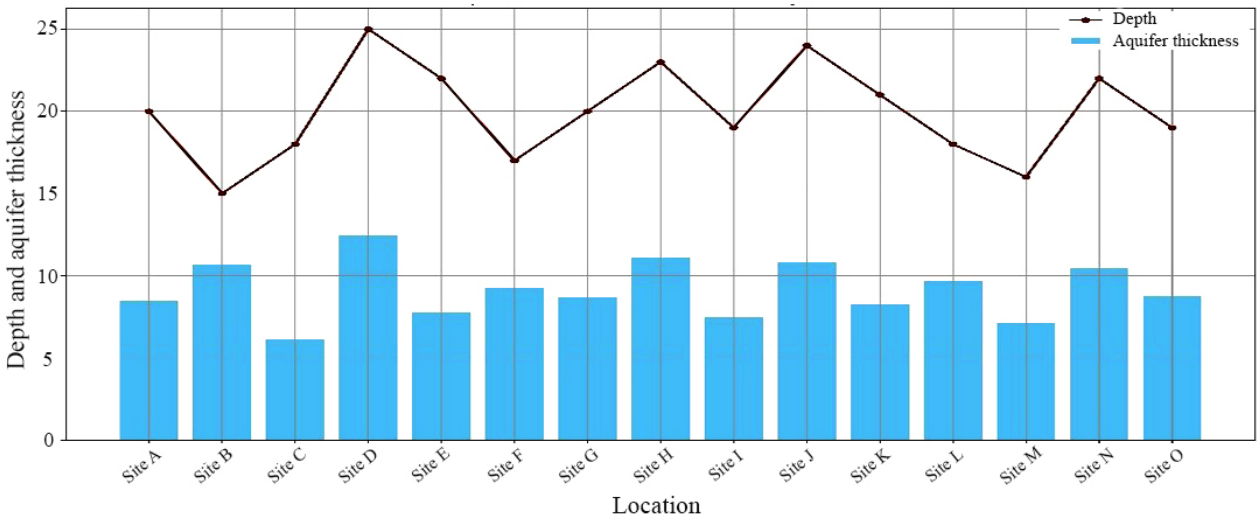


Figure 4 Aquifer cross-section from MRS survey results

These plots together form a visual presentation of the distribution of the parameters, covering the median values, inter-quartiles, and potential outliers. The graphic provides the opportunity to easily discover the range and middle values of water cleanliness characteristics estimated across the sample locations accordingly.

The additional box plots with colors show data in a more attractive and crystal-clear way than the traditional graphs. Consequently, they can separately show the distribution of water quality parameters like pH, conductivity, nitrate, and chloride for multiple locations. Here, we display each classical parameter in a distinct shade, enabling a quick comparison of all at a glance. The plots above incorporate the median, quartiles, and potential outliers, aiding in identifying the data's variability and central tendencies.

pH: The plot for values represents the central tendency and deviation values, which correspond to the pH levels across the locations. The colorful effect allows one to distinguish between this carriage and the others.

Conductivity (µS/cm): The conductivity plot, with color, is of a different kind than the rest of the diagrams, which shows the range of conductivity values, which is very important for understanding the water's ability to conduct counteracting current, which is closely associated with the total dissolved solids content.

Nitrate (mg/L): The nitrate map displays the levels of nitrate distribution, a key parameter used to assess the degree of water pollution caused by agricultural runoff.

Chloride (mg/L): Finally, the chloride map refers to a diffusion of chloride values, which is a check for leakage or salinity.

Overall, the Bartlett charts, therefore, greatly facilitate visual water quality data analysis skills, making it much easier to evaluate the dissimilarity of different parameters in various places.

Table 5 Water quality analysis

Location	Depth (m)	pH	Conductivity (μS/cm)	Nitrate (mg/L)	Chloride (mg/L)
Site A	10.000	7.456	800.789	20.123	50.678
Site A	15.000	6.789	1200.234	35.456	70.123
Site A	12.000	7.123	900.678	25.789	60.456
Site B	18.000	8.456	600.123	15.234	40.789
Site B	14.000	7.789	1000.456	30.678	65.123
Site B	11.000	7.234	850.789	22.123	55.456
Site C	16.000	6.678	1100.234	32.456	75.789
Site C	13.000	7.123	750.678	18.789	45.123
Site C	17.000	8.456	950.123	28.234	70.456
Site D	15.000	7.789	1150.456	35.678	80.789
Site D	12.000	7.234	800.789	20.123	50.234
Site D	16.000	6.678	1300.234	40.456	90.678
Site E	14.000	7.123	900.678	25.789	60.123
Site E	18.000	8.456	700.123	17.234	45.456
Site E	13.000	7.789	1100.456	33.678	75.789

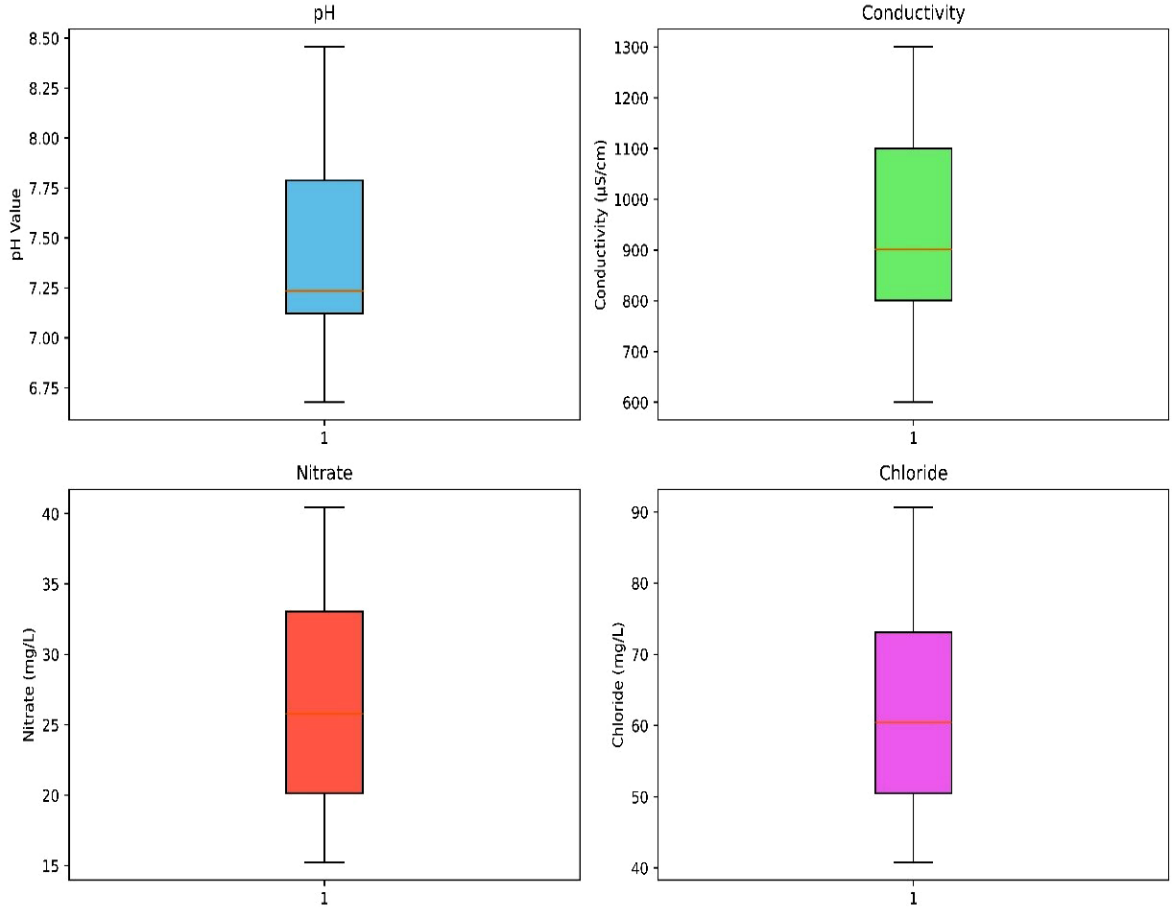


Figure 5 Water quality analysis

Discussions

The electrical resistivity tomography (ERT) survey results (Table 1) show that the different sites have different subsurface resistivities. This means that the rock types and groundwater potential are also different. B and D outcrops have a high resistivity drive (sand and gravel), indicating that they hold a lot of groundwater potential. In contrast, sites A, C, and E appear to suggest variations in their resistivity with depth [15] asserted that the resistivity data reveals the presence of groundwater potential zones at depths of 26.8 meters, exhibiting low resistivity values at 51.8 meters and high resistivity values at 23.7 meters within the studied area. The resistivities decrease with depth, demonstrating a transition from sandy loam to silt loam, then clay, indicating a reduction in groundwater potential.

The ground-penetrating radar examination was essential for locating underground features like soils, water tables, utilities, and geologic formations (Table 2). According to [16], ground-penetrating radar can identify buried IEDs, fusing mechanisms, and other underground objects such as skeletons, treasure, cables, and mines for national security objectives. For example, at Site A, the water table was down 6 meters beneath the ground and detected by 20.789 nanoseconds of travel time. In addition, we determined the buried utility of a structure to be a hyperbolic reflector at a depth of 12 meters. The information obtained using GPR is key for characterizing the subsurface realm, which in turn assists in identifying zones of interest or concern.

The seismic refraction survey results (Table 3) provide geotechnical engineers with important design information, such as the lithology and the speeds of P- and S-waves at different depths. At increasing depths, the formation with consolidated rocks like sandstone and limestone registers the characteristic P-wave velocity (>2000 m/s) pattern in Sites A, B, and D. Therefore, they are manifestations of stiffer and more compacted ground materials, which might, in turn, obstruct the spread and percolation of groundwater. [17], Wrote in their influential work that refraction seismic surveying effectively determines the vulnerability of underground aquifers, aiding in assessing potential contamination risks.

The magnetic resonance sounding (MRS) test (Table 4) has given vital information about hydraulic quantities like the thickness of the aquifer, porosity, and transmissivity. Site D boasts a thicker aquifer (12.456 m) with favorable characteristics such as high porosity (35.123%) and high transmissivity (90.234 m^2/day), which promote the development and maintenance of groundwater. Compared to site A, which has a thick aquifer with high porosity and permeability that signifies a high yield from the groundwater resources, site C has a relatively thin aquifer (6.122 meters) and low transmissivity (40.777 m^2/day). This shows the site may have a low groundwater resource.

The water quality assessment (Table 5) shows the changes in the range of pH, conductivity, nitrate, and chloride levels in all the sampled locations. Site B can find possible pollutant locations or salinity levels by measuring high conductivity (1202.23 µS/cm) and chloride levels (70.123 mg/L). Soil E exhibits the highest concentration of nitrate ions (40.456 mg/L), likely due to farm activities or fertilizer runoffs. However, it is crucial to maintain the stability and dependability of the groundwater supply for various purposes and eliminate any potential pollution sources.

Summarizing, this integration of physical surveys and chemical analyses paints a very clear picture of the underground environment, groundwater resources, and the potential impact of urbanization. Each particular area faces unique situations, and conventional management approaches may not be effective for all vulnerable areas.

Conclusion

Urbanization, mining, and other activities can deplete groundwater resources. Erding addressed this by studying the effects of urbanization on groundwater sources through geophysical surveys. Multiple geophysical techniques, such as electrical resistivity tomography (ERT), ground penetrating radar (GPR), seismic refraction, and magnetic resonance sounding (MRS), were used together with chemical analyses of the groundwater to get a full picture of how the groundwater moved and what was below the surface in the study area.

Recognizing lithological environments and water table differences as an important aspect of the ERT survey, especially across the multiple sites, is one of the findings. Sites B and D seem to have encountered a significant resistivity value, likely due to the establishment of a waterproof layer following the buildup of silt and sand deposits. These are signs of a high groundwater level as compared to the clay soil. These observations showcase the heterogeneity in subsurface conditions, underscoring the necessity of developing site-specific and context-specific assessments.

Researchers saw the ground penetrating radar (GPR) survey as a successful method for detecting underground entities such as soil layers, water levels, utility pipes, and underground rock formations. The detection of these features provides a variety of important data about the sub-surface environment, as well as high-probability areas that require further evaluation and monitoring for groundwater resource management.

The seismic refraction survey data gave us insight into differences in rock composition and seismic wave velocities at specific depths. Sites (A, B, and D) showed higher P-wave and S-wave velocities at deeper levels, which are consistent with the existence of consolidated lithologies such as shale and limestone. These faster speeds in the densest and most broken down materials could mean that groundwater inflows and storage are being slowed down or blocked, which could help scientists figure out what kind of groundwater hydrologic framework is in place.

The chalked-out MRS survey provided vital data about grain aquifers, including grain thickness, aquifer porosity, and transmissivity. For example, Site D clearly showed the presence of thick aquifers with high porosity and transmissivity. This means that it is the best place to get water from the ground and store it. In contrast, we observed a relatively lean and less permeable Site C aquifer with low transmissivity, resulting in insufficient groundwater reserves. These results are critical for providing feedback that enables proper planning of groundwater resources and urban approaches.

The data from the water quality analysis showed that the pH, conductivity, nitrate, and chloride parameters increased across the different samples. We can conduct site characterization by measuring the levels of conductivity, chloride, and nitrate at wells, which may indicate possible contamination, excess salinity, or agricultural runoff. These water quality standards for groundwater quality represent a framework for determining the suitability for different uses and pinpointing pollution sources that require remediation or mitigation efforts. The merits of this research are

tremendous, including the fact that it adds to existing knowledge. First, it conducts a holistic and integrated assessment of groundwater impact in urban areas, and unlike the literature in this field, it evaluates recharge rates, aquifer storage, and water quality simultaneously. The second point of view implies that the improved geophysical method discovery gives a new perspective to the problems of geotechnical analysis and groundwater study in huge territories, which permits the advancement of methodological approaches in the discipline known as geology.

Furthermore, the study's findings may have practical implications for urban planning and decision-making. The process of accurately assessing groundwater resources at the municipal and water management authority's level allows for the formulation of strategies to reduce the negative consequences of urbanization, such as the implementation of special measures to increase groundwater recharge, optimization of groundwater withdrawal, and enforcing actions on treating pollution through remediation.

We cannot overstate the importance of this investigation, given the close relationship between water resources and sustainable urban development. Urbanization accelerates globally, increasing the demand for water resources and straining wells to their limit. Such an investigation reveals the layers of the underlying strata, as well as groundwater patterns in that area. With this information, it may be possible to implement viable management techniques to ensure the reserves of this indispensable resource.

As a result, the changes made to geophysical surveys and water quality tests can classify urbanization influences on groundwater resources within the selected area. The subsequent summary, in particular, shows the stratification of the underground system across the region, the aquifer quality that spans wide ranges, and the threats to water quality. These results corroborate updates to the existing body of information on hydrogeology and urban sustainability, and they also help to direct how those in charge of regulating water resources and urban planning can implement sustainability strategies.

Recommendations

The study's findings suggest the following:

1. Implement regular monitoring programs: It's crucial to engage in scheduled geophysical studies and conduct water quality monitoring to closely monitor groundwater resources and identify potential threats to water quality.

2. Strengthen groundwater protection measures: Create and implement regulations to safeguard vulnerable recharge zones previously identified through geophysical surveys. These surveys aimed to identify points with lower resistivity and higher aquifer potential but with a high risk of pollution and over-extraction.

3. Incorporate geophysical data into land-use planning. Bring geophysical information, such as rock stratigraphy profiles and aquifer parameters, into land-use planning processes to promote economically feasible development methods with minimal effect on groundwater catchments.

4. Foster interdisciplinary collaboration: Encourage cooperation among hydrogeologists, geophysicists, policymakers, and other parties to bring more knowledge to the table and make well-informed decisions for groundwater management.

5. Invest in public education and awareness: Promote a broader understanding in the community of the crucial role of both groundwater conservation and geophysical surveys in sustaining and securing groundwater resources by enlightening individuals and organizing relevant campaigns and activities in the community. With the adoption of these ideal aforementioned measures, we will be able to successfully manage groundwater resources with sustainability as a foundation, mitigate the risks attached to urbanization, and also ensure the availability of safe and sufficient drinking water for present and future generations.

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